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Hesaplamalı Tasarımda Ekolojik Zeka

Editörden

İklim değışikliğı, kaynakların tükenmesi ve çevresel bozulma gibi acil sorunlarla yüzleşirken, tasarımcıların sürdürülebilirliğı, dayanıklılığı ve yenilenmeyi teşvik etmedeki rolü giderek daha hayati hale geliyor. JCoDe'nin on ikinci sayısı, geleneksel tasarımdan ekolojik refahı da ön planda tutan daha kapsayıcı, biyomerkezli bir yaklaşıma doğru bir paradigma değışimini teşvik ederek, hesaplamalı tasarım ile ekolojik düşüncenin ortaklığını keşfetmeyi amaçlamaktadır. Son yıllarda hesaplamalı tasarımda verimlilik, optimizasyon ve form oluşturma çalışmaları yoğunlaşırken bu tema, tartışma kapsamının, çevresel farkındalık, uyarlanabilir süreçler ve sistem düşüncesini tasarım metodolojilerine entegre eden "ekolojik zekayı" içerecek şekilde genişletilmesini savunmaktadır. Bu değışim doğal bir olasılıklar alanının önünü açmakta ve tasarımcılara, çalışmalarının çevrenin refahına aktif olarak katkıda bulunduğu ve hesaplamalı tasarımın potansiyellerinden yararlandığı bir gelecek yaratma konusunda ilham vermektedir.

Bu temanın merkezinde, ekosistemleri etkin bir şekilde onarmak, yenilemek ve canlandırmak için sürdürülebilirliğin ötesine geçen, yenileyici tasarıma bağlılık yer almaktadır. Mevcut tema, hesaplamalı tasarım metodolojilerini biyomimikri, permakültür ilkeleri, malzeme ve üretim teknikleri ve döngüsel ekonomi çerçeveleri gibi yenileyici uygulamalarla birleştirmeyi amaçlamaktadır. Tema ayrıca, yalnızca kaynak kullanımını optimize etmek için bir araç olarak değil, aynı zamanda daha entegre bir ekolojik tasarım anlayışı için bir katalizör olarak yapay zekanın sürdürülebilir mimaride gelişen rolünü de ele almaktadır. Tasarımcılar, yapay zekanın öngörülü becerilerinden yararlanarak farklı ölçeklerdeki çevresel değışiklikleri tahmin edebilir, yerleşik enerjiyi azaltabilir ve ekolojik döngülerle uyumlu yenileyici sonuçları modelleyebilir.

Bu bağlamda, JCoDe'nin on ikinci sayısı hesaplamalı tasarım, malzeme mühendisliğı, çevre bilimi, sistem ekolojisi ve etik alanlarından yararlanarak, çevreyle uyumlu bütünsel bir tasarım görüşünü yansıtan katkıları teşvik etmektedir.

Zanaatkarlığın kuramsal anlamda tartışmaya açıldığı ilk bölümde, Aysel Merve BARON, çağdaş hesaplamalı tasarım kültürü içinde zanaatkarlığı sorgulamakta ve geleneksel zanaattan dijital entegrasyona doğru tarihsel evrimi sunmaktadır. Zanaatkarlığı anlamak için bilişsel bir çerçeve öneren teorik çalışma, bilgi üretim ritimlerini, problem çözme ve problem bulma arasındaki etkileşimi ve yavaş, yansıtıcı beceri gelişimini öne çıkarmaktadır. Meryem Nurefşan YABANİĞÜL, zanaatkarlığın tarihsel evrimini tartışırken, seri üretimin geleneksel zanaat değerleri üzerindeki etkisini eleştirel bir şekilde incelemekte ve el yapımı benzersizlik ile makinede üretilen verimlilik arasındaki potansiyelli gerilimi vurgulamaktadır.

İkinci bölüm, hesaplamalı üretim teknik ve yaklaşımlarının güncel örneklerine odaklanmaktadır. Mina Hazal TAŞÇI ve Sevil YAZICI, dijital teknolojilerin geleneksel duvar örme uygulamalarını nasıl değiştirdiğini mercek altına alırken, zanaatkarlar cephesinde sezgisel karar almanın hem korunmasının hem de dönüştürülmesinin altını çizmektedir. Zeynep Sena SANCAK ve Bülent Onur TURAN, yapısal performansı ve tasarım verimliliğini artırmayı amaçlayan duvar kabuğu malzeme özelliklerinin hesaplamalı tasarım süreçlerine entegrasyonunu araştırmaktadır. Makale, duvar kabuğu tasarımına yönelik tarihi ve çağdaş yaklaşımları incelemekte ve üç aşamalı özgün bir hesaplamalı tasarım çerçevesi sunmaktadır. Barış UZYILDIRIM, Ayşegül Akçay KAVAKOĞLU ve Leman Figen GÜL, geleneksel sert kalıp sınırlamalarını aşmak için dinamik beton dökümünde açılabilir kumaş kalıbının kullanımını araştırmakta, döküm süreçlerinde esnekliği artıran ayarlanabilir, yeniden kullanılabilir kalıplara izin veren kumaşla birleştirilmiş açılabilir origami tabanlı bir kalıp sistemi önermektedir. Merve AKDOĞAN, çağdaş hesaplamalı teknikler kullanılarak, antik Zeugma mozaiklerinin dijital yeniden yorumunu sunan çalışmada, kültürel koruma ve eğitim için teknoloji ve geleneksel sanatı birleştirmeyi vurgulamakta, dijital sergilerde, korumada ve etkileşimli sanatlarda geleceğe dönük uygulamalar önermektedir. .

Üçüncü ve son bölümde Can UZUN, Mars'taki Echus Chasma bölgesinin topoğrafik ve suyla ilgili özelliklerine dayalı olarak gelecekteki yerleşimler için en uygun yerleri belirlemek amacıyla bölgelendirilmesi için bir hesaplama yaklaşımı önermektedir. Gauss Karışım Modeli algoritmasını kullanan çalışma, eğim, yön ve Normalize Edilmiş Fark Su Endeksi (NDWI) verilerini analiz etmektedir. Selen ÇİÇEK vd., mimari yarışmalarda kapsamlı eleştiriler sağlamak için Vizyon-Dil Modelleri'nden (VLM'ler) yararlanan yapay zeka odaklı bir çerçeve olan ArchiJury'yi sunmaktadır. Çalışma, yapay zekanın yapılandırılmış, ölçeklenebilir ve bağlam duyarlı incelemeler sunarak geleneksel jürileri tamamlama potansiyelini göstermektedir. Özlem Gök TOKGÖZ ve Mehmet Ali ALTIN, GAN'ların yüksek kaliteli mimari planlar üretme becerisini eleştirel olarak değerlendirmektedir. Mevcut GAN çalışmalarını inceleyen çalışma, gelecekteki GAN tabanlı yöntemlerin kullanılabilirliği ve mimari uyum düzeyini artırmak için nitel, nicel ve kural tabanlı stratejileri entegre etmesi gerektiği sonucuna ulaşmaktadır..

Ecological Intelligence in Computational Design

Editorial

As we confront the urgent challenges of climate change, resource depletion, and environmental degradation, the role of designers in promoting sustainability, resilience, and regeneration in architecture and design becomes increasingly vital. The twelfth issue of JCoDe seeks to explore the intersection of computational design and ecological thinking, encouraging a paradigm shift from traditional design to a more inclusive, biocentric approach that prioritizes ecological well-being alongside human needs. In recent years, computational design has mainly focused on efficiency, optimization, and form generation. However, this theme advocates for expanding the scope to include “ecological intelligence,” which integrates environmental awareness, adaptive processes, and systems thinking into design methodologies. This shift opens up a realm of possibilities and inspires designers to create a future where their work actively contributes to the planet’s well-being, harnessing the full potential of computational design.

At the heart of this theme is a commitment to regenerative design, which goes beyond sustainability to actively restore, renew, and revitalize ecosystems. The current theme is dedicated to combining computational design methodologies with regenerative practices such as biomimicry, permaculture principles, material and production techniques, and circular economy frameworks. By leveraging computational tools, designers can simulate ecological interactions in various scales, optimize resource use, reconfigure production methods, and create proposals that actively benefit their environments. The theme also addresses the evolving role of AI in sustainable architecture, not only as a tool for optimizing resource use but also as a catalyst for a more integrated ecological design understanding. By harnessing AI’s predictive capabilities, designers can anticipate environmental changes, reduce embodied energy, and model regenerative outcomes that align with ecological cycles. In this context, the twelfth issue of JCoDe draws on insights from computational design, material engineering, environmental science, systems ecology, and ethics, encouraging contributions that reflect a holistic view of design in harmony with the environment.

In the first section, where craftsmanship is discussed theoretically, Aysel Merve BARON questions craftsmanship within the contemporary programmatic design culture and presents the scientific evolution from traditional art to digital integration. The theoretical study, which proposes a systematic framework to ensure craftsmanship, reveals the rhythms of knowledge production, the interaction between problem solving and problem finding, and the development of slow, work skills.

While discussing the general evolution of productivity, Meryem Nurefşan YABANIĞÜL critically separates the values over the traditional data of mass production and emphasizes the potential tension between handmade uniqueness and machine production efficiency.

The second section focuses on current examples of programmatic production techniques and methods. Mina Hazal TAŞÇI and Sevil YAZICI investigate the transformation of crafting and fabrication processes in architecture, specifically within masonry, highlighting transitions from fully analogue to digitally integrated methods. Zeynep Sena SANCAK and Bülent Onur TURAN address the integration of material properties into computational design processes for masonry shell structures, aiming to enhance structural performance and design efficiency. The article reviews historical and contemporary approaches to masonry shell design, emphasizing the evolution from physical modeling to computational methods. Barış UZYILDIRIM, Ayşegül Akçay KAVAKOĞLU, and Leman Figen GÜL explore the use of deployable fabric formwork for dynamic concrete casting to overcome traditional rigid mold limitations. The research employs a deployable origami-based mold system combined with fabric, allowing adjustable, reusable molds that enhance flexibility in casting processes. Merve AKDOĞAN presents a digital reinterpretation of selected ancient Zeugma mosaics from Gaziantep, Türkiye, using contemporary computational techniques. The study emphasizes combining technology and traditional art for broader cultural preservation and education, proposing future applications in digital exhibitions, conservation, and interactive arts.

In the third and last section, Can UZUN proposes a computational approach for zoning the Echus Chasma region on Mars to determine optimal locations for future settlements based on topographic and water-related characteristics. Employing the Gaussian Mixture Model algorithm, the study analyzes slope, aspect direction, and Normalized Difference Water Index (NDWI) data. Selen ÇIÇEK et al. introduce ArchiJury, an AI-driven framework leveraging Vision-Language Models (VLMs) to provide comprehensive critiques in architectural competitions. The study demonstrates AI's potential to supplement traditional juries by delivering structured, scalable, and context-sensitive reviews. Özlem Gök TOKGÖZ and Mehmet Ali ALTIN critically evaluate the capability of Generative Adversarial Networks (GANs) in generating high-quality architectural plans. Reviewing existing GAN studies, the study concludes that future GAN-based methods should integrate qualitative, quantitative, and rule-based strategies to enhance usability and architectural relevance.

A Critique of Craftsmanship in Computational Design Practices

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A Critique of Craftsmanship in Computational Design Practices

Aysel Merve Baron¹

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Since its early manifestations in ancient civilizations, craftsmanship has always been a fundamental aspect of human ingenuity. Today, the integration of digital tools and computational methods has been introducing new possibilities for the craft process. From this perspective, this study aims to explore and understand the multifaceted nature of craftsmanship in contemporary computational design practices. To do so, the study first provides an overview of craftsmanship, scrutinizing its historical roots, transformations during industrialization, and its enduring relevance in the digital era. Then, a cognitive framework is proposed to understand the process of craft, emphasizing the rhythm of knowledge production, the interplay of problem-solving and problem-finding, and the concept of slow time in skill development. Through the lens of this framework, the main characteristics of craftsmanship in computational design practices are interpreted as openness, nonlinearity, and complexity. The study also highlights the role of tool-making and interdisciplinary thinking in enhancing craftsmanship in computational design practices. Nevertheless, the study critiques computational design practices that prioritize efficiency and functionality over exploratory and reflective processes, which may undermine the potential essence of craftsmanship.

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Hesaplamalı Tasarım Pratiklerinde Zanaatkarlığın Eleştirisi

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Antik uygarlıklardaki erken tezahürlerinden bu yana, zanaatkarlık her zaman insan yaratıcılığının temel bir unsuru olmuştur. Günümüzde dijital araçlar ve hesaplamalı yöntemlerinin entegrasyonu, zanaat süreci için yeni olanaklar sunmaktadır. Bu bakış açısıyla, bu çalışma, çağdaş hesaplamalı tasarım pratiklerinde zanaatkarlığın çok yönlü doğasını keşfetmeyi ve anlamayı amaçlamaktadır. Bunun yapmak için, çalışma ilk olarak zanaatkarlığın tarihsel kökenlerini, sanayileşme sürecindeki dönüşümlerini ve dijital çağdaki kalıcı önemini inceleyerek bir genel bakış sunar. Ardından, çalışmada, zanaat sürecini anlamak için, bilgi üretiminin ritmini, problem çözme ve problem bulma arasındaki etkileşimi ve beceri gelişiminde yavaş zaman kavramını vurgulayan bilişsel bir çerçeve önerilmektedir. Bu çerçeveden yola çıkarak, hesaplamalı tasarım pratiklerindeki zanaatkarlığın ana özellikleri açıklık, doğrusallık olmama ve karmaşıklık olarak yorumlanmaktadır. Çalışma ayrıca, hesaplamalı tasarım pratiklerinde zanaatkarlığı geliştirmede araç yapımının ve disiplinler arası düşünmenin rolünü vurgulamaktadır. Bununla birlikte, çalışmada verimlilik ve işlevselliği keşfedici ve yansıtıcı süreçlerin önüne koyan hesaplamalı tasarım uygulamaları eleştirilmekte ve bu durumun zanaatkarlığın potansiyel özünü zayıflatılabileceği belirtilmektedir.

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Anahtar Kelimeler: Zanaatkarlık, Biliş, Hesaplamalı Tasarım, Üretken Sistemler, Dijital araçlar.

1. INTRODUCTION

From its early manifestations in ancient civilizations to its adaptation in the digital age, craftsmanship has been a fundamental aspect of human ingenuity. In its broadest terms, craftsmanship encompasses not only the creation of physical artifacts but also the processes of refining skills, problematization, and profound engagement with materials, tools, media, and techniques (Sennett, 2008). Today, the integration of digital tools and computational methodologies has been redefining how craftspeople approach their work, introducing new possibilities for the process of craft. It is important to understand craftsmanship in computational design practices to ensure that new technologies enhance creative processes. The recent literature mainly focuses on developing pedagogies for digital craftsmanship (Cheatle & Jackson, 2023; Song, 2022; Tyler-Wood, 2022), integrating computational methodologies with traditional craft (Devendorf et al., 2023; Melnyk, 2020; Torres et al., 2016), implementing traditional crafts in the context of digital fabrication (Hansen, 2021; Shi et al., 2019; Van Der Veen et al., 2019), and situating computational design within craftsmanship (Noel et al., 2021). Although these studies provide valuable insights into digital craftsmanship by mainly examining the contributions of computational tools and methodologies, they often do not distinguish craftsmanship from mere technical proficiency in computational design. Hence, there is a lack of understanding regarding the specific characteristics that constitute craftsmanship in computational design. Understanding these characteristics means being able to recognize whether craftsmanship lacks or exists in computational design practices. Such understanding can also advance the field by stimulating more critical and reflective computational design practices that push the boundaries of creativity.

From this perspective, the main purpose of this study is to understand the multifaceted nature of craftsmanship in computational design practices by exploring characteristics that distinguish it from technical proficiency. To do so, the study first provides an overview of craftsmanship by scrutinizing its historical roots, transformations during industrialization, and its enduring relevance in the current digital age. It then explains the process of craft by composing a cognitive framework. Along with this framework and relevant examples from the literature, the study delves into the key characteristics of craftsmanship

encountered in computational design practices. At last, the lack of craftsmanship in computational design is discussed to address the counter point of view. According to Niedderer and Townsend (2014, p. 626), contemporary craft is almost always defined through what it is not rather than what it is. Here, from another perspective, this study prefers to approach craft in computational design through how it is and how it is not.

2. HISTORICAL CONTEXT AND DEFINITION OF CRAFTSMANSHIP

Defining craftsmanship is a seemingly simple task. Yet, as Adamson (2018) asserts, it must be done in an open-ended manner by accepting its versatility and cultural logic. Only then, we can draw connections across different disciplines and craft activities without reserving or restricting them. Since prehistoric times, humanity has always been interested in crafting tools and artifacts. Throughout history, craftspeople have been shaping cultures and influencing daily life by blending artistic skill with practical utility.¹ However, the attitude towards craftspeople and their positions in society varied over time and culture. Although craftspeople remained in control of their crafts and tools until the Industrial Revolution, the introduction of mass production through new manufacturing processes and machinery reduced the reliance on traditional craftsmanship (see Greenhalgh, 1987/2010). At the time, while craftsmanship praised expertise, effort, and material, mass production was promoting practicality, disposability, and deliberate obsolescence by reducing the material into a commodity or a resource (Risatti, 2007, pp. 194-205). In this regard, mass production has flooded the world with things and impacted traditional conceptions about craft, production, value, and scale, which used to be closely tied to human labor and abilities. This situation led to the Arts and Crafts movement emphasizing the value of handmade design objects and the crafter's societal role (Greenhalgh, 1987/2010). Key figures in the Arts and Crafts movement, such as William Morris and John Ruskin, criticized the dehumanizing aspects of factory labor and the superficiality of mass-produced goods. Morris (1888/2018), in

¹ One of the earliest showcases of respect toward craftsmanship appears in the 20th Homeric hymn that celebrates the master deity of craftspeople Hephaestus for advancing human civilization from a primitive state by bringing the knowledge of crafts to humanity, ensuring a prosperous and peaceful life (Hesiod, 1914, p. 447). In Archaic Greece, craftsmanship was a deeply developed, valued, and respected field, where it was integrated into daily life, economy, social norms, culture, and politics.

particular, advocated for a return to high-quality, artisanal design, Ruskin (1853/2018) emphasized the moral and aesthetic superiority of handcrafted objects. They believed that craftsmanship should be celebrated not only for its functionality but also for its ability to reflect the values and creativity of its maker.

Here, it is important to distinguish that the major issue was not necessarily machinery or technology itself, but rather the shift to mass production methods and the way these were implemented during the industrialization. Mass produced products became uniform because of the standardized processes on production lines. The production process was broken down into simple repetitive tasks, increasing efficiency but reducing individual craftsmanship. Factory workers became machine operators, performing particular tasks within a production line, rather than acquiring a different set of skills. Now again, this does not mean that technological advancements in machinery inherently threaten traditional crafts work. The actual impact depends on the specific ways these technologies are implemented in large-scale production processes. In fact, technological developments and the "new" can nourish crafts simply depending on how they are adopted. For instance, modern craft-based movements in the twenty-first century, such as Do-It-Yourself or Maker culture, utilize advanced technologies to enhance creativity, skill, and craftsmanship, not diminish it (Kuznetsov & Paulos, 2010; Nascimento & Pólvara, 2018). These movements embrace technology and machinery, using tools like CNC machines, 3D printers, and laser cutters to create unique and personalized products. It is then possible to combine traditional craft skills with new tools, which demonstrates that technology can coexist with and even support craftsmanship. New technologies provide craftspeople with new tools, media, and ways to perform their craft (e.g., Hansen, 2021; Tamke et al., 2017); therefore, changes in technology and tools force craftspeople to rethink and re-explore their craft.

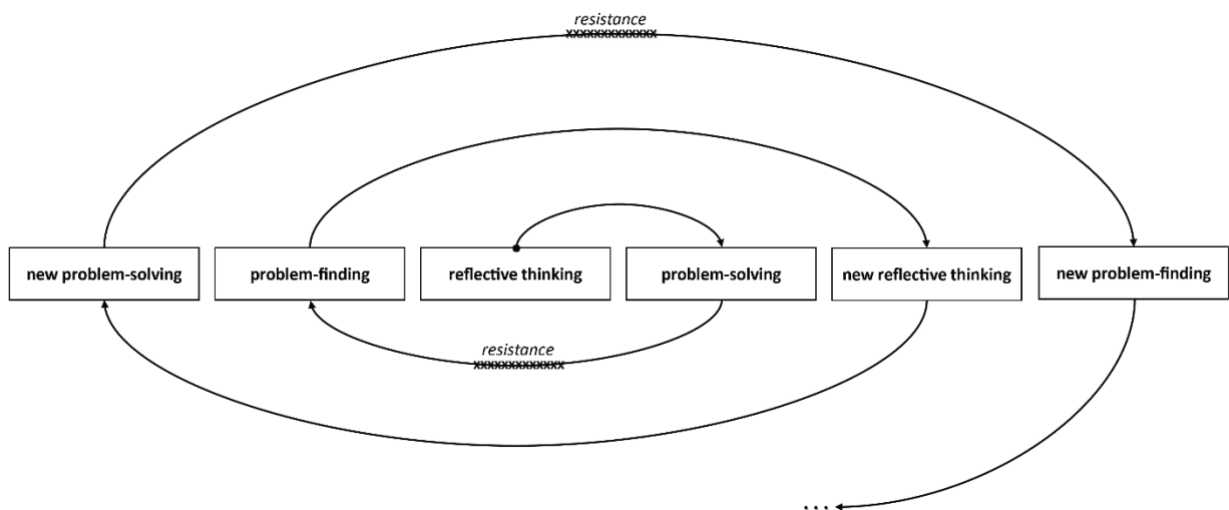
In the digital age of today, craft remains a fundamental part of human culture, evolving with technological advancements, integrating digital tools into traditional practices, adapting to societal changes, and maintaining a unique cultural identity. McCullough (1996) claims that digital technology not only offers new techniques and tools for crafting but can also become the basis of a medium – the digital medium. To

him, craft is the application of personal knowledge and habitual skilled practice by using particular materials, tools, machines, or media with the sole purpose of making increasingly well-executed artifacts (McCullough, 1996, p. 22). Taking this one step further, Sennett (2008) defines craftsmanship in an even broader sense by including artistic creation, designer activity, scientific research, and even software development. To him, craftsmanship refers to the enduring, basic human impulse to do a job well for its own sake (Sennett, 2008, p. 9). Not only do all crafts involve hand work and expertise, but they also involve an investigation into the capacities of their medium, a practice-driven passion, and moral value that transcends the final product. Hence, craftsmanship is not only about the final product but about the process itself.

3. A FRAMEWORK FOR THE PROCESS OF CRAFT

How exactly does a craftsperson develop their skills and obtain some sort of expert craft knowledge? How does a craft object become better in quality? The answer to these lies within the deep and ambiguous corridors of design cognition. The multifaceted process of craft encompasses how crafters think about, solve, and approach design problems, which also implicates practical experience. Here, the process of craft will be interpreted by associating the ideas of Richard Sennett with design cognition perspectives. According to Sennett (2008), there are three aspects that build up the quality of a creative craft practice: the rhythm of knowledge production, the relationship between

Figure 1: The craft process and skill development (developed by the author).



problem-solving and problem-finding, and the time of craftsmanship which is a slow time (Figure 1).

3.1 Rhythm of Knowledge Production

Think of a young ceramic artisan, let's call her Lola, learning the basic technique of throwing clay on a pottery wheel to create simple cylindrical forms. In the beginning, she consciously pays attention to every little movement from the pressure applied by her hands, and the speed of the wheel to the positioning of her body. She practices centering the clay while pulling it upwards and shaping it evenly. At this stage, Lola is extremely focused on each step, carefully following instructions, explicitly thinking, and making adjustments as she encounters difficulties. All these movements and actions she performs deliberately and with intense concentration are explicit knowledge. After repeated practice, centering the clay becomes second nature to Lola. She becomes adept at creating cylindrical forms without needing to think through each step explicitly. Her movements become more fluid and natural. What was explicit before, becomes tacit knowledge. Polanyi explains that such tacit knowledge "can be established only after it has been interiorized and extensively used to interpret experience" (1966, p. 21).

Lola may have mastered crafting cylindrical forms; however, she encounters a new challenge when she attempts to create bowls. Lola discovers that the techniques for throwing cylinders do not directly translate to bowls. For instance, the way she pulls the clay up to form tall, straight walls for cylinders does not work when she needs to create wider, curved shapes for bowls. She faces a dramatic resistance, as her bowls collapse or come out unevenly. At that point, there is a kind of explicit knowledge unpacking through the activity. What was formerly tacit becomes dredged into explicit consciousness because something does not work right.

3.2 Problem-Solving and Problem-Finding

Now, this is a problem Lola has to solve. Recognizing the problem, she revisits her technique. The initial tacit knowledge must be unpacked and re-evaluated. She reflects on her current knowledge repertoire and past experiences to try new design moves, make new decisions, and

take new actions. This here, is a reflective thinking² process that involves building design knowledge through exploration and experimentation. Lola experiments with the clay, applies pressure differently, uses her hands to widen the base, and gently curves the walls outward. As she engages in various interactions, different internal representations of the material get composed in her mind. Through experimentation, Lola discovers new ways to position her hands and apply pressure, transforming her skill into a more nuanced and varied practice. Over time, these new techniques also become tacit for her. She can now switch between different methods fluidly, without conscious thought. Yet again, once she solves this problem, new ones arise. In fact, each solution Lola discovers opens up a new set of challenges. For example, her mastering the technique of applying a consistent glaze leads her to explore how different glazes interact, prompting questions about the chemical properties of the materials she uses. This never-ending cycle of problem-solving leading to problem-finding, followed by problem-finding leading to reflective thinking, and so on, ensures the refinement of Lola's craftsmanship. Hence, the crafting process and skill development appear as a growing spiral. By taking inspiration from Gürer et al.'s (2015, p. 167) hermeneutical spiral visualization, **Figure 1** depicts the relationship between reflective thinking, problem-solving, and problem-finding. There are two remarkable implications of this cycle. First, there is no complete and finished craftsmanship because there is no one right way to do something. When we develop a skill, we learn many different ways to perform the same kind of activity. Second, craft only thrives when there is a resistance, a change because they lead to problems leading to reflective thinking leading to problem-solving.

3.3 Slow Time

Lola's journey in pottery is marked by the slow, deliberate practice that Sennett (2008) emphasizes. When learning to throw a pot, Lola works slowly, often spending hours just centering the clay and shaping a simple form. This slow practice allows her to deeply understand the material's behavior and how subtle changes in her technique affect the outcome. Hence, the time of craftsmanship is a slow time. When you slow down a practice, the consciousness of the activities comes to the fore in a sequence. To do something incredibly slowly stimulates a mini

² For more information on reflective thinking, see Schön (1987, pp. 44-79).

version of tacit-explicit-tacit rhythm as the craftsperson dwells in the things they do. However, this dwelling is different from what Heidegger talks about. To Heidegger (1971), dwelling is a form of immersion in which ultimately there is a release. When you dwell in something slowly, you gradually become absorbed, and there is a kind of catharsis, so you are at peace. Meanwhile, for Bergson (1910), when things are slow, you are less at peace. The slower the time gets, the less confident you get about what you are doing. Bergson (1910, pp. 100-122), describes such immediate knowledge of consciousness as being temporal, or in his terms *la durée* (the duration). In *la durée*, there is no juxtaposition of events over time; hence, no mechanical causality. It is the lived time that is filled with subjective lived experiences. Therefore, the slow time of the craftsmanship is more of a Bergsonian time. When Lola practices pottery, she inhabits the time of *la durée* rather than the time of surrender to being.

4. CRAFTSMANSHIP IN COMPUTATIONAL DESIGN PRACTICES

Computational design acts as an umbrella term referring to design practices that employ computing techniques and computational thinking such as algorithmic, parametric, and generative design (Caetano et al., 2020). Computational design practices leverage a variety of digital tools to facilitate the design process or optimize performance, such as Computer-Aided Design (CAD) tools, parametric design tools, graphic programming tools, scripting and programming languages, Building Information Modeling (BIM) software, various simulation, visualization, and analysis tools. The framework of the craft process can be observed in computational design practices, where craftsmanship intersects with digital tools and algorithms. Sennett (2008) argues how problematic it is to put digital and craft in opposition because such opposition assumes that the digital era leaves the traditions and modalities of performing a craft behind. On the contrary, digital simply introduces another form of craftsmanship. Devendorf et al. (2020) point out how researchers tend to inadvertently romanticize craft, presenting it as a primitive or poetic counterpart to modern computational methods, and how such a dichotomy overlooks the inherent technical expertise within craft practices themselves. In reality, both traditional crafts and computational design involve complex problem-solving, skill development, and technical proficiency (Cheatle & Jackson, 2023). Therefore, rather than seeing computational

design as a departure from traditional craft, it can be seen as a continuation and evolution of craftsmanship, where digital tools and algorithms are integrated into the craft's long-standing iteration, creativity, and expertise processes. Digital or not, any skillful practice can be considered as a form of craftsmanship. It just depends on whether the practice is performed as a craft or not. Hence, there is the craft of the digital rather than the craft being inserted within a kind of digital envelope. This craft manifests itself in computational design through several key characteristics. To fully understand computational design as a craft, it is essential to examine its key characteristics, such as open systems, nonlinearity, complexity, ambiguity, thinking outside the discipline, and tool-making. These characteristics are fundamental to demonstrating how computational design practices can extend beyond mere technical processes and incorporate a dynamic interplay of skills, creativity, and adaptability.

4.1 Open Systems and Nonlinearity

The computational design practice that arouses problem-solving, reflective thinking, and problem-finding, consists of a nonlinear open system. In systems theory, open systems imply systems that engage in exchanges of energy, matter, or information with their environments through input and output flows (Von Bertalanffy, 1950). If a practice is structured to achieve a certain specific goal, the person in training will reach the goal and be done with the problem (Sennett, 2008, p. 38). In contrast, an open system does not have a fixed end. It connects problem-solving to problematizing rather than closing a problem down and encourages exploration. Now, why nonlinear? In mathematics, linear equations or linear systems can be broken into pieces. Each piece can be analyzed separately and solved, and finally, all the separate answers can be combined. The whole is exactly equal to the sum of its parts. Whereas the parts in a nonlinear open system cannot be broken down this way. There is a non-proportional relationship between the input and output changes. Thus, the whole system has to be examined at once as a coherent entity. For example, Flemming Tvede Hansen's 3D clay printing practice embodies a nonlinear open system in computational craft (Hansen, 2021; Hansen et al., 2019). By integrating robotics with traditional ceramics, he extends the craftsperson's capabilities, fostering continuous exploration and allowing for intricate detailing and repetitive patterns beyond manual limits. Similar to evolving from explicit to tacit knowledge through gradual practice,

Hansen's work evolves through iterative experimentation and reflection. The process is not linear but involves constant experimentation, leading to new questions and challenges rather than merely solving predefined problems. The integration of new technologies with traditional methods exemplifies the dynamic nature of open systems and highlights the importance of flexibility and responsiveness in creative practices. Celani and Vaz (2012) also emphasize how open systems and non-linear design processes enable designers to create flexible models that can respond to a variety of inputs and constraints in real time. This flexibility is crucial in creative practices as it enables designers to maintain a balance between artistry and technique, ultimately leading to more refined and meaningful creations.

4.2 Complexity and Ambiguity

A complex system is "a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" (Mitchell, 2009, p. 13). This means that complexity emerges in the course of evolution through the feedback and sifting of information, rather than existing in a preordained and programmed outset. For instance, in computational design, generative approaches employ systems with unpredictable behavior, where simple rules lead to complexity. These include Shape Grammars, Lindenmayer Systems, Cellular Automata, Agent-Based Systems, and Genetic Algorithms (Singh & Gu, 2012). Generative approaches can be utilized in design in a functional and exploratory way. The functional way focuses on specific problems, seeks answers, improves the design and related efficiencies, and closes the topic. The exploratory way connects problem-solving to problem-finding and encourages reflective thinking. In an exploratory generative design, the designer may play with parameters and rules, reflect on changes, form analogies, interpret and reformulate behaviors, explore randomness, and look for emergence (Topaloglu, 2023). Here, generative systems act as open complex systems, where parts of the system interact within a larger context. Sometimes, the system exhibits properties or behaviors that are absent in its individual components – known as the emergence (O'Connor, 2021). Along with the complexity, the randomness of both emergent properties and the whole system leads to ambiguity. Oxman (2006) claims that such ambiguity in exploratory computational design

serves as a source of creative potential. The ambiguity directly corresponds to the resistance in the craft process. To deal with unexpected outcomes and anomalies, the designer is forced to have a rhythmic journey between explicit and tacit knowledge. In this regard, 3D clay printing often embodies ambiguities because it involves taking actions with no clear outcomes (see Shi et al., 2019; Van Der Veen et al., 2019). We also see this in Michael Batty's computational design study in the field of urban planning and design. Batty creates complex urban growth models of cities through Cellular Automata, Agent-Based Systems, and Lindenmayer Systems (see Batty, 2007a, 2007b). As the simulation runs and urban patterns emerge, Batty's understanding emerges from the system's behavior rather than explicit programming. He encounters resistance and explicit knowledge unpacking when unexpected urban patterns or challenges (e.g., traffic congestion, resource allocation) emerge that require revisiting. He experiments with the model's parameters, navigates through ambiguities, and reflects on emerging properties. Engaging with complex datasets, varying parameters, and unpredictable outcomes enriches his computational craft process and fosters deeper understanding.

4.3 Thinking Outside the Discipline, and Tool-Making

Computational design encourages interdisciplinarity by combining knowledge and techniques from diverse fields like art, architecture, engineering, and computer science. This interdisciplinary nature forces practitioners to think outside the traditional boundaries of their discipline and embrace new insights. For instance, Hansen (2021) and Batty (2007a) both ventured beyond their comfort zones and experimented with new methodologies. Without the impetus for growth and challenge, practitioners risk stagnation in their craft, limiting their skills and knowledge. In contrast, thinking outside the discipline invites open-ended inquiries and continuous exploration. Such a mindset leads to countless opportunities for problem-finding and the dynamic interplay between tacit and explicit knowledge, resulting in the continuous refinement and evolution of one's craft. Furthermore, tools that are used in computational design practices are generally not served on silver plates. There are countless examples regarding the tool-making aspect of computational design. For instance, Devendorf et al. (2023) created a parametric design tool for complex weaving patterns. Tamke et al. (2017) developed simulations utilizing various algorithms and artificial neural networks to be able to

design and build their *Lace Wall*. Most of the time, computational designers need to become proficient in some coding languages like C#, JavaScript, and Python, or visual programming software like Grasshopper for Rhino. This necessity highlights the significant challenge posed by the absence of readily available design tools tailored to their specific needs. Computational designers often find themselves in a landscape lacking comprehensive tools that align with their design problems and processes (Nisztuk & Myszkowski, 2018). This landscape compels designers to develop their own tools and scripts, a task that requires not only technical proficiency but also creativity and resourcefulness. In this context, the lack of a concrete design tool awaiting the designer to use echoes Heidegger's notion of the broken hammer. Heidegger (1927/2007) points out that the moment a hammer breaks, it loses its utility and simply exists as an object, separate from useful tools until it is repaired or replaced. It is when we encounter the broken hammer that we consider the network of purposes that it is a part of. The ordinary immersion into the craft process does not make room for such reflection. Only when something – a resistance, a change, or a challenge – disrupts this absorption into practice, does the crafter get to have the necessary distance to contemplate their practice. Just as a broken hammer prompts reflection not only on its raw materials but also on its role within our network of purposes, so too does the absence and the creation of digital tools in computational design invite us to contemplate the essence of our creative processes. The act of tool-making requires a deliberate pause in ordinary absorption into tasks, in which designers can gain critical distance and reflect on the broader implications of their design decisions. Moreover, the process of coding itself becomes an exercise in problem-finding and solving (as we also see in Sennett, 2008), where designers navigate complexities and uncertainties outside of their discipline to craft custom algorithms and parametric models.

5. WHAT ABOUT THE LACK OF CRAFT?

Now, let's sit on the opposite side of the table. While computational design practices can embody many principles of craftsmanship, there are instances where we cannot consider it a true craft. Craftsmanship is inherently exploratory and involves a profound engagement with the material or medium, continual problem-finding, and iterative problem-

solving. However, certain computational design practices fall short of these criteria. If a computational design practice is overly rigid, aiming solely for efficiency and optimization without room for exploration and experimentation, then it should not be considered as a craft. For instance, when a designer relies heavily on predefined algorithms and templates to generate designs without questioning or modifying them, the process becomes mechanical. Again, if the focus is merely on solving predefined problems without seeking new challenges or questioning existing parameters, the practice becomes static. Or when designers use automated tools just to shortcut generate designs with minimal input or understanding, it fails to become craftsmanship. These kinds of approaches lack the open-ended inquiry and reflective practice that are central to craftsmanship.

In this regard, resistance in traditional craftsmanship plays a crucial role in fostering a deep engagement with the material and shaping the crafter's skills and design approach. Although it is often neglected in computational design practices, the idea of resistance is essential to understanding the potential and limitations of computational methods and digital tools. Resistance in this context does not solely refer to physical material constraints but also to the inherent challenges posed by the algorithms, tools, and processes used. For instance, as it was mentioned before, ambiguity can serve as a form of resistance. However, computational practices have a tendency to streamline design processes to ironically eliminate the resistance and create a more efficient but less engaging design environment. When computational design tools and algorithms are too accommodating, they remove the need for iterative exploration and experimentation. Such an absence of resistance can lead to a superficial design process in which the designer merely follows predetermined paths without any skill development. Therefore, computational craftsmanship requires design environments that challenge and stimulate reflective thinking, capable of introducing conceptual and procedural obstacles to force designers to think critically and creatively.

Another issue that dries out the potential craftsmanship in diverse studies conducted at the dissertation level by computational design researchers is the development of linear workflows. Such workflows present a simple formula that will lead to a certain design "solution" if you do this from point A to point B. It leaves no space for exploration

and kills the potential of craft in the practice right away. Furthermore, the over-reliance on computational efficiency can strip away the unexpected discoveries that are important in craft-based practices. By prioritizing speed and accuracy over the creative process, designers may miss out on unique outcomes that emerge from a more hands-on, inquisitive approach. If computational design is to be elevated to the level of true craftsmanship, it must embrace a philosophy that values process as much as product, allowing for unexpected insights and growth. If we want to nurture craft in computational design practice, then our workflows must invite complexities and ambiguities themselves, and be nonlinear.

6. CONCLUSION

In conclusion, computational design practices possess great potential with the transformative capabilities of digital tools and methodologies for today's craftsmanship. Deeply rooted in human history and culture, craftsmanship has significantly evolved from its origins in ancient civilizations to its current state in the digital era. Today, computational design further expands the horizons of craftsmanship via tools and techniques like 3D printing, parametric design, and generative algorithms, enabling craftspeople to explore new creative avenues and problem-solving methods. The study explored how the rhythm of knowledge production and problem-solving in slow, deliberate practice characterizes traditional craftsmanship. In computational design practice, these principles manifest in open and nonlinear systems that encourage exploration and experimentation. Complexity and ambiguity are embraced as opportunities for growth rather than rigid obstacles, mirroring the iterative and reflective nature of traditional craftsmanship. Moreover, the act of tool-making in computational design underscores a critical aspect of craftsmanship: the deliberate and thoughtful engagement with technology. Just as craftspeople select and hone their tools, computational practitioners craft algorithms and parametric models, reflecting on their design decisions and the broader implications of their work. However, it is essential to acknowledge the potential pitfalls in computational design that may undermine craftsmanship. Processes that prioritize efficiency or functionality over exploration risk eliminating craftsmanship and turning it into a mechanical practice devoid of creativity and the human touch. To preserve and nurture craftsmanship in computational design,

it is imperative to foster complexity, ambiguity, continuous exploration, and reflective thinking. Integrating these elements ensures that the essence of craftsmanship endures, even as technology evolves, maintaining a balance between tradition and contemporary. By recognizing and appreciating the human element within digital practices, we can pave the way for a future where craftsmanship continues to thrive in new and unexpected forms.

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The Evolution of Craftsmanship from Necessity to Creativity

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This research explores the link between traditional craft and contemporary technology, with an emphasis on the Ancient Greek concepts of *Techne* and *Episteme*. Analyzing the historical evolution of craftsmanship and the relationship between theoretical knowledge and practical proficiency, the study shows how technological innovations in tools and processes have continuously revolutionized human creativity. The study also discusses current issues such as how mass production affects craftsmanship and whether robotic production can be integrated with traditional craftsmanship values. This integration addresses issues such as the continued functioning of the craftsman in a rapidly changing technical environment and the preservation of the essence of craftsmanship in the age of automation. In this context, this study highlights the importance of process-oriented and adaptive approaches to production by examining the dynamic interaction between tools, techniques and creative processes. It also explores how robot technology can mimic the flexibility of traditional crafts by introducing elements of improvisation and creativity into the production process. In the field of craft and technology, this method encourages the coexistence of tradition and innovation, providing new paradigms for the production of distinctive, high-quality products.

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Zorunluluktan Yaratıcılığa Zanaatkârlığın Evrimi

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Bu araştırma, Antik Yunan'ın Techne ve Episteme kavramlarına vurgu yaparak geleneksel zanaat ile çağdaş teknoloji arasındaki bağlantıyı incelemektedir. Zanaatın tarihsel gelişimini ve teorik bilgi ile pratik yeterlilik arasındaki ilişkiyi analiz eden çalışma, araç ve süreçlerdeki teknolojik yeniliklerin insan yaratıcılığında nasıl sürekli devrim yarattığını göstermektedir. Çalışma aynı zamanda seri üretimin zanaatkârlığı nasıl etkilediği ve robotik üretimin geleneksel zanaatkârlık değerleriyle entegre edilip edilemeyeceği gibi güncel konuları da tartışılmaktadır. Bu entegrasyon, hızla değişen teknik ortamda zanaatkârın işlevini sürdürmesi ve otomasyon çağında zanaatkârlığın özünün korunması gibi konuları ele almaktadır. Bu bağlamda, bu çalışma araçlar, teknikler ve yaratıcı süreçler arasındaki dinamik etkileşimi inceleyerek üretime yönelik süreç odaklı ve uyarlanabilir yaklaşımların önemini vurgulamaktadır. Ayrıca, robot teknolojisinin üretim sürecine doğaçlama ve yaratıcılık unsurlarını katarak geleneksel zanaatların esnekliğini nasıl taklit edebileceğini araştırmaktadır. Zanaat ve teknoloji alanında bu yöntem, gelenek ve yeniliğin bir arada var olmasını teşvik ederek özgün, yüksek kaliteli ürünlerin üretimi için yeni paradigmalar sunmaktadır.

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Anahtar Kelimeler: Zanaatkârlık, Techne, Episteme, Robotik Üretim, Teknoloji.

1. INTRODUCTION

From the dawn of civilization, crafting has been integral to human survival and cultural expression, bridging the gap between necessity and creativity. The ancient Greek concept of *Techne*, often translated as 'craft', embodies the skillful practice of making and doing. Heidegger emphasizes this connection by stating that the essence of *techne* lies not merely in the act of making or manipulating, but an act of revealing and bringing something into being (Heidegger, 1977). Through this act of revelation, *techne* establishes a connection with *episteme* which is translated as 'knowledge', which pre-exists in the activity of making and its application in the act of producing something that responds to an anticipated need. The link between *episteme* (knowledge) and *techne* (craft) is close to the relationship commonly attributed to the concepts of 'theory' and 'practice' today. Such distinctions, again, blur when we view craft, as it is an activity that incorporates these two concepts, where both practical and theoretical knowledge coexist.

As humans developed sophisticated tools, the relationship between practice and theory or *episteme* and *techne* became even more evident. The notion that tools are essentially embodiments of technology is fundamental to understanding the evolution of human innovation (de Beaune, 2004). Each technological innovation reflects an advancement in both theoretical understanding and practical application, demonstrating the evolving relationship between tools and techniques required to use them. Craft is the embodiment of this dynamic interaction (Sinclair, 1995). Each new technique offers a fresh perspective on how tools can be used, which encourages further advancements in technique. This cycle is at the center of human creativity, driving progress across all domains of craft and technology. Over time tools have played an important role in shaping the outcomes of craft, and the very nature of what we consider craft itself.

Traditionally, the craft is understood as the creation of functional items made by hand (Risatti, 2007). Over the years, craft objects have evolved, carrying with them techniques honed over centuries to produce the most functional and efficient products. This transformation reflects a shift from merely creating functional items to embodying a culture's accumulated knowledge and skills. The meaning

of craft has evolved, especially as new tools have diminished the necessity of human labor in everyday objects. Technological advancements have introduced new tools and methods, enabling faster production while maintaining or enhancing quality items with the same functionality. In this context, the direct relationship between technology and the evolution of craft plays a crucial role in this development. While mass production is based on the manufacture of the final products, the craft can be considered as a process-oriented production where the product emerges from the craftsperson's direct interaction with the material, using hands-on knowledge. This shift represents the transition from hands-on knowledge to the dominant authority of explicit knowledge (Sennett, 2008). The shift from the use of technology as a tool in the production process to employing technological tools that manage the entire process reduces the role of the craftsperson within the process. Machine-made products, which are cheaper, faster to produce, functionally equivalent, and often artistic imitations of handmade items, have gradually replaced the time-consuming, imperfect yet uniquely crafted products of artisans (Risatti, 2007). This change marked a decline in the importance of craft culture in daily life objects as machine-produced items became more prevalent.

Over time, instead of craft as a handmade practice, as a method of producing everyday objects, the use of manufactured products as a result of mechanized processes has become widespread. As a result of this popularization, the handmade craft object has become, so to speak, an object to be looked at. However, in every period, craft has been reintroduced with a different perspective by using contemporary tools. This article aims to trace the development and transformation of craft and craft objects with mechanization. In particular, it questions what qualifies or can qualify as 'craft' in a world where technological developments are increasingly integrated into production processes. It also aims to explore the changing definition of craft in relation to evolving means of production. Through a review of historical perspectives on techne and episteme as well as contemporary debates on craftsmanship, the paper highlights the complex relationship between human creativity, technological tools, and evolving understandings of craft.

2. CRAFTSMANSHIP IN THE MODERN ERA

The meaning and even the use of the word 'craft' has changed considerably over time. Today, the verb 'to craft' describes a production process and skillful participation. This shift introduces a broader understanding of craft as an approach that integrates knowledge, skills, and work (McCullough, 2010). Before delving into deep discussions about what qualifies as craft, we need to understand the different approaches to producing craft objects. We can classify two main production approaches: result-oriented and process-oriented. In result-oriented production, interventions are made to achieve the envisioned final product by applying pressure to the encountered obstacles. By contrast, process-oriented production evaluates these obstacles and allows decisions about whether to intervene, shaping the outcome as the process unfolds. The resistances we impose on ourselves arise from the expectations we set for the desired result. This can exist in both result-oriented and process-oriented approaches, but the frequency and intensity differ depending on the method. For example, how a carpenter intervenes in a grain of wood depends on whether they are working toward a result or adapting step-by-step within the process.

In result-oriented production, uncertainty can become a problem, leading to frustration as the craftsperson struggles to reach the outcome. On the other hand, the process-oriented production method does not require a clear image of the result. Instead, the craftsperson accepts that the resistance encountered during the process will shape the outcome. They manage the process accordingly, improvising during the process. However, this does not imply that the craft is produced entirely within uncertainty; a stone carver may have an image of the final product in mind, but this image takes shape through various decisions made during the process, considering the stone's hardness, grain structure, and even the color.

Ultimately, it is the management of the production process that determines whether something is considered a craft. A rigid structure based on repetitions in the production process can negatively impact the skills of the craftsperson. The active engagement of the

mind in the practical process enables the creation and use of knowledge. Sennett (2008) emphasizes that skill is an educated practice that involves knowledge and highlights that modern technology should not deprive the development of skills by turning the process into a rigid and repetitive one. While modern machines can assist in production, the craftsperson's theoretical and practical skills weaken when they dominate the entire process. Craftsmanship requires a balance where machines are used as tools rather than replacing human skill and creativity. When employed appropriately, technology can enhance precision and efficiency while preserving the craftsperson's engagement in the hand-making process.

In the traditional production approach, the maker also takes on the role of the designer and creates a craft with a balance of aesthetics and functionality. Mass production, as a derivative of this culture, is designed to imitate traditional production methods. When handmade objects began to be mass-produced, significant effort was devoted to replacing the unique qualities of handmade items. However, the widening gap in aesthetic concerns between craft products and machine-made products led to the emergence of a new culture of machine production. Discussions about the machine production of craft objects shifted to debates about the methods and processes of machine production. In this new cultural environment, the focus of machine production broadened to include both functional and aesthetic concerns. This triggered new debates on how craft production can exist when machines are used as tools rather than controllers of the production process.

A pivotal moment in this evolution was the founding of the Deutsche Werkbund in 1907, which brought together artists, industrialists, and art enthusiasts. Werkbund sought to reconnect designers with producers and reintegrate art into the industry, recognizing the value of artistic quality in industrial products. These discussions aimed to develop thoughtfully designed products using new technological tools, even if they differed aesthetically from previous craft cultures. This raises the question: Can production using the latest technological tools still be considered craft? This question challenges the criteria we use to define what constitutes a craft today.

3. CRAFTSMANSHIP IN ROBOTIC MANUFACTURING

The fundamental difference between the use of machines in production and the use of tools in craft lies in direct control through the human body. When guided by the sensitivity of the body and the precision of human hands, tools enable a more direct and intimate relationship between the material and the maker. This human touch brings uniqueness to the production process, allowing the craftsperson to make spontaneous, on-the-spot decisions in response to material, function, and design, and becomes a process of production that reflects the craftsperson's knowledge and intuition. In this process, the craftsperson is a producer with full control over both design and implementation. On the other hand, the rise of mechanization fundamentally changed the dynamic between design and production, creating a distinction between the two. As machines have taken over much of the production process, a new practice has emerged that increasingly determines design by the capabilities of the machines. Unlike the human hand, machines follow preset programs, repeating the same task with the same precision over and over again. This static, standardized production form not only reduced the designer's direct involvement in the production process but also led to designs being shaped according to what machines could achieve rather than the creative decisive process of the designer.

The alienation between the designer and production, created by the decline of tool use in favor of machine dependency, has begun to change with the use of machines as tools. In 2006, Gramazio and Kohler pioneered research into the possibility of experimental use of machines in design and fabrication. Utilizing the precision of this advanced tool, they introduced a new form of production and design by laying bricks according to computationally designed patterns (Bonswetch et al., 2006). Initially, the focus was on understanding the potential of robots through an experimental approach. This approach can be interpreted as bridging the gap between craft and mechanization, allowing machines to become tools in the hands of designers. Designers could now engage directly with the material and the fabrication process reminiscent of traditional craftsmanship. The exploration of the potential of machines has created interest within the discipline of design, especially in the context of fabrication and creation. But can we consider production through machines as an act of craftsmanship? In a

process where the human hand does not directly manipulate the material, but instead designs how that manipulation will take place and anticipates its outcomes, can robotic production be classified as craft? These questions lead us to reconsider what the act of craft is. Craft is the process of manipulating material through tools with technique (McCullough, 2010; Risatti, 2007). This manipulation emerges through knowledge of the tool, the material, and the technique (the use of the tool) with a skillful application of the knowledge.

For a craft product to be considered “successful”, the craftsperson must have extensive knowledge and expertise in all three key areas: material, tool, and technique. With a deep understanding of these parameters, both individually and together, a master craftsperson can intuitively control the process. This tacit knowledge enables the craftsperson to successfully manipulate the material and the tool through their intuitive actions. When a ceramic artist shapes clay on a wheel, they are aware of how each movement will shape the material. This process is guided by an intuitive “feel” for the act of clay shaping. The artist senses the amount of water in the material and adds water intuitively, or they adjust the pressure applied to the material where they perceive the uneven thickness. Therefore, integrating the principles of craft into robotic manufacturing, several fundamental questions arise: How can a hand’s intuitive knowledge be translated into a robotic process? How can the relationship between material and tool be preserved when the hand is replaced by a robot?

Perhaps it is too early to answer these questions. Considering the evolution of traditional craft production methods over the centuries, the culture created and the knowledge accumulated, a similar culture is certainly possible to build in the field of robotic fabrication, which dates back only 20 years. Research so far has been invaluable for the development of this culture. Early work has focused primarily on understanding the robot's capabilities and exploring what is possible to achieve with it. As researchers became more skillful in using the robot, the goal of understanding the robot shifted to work on outcome-oriented productions. Current research continues to push the boundaries of the robot's capabilities and develop its creative fabrication potential. In all this robotic fabrication research, the three main parameters, material, tool, and movement, which are parallel to the craft, are studied in detail. Many schools and projects have been

working for years on studying and improving these parameters. Some of them extend their research by working over the years using the same tools and materials. An important example is the research at ICD/ITKE, University of Stuttgart, which has been developing the production method used in the project they started in 2012 with new trials until 2024. During this time, both the materials used and the tools attached to the robotic arm have evolved and diversified. This research, the ICD/ITKE Research Pavilion, involved the construction of a pavilion using a resin-saturated fiber stretching technique with a robotic arm (Waimer et al., 2013; Knippers et al., 2015). Over the years, knowledge has developed between the tool and the researchers in the same way as in a traditional craft production process, and the technique and skill of using the tool have been mastered (Prado et al., 2014; Schieber et al., 2015; Koslowski et al., 2017; Solly et al., 2018; Rongen & Koslowski, 2019; Gil Pérez et al., 2022; Pérez et al., 2022; Schlopschnat et al., 2023).

Nevertheless, it may be too early to consider these robotic productions as 'craft'. The knowledge generated in these long-term research processes is closer to the outcome-oriented production methodology discussed in Chapter 2. In contrast, traditional craft is typically associated with a process-oriented production methodology where the making process is as important as the final product. The relationship and intuition built on years of practice between hand and material remain difficult to emulate in robotic processes despite advances in robotic skill and precision. However, if robotic manufacturing can evolve to integrate process-oriented values rather than just outcome-oriented ones, a new form of craftsmanship may emerge. By combining human intuition with the precision and flexibility of robotic systems, this "new craft" will open new avenues for creative expression and push the boundaries between humans and machines in the act of making.

4. THE FUTURE OF CRAFT AND ROBOTIC MANUFACTURING

The ability to integrate the precision and efficiency of robotic systems with the flexibility, adaptability, and process-oriented nature of traditional craft is a development that will define the viability of craft in robotic manufacturing. This integration is not just about the application of existing robotic technologies to craft processes but requires that how robots are used within the design and manufacturing continuum is

appropriate to the parameters of craft production. Current research over the past few years has demonstrated developments that could go beyond treating robots as basic tools, such as a hammer or a pencil. Instead of being machines that perform defined tasks, robots can become adaptive and dynamic tools that can respond to the ever-changing needs of both design and fabrication. This method allows the designer to perceive, organize, and improve the connection between materials, tools, and techniques in real-time. Therefore, robots become more than just tools, they become collaborators in the creative process. To realize this vision, two human characteristics need to be integrated into the robot: perception and decision-making.

Robots have one-way information transfer due to their design. The code that instructs the movement is programmed and transferred to the robot system and the robot completes the task given to it according to these instructions. During this process, the robot operates 'blindly' by following the given motion coordinates without precepting and receiving any feedback from its environment. While this one-way information transfer can be limiting for production processes that focus on achieving a predefined result, it becomes a highly productive feature in creative processes where the aim is to explore the potential for randomness and emergence. The robot's 'blind' movements, in this case, offer a context for generating the unpredictability and emergent behaviors fundamental to innovative discoveries in design and fabrication. Such studies are frequently found in the literature (Dörfler et al., 2014; Romana et al., 2016; Tokac et al., 2021; Bar-Sinai et al., 2023). However, relying only on one-way information transfer can create limitations as more complex interactions with the robot's environment and material are required. This creates the need for two-way information flow, where the robot not only executes commands but also perceives its environment and relays it to the designer. This need has led to research focusing on enabling robots to sense and interact with their environment in real-time. Researchers have developed ways for robots to receive feedback from their environment by integrating various sensors into robotic systems (Luo et al., 2020; Mitterberger et al., 2020; Burden et al., 2022; Luo, 2023). This has created a two-way flow of information between the robot and the environment in which it operates. This sensory capability gives the robot an awareness of its environment, allowing adjustments to be made according to real-time conditions. For the designer, this creates

the possibility of controlled randomness in the creative fabrication process. Instead of simply following predefined movement coordinates, the robot can now detect changes in the properties of the material and adapt its actions accordingly. This dynamic interaction between the robot and its environment introduces an element of instability that can be used creatively, blending the precision of robotic manufacturing with the fluidity and randomness typically associated with craftsmanship.

For decision-making, artificial intelligence (AI) and machine learning are being introduced into the manufacturing process (Brugnaro & Hanna, 2019; Gu & Yuan, 2024). These technologies enabled robotic systems to “learn” from their perceptions of materials and the environment to improve their actions over time (Liu et al., 2022). Such advances allow robots to exhibit a level of intuitive behavior approaching human-like decision-making and responsiveness. For example, a robot equipped with sensors and AI capabilities can detect subtle changes in the texture or resistance of a material and adjust its movements accordingly, much as a skilled craftsman does when shaping clay or carving wood. This ability to react and adapt in real-time is essential for achieving the nuanced results typically associated with handmade objects. Moreover, incorporating controlled randomness and unpredictability into robotic processes can further enhance the uniqueness of each handmade product, creating results that reflect the randomness and variety that are distinctive features of traditional craft.

Is it possible to define the results of fabrication in which a robot's perception and decision-making abilities are developed as “craft”? Can this more autonomous form of production be categorized within the craftsmanship? Answers to these questions depend to an extent on how we approach fabrication and the tools used in the craftsmanship process. Craftsmanship is not just a method of making, but a holistic approach to creation that emerges from the creator's relationship with materials and the environment. Each act of creation becomes an instrument for exploring and refining ideas, adapting them to the needs of the object, the materials at hand, and the context in which it is situated. Craft, then, is defined not only by manual labor or the use of specific tools but by the subjective experience that shapes the process and the product. Applying this understanding of craft to robotic manufacturing, the distinction lies in how the robot is perceived and

used. The robot can indeed fit a broader, evolving definition of craft if it is seen as an advanced tool that works, learns, and adapts in a structured yet dynamic creative process that is an extension of the designer's vision. Craft in this case lies in the deliberate design of the production process, where both human creativity and robotic skills work together to achieve a thoughtful and refined outcome.

5. CONCLUSION

Although it may be a bit of a paradox to conduct craft processes using contemporary technologies in the digital age (McCullough, 2010), the desire to rethink the enriching world of craft with current technologies is quite meaningful and valuable. As robots become part of the creative process, not only the role of the craftsperson inevitably transforms, but also the traditional concept of craft is being redefined in the context of robotic fabrication. This redefinition opens up new creative possibilities, allowing designers and makers to explore the full potential of combining technology with the process-oriented nature of traditional craft. In this new paradigm, the craftsperson is not a maker who manipulates materials by hand, but a designer, controller, and executor of robotic fabrication processes. In this context, craftsmanship becomes less about the physical act of making and more about the thoughtful arrangement of materials, processes, and tools, whether human hands or robotic arms. However, does the absence of the hand in the production process imply that the product and the process can no longer be characterized as craft? It is worth remembering that craftsmanship (*techne*) emerges through knowledge (*episteme*). Craftsperson's deep knowledge of the material, combined with the robot's precision and efficiency, can create a class of innovative products that push the boundaries of what is possible with traditional manual methods (Ingold, 2013). Through countless trials and errors, the designer, or in this case craftsperson, masters the skill of controlling the robot. This process of trial and error is a learning space for the designer where knowledge is generated and further refined. Unlike the traditional craftsperson who engages in hands-on learning, the designer's process is much slower and less instantaneous due to the absence of direct haptic feedback. This lack of physical, tactile feedback interrupts the flow of knowledge generation that is typically at the very center of the craft process. As a result, the development of skills in robotic manufacturing has taken place over the years, and knowledge

accumulates more slowly compared to the fast, intuitive learning that occurs in hand craftsmanship. The blending of these elements creates a new art form that embraces the precision and capabilities of modern technology while preserving the spirit of traditional craftsmanship.

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Conflict of Interest Statement

The manuscript titled “The Evolution of Craftsmanship from Necessity to Creativity” has not been published, in the press, or submitted simultaneously for publication elsewhere.

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An Inquiry on Analogue and Digital Making Processes in Architecture: Craft and Fabrication within the Scope of Masonry Structures

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This study explores the evolution of crafting and fabrication techniques, particularly focusing on the intersection between analogue and digital methods in the field of bricklaying. The inquiry seeks to address how digital advancements have influenced the way we build, comparing historical, conventional, and digital processes to highlight their similarities and differences. By using masonry, one of the oldest and most widespread construction methods, the study aims to trace the transformation of craftsmanship from fully analogue methods to digitally enriched practices.

The methodology is threefold: First, a literature review is conducted to identify contemporary fabrication approaches that blend digital and analogue techniques. This review helps categorize and analyze recent tendencies in digital fabrication, focusing on the integration of real-life data, feedback loops, and geometrical investigations. Secondly, a case study investigates different bricklaying fabrication methods to analyze how these digital-analogue interactions manifest in actual practice. Finally, a focused strategy based on four workflows is presented to compare different crafting processes, ranging from fully historical to highly digitized methods.

Consequently the study explores the evolving relationship between physical craft and digital environments via bricklaying techniques. Typical-conventional and semi-digitized practices seem to reduce the craftsman's intuitive decision-making role. On the other hand, the resemblance between completely digital and historical fabrication, in terms of allowing the craftsman to make intuitive decisions during crafting, is significant. The study suggests that future fabrication methods may continue to blend digital precision with human creativity, potentially leading to an archaic revival of traditional craft approaches in a contemporary context. Further research could expand into more complex volumetric structures to better understand this evolution.

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Mimarlıkta Analog ve Sayısal Yapım Süreçleri Üzerine Bir İnceleme: Yığma Yapılar Kapsamında Zanaat ve Üretim

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Bu çalışma, tuğla örme alanında özellikle analog ve sayısal yöntemlerin kesişim noktasına odaklanarak, zanaat ve üretim tekniklerinin evrimini araştırmaktadır. Sayısal alandaki ilerlemelerin inşa etme yöntemlerimizi nasıl etkilediğini inceleyen çalışma, tarihsel, yaygın-konvansiyonel ve dijital süreçleri karşılaştırarak benzerliklerini ve farklılıklarını vurgulamayı amaçlamaktadır. Çalışma, en eski ve en yaygın yapım yöntemlerinden biri olan duvarcılığı araştırma odağına koyarak, el işçiliğinin, tamamen analog yöntemlerden sayısal yöntemlerle çeşitlenmiş uygulamalara dönüşümünü izlemeyi hedeflemektedir.

Metodoloji üç aşamadan oluşmaktadır: İlk olarak, sayısal ve analog teknikleri harmanlayan çağdaş üretim yaklaşımlarını belirlemek için bir literatür taraması yapılmıştır. Bu tarama ışığında sayısal fabrikasyon eğilimleri, gerçek dünya verilerinin süreçlere entegrasyonu, geri-besleme döngüleri ve geometrik araştırmalar bağlamında incelenerek kategorize edilmiştir. İkinci olarak, sayısal-analog etkileşimlerinin uygulamadaki yansımalarını analiz etmek amacıyla çeşitli tuğla örme yöntemleri gruplanmış ve bir vaka çalışması önerilmiştir. Son olarak, tamamen tarihsel yöntemlerden yüksek düzeyde sayısallaşmış süreçlere kadar farklı fabrikasyon süreçlerini karşılaştırmak amacıyla, anlamlı bir örneklem oluşturacak dört vaka, derinlemesine incelenmiştir.

Çalışma, fiziksel sayısal ortamlarda gelişen zanaat ve üretim biçimleri arasında değişen ilişkiyi, tuğla örme teknikleri üzerinden incelemektedir. Yaygın-konvansiyonel ve yarı-sayısal uygulamaların, zanaatkarın sezgisel karar verme rolünü azalttığı görülmüştür. Bununla birlikte, tümüyle sayısal ve tarihsel üretim biçimleri arasındaki benzerlikler tespit edilmiştir. Bu çıkarım, söz konusu üretimlerin, zanaatkarın sezgisel kararlar vermesine olanak tanıdığını göstermesi açısından önemlidir.

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Anahtar Kelimeler: Zanaat, Hesaplamalı Tasarım, Sayısal Üretim, Yığma Yapı.

1. I 'THING,' THEREFORE I AM

The thin line between how we think of making and how we make things is a very long-lasting debate in the intellectual journey of humankind. The most striking point partially provoking the Enlightenment, emerged from the Cartesian *ethos*, which led to a school of thought, “ghost in the machine (Koestler, 1968)”, assessing mind and body into two segregated realms. Yet it can be traced until Aristotle when he defined *theoria* (theory), *praxis* (practice), and *poiesis* (application) separately in ‘Metaphysics’ in which he concurrently divided the domain of thinking and action. Although contradictory approaches and theories always remain consistent, it was not until the 1990s that scientific opposition was constituted, which is possible only in light of the advancements in the cognitive sciences.

These oppositional approaches are gathered under *enactivism*, which defines cognition as a dynamic interaction between an acting organism and its environment (Iliopoulos, 2018). Enactivism thinking tries to inject the physical world ergo, the knowledge of the body, into thinking, i.e. “*thinging* (Malafouris, 2013)” to highlight the reciprocity between the inner self and the outer world. It is, rather, an existential endeavour to make or build things. Thus, design disciplines serve as excellent realms for discussing these topics because their epistemology is inherently dependent on the act of ‘making’ itself.

The debates about mind-body duality and holistic understanding of making became even more complicated with the rise of computational abilities as computers radically transformed the act of ‘making’. There were early indicators of this tendency to redefine the mind-body duality by considering reciprocity between the two realms. For example, systems theory, followed by cybernetics, investigates the intersection between artificial and biological systems (e.g., human-machine interfaces) as a circular and causal chain of actions that move from action to sensing, to comparison, and then back to action (Pask & Scott, 1972), which interpret the relation between the machine and the human as an interactive and reciprocal feedback loop (Cantrell & Yates, 2009).

Today, orthodox computational designers argue that the digital environment, with its enhanced tools, has an overwhelming primacy

over conventional practices. Designers will soon be semi-engineers, mastering computerized processes (Caetano & Leitão, 2019). Moreover, digital environments may not only change the way we design but also our perception of the geometric properties of reality (Burry, 2010). Yet, some designers attempt to find a unified understanding of design in today's digitized world, where the boundaries between the real and the digital are blurred.

McCullough is one of the mediators, as he believes that computing is not exactly a radical departure, but rather a natural extension of intellectual development. To unify the physical and digital worlds, he has opted to strike the “crude analogy in the relation between a tool and a medium: a tool conducts intent, a medium forms a background of possibilities, and the two are inseparable. (McCullough, 1996, p. 108)”. Conventional craftsmanship requires the integration of mind and body, intuition and practice anyway (Sennett, 2008) very similar to Cullough's definition of digital crafting which can only be achieved “through the complementary role of personal sensibility”, which requires consistency and endless practice to have a satisfactory result, as classical craftsmanship demands (McCullough, 1996, p. 102). Thus, McCullough is willing to overcome the concern among designers that computers will eliminate humane attributes such as individuality, creativity, and intuition, the ‘black box’ that manifests the unique existence of each designer.

The amount of data from physical reality that can be represented in a digital interface is highly significant. For example, some material properties such as “strength, stress, and texture can only be experienced in the physical realm (Norman, 2004, p. 114)”. Additionally, the computational approach to problems related to form and load-bearing capacity is crucial for bridging the gap between the digital and physical realms. Rationalization processes, in this sense, are attempts to close that gap between physical and digital realities, as well as between design and craft, by relying on calculations of structural and material possibilities to align a digitally designed entity with real-life constraints.

Kwinter (2011, p. 91) proposes a more radical approach to overcome both disamenities (loss of personality and representation of reality) with the concept of the *archaic revival*, which implies “a new regime of

subjection”, by returning to “matter, complexity, and free development” using digital fabrication methods.

Our main objective is to shed light on what ‘making, crafting, and fabricating’ have become in today’s digitized world. The following research questions emerge under the influence of the aforementioned points of view. What are the similarities and differences between technologically induced fabrication methods and analogue ways of making? In this context, is it possible to identify traces of an ‘archaic revival’ by analyzing the evolutionary transformation of producing one of the most basic elements of architecture—a wall?

Our methodology is three-fold. First, to reveal the latest fabrication methods at the intersection of digital and analogue processes, a literature review is conducted, aiming to identify key themes and tendencies. Secondly, we perform a case study to test these tendencies. Since our goal is to trace the gradual transformation from analogue to digital fabrication techniques, we chose a practice that encompasses various methods of making: masonry. Masonry, with its ancient roots in human architectural endeavors and its continued use in both conventional and experimental contexts, provides a rich subject for analysis. Thus, it serves as a comprehensive case that includes historical, conventional, and cutting-edge practices of wall construction. Finally, a focused study is conducted to enable a thorough comparison of the workflows between these approaches.

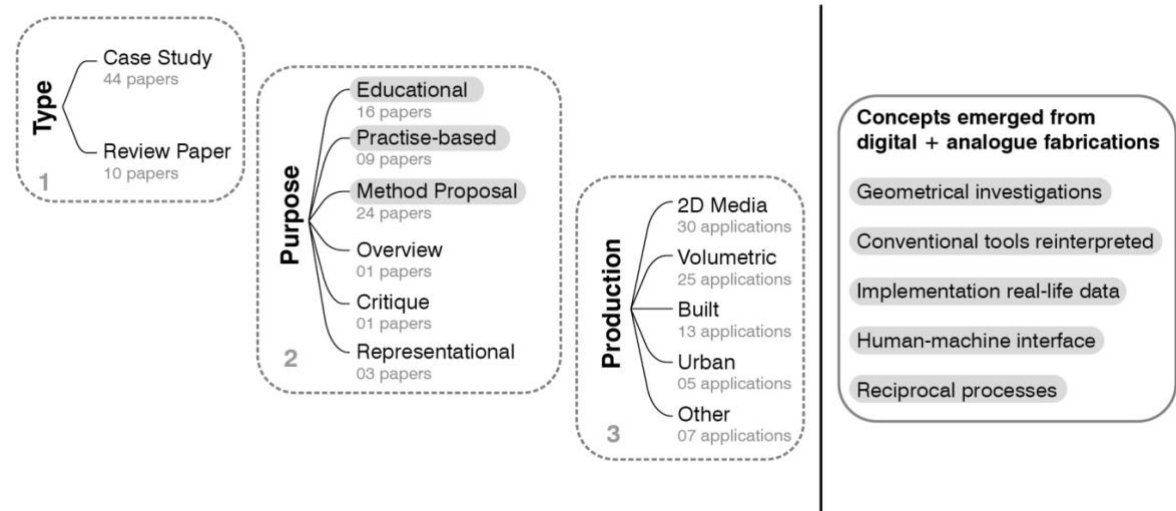
2. WAYS TO MAKE IN THE DIGITAL ERA

Just 50 years ago, architectural design and drafting required drawing boards, paper, T-squares, and probably a lot more backache from stooping, bending, and poor posture. Today, it is impossible to imagine architectural practice without computers, whether as a mere drafting tool that accelerates, yet does not enrich design and/or fabrication; or as an aid, both for design and fabrication. In today’s architectural practice, nothing remains purely analogue.

However, Leach (2018) points out that the computational paradigm shift is not yet complete even though computers are already widely used. What one now calls digital fabrication is actually “an analogue process that is merely digitally controlled” (Leach, 2018, p. 26); computers are not creatively

involved. Therefore, in the context of this research, it is crucial to trace the evolution of making, from craft to fabrication, and to explore the transformation of realization from the pre-digital era to the computerized world.

In order to understand the gradual shift to the digitized world of design and eventually to making, it is essential to first understand computational production methods and their impact on conventional and contemporary practices. Therefore, the “Computer Aided Architectural Design (CumInCAD)” database, as it is a database containing only computer-aided methods, scanned with the keywords ‘analog’ and ‘analogue’ separately between 1998 and 2024 in this article, to reveal the intersection and predominant themes between analogue and digital methods to make. The analysis of the CumInCAD database is divided into three main sections (i.e., type, purpose, and production), along with their corresponding subsections as shown in **Figure 1**. Of the 54 papers reviewed, 44 were categorized as 'case study' and 10 as 'review paper' under the 'type' section.



Under the ‘purpose’ section, one paper was classified as an 'overview', as it briefly explores the associational heritage of EAEA conferences from 1993 to 2003 (Martens, 2005). Another paper provided a 'critique' of societal inertia in adopting digital tools (Leach, 2018). Three additional papers were categorized as 'representational' (Martens et al., 2006; Schneider & Petzold, 2009; Rucker, 2010). While these papers

Figure 1: Categorization of 54 papers from the CumInCAD database on exploring conventional ways to make

were informative, they were deemed unrelated to this study's context and were excluded from further analysis.

A total of 49 papers were relevant to the scope of this study. These were further analyzed based on their objective—whether for 'educational' use, developed from 'practice-based' understanding, or proposing a novel 'method'.

Finally, under the 'production' section, the final productions or outcomes (e.g., 2D media, volumetric objects, realized structures/buildings, urban approaches) of the papers were examined to uncover the strategies emerging between analogue and digital fabrication methods.

2.1 Review of the selected Papers: Predominant Themes in Contemporary Ways of 'Making'

The main themes that emerge from the analysis of the papers in the CumInCAD database that are at the intersection of analogue and digital can be grouped into five main categories according to their main tendencies of evaluating the fabrication methods.

These themes involve (1) geometrical investigations, (2) implementations of real-life data, (3) examinations of human-machine interfaces, (4) reinterpretations of conventional tools, and (5) explorations of reciprocal processes. These categories are elaborated further below as well as in **Figure 2**:

- (1) Geometrical investigations aim to tessellate or reinterpret the form by manipulating the surface (Cheng, 2012; Stavrić, et. al 2012; Forren & Nicholas, 2018), or volume (Jabi, 2004; Griffiths, 2011; Anderson & Tang, 2014; Lanham, et. al. 2017; Suzuki & Knippers, 2018). The results are mostly variations rather than an ultimate geometrical solution, and these results are generated by complex outputs starting from an extremely basic level. However, all these studies focus on digital fabrication methods rather than creating a common ground with analogue methods.
- (2) The studies aimed at implementing real-life data into digital manufacturing processes implement many different data sets – including structural, material, performative, haptic, gestural, etc.– and their modification after being confronted with real-life constraints. These studies examine the behaviour of the materials

(Imbren, 2014; Norell & Rodhe, 2014; Vercruysse, 2019; Norman, 2004); human scale (Lengyel & Toulouse, 2007; Knapp, 2013); gestures (Pinochet, 2016; Motalebi & Duarte, 2017); cultural aspects (Wallisser, et. al., 2019); photogrammetry (Römert & Zboniska, 2021) urban inputs (Diniz, et. al., 2012; Tian & Yu, 2020); on-site applications (Hitchings, et. al., 2017) and nature-inspired methods and/or natural conditions (Cantrell & Yates, 2009; Moya, et. al., 2014; Dimopoulos, et. al., 2020) that are implemented in the digital processes (Quijada, 2008).

- (3) Studies that investigate the human-machine interface introduce a gadget or tool that allows additional inputs into the design and fabrication process, such as Augmented Reality/Virtual Reality (AR/VR) (Dorta, 2006; Poustinchi, et. al. 2018; Fong, et. al., 2020; Bevilacqua, 2021) or Artificial Intelligence (AI) (Cudzik & Radziszewski, 2018). However, it is not straightforward to define the boundaries of this theme since the 'human-machine interface' will encompass every profession after digitalization.
- (4) Some studies are aimed at reinterpreting conventional tools and propose a novel understanding of already existing tools. The focus of these studies is diverse, whether based on a pre-digital method (Dritsas & Becker, 2007; Voordouw, 2015; Jaminet et. al, 2021; Hamzaoglu, et. al., 2022); a digital method (Serriano, 2003; Parthenios, 2008; Kenzari, 2010; Asanowicz, 2012; Dounas & Spaeth, 2016); or preliminary examples aimed to find implementations of digital tools for design studies (Neiman & Bermudez, 1998; Donath et. al., 2001).
- (5) Studies that analyze reciprocal processes include collaborative (Schubert et. al., 2011) and responsive processes (Burry, et. al., 2010; Davis, et. al., 2011; Zandavali, et. al., 2020) which include feedback data (Ahlquist & Fleischmann, 2008). Some studies may incorporate cybernetic/bio-cybernetic theories (Viscardi, 2002; Wójcik & Strumiłło, 2017). These studies aim to consistently transfer analogue data to the digital environment and by mostly using hybrid techniques such as file-to-factory processes (Dunn, 2012) Reciprocity is clearly associated with the two previous themes, as feedback loops are crucial for cybernetics and systems theory and reciprocity makes it possible to implement real-life data into the digital environment.

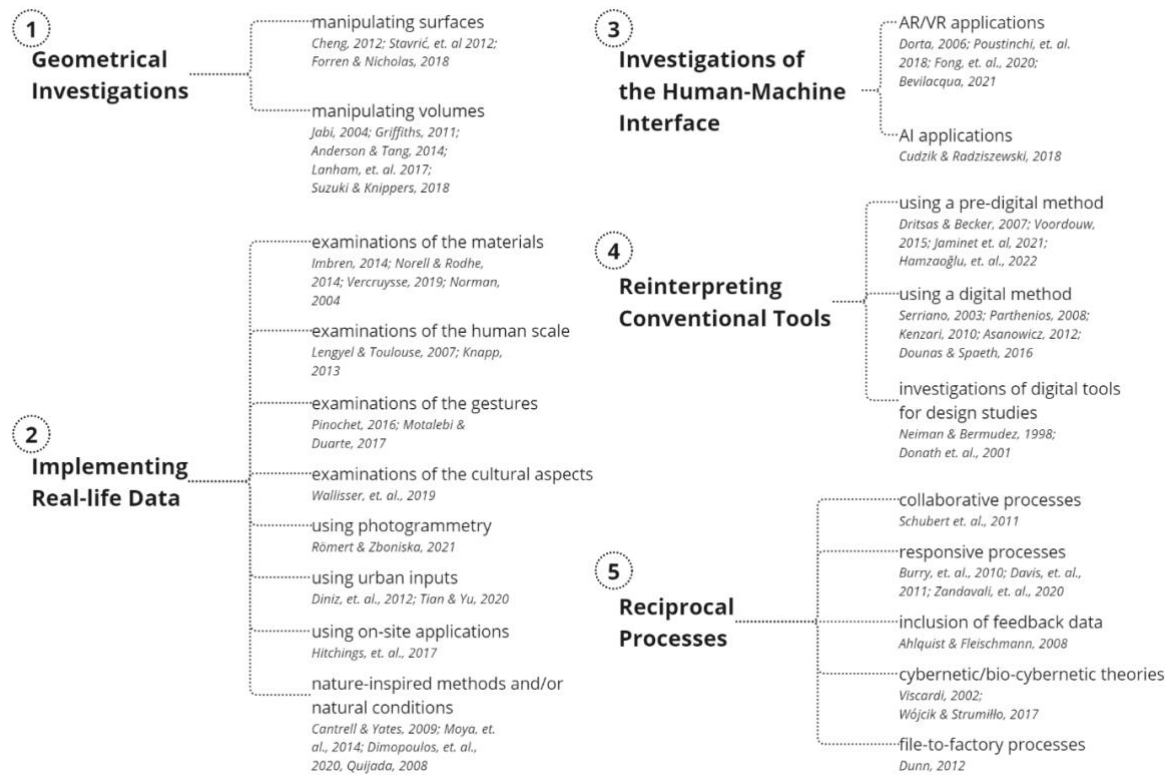


Figure 2: Classification of the reviewed papers.

2.2 Interpretation of the Review Results

This literature review helps us identify contemporary approaches to making in the digital era, focusing on the intersection between analogue and digital fabrication, as well as completely digital methods. In general, contemporary approaches emphasize the importance of reciprocity. While some efforts focus on geometric variations of form, it is crucial to oscillate between digital and physical realms for the realization and making processes. A common feature of all these approaches is that the fabrication process is characterized by constant feedback loops in which the digital and real data consecutively transform each other.

For hybrid methods, some approaches primarily use analogue techniques, with digital tools providing supplementary data. In these cases, the origin of the design process is completely analogue and the crafting process can be enriched by digital data. Other methods rely on digital fabrication, though the process is bred by physical constraints,

particularly in terms of material and form. Rationalization plays a crucial role when the design process starts entirely within a digital medium. These thresholds determined the classification of fabrication methods and the focused research area, as represented in **Figure 4**, along the fabrication method axis.

For completely analogue practices, when there were no computers, the crafting process required a certain degree of sensitivity to real-world conditions, ‘a mutual understanding’; however, it is highly undesirable to make alterations on site. In principle, the draft is an idealized prediction of real-life, which must function like clockwork, as inherited from the modernist paradigm. Therefore, any improvisations that have to be made during construction are seen as a weakness of the design, therefore, the designers.

Contemporary digital technologies allow designers to better prepare for the constraints of real-life before actually realizing the project. With the help of computers, it is indeed possible to make more accurate predictions, and this ability is increasing every day. At first glance then, digital tools seem to define a pinnacle of the obsession with perfection. But as much as designers are prepared for the real world, ‘to make’ still requires a challenge between two realms of information. Crafting in the digital era does not entail homogeneously ‘blending’ the digital and real-world (Norman, 2014); instead, it is an intuitive and chaotic process. As the tools advance, more possibilities expand proportionally, making the process even more complicated, not simpler.

The main hypothesis of this inquiry is that, throughout the evolution of architectural fabrication, improvisation or the realm of creativity that used to manifest itself during making was initially completely normal at first, then highly undesirable, and then relocated to different phases of the process. But has not ‘evaporated’ as modernity or orthodox computational designers might postulate.

To trace the relocation and involvement of intuitive and creative knowledge in the design and fabrication phases, brickwork serves as an excellent research area for the following reasons:

- It is one of the oldest and most widely used fabrication methods to date, employing both ordinary molded bricks and stereotomic units.

- The oldest examples of brickwork required on-site improvisation and an intuitive approach due to the lack of technological advancements, making brickwork highly relevant to this inquiry.
- It is the most common conventional practice, found across nearly every culture and location.
- Brickwork is also extensively applied in digital fabrication methods, utilizing either ordinary bricks or manufacturing unique blocks that allow for a degree of tessellation.
- Even before computational technologies, there were experiments with masonry techniques using isomorphic or custom-shaped bricks.
- The crafting methodology remains consistent in nearly all practices evaluated under tessellated methods. For this research, tessellated structures are analyzed, meaning repeated units are combined to form a larger structure.

For these reasons, brickwork provides a meaningful basis for comparing different degrees of digitalization in crafting.

3. MASONRY AS A REALM OF INVESTIGATION

For the reasons mentioned above, masonry practices are highly relevant for investigating the different ways of making, from fully analogue methods to computational techniques. Masonry brickwork will be examined through its various implementations and actual built examples. To cover all stages of the evolutionary development of brickwork, its historical, typical-conventional, and digital applications will be thoroughly analyzed. In addition, its experimental applications, even before the advent of computational technologies, will also be explored.

Starting with historical masonry practices **Figure 3(a)**, that are *bricoleur* processes (Lévi-Strauss, 2021), meaning that, what is available in the immediate environment is used directly to solve the spatial needs and requirements. An ancient practice of masonry with plano-convex bricks that is common in the Mesopotamian region is an elaborate example of such a *bricoleur* process. Mud bricks evolved into plano-convex bricks, eventually making it possible to create more complex spatial arrangements (Kawami, 1982).

In the ancient Mesopotamian vernacular, the use of plano-convex bricks favoured speed and ease of craft over precision and perfection (Erarslan, 2018). This ‘imperfection’ is mainly caused by the irregularity of plano-convex bricklaying –they are prismatic bricks with a convex surface that have been moulded by hand so that they are out of balance–, although the bricks are similarly shaped, they are not isomorphic.

The herringbone pattern is very common in the plano-convex period because the bricks were laid on their edges rather than flat (Erarslan, 2018). The load-bearing capacity of the wall must be recalculated at the same time as each brick is laid because each brick determines the location and position of the next brick. For these reasons, the form of the wall cannot be predefined and the craft is rather ‘sloppy’.

Typical-conventional practices **Figure 3(b)** with isomorphic and mostly rectangular-shaped regular bricks are analogue processes. Regular bricks require more precise craftsmanship according to very basic principles that result in bricks to laid one on top of the other. To avoid a line of weakness, bricks should be arranged as staggered vertical joints. To achieve this, some bricks may need to be cut in half or in a certain proportion, and rough edges can then be chipped off.

The attributes of the wall (height, length, width, position, orientation, etc.) are predetermined. However, to a certain extent, it is sometimes necessary to make minor on-site (for example, on which line to use the chipped bricks to create the staggered verticality) decisions. Besides, the linearity and order of the wall must be constantly checked with a rope or a water gauge.

There are also some innovative and experimental masonries (Imbren, 2004) that date back to the pre-digital age. For example, the masonry wall of ‘La Ricarda House’, built in 1963 by architect Antonio Bonet Castellana, has the same principle as conventional techniques (repeating and stacking), but it was possible to create an original surface by using custom designed, hollow bricks. Even before computers, it was possible to create weaving walls as in the ‘Atlantida Church’ built by Elado Dieste in 1952. These examples are precedents of what digital fabrication will technically achieve in the coming years.

Digitally designed and/or fabricated projects using bricks **Figure 3(c)** are methodologically assessed under ‘tessellating’ (Iwamoto, 2009) or ‘tiling’ (Dunn, 2002) techniques, in the literature of digital fabrication. Both terms refer to inductive processes, where smaller units combine to form the overall geometry. However, there are some exceptions, for example, in the case of the facade of ‘Mulberry House (2007)’ in New York, SHoP Architects designed the overall geometry of the facade, and the variations of units/bricks were determined later in the process. Another example is the facade of ‘Gantenbein Vineyard (2006)’ in Fläsch, 2006 by Gramazio & Kohler, where the bricks are laid to reflect a grape pattern. ETH Zurich created a freeform structure in Switzerland in 2011, which was rationalized using ‘RhinoVAULT’ software. These examples involve reverse engineering by first creating the overall geometry and then defining its units.

Gramazio & Kohler have conducted other experiments that push the limits of masonry, such as ‘Domoterra Lounge (2007)’ in Basel or ‘Structural Oscillations (2007–8)’ in Venice. Both of the weaving walls are digitally designed and crafted by robotic arms to create curvilinear forms, which is not easy to achieve considering how coherent brick is to rectangular forms. Gramazio & Kohler went a step further with ‘Pike Loop (2009)’ in New York, by applying the same principles volumetrically.

Greg Lynn reinterprets bricklaying using ‘Binary Large Object [Blob] Architecture’ and digital fabrication methods. Lynn’s rather small-scale experiment was ‘Duck Table’ in 2008, where he looked for novel ways to assemble customized and tessellated objects. For ‘Duck Table’ for example, Lynn scanned rubber ducks and tried out variational geometries that emerged from their intersections.

Lynn’s large-scale and more sophisticated experiment with the same principles is called ‘Blobwall’, first realized as an installation in 2005. Lynn (2005; 2017) reinvented the bricks as hollow, plastic rotomolded and customized units, by cutting them with a ‘Computer Numerical Control (CNC)’ robotic arm and assembling them by heat welding to form a freestanding wall or enclosure. A robotic arm is programmed by using inverse kinematics which is commonly used by animators (Lynn, 2017) that simulates the movement of an arm more accurately compared to the other kinematic models.

Up to this point, all projects have illustrated digital fabrication with real-life information, either with rationalization processes or additional tools for simulation that partially imitate real life, however, to make is mainly aided by digital technologies. In the following examples, digital tools are used but crafting procedures are relatively analogue.

Omar Rabie's adobe experiments 'One Curve Four Walls & Engineered Earth Project (2008)' are compressed, rammed, and cast into moulds (Gelirli and Arpacioğlu, 2020), all of which respond to material properties and require human craftsmanship. Fologram, an experimental design initiative, implemented AR technologies into the masonry process. The process resembles the aforementioned experiments of Gramazio & Kohler, in which the bricks were laid robotically; however, in Fologram's example, AR and a human subject are involved. They believe that "even the most sophisticated computer vision algorithms cannot match the intuition and skill of a trained bricklayer (Franco, 2019; Bensley-Nettheim, 2020)". This is a particular example because the craftsman is assisted with additional technologies rather than following a completely computational process.

There are a multitude of examples of various kinds of craftsmanship in brickwork. Since it is impossible to enumerate them all, both widespread examples and important exceptions of brickwork are mentioned here. The aim is to categorize these examples based on their scale of spatiality (ranging from units to volumes) and their level of digitalization (scaled from completely analogue to digital) as in **Figure 4**.

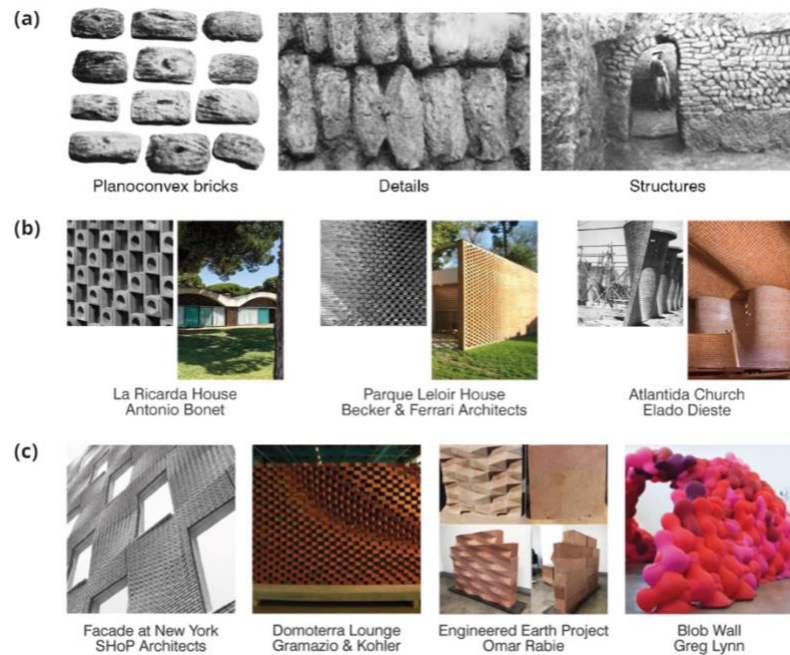


Figure 3: Examples of (a) historical, (b) conventional, and (c) digital brickwork

Along with this categorization, a ‘focused research area’ is defined to compare and track the transformation from analogue to digital bricklaying methods. The focused research area was selected to allow for a meaningful comparison by concentrating on tessellated examples of brickwork, rather than more volumetric or spatially complex examples, as shown in **Figure 4**. These examples encompass historical, typical-conventional, digitally informed analogue fabrication, and digital fabrication enriched by real-life data.

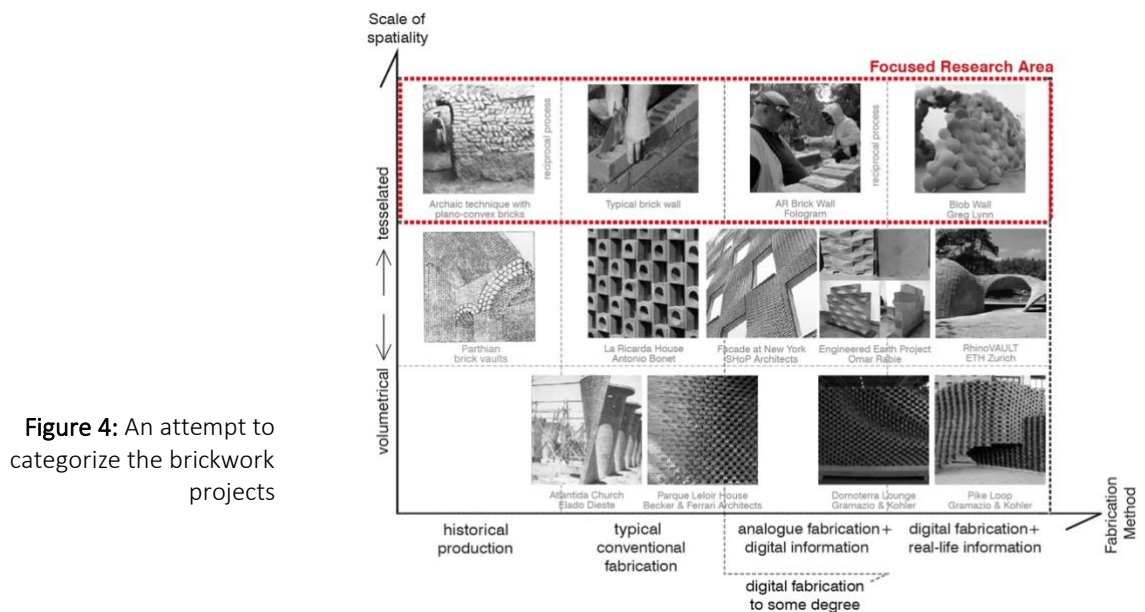


Figure 4: An attempt to categorize the brickwork projects

4. COMPARISON OF DIFFERENT WAYS TO MAKE

The focused research is based on comparing the crafting processes of the aforementioned fabrication methods to highlight the nuances in decision points and crafting procedures. Therefore, four distinct workflows representing different approaches to making will be presented in this section. The workflows for the craft processes are also displayed in **Figures 5, 6, 7, and 8**.

A historical way to make with plano-convex bricks: Most decisions are made at the moment of laying bricks, considering the properties of the resource, e.g., ‘is the gap bigger than the average brick?’ or ‘is there a brick that fits?’. Each problem is solved separately, depending on the structural performance at that moment from a relativistic point of view. The main challenge in the decision-making process is determining how to place bricks of various sizes and shapes horizontally, vertically, or in both directions consecutively. To achieve stability, a brick can be broken from a random point (rather than according to predetermined proportions as in typical conventional masonry practices) or replaced by another. All these decisions are made by the craftsman, which at the same time requires a high degree of sensitivity to real-life conditions, which means that in case of failure, the course of the decisions must be changed immediately. Nevertheless, it is not possible to decide where to place the next brick without first positioning the initial one. The process is therefore highly reciprocal and intuitive to a certain extent **Figure 5**.

The typical conventional building techniques with regular bricks: First the ground is tested with a water gauge, only when the ground is flat the operation can start. The procedure is highly recursive and follows staggered characteristics. The rectangular and isomorphic characteristics of the regular bricks lead to repeated actions and bring ease to the craft. Only at the end, to create a neat finish in every two rows and not to decrease load-bearing capacity, the bricks are broken in a prefixed predetermined ratio of 1/2, 3/4, and so on. In the meantime, the regularity of the walls must be checked constantly by using some additional equipment.

Figure 5: Workflow of historical brick wall fabrication with plano-convex bricks.

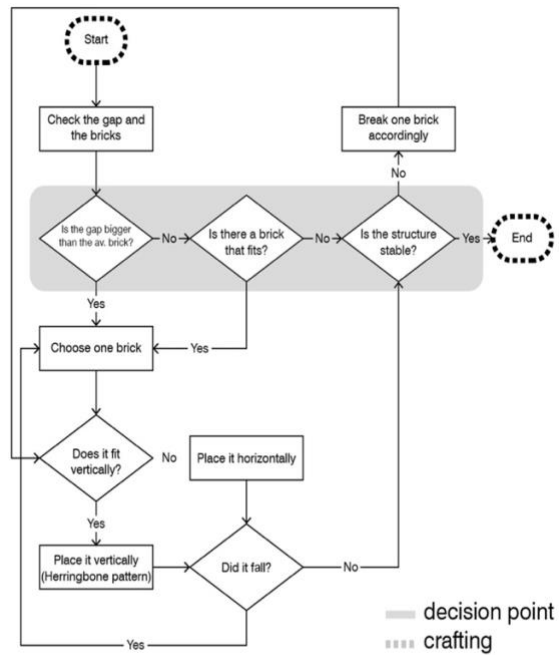
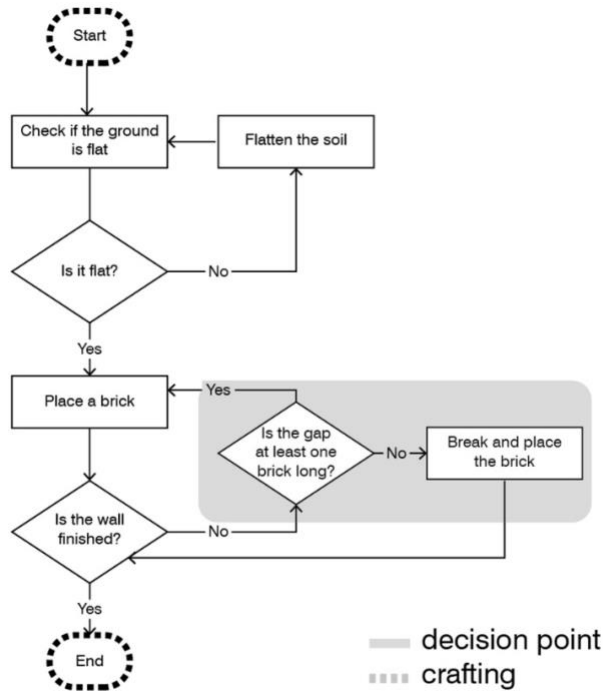


Figure 6: Workflow of conventional brick wall fabrication.



The most significant feature of the typical conventional way of fabricating a brick wall is that it requires manipulation of real-life circumstances to produce a well-defined, predetermined result,

whereas in the first example of historical craft, real-life data directly influences the result; real-life is not just a to be controlled as in the typical procedure, but rather a companion of the process. The workflow in **Figure 6** shows that in the typical procedure, the process is comparatively scarce, the key points are very few and descriptive; the feedback loops are limited and isolated, unlike the other examples.

The digitally informed analogue fabrication of brickwork: The procedure gains dual characteristics with AR. The final product is precisely designed in the digital environment beforehand and two sets of data from the digital environment and the physical world are intertwined during crafting.

Craft is led by a human subject as in regular bricklaying. However, the process is constantly controlled via AR glasses in accordance with the initial design. The fabrication phase is not as defined as in the latter example yet the digital data is still involved. It is more of a hybrid process between the analogue and the digital ways of making. On-site decisions are minimized although not neglected, so that the bricklayer's intuitive knowledge has a correspondence during the fabrication process as shown in **Figure 7**.

The digital fabrication, enriched by real-life data, of Blobwall: : Blobwall features a process that chronologically precedes the example of the AR-implemented brick wall. Lynn has many trials to assemble complex, curvilinear forms of tri-lobed blobs. He first generates the units, whether they are isomorphic or not, and then begins to create variational intersections between them. When the result is geometrically sufficient and structurally satisfactory, it is translated into volumetric knowledge and then to a path, thereby the movement of the robotic arm can be programmed (Lynn, 2017).

There are two important features of the fabrication. First, the design process has a direct reflection on reality that is almost seamless, at least it is relatively much more advanced than the previous example. In other words, the design has advanced to the level of fabrication in the digital environment, which means that the process that brings the project into reality, does not contain any ambiguous points prior to the building phase as shown in **Figure 8**.

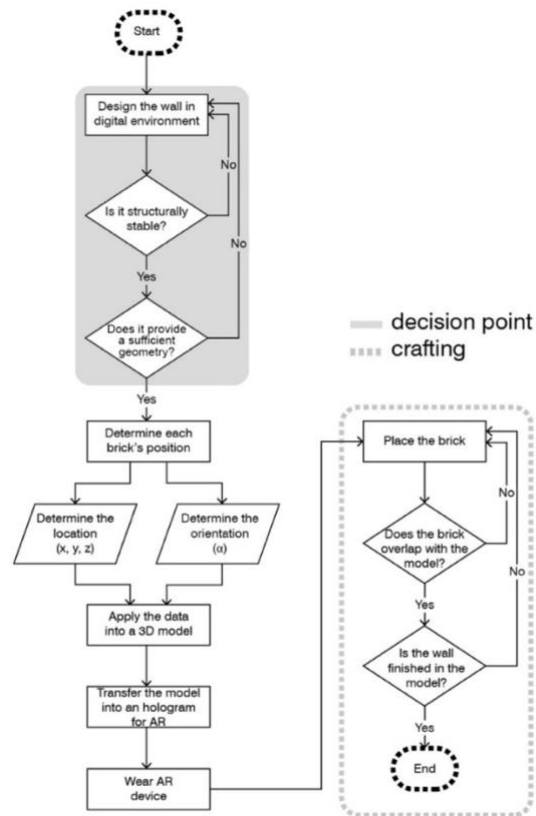


Figure 7: Workflow of AR-Implemented brick wall fabrication.

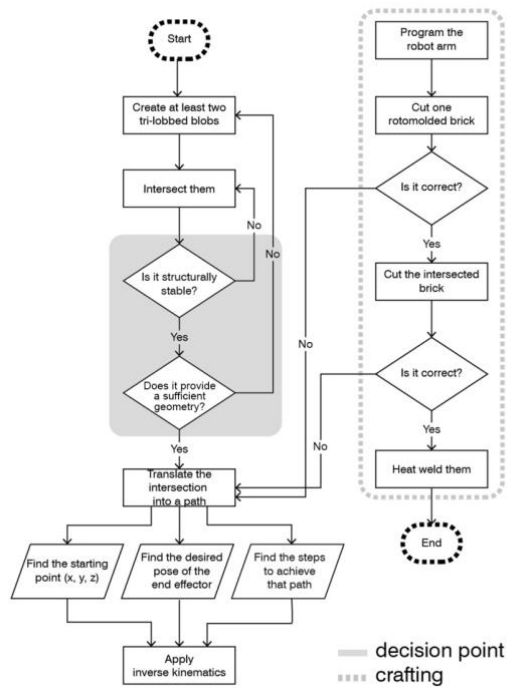


Figure 8: Workflow of the Blobwall fabrication.

This aspect contrasts with historical practices that require many decisions during the making of the structure. This level of precision is only possible because most of the crucial decisions regarding structural stability and geometrical preferences are made in the early stages of design in the digital environment. The result is constantly revised with additional data sets, creating feedback loops that influence the result itself.

Secondly, it is also significant that inverse kinematics is used instead of forward kinematics for programming the robotic arm. Forward kinematics is a simpler and more conventional method for modeling motion. By defining the movement of the child effector as a function of the mother effector, the movement is systemized hierarchically. Inverse kinematics, on the other hand, is more successful in modeling organic movement. Lynn (2017) preferred the robotic arm's movement to resemble a more 'humanoid'/natural motion, to realize the complex forms of blobs.

From the above examples, we can easily trace the transformation in fabrication methods. It begins with an intuitive approach, where decisions are made during the fabrication process, making design and craft inseparable. The decisions made at each point have a broad, horizontal impact on the entire process.

The typical conventional tendency, however, is to prevent unexpected situations during the making process by relying on *a priori* decisions. Very few decisions are made during fabrication, as most are separated from the normal flow of the process. This leads to an automated point where design and fabrication become completely dissociated.

In the latter two examples –semi-digitized and fully digitized– the separation between design and craft becomes evident. In both cases, the properties of the final product are precisely defined in advance, though there is a significant difference between them. In the case of the AR application, two datasets –physical and digital– overlap, and the craftsman simply follows the digital instructions. However, with Blobwall, there is an intense trial-and-error phase before fabrication begins.

5. EPILOGUE

This study primarily investigates the evolving relationship between physical craft and digital environments within the context of fabrication and crafting of bricklaying techniques. There are distinct nuances between different fabrication techniques from an evolutionary perspective. However, offering the craftsman the ability to intuitively decide the next step without knowing the final outcome in advance does not always appear to be positively correlated with the advancements in technology and computational design tools.

In historical, typical conventional, and digitally informed practices, the craftsman had a direct, on-site presence. In historical crafting, the craftsman made intuitive, real-time decisions based on materials and immediate conditions. In typical practices, however, the craftsman's influence on the outcome was more limited. In digitally informed bricklaying processes using AR headsets, the craftsman still has an on-site role, but it is guided by a digitally predesigned layout. Finally, in the digital fabrication of Blobwall, although most of the process occurs within a digital interface, real-life constraints are accounted for –not only through structural considerations but also by simulations that closely resemble real-world conditions.

The most inefficient and alienating method of brick wall fabrication among these examples is found in typical practices. These practices are highly insensitive to real-life data, reducing the craftsman to a mere mediator –a hand responsible for laying bricks according to a blueprint based on a rigid, rule-based system. As a result, the distinction between using a human or a robotic arm becomes negligible. The craftsman's decisions are extremely limited, evoking a sense of deep alienation, similar to that of a worker on an assembly line, placing objects with little connection to the overall outcome.

In the AR-implemented version, the process is enhanced and guided, but since the final product is fully determined in the digital interface in advance, it offers little opportunity for the craftsman to improvise or make on-site decisions.

A significant similarity is found between historical practices and the most digitized fabrication method, the Blobwall, in terms of allowing

the craftsman creative freedom for improvisation and making instantaneous decisions during the crafting process. The key difference is that historical methods require physical presence on-site and direct engagement with the material, while in the Blobwall example, the craftsman is actively experimenting within a digital interface. However, the overall process of intuitive decision-making is strikingly similar in both approaches. From this point of view, the concept of an 'archaic revival' seems to be a valid discussion, regarding how fabrication methods may evolve in the coming years.

While this study focuses on tessellated structures, further research could explore more complex, volumetric approaches to gain a broader understanding of the transformation in fabrication processes. Moreover, as computational design continues to evolve, it is likely that new hybrid methods will emerge, further blurring the lines between human and machine in the crafting process.

In conclusion, the transformation of crafting from analogue to digital methods reflects a broader shift in architectural practices. Although digital fabrication may reduce the physical involvement of the craftsman, it opens new possibilities for design and construction that were previously unimaginable. The ongoing integration of digital tools into traditional methods suggests that the future of crafting will likely involve a harmonious blend of both physical and digital worlds, where 'thinging' becomes the norm, combining the precision of digital techniques with the adaptability and creativity of human craftsmanship.

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Statement

The manuscript is entitled "An Inquiry on Analogue and Digital Making Processes in Architecture: Craft and Fabrication within the Scope of Masonry Structures" has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere. Additionally, the authors of the study declare that there is no financial

or other substantive conflict of interest that could influence the results or interpretations of this work.

Author Contribution Statement

All authors contributed equally to this article.

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A Material-Based Computational Framework for Masonry Shell Structures

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Shell structures have been an interesting subject from past to present due to their ability to cross wide openings, produce free forms, efficient material usage and design potential. In addition to all these advantages, design and production processes also bring various difficulties. The oldest examples of shell structures, masonry shell structures, have come to the fore again with the increasing use of digital design technologies. Forms produced by making physical models have given way to simulations, models and calculations performed in digital environments. However, material information is generally ignored while performing form finding studies. Based on this observation, the study aimed to examine the relationship between form, material and structural performance. First, a literature review was conducted and shell structures were classified. Then, masonry shell structures were discussed; and the changes in form finding, material usage and production methods from past to present were examined. Finally, a three-stage algorithm proposal was developed in which material information was integrated into the early design phase of masonry shell structures. In the first stage, the shape generation was performed with the RhinoVault plugin, which handles the Thrust Network Analysis method. In the second stage, the surface was divided into sub-parts using the NGon plugin and the thickness was given. In the third stage, the Young's Modulus, tensile and compressive strength information of six different materials, namely C20 concrete, C40 concrete, clay brick, firebrick, limestone and sandstone, were integrated into the algorithm using the Karamba3D plugin. Then, performance analysis was performed using the Finite Element Method (FEM). As a result of the analysis, it was observed that limestone was the best performing material among the six materials, while clay brick was the lowest performing material. Considering the properties of the materials and their performances, it was observed that the Young's Modulus value was the parameter that affected the performance the most.

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Yığma Kabuk Strüktürler İçin Malzeme Tabanlı Hesaplamalı Bir Çerçeve

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Kabuk strüktürler geniş açıklık geçebilme, serbest biçim üretebilme, verimli malzeme kullanımı ve tasarım potansiyeli sebebiyle geçmişten günümüze ilgi çekici bir konu olmuştur. Bütün bu avantajlarının yanında tasarım ve üretim süreçleri çeşitli zorlukları da beraberinde getirmektedir. Kabuk strüktürlerin en eski örneklerini oluşturan yığma kabuk strüktürler, sayısal tasarım teknolojilerinin kullanımının artmasıyla beraber yeniden gündeme gelmiştir. Fiziksel modeller yapılarak üretilen biçimler yerini dijital ortamda gerçekleştirilen simülasyonlara, modellere ve hesaplamalara bırakmıştır. Fakat biçim bulma çalışmaları gerçekleştirilirken genellikle malzeme bilgisi göz ardı edilmektedir. Bu gözlemden yola çıkılarak yapılan çalışmada biçim, malzeme ve strüktürel başarımlar arasındaki ilişkinin incelenmesi amaçlanmıştır. İlk olarak literatür taraması yapılarak kabuk strüktürlerin sınıflandırılması yapılmıştır. Ardından yığma kabuk strüktürler ele alınıp; geçmişten günümüze biçim bulma, malzeme kullanımı ve üretim yöntemlerinin değişimi incelenmiştir. Son olarak yığma kabuk strüktürlerin erken tasarım evresine malzeme bilgisinin entegre edildiği, üç aşamadan oluşan bir algoritma önerisi geliştirilmiştir. Birinci aşamada İtme Ağı Analizi yöntemini ele alan RhinoVault eklentisi ile biçim üretimi gerçekleştirilmiştir. İkinci aşamada NGon eklentisi kullanılarak yüzey alt parçalara ayrılmış ve kalınlık verilmiştir. Üçüncü aşamada ise Karamba3D eklentisi kullanılarak; C20 betonu, C40 betonu, kil tuğlası, ateş tuğlası, kireçtaşı ve kumtaşı olmak üzere altı farklı malzemenin Young's Modülü, çekme ve basınç dayanımı bilgileri algoritmaya entegre edilmiştir. Ardından Sonlu Elemanlar Yöntemi (SEY) kullanılarak performans analizi yapılmıştır. Yapılan analiz sonucunda altı malzeme arasında kireçtaşının en iyi performans gösteren malzeme olduğu gözlemlenirken, kil tuğlası en düşük performans gösteren malzeme olmuştur. Malzemelerin özellikleri ve gösterdiği performanslar göz önüne alındığında, Young's Modülü değerinin performansı en çok etkileyen parametre olduğu gözlemlenmiştir.

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Anahtar Kelimeler: İtme Ağı Analizi, Malzeme, Sonlu Elemanlar Yöntemi, Strüktürel Başarımlar, Yığma Kabuk Strüktürler

1. GİRİŞ (INTRODUCTION)

Kabuk yapılar, üç boyutlu eğrisel yüzeyler ile oluşturulan, bir boyutu diğer iki boyutuna göre küçük olan yapılar olarak tanımlanmaktadır (Adriaenssens ve diğ., 2014). Yığma taş, tuğla, ahşap, kompozit betonarme gibi çeşitli malzemelerle inşa edilebilen kabuk strüktürler; malzeme verimliliği sağlaması, hafif olması, geniş açıklıklar geçebilmesi ve tasarım özgünlüğü sunması gibi sebeplerle mimarlık ve mühendislik alanları için önemli bir yapı grubu haline gelmiştir. Roma ve Bizans İmparatorlukları döneminde kubbe ve tonoz şeklinde üretilen kabuk strüktürler, günümüzde ileri analiz teknikleri sayesinde çeşitli malzemeler kullanılarak serbest biçimlerde tasarlanabilmektedir. Özellikle Felix Candela ve Eduardo Torroja gibi mimarların öncülüğünde, 1930'lu ve 1940'lı yıllarda ince beton kabukların kullanımı popülerlik kazanmıştır (Ejaz, 2023).

Kabuk yapıların ilk örnekleri olan yığma kabuk strüktürler, kendi ağırlığını ve üzerine gelen yükleri verimli bir şekilde dağıtabilmesi sebebiyle geçmişten günümüze kadar sağlam bir şekilde ayakta kalabilmiştir. Tonozlar ve kemerler gibi yığma kabuk formları, estetik ve işlevsel bir mimari anlayışın temsilcisi olmuştur. Yığma kabuk strüktürler, geniş açıklık, hafiflik ve yüksek mukavemet gibi avantajları nedeniyle yüzyıllardır dünyanın dört bir yanında kemerler, kubbeler ve tonozlar şeklinde inşa edilmiştir (Adriaenssens ve diğ., 2014). Özellikle tarihi dönemlerde; taş, tuğla veya benzeri malzemelerle oluşturulan bu yapılar hem estetik hem de işlevsel açıdan üstün bir performans sergilemiştir (Heyman, 1995). Günümüzde, geleneksel yığma tekniklerinin hesaplamalı tasarım araçlarıyla ele alınması, bu yapıların yeniden ilgi odağı haline gelmesine neden olmuştur.

Sayısal tasarım teknolojilerinin mimaride kullanılmasıyla beraber; algoritmik tasarım ve simülasyonlar aracılığıyla erken tasarım evresinden itibaren; tasarımın bitmiş halini tahmin edebilmek, çıkabilecek olası problemleri öngörmek, çeşitli sayıda tasarım alternatifi oluşturup değerlendirmek kolaylaşmıştır. Yığma kabuk strüktürlerin de tasarım ve üretim süreci doğası gereği ciddi bir hesaplama ve karmaşık analizler gerektirir. Bu nedenle sayısal tasarım teknolojilerinin tasarım ve üretim sürecine dahil olması zaman ve nitelik açısından verimliliği artırmıştır. Kabuk strüktürlerin tasarım sürecini verimli bir hale getirmek için hesaplama araçlarının kullanılmasının yanı sıra tasarım

aşamalarından itibaren mimarlar ve mühendisler arasında yakın bir işbirliği önem kazanmıştır (Tessmann, 2008). Yığma kabuk strüktürler üzerine yapılan çalışmalar hesaplamalı tasarım bağlamında incelendiğinde; parametrik modelleme tekniklerinin geliştirilmesi, biçim bulma, biçim optimizasyonunun gerçekleştirilmesi, davranış testleri, tarihi yığma yapıların restorasyon projelerinde dijital ikiz modellemeleri ile mevcut yapıların detaylı analizini yaparak hasar tespitinde kullanılması ve dijital fabrikasyon araçlarının üretim sürecine dahil edilmesi üzerine yapılan çalışmalar mevcuttur. Bu bağlamda yığma kabuk strüktürler için erken tasarım evresinden itibaren kullanılabilecek; biçim, malzeme ve strüktürel başarımlar arasındaki ilişkiyi inceleme konusunda literatürde boşluk bulunmaktadır. Günümüz mimari uygulamalarında, form, malzeme, form ve performans arasındaki ilişkiler dikkate alınmadan genel tasarım sürecine diktelenmektedir (Yazici & Tanacan, 2018). Malzeme parametresi sonuç ürün için en önemli kriterlerden biri olmasına rağmen genellikle tasarım sürecinde değerlendirilmemektedir. Bu nedenle yapılacak olan çalışmada, malzeme bilgisinin erken tasarım evresine entegre edilerek, biçim, malzeme ve strüktürel başarımlar arasındaki ilişkinin incelenmesi amaçlanmıştır. Yapılacak olan bu konuda bir çerçeve çizmeyi amaçlarken, sonraki çalışmalar için kapsamı genişletilerek malzemenin erken tasarım evresinden itibaren değerlendirilmesine olanak sağlayan bir yöntem olma potansiyeli taşımaktadır.

2. YÖNTEM (METHOD)

Yığma yapı tekniği, mimarlık tarihinin en eski inşaat yöntemlerinden biridir. Kökenleri, insanlığın yerleşik hayata geçişine kadar uzanır ve farklı coğrafyalarda binlerce yıl boyunca kullanılmıştır. Yığma teknikle üretilen kabuk strüktürler ise tasarımdan uygulamaya kadar mimarlık ve mühendislik başta olmak üzere birden çok disiplinin rol aldığı çok katmanlı bir tasarım sürecine sahiptir. Günümüzde hesaplamalı tasarımın geleneksel üretim yöntemi olan yığma teknikle olan ilişkisi incelenen bir araştırma konusu olmuştur. Yaklaşık son yirmi yılda mimarlık alanında kullanımı yaygınlaşan hesaplamalı tasarım araçları biçim, malzeme ve strüktürel başarımlar arasındaki ilişkiyi tasarımın erken evresinden itibaren irdelemeye olanak sağlayarak sürecin verimliliğini artırmaktadır. Bu gözlemden yola çıkılarak çalışmanın amacı, karmaşık bir hesaplama süreci olan yığma kabuk strüktürlerin erken tasarım evresinin irdelenerek, tasarımda önemli bir parametre olan malzeme

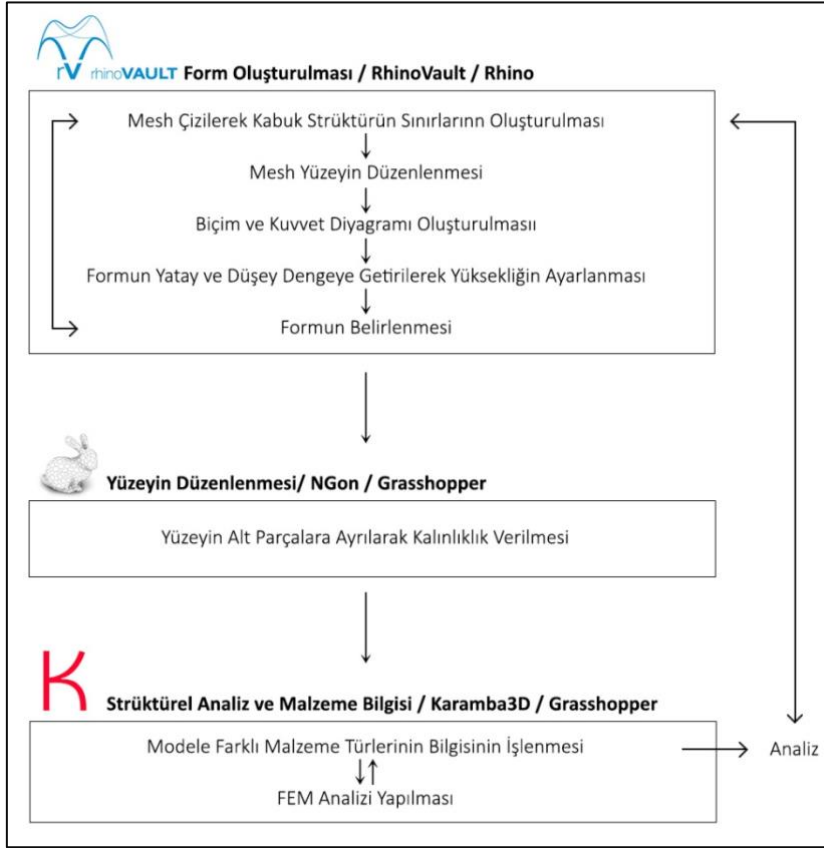
bilgisinin de sürece entegre edilebildiği; biçim, malzeme ve strüktürel başarımlar arasındaki ilişkinin beraber ele alındığı bütünleşik bir çerçeve oluşturmaktır.

İlk olarak literatür taraması yapılarak kabuk strüktürlerin sınıflandırılması yapılmıştır. Ardından yığma kabuk strüktürler ele alınıp; geçmişten günümüze biçim bulma, malzeme kullanımı ve üretim yöntemlerinin değişimi incelenmiştir. Son olarak yığma kabuk strüktürlerin biçim üretiminin yapılabileceği ve tasarım sürecine malzeme bilgisinin entegre edilip strüktürel performansının analiz edilebileceği bir algoritma tasarlanmıştır. Yığma kabuk strüktürler basınca dayanıklı olarak çalışırlar. Bu durum yığma kabuk strüktürler için gerilme olmadan yerçekimi karşısında sadece basınç yükleri oluşturan geometrilerin arayışını doğurmuştur (Er, 2022).

Algoritma üç aşamadan oluşmaktadır (**Şekil 1**). Birinci aşamada Matthias Rippmann tarafından geliştirilen RhinoVault eklentisi kullanılarak biçim oluşturulmuştur (Block Research Group, 2024). RhinoVault, föniküler kabuk yapıları tasarlamak için kullanılan ve İtme Ağı Analizi'ni temel alan bir Rhinoceros eklentisidir. Yapı içindeki kuvvetler arasındaki ilişkiye odaklanır ve biçimin uygulanan yükleri gerilim veya bükülme olmadan tamamen sıkıştırma yoluyla dengede kalmasını sağlar. Tasarımcının iki boyutlu yüzeyde kuvvet ağlarını etkileşimli olarak değiştirmesine ve sınırları düzenlemesine olanak tanıyarak, biçimi sezgisel bir şekilde oluşturur. Eklenti, iki boyutlu yüzeyleri manipüle ederek üç boyutlu hale getirerek yığma kabuk strüktürler için en uygun biçimi bulmayı sağladığı için tercih edilmiştir.

İkinci aşamada Petras Vestartas tarafından geliştirilen, Grasshopper eklentisi olan NGon kullanılmıştır (Golay, n.d.). Ngon eklentisi mesh oluşturma, düzenleme ve alt parçalara ayırmaya olanak sağlar. Algoritmada RV3 eklentisinin çıktısı olan mesh yüzeyinin alt parçalara ayrılması ve kalınlık verilmesi amacıyla kullanılmıştır. Üçüncü aşamada ise Karamba3D eklentisi kullanılarak, algoritmaya farklı türlerde malzeme bilgisi entegre edilmiştir ve Sonlu Elemanlar Yöntemi (SEY) kullanılarak strüktürel olarak gerilim gösteren alanların analizi yapıp sonuçlar karşılaştırılmıştır. Karamba3D, Grasshopper ortamında çalışan yapısal analiz eklentisidir (Preisinger, n.d.). Yapıları analiz edip performans olarak değerlendirmeyi ve optimize etmeyi sağlar. Aynı zamanda kullanılacak malzemenin mekanik özellikleri algoritmaya

eklenerek yapısal davranışı malzeme bilgisi ile birlikte analiz etmek de mümkün olmaktadır. Karamba3D eklentisi ile malzeme ve performans arasındaki ilişki eşzamanlı olarak incelenebildiği için tercih edilmiştir. Algoritmaya C20 ve C40 olmak üzere iki farklı beton; kil tuğlası ve ateş tuğlası olmak üzere iki farklı tuğla; kireçtaşı ve kumtaşı olmak üzere iki farklı taş türünün mekanik özellikleri entegre edilmiştir. Malzemeler seçilirken Young's modülü, çekme dayanımı ve basınç dayanımı özelliklerinin birbirine benzer olmaması göz önünde bulundurulmuştur.



Şekil 1: Çalışmaya Ait Yöntem Şeması (Method Chart of the Study) (Produced by the Authors).

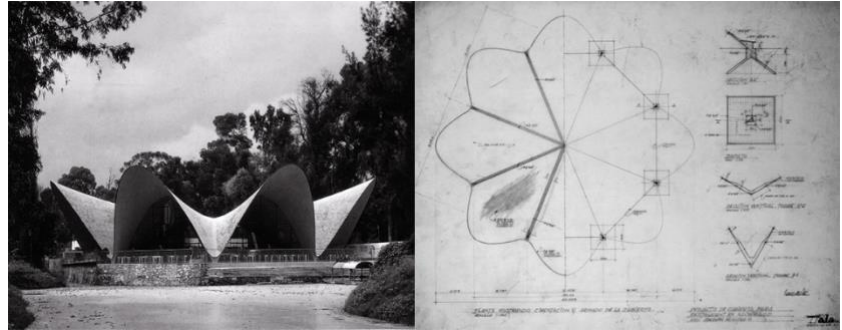
3. KABUK STRÜKTÜRLER (SHELL STRUCTURES)

Kabuk strüktürler, mimaride geniş açıklıklar geçebilme, verimli malzeme kullanımı ve çeşitli biçim denemelerine imkân sağlayan yapılardır. Tasarım olanakları ilgi çekici olan kabuk strüktürler; malzeme bilimi, mimarlık ve yapı mühendisliği gibi çeşitli alanları kapsamakta, bu nedenle farklı disiplinlerin birlikte ele alması gereken bir konudur. Sayısal tasarım teknolojilerinin gelişmesiyle beraber, geleneksel üretim yöntemlerinden öğrenilen bilgilerle kabuk strüktürler günümüzde

hesaplamalı tasarım ortamında yeniden ele alınmaktadır. İlk örnekleri yağma kabuk strüktürler olan bu yapı grubu, 20. yüzyılın başından itibaren teknolojinin olanaklarının genişlemesiyle ve beton malzeme kullanımının yaygınlaşmasıyla beraber üzerine yapılan çalışmalar artmıştır (Ejaz, 2023).

Alman mühendis ve mimar Franz Dischinger ile mimar Walter Bauersfeld tarafından 1920'lerde tasarlanan Zeiss-Dywidag fabrika binaları, ilk beton kabuk yapılarından biri olarak örnek verilebilir. Bu yapı grubu arasından en dikkat çeken, yapımı 1924'te tamamlanan Almanya'nın Jena kentindeki Zeiss Planetaryumu'dur. Bu yapı, beton malzeme kullanılarak hafif ve estetik açıdan yeni biçimler oluşturulabileceğine örnek olan ince kabuklu beton bir kubbeye sahiptir. 1930'lu ve 40' lı yıllarda İspanyol mühendis Eduardo Torroja ve Meksikalı mühendis Felix Candela, beton kabuk yapılar üzerinde çalışmalar yaparak bu alanda önemli ilerlemeler kaydetmişlerdir (Ejaz, 2023). Candela, iki boyutlu bir eğriyi bir eksen etrafında döndürerek üç boyutlu formlar oluşturmuştur. Yapımı 1958 yılında tamamlanan Mexico City'deki Los Manantiales Restoranı'nın çatısı bu yöntem kullanılarak tasarlanmıştır (**Şekil 2**). Candela ayrıca, çift eğrilik ve yükü yapı üzerinde dağıtmanın etkili bir yolu ile karakterize edilen "hiperbolik parabolit" yöntemini de geliştirmiştir (Cassinello ve diğ., 2010).

Şekil 2: (Solda) Los Manantiales Restoranı, (Sağda) Tasarım Aşaması ((Left) Los Manantiales Restaurant, (Right) Design Stage) (Miller, 2014).



1950'ler ve 60'lar, özellikle ince beton kabuklar ve germe membran yapılar için önemli bir zaman dilimi olmuştur. Bu dönemde Eero Saarinen tarafından tasarlanan Kresge Oditoryumu, Luigi Nervi tarafından tasarlanan Palazzetto dello Sport ve Frei Otto tarafından tasarlanan Expo 67 Alman Pavyonu, kabuk strüktürlere örnek olarak verilebilir. 1970'li yıllardan sonra kabuk strüktürler popülerliğini kaybetmeye başlamıştır (Vatandoost ve diğ., 2024). Bunun sebebi,

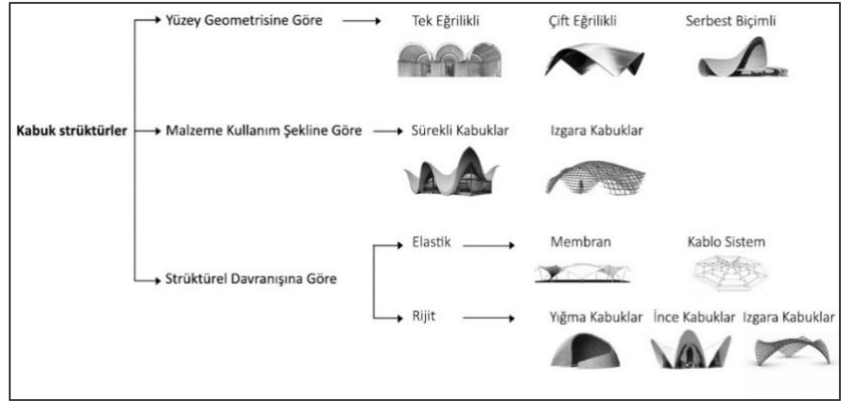
kısmen inşaat aşamasında gerekli olan karmaşık inşaat tekniklerine bağlanabilir (Hines ve diğ., 2004). 2000'li yılların başından itibaren bilgisayar destekli tasarım (CAD) ve bilgisayar destekli üretim (CAM) teknolojilerinin yaygın kullanımı, kabuk strüktürlerin daha karmaşık ve optimize edilmiş formlarda tasarlanmasını ve üretilmesini sağlamıştır.

Literatür taraması yapıldığında kabuk strüktürlerin birçok farklı şekilde sınıflandırıldığı gözlemlenmiştir. Özet olarak kabuk strüktürler yüzey geometrisine göre, malzeme kullanım şekline göre ve strüktürel davranışına göre üç ana başlıkta sınıflandırılabilir (**Şekil 3**). Kabuk strüktürler, yüzey geometrilerine göre sınıflandırılırken Gauss Eğriliği baz alınır. Gauss Eğriliği pozitif olan yüzeyler tek eğrilikli, Gauss Eğriliği negatif olan yüzeyler ise çift eğrilikli yüzeyler olarak tanımlanır. Serbest biçimli strüktürler ise, eğri yüzeylerin kesiştirilmesi ve basit geometrilerin birbirleriyle kombinasyonu ile oluşturulan karmaşık yüzeylerdir ve serbest biçim çalışmalarıyla veya deneysel yöntemlerle türetilirler (Türkçü, 2017, s. 111).

Malzeme kullanım şekline göre ise sürekli kabuklar ve ızgara kabuklar olarak ikiye ayrılabilirler. Sürekli kabuk strüktürler, kullanılan bir malzemenin tüm yüzeyde devam ettiği ve yapısal eleman olarak davranış gösteren yapılardır. Sürekli kabuk sistemleri dikey ve yatay olarak ayrıık yapısal elemanlardan oluşmazlar; bunun yerine yükleri geometrileri aracılığıyla taşırlar (Ağırbaş, 2019). Sürekli kabuk strüktürlerde ağırlıklı olarak beton, tuğla, taş gibi malzemeler kullanılmaktadır. Izgara kabuk strüktürler ise sürekli kabuk strüktürlerin aksine katı bir yüzeyden oluşmazlar. Ortaya çıkan yapı, birbirine bağlı ayrıık yapısal elemanlardan oluşan bir uzay-çerçeve yapısıdır (Ağırbaş, 2019).

Strüktürel davranışlarına göre ise elastik ve rijit olmak üzere ikiye ayrılabilirler. Elastik davranış gösteren kabuk strüktürler, çevresel kuvvetler altında şekil değiştirebilen sistemlerdir. Membran ve kablo sistemler hafif olmaları sebebiyle bu gruba örnek olarak verilebilir. Rijit davranış gösteren kabuk strüktürler ise çevresel kuvvetler altında şekil değiştirmezler. Belirli bir kalınlığa sahip olan yığma kabuk strüktürler, ince kabuk strüktürler ve ızgara kabuk strüktürler bu gruba örnek olarak verilebilir.

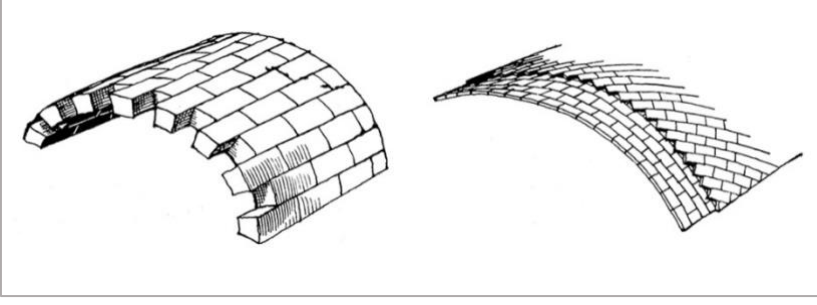
Şekil 3: Kabuk Strüktürlerin Sınıflandırılması (Classification of Shell Structures) (Produced by the Author).



4. YIĞMA KABUK STRÜKTÜRLER (MASONRY SHELL STRUCTURES)

Yığma yapım tekniği; taş, kil, tuğla veya beton gibi blok malzemelerle inşa ve üretim sanatı olarak tanımlanmaktadır (DeJong, 2009). Antik Mısır ve Roma döneminde de yığma yapım tekniğine sıklıkla rastlanmaktadır. Orta Çağ'da, özellikle Avrupa'daki katedral ve kalelerin inşasında tuğla ve taş işçiliği gelişmiştir. Günümüzde de sayısal tasarım teknolojileri benimsenerek yığma yapım tekniği yeniden ele alınmakta ve çeşitli potansiyeller araştırılmaktadır.

Geleneksel yığma kabuk strüktürlerin mimaride ve inşaatda uzun bir geçmişi vardır ve belli boyuttaki malzemelerin bir araya gelmesinde her ne kadar sınırlamalar olsa da etkileyici yapılar inşa edilmiştir. Yığma kabuk strüktürlerin ilk örnekleri kubbeler ve tonozlar olarak karşımıza çıkmaktadır. Bu tür kabuklar öncelikle basınç altında bulunurlar çünkü tuğla ve taş gibi duvar malzemeleri basınçta güçlü, çekmede ise zayıftır (Ochsendorf & Block, 2014). Bu strüktürlerin biçim bulma sürecinde tamamen sıkıştırma ile çalışan formlar bulmak konusu kısıtlayıcı olmuştur. Katalan tonozu ve Guastavino tekniği yığma kabuklar için önemli çözümler sunmuşlardır. 14. yüzyılda İspanya'da ortaya çıkan Katalan tonozu, kemer veya tonoz oluşturmak için kalıp yüzeyinin ince tuğlalarla kaplanması ile oluşur (Ochsendorf, 2014). Tuğlalar, alışlagelmiş uygulamanın aksine, yan yana monte edilir. Bu teknikte, tuğlaları oluşturmak için kil ve tuğlaları birbirine bağlamak için harç gibi bağlayıcı bir malzeme kullanılması yeterlidir.



Şekil 4: Geleneksel taş tonoz ile Guastavino kiremit tonozunun karşılaştırılması
(Comparison of the traditional stone vault and the Guastavino tile vault)
(Moya, 1947).

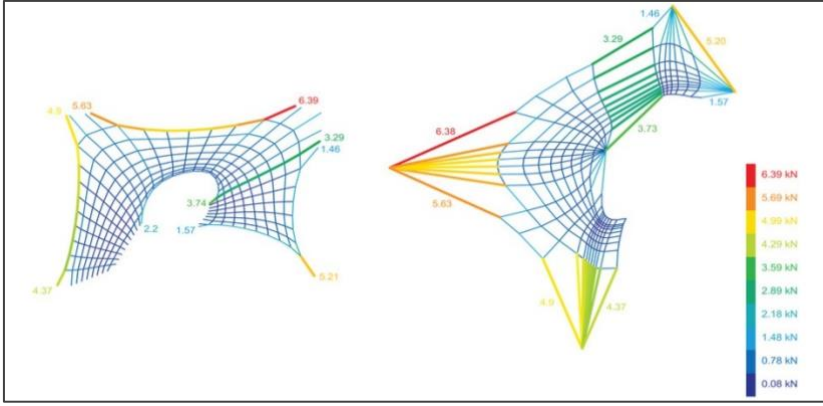
Kökleri Akdeniz'e uzanan bu tekniğin tarihi, Arapların ve Romalıların benzer inşaat tekniklerini kullandıkları antik çağlara kadar uzanmaktadır (Ritisan ve Pierre, 2022). 19. yüzyılın sonlarında Rafael Guastavino Sr. (1842-1908) ve Jr. (1872-1950), geleneksel Akdeniz tonoz yöntemini Amerikan inşaatının taleplerine uyarlayarak Amerika Birleşik Devletleri'nde büyük bir etki yaratmıştır (Ochsendorf, 2014). Katalan tonozunu temel alan bu yöntemde birden fazla sıra halinde düz olarak döşenen yaklaşık 15 x 38 x 2,5 cm ölçülerinde ince kiremit karolar kullanılmıştır. Geleneksel olarak taş kullanılan tonozlara göre Guastavino yönteminde daha az malzeme kullanılır (**Şekil 4**). Ağırlık olarak da Guastavino yöntemiyle inşa edilen strüktürler daha hafif olduğu için geleneksel yönetime göre yatay itme kuvveti daha azdır. Geleneksel yığma kabuklar çoğu zaman yapısal hesaplamalar yapılmadan inşa edilmiş olsa da tarihi tonoz inşaatçıları çift kavisli yığma kabuklarda mümkün olan çoklu denge durumları konusunda önemli bir farkındalık geliştirmişlerdir (Ochsendorf & Block, 2014).

Geleneksel yığma yapım yöntemlerinde, ustalar orantı ve geometri kurallarına dayalı tasarım yöntemlerini kullanmışlardır. Yığma yapıların stabilitesine ilişkin ilk bilimsel anlayış olan Hooke'un tersinme yasası, 1676 yılında İngiliz bilim adamı Robert Hooke tarafından, ters asılı zincir şeklinde formüle edilmiştir (Block & Ochsendorf, 2007). Bu anlayış birçok yığma kabuk strüktürün biçim bulma sürecine önemli katkılar sağlamıştır. Asılı bir ipe her bir parçanın öz ağırlığı ile orantılı olacak şekilde ağırlıklar eklenir ve oluşan geometri ters çevrildiğinde kemerin yaklaşık olarak sıkıştırma dengesi ortaya çıkmaktadır. Londra'daki St Paul Katedrali'nin tasarımı sırasında Robert Hooke ile Christopher Wren beraber çalışmıştır ve kubbenin tasarımına yardımcı olmak için Hooke'un tersinirlik yasasını kullanmışlardır (Addis, 2014). 33 m çapındaki kubbeye ilişkin çizimlerde binanın kesiti üzerinde asılı duran bir zincir şekli gözükmemektedir. Bu model testi, Hooke ve Wren'in kubbenin bir sıkıştırma yapısı olarak iyi bir şekilde çalışacağına ve bir

yapının biçimini belirlemeye yardımcı olmak için kullanılan fiziksel bir modelin bilinen en eski kullanımı olduğuna dair bir kanıt olmuştur (Addis, 2014).

Giovanni Poleni (1683–1761), 1740'larda Hooke ilkesini, bir dizi endişe verici radyal çatlak geliştiren Roma'daki Aziz Petrus Katedrali'nin yüz yıllık 41,9 metre çapındaki kubbesinin güvenliğini değerlendirmek için kullanmıştır (Addis, 2014). Poleni, modeli taş kemerlerin ideal şeklini belirlemek için kullanmıştır. Heinrich Hübsch (1795-1863) de Hooke'un tekniğini kullanarak, istenilen kemer veya tonoz şeklini elde etmek için gereken kemerlerin ağırlıklarını belirlemek amacıyla askı ipi modelleri yapmıştır (Addis, 2014). Bu yöntem 1837'de bir dökümhanenin 16 m çapındaki yarım küre şeklindeki kubbesinin yapımında kullanılmıştır. Hafif ve içi boş kil çömlerle yapılan kubbenin bir kısmının kalınlığı 17,5 cm'e düşürülebilmektedir. 19. yüzyılda da kemerler ve tonozların ideal biçimini bulmak için askı modelleri sıklıkla kullanılmıştır. Antoni Gaudí (1852–1926) bu dönemde tasarladığı birçok yapıda üç boyutlu askı modeli kullanmıştır. Bunlardan en iyi bilineni Colònia Güell'in mezarıdır (Tomlow, 2011).

Günümüzde yağma kabuk strüktürlerin biçim bulma sürecinde ETH Zürih Blok Araştırma Grubu tarafından geliştirilen İtme Ağı Analizi yöntemi kullanılmaktadır (**Şekil 5**). Bu yöntem, yağma yapıların askı zincirleri ile bindirme çizgileri arasındaki benzerliklerden ilham almıştır (Saltık, 2018). Matthias Rippmann tarafından geliştirilen Rhinoceros yazılımı eklentisi olarak çalışan RhinoVault aracıyla kolaylıkla biçim üretimi yapılabilmektedir. Eklenti aracılığıyla biçim üretimi iki adımda gerçekleştirilir. İlk olarak, yağma kabuk strüktürün sınırları belirlenir ve biçim diyagramı oluşturulur. Ardından, oluşturulan biçim diyagramından hareketle kuvvet diyagramı oluşturulur. Bu adımda yatay itme kuvvetlerinin dengesi çözülmektedir. Hem biçim hem de kuvvet diyagramları manipüle edilebilir. İkinci adımda ise dikey yüklere ve yüksekliğe bağlı olarak itme analizi gerçekleştirilir. İtme Ağı Analizi'ndeki temel strateji, tasarımcıya sistemdeki itkilerin dağılımı üzerinde doğrudan kontrol vermektir (Saltık, 2018). İtme Ağı Analizi yönteminde kullanılacak malzemeden bağımsız olarak geometrik bir biçim bulma gerçekleştirilir.



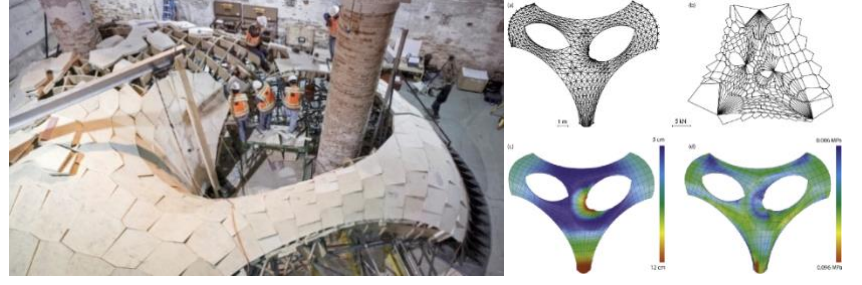
Şekil 5: İtme Ağı Analizi Yöntemi (Thrust Network Analysis Method) (Rippmann ve diğ., 2012).

Malzeme bilgisi mimari tasarım sürecinde sonuç ürünü elde etmek adına en önemli parametrelerden biridir. Geleneksel tasarım sürecinde, kullanılacak olan malzemelere genellikle proje aşaması bittikten sonra üretim aşamasında deneme-yanılma yoluyla karar verilmektedir. Sayısal tasarım araçlarının gelişmesiyle beraber hem malzeme kavramına bakış değişmiş hem de malzeme kullanımını sürece dahil etmek daha kolaylaşmıştır. Ancak yine de pratik olarak bu yaklaşım çok yaygınlaşmamıştır. İlk kez Gramazio ve Kohler tarafından tanımlanan 'dijital materyalite' kavramı malzeme kavramını yeniden değerlendirmeye olanak sağlayıp tasarım sürecine dahil olma biçimini değiştirmiştir. Geçmişten günümüze kadar yığma kabuk strüktürlerin tasarımında malzeme kullanımı ve üretim biçimleri şekil değiştirmiştir. Zanaat, mimarlık ve mühendislik birleşimi olan yığma kabuk strüktürler geçmişte insan gücüyle üretilirken, günümüzde insan gücü ve robotların iş birliğiyle de üretilabilmektedir.

2016 yılında ETH Zurich Blok Araştırma Grubu tarafından Venedik Bienali için tasarlanan Armadillo Vault, takviyesiz ve harçsız olarak birleştirilen 399 ayrı kireçtaşı parçasından oluşmaktadır. Tarihi taş katedrallerin tasarım prensiplerinden yola çıkarak oluşturulan bu strüktür, tasarım süreci ve malzeme kullanım biçimiyle yenilikçi bir yaklaşım sunmaktadır (Şekil 6). Tonoz, basınç altında durmakta ve sınırı boyunca üç doğrusal destek ve ortada bir destek ile toplam 75 m²'lik bir alana yayılmaktadır (Rippmann ve diğ., 2016). Hesaplamalı tasarım ve optimizasyon yöntemleri kullanılan tasarım sürecinde, bilgisayar ortamında formları belirlenen ayırık birimler 5 eksenli CNC kullanılarak oluşturulmuştur. Kontrplak kullanılarak yapılan kalıp üzerine birimler yerleştirilmiştir. Montaj sırasında taş ustalarının hassas bir şekilde birleşimleri yapmaları gerekmiştir (Rippmann ve diğ., 2016). Proje, karmaşık bir tasarım ve üretim sürecinin hesaplamalı tasarım ve dijital

fabrikasyon yoluyla en az hatayla sonuçlandırılabilceğini göstermektedir.

Şekil 6: (Solda) Armadillo Vault İnşa Süreci, (Sağda) Tasarım Süreci ((Left) Armadillo Vault Building Process, (Right) Design Process) (Rippmann ve diğ., 2016).



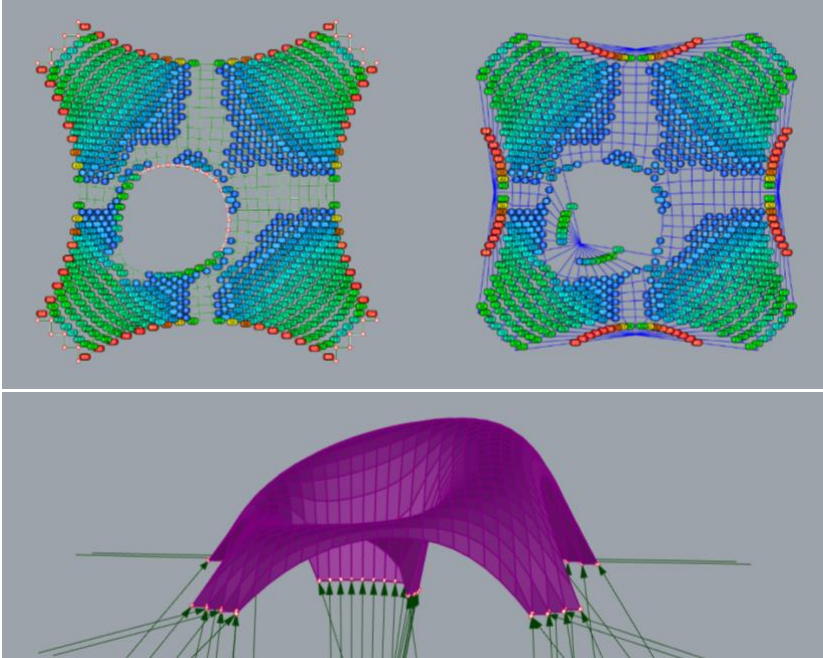
2023 HCCH Studio tarafından tasarlanan Konsept Kütüphane, çağdaş yapım teknikleri ve yerel malzeme kullanımının birleşimidir. Kütüphane yaklaşık 10 m çapında ve 5 m yüksekliğindedir ve malzeme olarak yerinde dökme tuğla kullanılmıştır. Kütüphanenin yapımında tamamen insan gücü kullanılmıştır. Çift kavisli yüzey üzerine tuğlaların yerleştirilmesi projenin en zor kısmı olmuştur. Çelik iskelet arasında tuğlalar yerleştirilmiş ve araları yüksek dayanımlı betonla doldurulmuştur. Radyal devamlılığı sağlamak için 12 farklı genişlikte tuğla kullanılmıştır. Stüdyo, en eski malzemelerden biri olan tuğlayla çağdaş yapım teknikleri ve tasarım yöntemleri kullanarak biçim denemesi gerçekleştirmiştir (Shuangyu, 2023).

Bilgi teknolojilerinin mimarlık alanındaki artan etkisi, malzeme ile mimari tasarım arasında, malzemenin temel itici güç haline geldiği yeni bir ilişki tanımlamıştır (Yazici & Tanacan, 2020). Mimaride sayısal tasarım araçlarının kullanılmasıyla birlikte malzeme bilgisi modele entegre edilebilmektedir. Bu sayede modelin strüktürel başarımı, maliyet bilgisi ve çevresel etmenler ile ilişkisi tasarım evresindeyken değerlendirilebilir ve optimum seçenekler belirlenebilir.

5. VAKA ÇALIŞMASI (CASE STUDY)

Geliştirilen algoritmada, yığma kabuk strüktürlerin tasarım sürecine malzeme bilgisinin de entegre edilebildiği; biçim, malzeme ve strüktürel başarımlar arasındaki ilişkinin birlikte ele alındığı bütünsel bir çerçeve oluşturulması amaçlanmıştır. Algoritma üç aşamadan oluşmaktadır. Birinci aşamada Rhinoceros eklentisi olan RhinoVault kullanılarak biçim oluşumu gerçekleştirilmiştir. RhinoVault eklentisi, yapısal biçim bulma sürecinde kullanıcı odaklı ve kontrollü bir keşif için gerekli olan görsel

diyagramlarda temsil edilen biçim ve kuvvetlerin doğal, çift yönlü karşılıklı bağımlılığından yararlanır (Rippmann & Block, 2013). Bu eklenti, kubbe ve tonoz gibi yapıların denge durumunu inceleyen İtme Ağı Analizi yöntemini temel alır. İtme Ağı Analizi, yapıların sıkıştırma kuvvetiyle çalıştığını varsayarak, bu kuvvetin dağılımını inceler. Sıkıştırma kuvvetinin yapıda nasıl dağıldığı iki boyutlu olarak bir ağ sistemi olarak temsil edilir. RhinoVault ile biçim oluşturulurken ilk olarak 15m x 15m ölçülerinde bir mesh çizilmiştir. Ölçüye sezgisel olarak karar verilmiştir. Ardından mesh düzenlenerek bir kısmında açıklık oluşturulup destek noktaları belirlenmiştir. Mesh düzenleme kısmındaki 'Relax' komutu kullanılarak köşelerdeki gerilimi azaltmak amacıyla köşelere eğim verilmiştir. İstenilen eğim elde edildikten sonra, ilk önce biçim diyagramı ardından da kuvvet diyagramı oluşturulmuştur (Şekil 7). Diyagramlar oluşturulduktan sonra, ilk önce yatay denge, ardından da insan ölçeği göz önünde bulundurularak 4 m yükseklik verilerek düşey denge oluşturulmuştur (Şekil 8).



Şekil 7: (Solda) Biçim Diyagramı, (Sağda) Kuveet Diyagramı ((Left) Form Diagram, (Right) Force Diagram) (Produced by Authors).

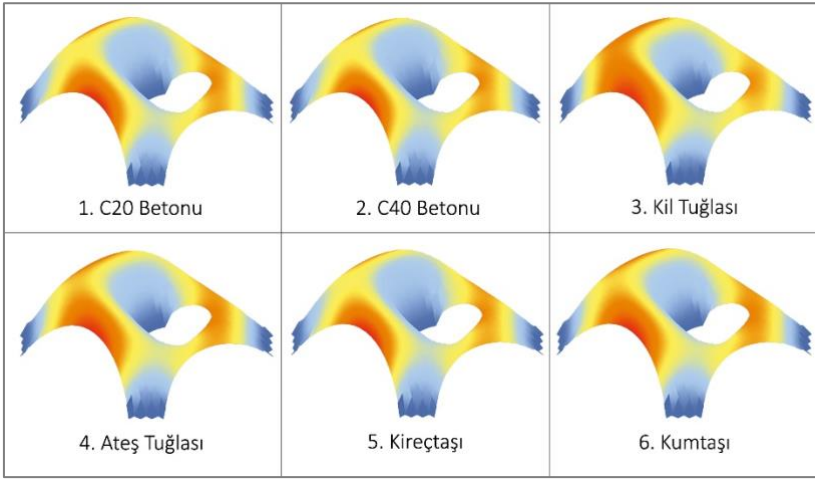
Şekil 8: Düşey Denge (Vertical Equilibrium) (Produced by Authors).

İkinci aşamada oluşturulan yüzey, Grasshopper ortamında Ngon eklentisi kullanılarak alt parçalara ayrılmış ve kalınlık verilmiştir. Üçüncü aşamada ise Karamba3D eklentisi kullanılarak malzeme bilgisi algoritmaya entegre edilmiştir ve Sonlu Elemanlar Yöntemi (SEY) kullanılarak farklı malzemeler için gerilmelerin olduğu kısımlar karşılaştırılmıştır. Sonlu Elemanlar Yöntemi, yapının bileşenlerinin çeşitli yükler altında gösterdiği davranışı inceleyen yapısal analiz için kullanılan bir yöntemdir. Tasarımcıların geleneksel yöntemlerle değerlendirmesi zor olan karmaşık yüzeylerin analiz edilmesini sağlar.

Modele iki farklı beton, iki farklı tuğla ve iki farklı taş olmak üzere toplamda altı adet farklı malzeme bilgisi entegre edilmiştir (**Şekil 9**). Malzemelerin Young's Modülü, çekme dayanımı ve basınç dayanımı bilgileri belirlenerek kN/cm^2 birimi olarak algoritmaya eklenmiştir. Beton malzemesi için TS500 Standardı kaynak olarak kullanılırken; tuğla ve taş malzemeler için MatWeb (2024) veri tabanından yararlanılmıştır. Malzemelerin özellikleri, içeriğinin bileşenlerine göre değiştiği için Şekil 10'da verilen değerler ortalama bir değer olarak belirlenmiştir. Beton malzemesinin basınç dayanımı yüksek, çekme dayanımı ise düşüktür. Young's Modülü ise malzemenin basınç altında ne kadar esneyebileceğini ifade eder. Beton malzemesi sert bir malzeme olarak kabul edilir. Algoritmaya C20 ve C40 olmak üzere iki farklı beton türü entegre edilmiştir. Tuğla malzemesinin ise çekme dayanımı, basınç dayanımına göre daha zayıftır. Young's Modülü ise tuğlanın türüne göre farklılık göstermektedir. Algoritmaya düşük yoğunluktaki kil tuğlası ile ateş tuğlası entegre edilmiştir. Taş malzemedede ise basınç ve çekme dayanımları taşın türüne göre değişiklik göstermektedir. Genellikle basınç dayanımları yüksektir ve çekme dayanımları basınç dayanımına göre daha düşüktür. Young's Modülü ise taşın türüne göre değişiklik göstermektedir. Belirlenen altı adet malzeme özelliklerine göre kıyaslandığında; en yüksek Young's Modülü değerine kireçtaşı sahipken, en düşük değere kil tuğlası sahiptir. Kireçtaşı en yüksek çekme dayanımına sahipken, kil tuğlasının çekme dayanımı en düşüktür. Basınç dayanımında ise en yüksek değere C40 Betonu sahipken, kil tuğlası en düşük basınç dayanımına sahiptir.

Şekil 9: Kullanılan Malzemelerin Mekanik Özellikleri (Mechanical Properties of the Materials Used) (Produced by Authors).

Sıra	İsim	Sınıf	Young's Modülü [kN/cm^2]	Çekme Dayanımı [kN/cm^2]	Basınç Dayanımı [kN/cm^2]
1	C20	Beton	2800	0,16	2
2	C40	Beton	3400	0,22	8
3	Kil Tuğlası (Düşük Yoğunluk)	Tuğla	300	0,1	1
4	Ateş Tuğlası	Tuğla	1000	0,3	3
5	Kireçtaşı	Taş	3500	1,6	7
6	Kumtaşı	Taş	1300	0,5	1,3



Şekil 10: Kullanılan Malzemelerin SEY Analizi Yapılarak Karşılaştırılması (Comparison of Used Materials by FEM Analysis) (Produced by Authors).

Seçilen malzemeler sırayla modele entegre edilmiştir ve SEY analizi yapılmıştır (**Şekil 10**). Maviden kırmızıya doğru gittikçe gerilim artmaktadır. Yapılan analiz sonucunda altı malzeme arasında kireçtaşının en iyi performans gösteren malzeme olduğu gözlemlenirken, kil tuğlası en az performans gösteren malzeme olmuştur. Malzemeler kendi sınıfları arasında kıyaslandığında C20 ve C40 betonları arasında belirgin bir fark gözlemlenememiştir. Kil tuğlası ile ateş tuğlası arasında ve kireçtaşı ile kumtaşı arasında ise belirgin bir fark gözlemlenmiştir. Malzemelerin özellikleri ve gösterdiği performanslar göz önüne alındığında, malzemelerin Young's modülünün performansı en çok etkileyen parametre olduğu gözlemlenmiştir.

6. SONUÇ (CONCLUSION)

Çalışma, yığma kabuk strüktürlerin erken tasarım evresine malzeme bilgisini entegre edip; biçim, malzeme ve strüktürel başarımlar arasındaki ilişkiyi incelemiştir. Öncelikle kabuk strüktürler incelenmiş olup; yüzey geometrisine göre, malzeme kullanım şekline göre ve strüktürel davranışına göre sınıflandırılmıştır. Rijit davranış gösteren sürekli yüzeye sahip yığma kabuk strüktürler çalışmanın odak noktasını oluşturmuştur. Ardından yığma kabuk strüktürlerin biçim bulma, malzeme kullanımı ve üretim yöntemlerindeki geçirdiği değişimler ele alınmıştır. Fiziksel deneyler yapılarak gerçekleştirilen biçim bulma denemeleri, yerini sayısal tasarım teknolojilerinin gelişmesiyle beraber bilgisayar ortamındaki çeşitli simülasyonlara ve araçlara bırakmıştır.

Günümüzde ise çeşitli eklentilerin yanında İtme Ağı Analizi yöntemini temel alan RhinoVault eklentisi kullanılmaktadır. Geçmişte genellikle benzer boyutlarda tuğla, taş, kerpiç blok gibi malzemeler kullanılırken, günümüzde ise 5 eksenli CNC gibi dijital fabrikasyon araçlarının ve sayısal hesaplama araçlarının yaygınlaşmasıyla çeşitli biçimlerde ve ebatlarda malzemelerle çeşitlilik sağlanabilmektedir.

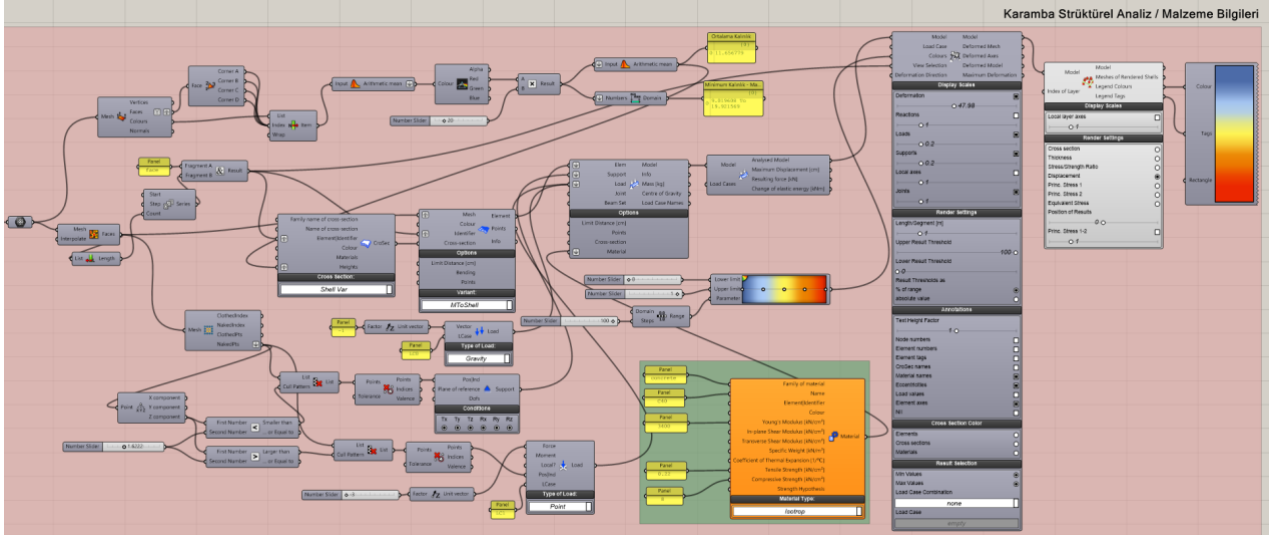
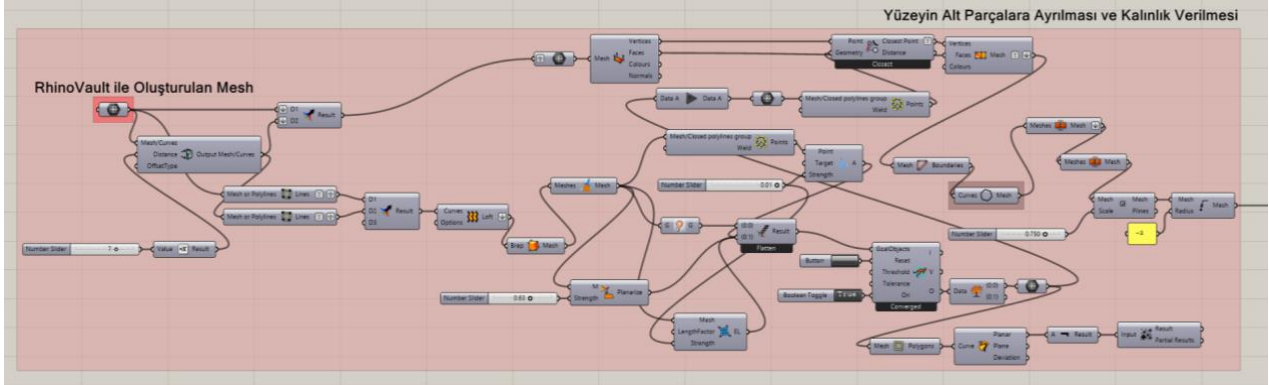
Yapılan çalışmada biçim, malzeme ve performans arasındaki ilişkiyi incelemek amacıyla üç aşamadan oluşan bir algoritma geliştirilmiştir. Birinci aşamada Rhinoceros eklentisi olan ve İtme Ağı Analizi yöntemi temelli RhinoVault eklentisi ile biçim bulma denemesi yapılmıştır. 15 m x 15 m ölçülerindeki mesh yüzey üzerinde düzenlemeler yapıp 4 m yüksekliğinde bir strüktür oluşturulmuştur. İtme Ağı Analizi yönteminde malzemeden bağımsız olarak statik dengeyi sağlamak amacıyla bir biçim bulma işlemi gerçekleştirilir. İkinci aşamada RhinoVault eklentisi ile elde edilen 'mesh' yüzey NGon eklentisi kullanılarak yüzeyin alt parçalarına kalınlık verilmiştir (**Şekil 11**). Üçüncü aşamada ise Karamba3D eklentisi kullanılarak tasarım sürecine malzeme bilgisi entegre edilip Sonlu Elemanlar Yöntemi (SEY) kullanılarak, strüktürün farklı malzemeler tercih edildiğinde gösterdiği performans değişimi incelenmiştir (**Şekil 12**). Malzeme olarak C20 betonu, C40 betonu, kil tuğlası, ateş tuğlası, kireçtaşı ve kumtaşı olmak üzere altı farklı malzeme tercih edilmiştir. Kıyaslama yapılabilmesi için malzemelerin mekanik özelliklerinin birbirine benzer olmamasına dikkat edilmiştir. Ardından beton malzemeler için TS500 standardından, tuğla ve taş malzemeler için ise malzemelerin özelliklerinin bulunduğu veritabanına sahip olan MatWeb üzerinden ortalama sayısal değerler alınmıştır. Alınan bu değerler Karamba3D eklentisi ile algoritmaya entegre edilmiştir ve performans analizi yapılmıştır. Kırmızı olan bölgeler strüktürel zorlanmanın fazla, mavi olan bölgeler ise strüktürel zorlanmanın az olduğu yüzeyleri göstermektedir. Yapılan kıyaslama sonucunda kireçtaşı en iyi performansı gösterirken, kil tuğlası en düşük performansı gösterdiği gözlemlenmiştir. Malzemelerin mekanik özelliklerinden Young's Modülü değeri analiz için en önemli parametre olmuştur. Young's Modülü değeri arttıkça performans artmıştır.

Gerçekleştirilen algoritma yığma kabuk strüktürlerin tasarım süreci için deneysel bir çalışmadır ve geliştirilmeye devam edecektir. Farklı malzemelerin farklı performanslar gösterdiği gözlemlenmiş olup; tasarım sürecinin erken evresinden itibaren malzeme bilgisinin de

sürece katılması, üretim aşamasında çıkabilecek problemleri minimuma indirmeyi sağlayabilir. Kullanılan malzemelerin mekanik özellikleri için ortalama değerler kullanılmıştır. Çalışmanın daha özelleştirilmiş sonuçlar vermesi için, kullanılabilecek malzemelerin numuneleri hazırlanıp test edilmelidir. Gelecek çalışmalarda birim malzemelerin özelliklerinin modele nasıl entegre edilebileceği, oluşabilecek tesselsasyonların biçimi ve strüktürel başarımı nasıl etkileyeceği, biçim ve malzeme ilişkisinin optimizasyon yöntemleri araştırılabilir.

Şekil 11: Algoritmanın 2. Aşaması (2nd Stage of the Algorithm) (Produced by Authors).

Şekil 12: Algoritmanın 3. Aşaması (3rd Stage of the Algorithm) (Produced by Authors).



Çıkar Çatışması Beyanı (Conflict of Interest Statement)

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Dynamic Casting: Using Deployable Fabric Formwork

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The utilization of fabrics as formwork can facilitate a certain degree of flexibility in design, particularly when combined with deployable structures. Regarding this statement, the aim of this study is to explore the potential of a fabric formwork with deployable structure principles to prevent rigidity in the casting process. The deployable approach combined with fabric contributes to the study by allowing various configurations and reusability. A design-led methodology is adapted during this exploration based upon five phases: (1) crease pattern selection, (2) digital pattern creation, (3) deployable fabric formwork construction, (4) casting the concrete and (5) comparing the physical model to computational model. Various models and mediums are used to examine the form behaviors along with the material relationship to highlight the collaboration between tools and craft to achieve a common goal. Therefore, the utilization of digital mediums is expected to improve the understanding of such a complex system as a dynamic mold fed by interdependent parameters. The results comparing the digital simulations and the several attempts to create the casting products displayed similar, if not identical, attributes. The differences between these models depend on the properties of the selected materials for both the deployable skeleton and the fabric.

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Keywords: Casting, Deployable Mold System, Fabric Formwork, Fabric Mold, Folding

Dinamik Kalıp: Konuşlandırılabilen Kumaş Kalıp Kullanarak Döküm

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Kumaşların kalıp olarak kullanılması, özellikle konuşlandırılabilir yapılarla birleştirildiğinde tasarımda esneklik sağlayabilir. Bu ifadeyle ilgili olarak, bu çalışmanın amacı, döküm sürecinde sabitliği önlemek için konuşlandırılabilir yapı prensiplerine uygun kumaş kalıpların potansiyellerini araştırmaktır. Kumaş ile birleştirilen konuşlandırılabilir yaklaşım, çeşitli konfigürasyonlara ve yeniden kullanılabilirliğe izin vererek çalışmaya katkıda bulunmuştur. Bu araştırmada beş aşamaya dayanan tasarım odaklı bir metodoloji uyarlanmıştır: (1) katlama şablonu seçimi, (2) katlanma şablonunun dijital ortamda üretimi, (3) konuşlandırılabilir kumaş kalıp yapımı, (4) betonun dökülmesi ve (5) karşılaştırma. Üretilen fiziksel, hesaplamalı ve dijital modellerin form davranışlarının yanı sıra malzeme ilişkisinin de incelenmesi için çeşitli model ve dijital ortamlar kullanılmıştır. Ortak bir hedefe ulaşmak için araçlar ve zanaat arasındaki iş birliğini vurgulamak amacıyla form davranışlarının yanı sıra malzeme ilişkisini incelemek için çeşitli modeller ve ortamlar kullanılmıştır. Bu nedenle, dijital ortamların kullanımı, birbirine bağlı parametrelerle beslenen dinamik kalıp gibi karmaşık bir sistemin anlaşılmasında yardımcı olmuştur. Dijital simülasyonları ve döküm ürünlerini oluşturmaya yönelik çeşitli çalışmaların karşılaştırıldığı sonuçlar, birebir aynı olmasa da benzer nitelikler sergilemiştir. Modeller arasındaki farklar hem konuşlandırılabilir iskelet hem de kumaş için seçilen malzemelerin özellikleriyle bağdaştırılmıştır.

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1. INTRODUCTION

The concept of craft obtains many meanings, such as an activity involving a special skill at making things with your hands (Oxford Dictionary, 2024). It is the combination of different operations to form the same products repeatedly. The inclusion of the hands is one of the prominent features encountered during the explanation of craft, whether digital or traditional. McCullough (1996) mentions the supportive and opposed relationship between technology and craft in his book, “Abstracting Craft: The Practiced Digital Hand”. Although the technology and tools advanced through the years, the use of the hand for the craftsman did not diminish but evolved into different motions that rely more on fast and small notions. The change shows how the skill and dedication of the craftsman can adapt to the technological advancements of the tools. Since the meaning of craft implies the inclusion of skill in putting something together, partnerships with technology are better than autonomous technology (McCullough, 1996). This project aims to follow this partnership with tools to benefit from the different utilization of hands in the digital environment and physical realm to perform holistic research on the casting process.

Casting using concrete or cement has been a commonly applied method in various fields of architecture and engineering since its invention. The use of rigid and planar mold structures utilizing timber or steel for the formwork during the casting process has created a norm in these fields for the concrete elements to have simple, prismatic, and uniform cross-sections (Hawkins et al. (2016). These applications lack flexibility and limit the creativity of designers while increasing production costs, duration, the material usage, and waste since these rigid molding systems are not reusable (Elmas & Alaçam, 2018). Although it is suitable for various cases, the usage of different materials as molds can enhance the flexibility and material-based design approach by making the parameters of the molding material a crucial point of the design. The usage of fabric formwork has increased due to the enhancements in synthetic production technologies and concrete pumping (Ghaib & Górski, 2001) since the early 2000s. The application of the fabric formwork allows a variety of forms with the help of the changing parameters of the fabric and poured mixture, thus preventing the system from being rigid.

Concrete casting is a dynamic process with the liquid nature of the initial phase of the mixture. The mixture adapts and follows the shape of the formwork. The use of the planar mold systems fails to reflect the properties of the compound and makes the process rigid. Regarding the issue of rigidity, it is necessary for the molding system to be supported by a structure that enables the desired form to be imparted to the fabric. While many studies focus on the flexibility of the fabric formwork through a state of form and structure generation (Kostova et. al, 2019; Popescu et al., 2021), there are few studies concentrating on the dynamic nature of fabric formwork in terms of generating variations of form through a sole reusable mold system (Akçay Kavakoğlu, 2020; Baghi et.al, 2022). The proposed system of Akçay Kavakoğlu (2020) took advantage of the fabric's deformation resistance, thus preventing the need for additional materials in the production of each new product and enabling the use of the same fabric mold in the generation of multiple products. In light of these pioneering studies, more research is aimed at exploring the possible methods to enhance the flexibility of mold systems in terms of material usage, reusability, and sustainability. Deployable support systems have huge potential for incorporating dynamic molds and fabric formwork.

Deployable structures are defined as those that are capable of undergoing a change in appearance, whereby they enable transition from a larger configuration to a smaller one, typically through the process of folding. During this process, the parameters, such as geometry, material properties, and mechanical considerations, play a pivotal role in the design (Rivas-Adrover, 2015). Deployable systems are lightweight, reusable, and, most importantly, flexible structures due to their changing and evolving nature (Rivas-Adrover, 2015). Consequently, these characteristics have potential to enhance the flexibility of the fabric formwork as aforementioned. Regarding these, this study aims to elaborate dynamic mold system through a deployable fabric formwork application. Tang and Pedreschi (2015) conducted several experiments with a deployable and reconfigurable fabric formwork system to produce concrete grid shells. These applications proved feasible and flexible by reusing the same deployable mold for the rapid creation of products with different sizes, compared to the rigid formworks (Tang & Pedreschi, 2015). To that end, exploring the related literature is essential to understanding the existing practices

and applications in the field of fabric formwork and dynamic mold systems.

2. LITERATURE REVIEW

This paper initially focuses on breaking the rigidity in formwork applications while casting. Therefore, the literature review emphasizes the successful and efficient approaches to fabric usage as formwork, which emerged in the late 1800s (Hawkins et al. (2016). Veenendaal et al. (2011) provide a definition for fabric formwork as a non-rigid membrane system affected by environmental parameters and fabric type that supports fresh concrete and earth. In the planar formwork systems for concrete casting, the relationship between the mold and the mixture becomes inactive. The properties of the mix cannot affect the result of the hardened object. In the case of fabric formworks, the weight and the plasticity of the mixture are the defining features of the final shape (West, 2017). The tension created by the combination of flexible fabric with concrete, a static and rigid material that works under pressure, has potential research opportunities in terms of creativity. (Elmas & Alaçam, 2018). This new relationship allows the formwork to be more responsive to the unique properties of the casting mixture. These responsive structures results with high plasticity in construction also in terms aesthetics (West, 2017).

Beside these, fabrics offer sustainable ease in transportation and production, in addition to the robust fabrication process (Hawkins et al. 2016; Li et al., 2022). Easy transportation allows the fabric formwork system to be built off-site by professionals and sent to the construction area to be utilized without excessive knowledge (Hawkins et al. 2016). The characteristics of the fabric have been studied widely in terms of resistance and reusability, especially for providing non-sticky molds and clean concrete surfaces that emerge from the permeable surface of the fabric's ability to prevent air bubbles and increase durability (Wagiri et al., 2023; Veenendaal et al., 2011). These properties make such materials highly durable and enable the reuse and recycling of the fabrics. The production footprint can be reduced by reusing the same fabrics (Le Quéré et al., 2018).

The literature displays studies on creating forms from various materials with the help of fabric molds. O'Green and Harris (2023) created

prototypes that move from the conventional planar formworks to a more flexible approach using geotextile fabric to produce nonstructural clay objects. The experiments comparing the fabric and planar formworks showed that the clay mixture hardened faster than the traditional approaches. The fabric formwork displayed smoother surfaces with fewer cracks than the conventional examples. Although the study presented in this paper benefits from the material properties to shape the fabric as mold, the emphasis is on the drying time, cracking, and shrinkage of the clay, which improved the parameters positively, rather than the rigidity issue of the planar formworks. The flexibility in the casting process of fabric formwork is studied with a wide range of materials, such as living organisms. Elbasdi and Alaçam (2019) worked on mycelium's ability to grow in a fabric formwork and aimed to create a free-form mycelium geometry. Unlike the drying process of concrete, mycelium can remain open to manipulation for a prolonged period (Elbasdi & Alaçam, 2019). Although this approach demonstrates the opportunities of the fabric formwork, this study focuses more on the concrete and cement casting process. The opportunities of the fabric formwork in terms of plasticity using concrete are displayed by Wagiri et al. (2023). In their paper, several attempts are presented using polyester with flexible properties to examine the relationship between the wet concrete and the fabric. The study demonstrates end products made from different tessellation patterns. As in the previous example, this study highlights the influence of the concrete parameters in changing the output of the casting process. Additionally, the changing patterns emphasize the level of adaptability of the fabric formwork to the changing parameters of the mold. Surface manipulations like pushing, pulling, etc., create varied expressive results (West, 2017) that enhance the interactive value.

These surface manipulations open a gate at incorporating deployable structures which can further encourage the mixture's adaptability to the mold. Kinetic structures provide complex behaviors that enhance the flexibility of the architectural elements. The implementation of new environments and tools is indispensable to display these behaviors efficiently. The concept of origami is a suitable technique that helps the architects understand such complex systems (Gönenç Sorguç et al., 2009). The folding process can easily be executed with these approaches and combined with the fabrics to diminish rigidity in casting.

Akçay Kavakoğlu (2020) proposes a different dynamic molding system combining folding fabrics with origami understanding called Fabrigami. Unlike origami, which is based on folding, fabrigami needs more hinge operations and anchor points (Akçay Kavakoğlu, 2020). This approach creates a system that works like deployable structures that further improve the flexibility of the molding. The paper also highlights the importance of the feedback loops between the digital environments and the physical products for material reduction and sustainability purposes. The result of this technique can be both predicted and uncertain (Akçay Kavakoğlu, 2020) at the same time. In order to minimize production costs, time, and waste caused by uncertainty, digital simulations help predict the behavior of the materials by taking real-world parameters into account. The results of the simulations operate as both output and input in this system, thus helping to create a holistic study (Elmas, Alaçam, 2018) that contributes to the collaboration between hand and computational tools. Therefore, a comparison between digital and physical products is needed to establish a complementary relationship based on feedback to evaluate the accuracy of the models during each step of the design phase.

3. METHODOLOGY

The literature indicates that the studies utilizing fabric formwork have proven benefits for casting activities in terms of flexibility, sustainability and reusability. Consequently, the objective of this research is to utilize diverse casting patterns and elucidate the interrelationship between the digital environment and the physical casting process to understand the complex nature of the dynamic fold combined with fabric. Based upon Akçay Kavakoğlu's (2020) dynamic mold system proposal, the methodology of the study is constructed accordingly and represented below (**Figure 1**) and stated as follows: The initial phase of the study is designated as the pattern selection stage. In this stage of the study, a crease pattern for the creation of a foldable origami pattern is selected, and the parameters that render the pattern suitable for the casting process are elucidated. The second stage of the study outlines the process of creating the crease pattern in a digital environment and the subsequent simulations. The Rhino7 and Grasshopper environments are employed for these applications. Once the pattern has been

created, the adjustments are made to perform a folding simulation. The Crane plug-in for Grasshopper is used, as the extension is specifically designed for folding simulations. As the objective of the study is to develop a dynamic formwork system utilizing fabric, the model was further adapted to be used with the Kangaroo plug-in. The extension was selected due to its ability to perform cloth simulations according to the loads, which are similar to a casting process. The fabric mold studies of contemporary fabric pioneer West are conducted primarily through making and prototyping, which allowed for the detailed evaluation of structural forms and formwork that utilized a variety of fabric types and methods (Manelius, 2012). Consequently, the third stage is the assembly of the physical model, which should reflect the behavior of its digital counterpart. This section presents the material selection for the deployable system and the fabric parameters. This stage also encompasses the casting process. The section consists of a series of casting experiments, in which the parameters of the mixture, fabric, etc. are varied to examine the differences between the end products. Once the final products have been created, they are scanned using photogrammetry method. These approaches permit a comparison between the digital and the physical models in terms of accuracy. In the final stage of the process, the future studies are discussed, and several designs are established, including panel combinations and microstructure examples.

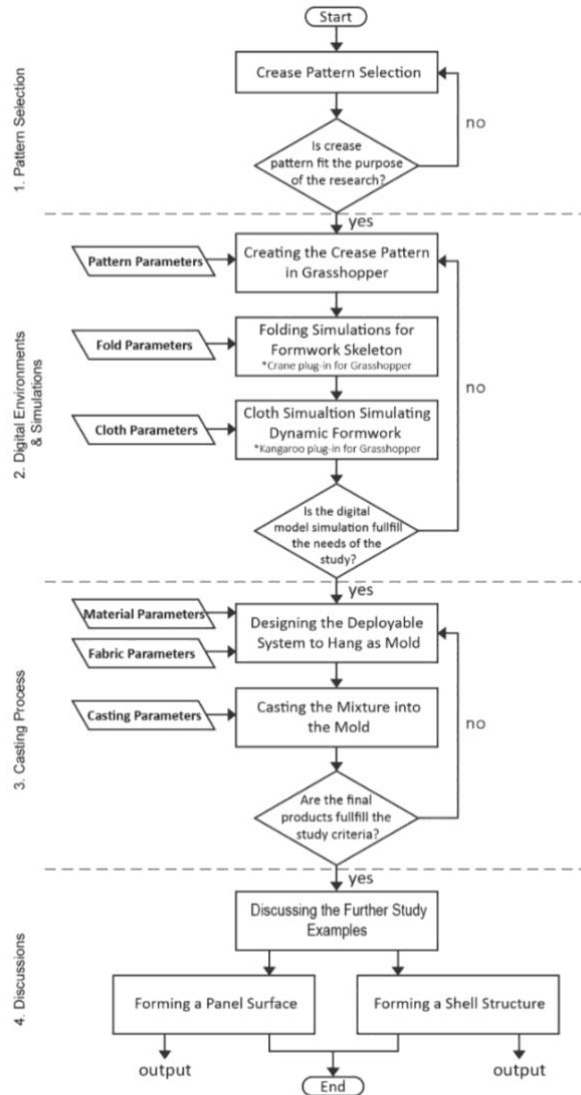


Figure 1: Methodology of the Study.

3.1 Design Process

3.1.1 Crease Pattern Selection

The reusability of the system without experiencing disruption or breakdown is one of the most important parameters for the selection. The motion of opening and closing with folding eliminates the risk of system failure and allows the system to be used in long-term operations (Çavuş & Gönenç Sorguç, 2023). The folding pattern selection is made according to the potential depth creation for supporting the casting mixture without any additional elements. In terms of aesthetics, the dynamic qualities of the pattern surfaces are aimed to be maximized. Therefore, during the folding process, the vertical movement of the pressure points on opposite sides is aimed to be achieved and the solid

void relationship of the product's surface is highlighted, as observed in **Figure 2**.

2D representation of crease pattern shown in **Figure 3** which is found suitable based on the given criteria. This type of pattern is created by rotating a single unit from the bottom right corner point three times. The resulting rotation composes a pattern that consists of two squares, one of which is reduced by half towards the center, and lines going from its center to all corners and midpoints of all edges. Through this process, seventeen pressure points are created from the intersections of the folding lines. These movement axes of these pressure points provide the intended depth and interior movement according to the mountain and valley line analysis (**Figure 4**).

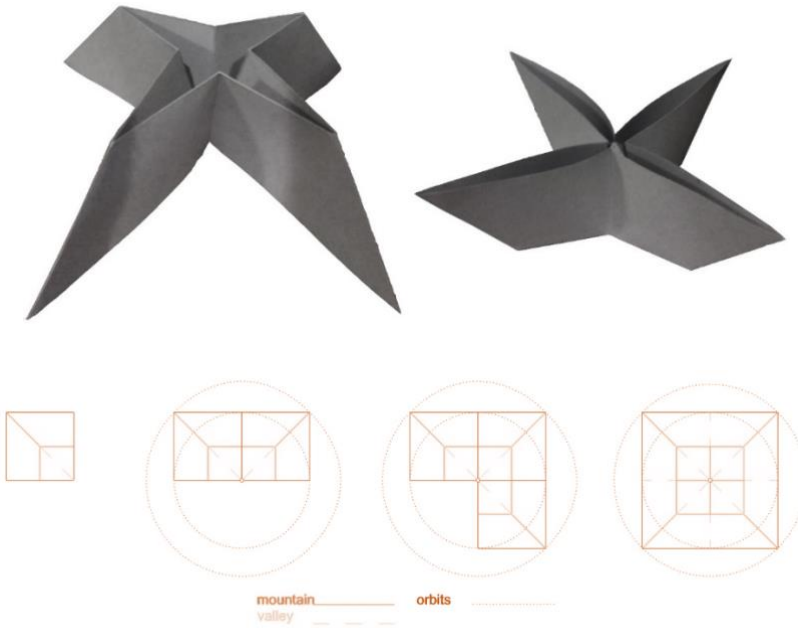


Figure 2: Folded pattern using paper and cardboard.
(Photograph by the authors)

Figure 3: Formation steps of the crease pattern.

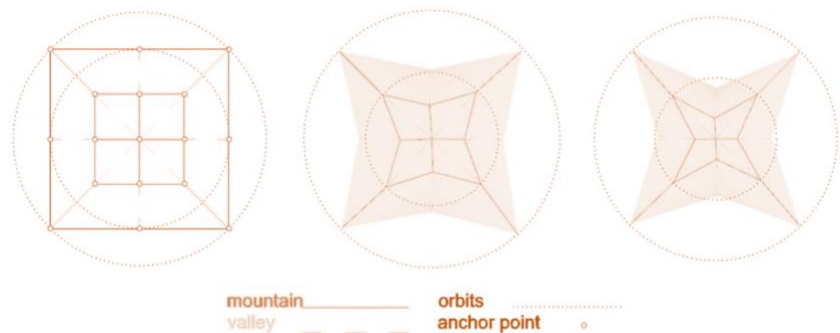
3.1.2 Digital Creation of the Pattern

The visual programming medium (Grasshopper) is used for generating the computational model of the selected crease pattern. In the previous section, the formation steps of the selected pattern are explained using a deductive method. In contrast, the computational process follows an inductive procedure that originates from a 20x20 square. The square is copied and scaled by 0.5 to the center and each square is divided into eight equal segments covering the corner and middle points. Each point is connected with the center in a straight line

to achieve the crease pattern. The produced lines are grouped according to their folding behavior to work as input valley, mountain, or boundary lines for the folding stage.

The folding is achieved using a Grasshopper add-on Crane. For the first step, a 20x20 mesh square is created from the boundary as a base for the pattern. The Crane folding solver obtains the data for the folding mesh and the crease lines to perform the folding simulation. Therefore, each face of the mesh is individually defined to allow their movement. These surfaces are created by including all crease lines as cutting elements. Once the original mesh is divided into sixteen pieces and welded, the crease lines are grouped according to their folding directions as Mountain and Valley Lines. In the figure below (**Figure 4**), the Mountain lines are represented with continuous lines, and the valley lines with dashed ones. Mountain lines make the adjacent surfaces move in the negative Z-axis, while the Valley lines allow the movement in the axis (**Figure 5**).

Figure 4: The pressure points of the crease pattern and folding behaviour.



One of the constraints of the Crane tool is that it works with speed while folding the structure rather than direct angles. So, the folding angle is determined by the speed of folding during the amount of time which the simulation is running. Therefore, it is possible to measure the level of folding from these inputs according to the set speed.

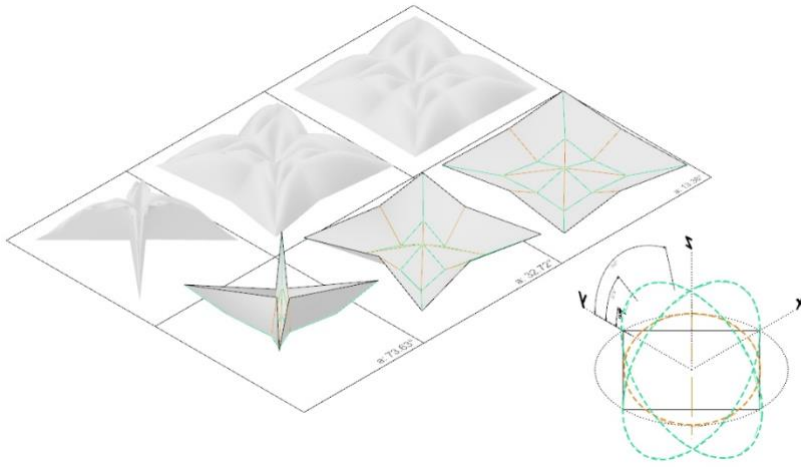


Figure 5: The folding angles of the simulations and the cloth simulations.

In the next stage, since the study focuses on the fabric formwork, the fabric behavior under the mixture load is aimed to be simulated with the help of the Kangaroo plug-in. To achieve the digital models in **Figure 5**, the vertex amount of each folded mesh face is increased using the Weaverbird add-on. The load of the mixture is applied to each vertex, and the length factors are identified approximately as the fabric stretching value. Before the simulation, vertex points intersecting with the crease lines are used as anchor points since the deployable skeleton will limit the stretching of the fabric in those regions.

3.1.3 Deployable Fabric Formwork Construction

In the previous section, the pressure points of the pattern are analyzed to understand the folding dynamics of the system. In the formwork stage, these pressure points are used as the base for constructing the deployable system. Seventeen points are grouped according to the number of lines that are connected to each point (**Figure 6**). After that, the required connection types are analyzed, and the material search is started. The material selection is based on the flexibility of the material and the ability to fold and stay in the desired position (**Figure 7**).

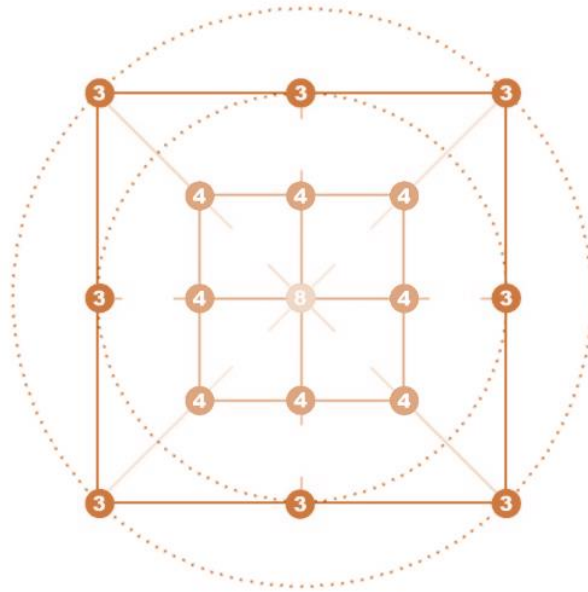


Figure 6: Grouping of the pressure points based on the amount of connections.

Based on the defined criteria, a 1:1 prototype of one of the pressure points is designed consisting of the two exact elements. In the first stage, plastic straws and rods are experimented with. The cylindrical straw is cut into 5 centimeters, and 5-millimeter rods are inserted from both sides. During this process, these rods are prevented from touching, and a 1 cm gap was left in the middle of the straw to allow folding in XZ axis. The rods, whose locations were determined, were fixed to the correct places with the help of paper tape to explore the folding behavior. It is examined that the usage of straw presents the desired folding movement with the folding force but returns to its initial form after the force concludes. Therefore, an additional element is introduced to make the unit remain stable, which is wire. The wire changes its form with the applied force and provides the crucial strength to keep the straw constant at the desired angle. The material properties of the plastic straw allowed the system to be flexible in various directions apart from its main folding axis. Another advantage of this technique is that the straw has a structure that can be easily pierced. Holes are created in the middle of each element, and identical elements are connected through the holes, as shown in the second step of **Figure 8**. This approach allowed the joints to perform folding behavior in two directions, benefiting from the material properties of the straw. By pursuing this process, a pressure point connecting four lines is created and replicated for the whole pattern except for the center of the pattern. A similar procedure was followed in the second

group of pressure points but only used to connect three rods. The remaining excess connection was left empty to make it easier to remove the mold during the casting stage. The connection on the middle point is left to unravel while preparing the fabric joints. The step-by-step explanation is presented below (Figure 8).

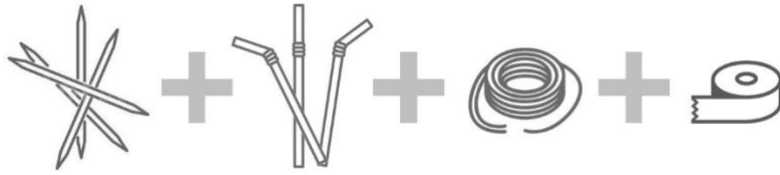


Figure 7: Deployable system materials.

The selection of the plastic allows the system to be folded several times without any deformation. The system can also reuse the waste straw to create this molding unit. The advantage of using the tape is the easy fixing of the mistakes or deformations without breaking the whole system. The usage of accessible materials makes this system easy to build and replicate when faster production is required. As a whole, each of these elements has a level of flexibility that allows this system to be easily deployed.

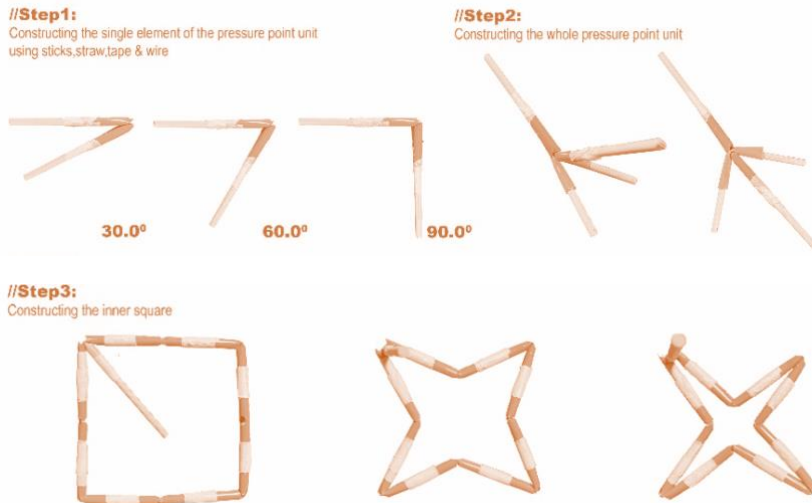


Figure 8: Construction steps of the deployable skeleton structure. (Photograph by the authors).

In the later stage, the flexibility of the system is aimed to be protected. So, the application of the fabric surface needs to allow movement and not be tightly fixed. Since the structure deals with the use of fabric, sewing is considered an appropriate technique to combine the skeleton

and the fabric (**Figure 9**). The skeleton is placed on the fabric, and the location of the sticks is traced with a little offset to allow flexibility. Small flaps are produced for each stick to get in these locations, allowing the fabric to work together with the deployable system. On the center point, it is necessary to create a connection detail for eight rods. Since the straw technique used at other points only allowed four sticks to join, a new solution is considered for that region. The endpoints of each stick are sewn onto the center of the fabric. This way, the eight rods worked together to ensure the correct operation of the folding system (**Figure 10**).

Figure 9: Construction steps of the deployable skeleton structure and sewing. (Photograph by the authors)

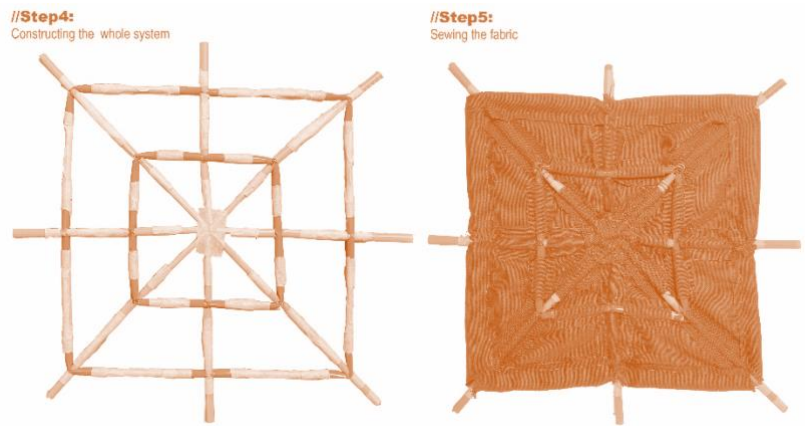
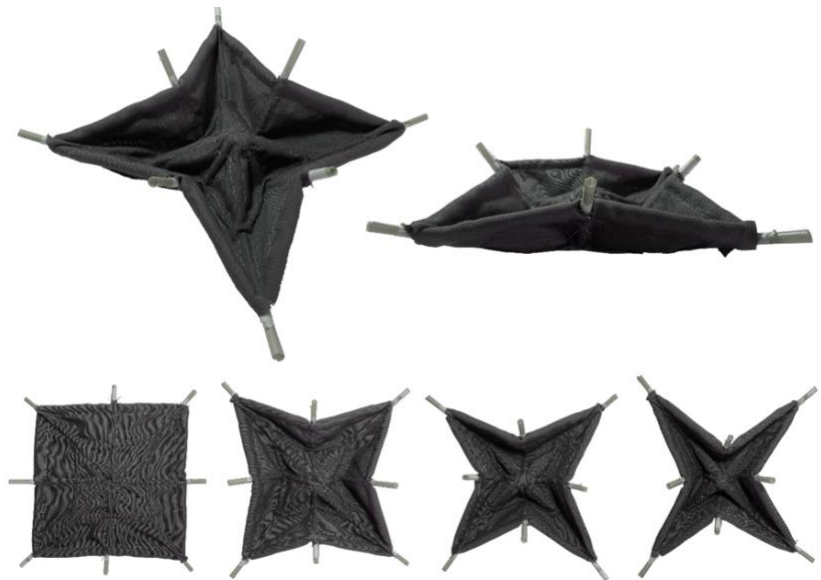


Figure 10: Deployable system with a fabric surface. (Photograph by the authors)



Gravity-induced parameters play a major role in determining the final shape of the output product. Utilizing fabric for the mold surface helps create a dynamic system. This dynamic system differs from traditional formwork approaches by changing its form in relation to the parameters of environment, mixture, and mold components. The aim is to improve the surface deformation caused by gravity in the final product by stretching the selected fabric. Several attempts have been made to determine the fabric type that fits this purpose. Hawkins et al. (2016) mention that woven fabrics are preferred for formwork examinations to benefit from their availability, cost, surface qualities, and durability since the study aims to reuse the same fabric for multiple creations. The first test is conducted with the duck fabric, which consists of cotton and polyester. This material is selected since it can support the weight of the casting material due to its thickness and leak less liquid after the material is cast. Although these features prevent wrinkling, one disadvantage is that this type of fabric has a slight stretch value, and the effects of the gravity-related are minimal. Thus, it defeats the purpose of using fabric as a mold. Therefore, as a second attempt, the same structure is recreated using the combed cotton fabric. This fabric type can stretch more than the duck fabric due to its thinner surface properties and perform surface deformations more clearly than the previous selection. Therefore, wrinkling behavior is ignored in this study since it is difficult to predict in material simulations.

The folding behavior under gravity is aimed to be reflected in the digital environment. **Figure 11** represents the digital folding sequence using the Kangaroo plugin. This plugin allows the user to reflect the loads of the physical environment to the computational model but fails to include data on gravity and material. Therefore, the mathematical calculations regarding the load of the mixture under gravity or fabric's stretching values, instead, a realistic representation is achieved. The surface of the computational model is divided into points, and the points corresponding to the deployable skeleton are entered as the anchor points. On the other hand, a load is assigned to the remaining points to represent the load of gravity.

Figure 11: Digital folding process of the deployable system.



The last stage before casting is the production of a hanging system for the deployable structure to operate and maximize the stretching using gravity. The deployable system is located inside of a rectangular skeleton. Operational axes covering different lines are created in two layers of this box. When the deployable system is placed inside the box, the points will operate in the corresponding axes, shown in the diagram below (**Figure 12**). Each marked point is tied to the related axes to achieve this relationship (**Figure 13**). The formwork system is tightly connected to the axis on the upper layer with the help of a rope so as not to hinder the movement of the cube. The ropes are connected to the four pressure points at the corners of the folding pattern and help the system fold when the ropes are pulled to the center (**Figure 14**). The folding angles of the physical mold are prepared in accordance with the digital simulations.

Figure 12: Steps of the hanging system design.

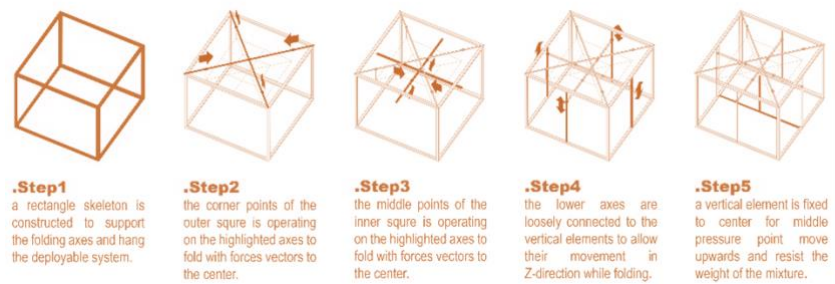
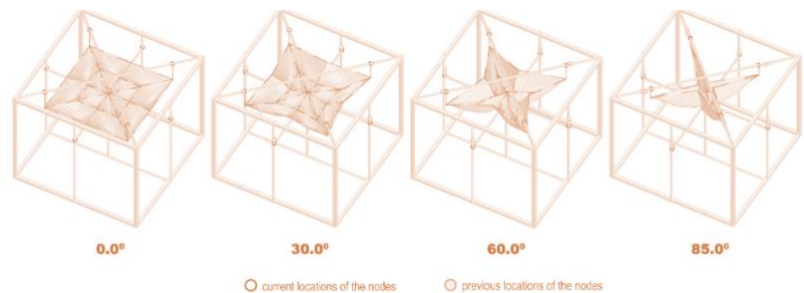


Figure 13: Digital folding hanging deployable system.



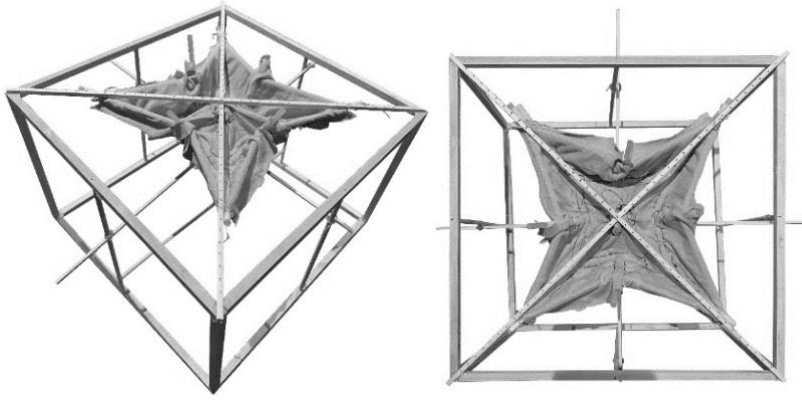


Figure 14: Constructed deployable mould system (Photographed by the authors)

3.2 Casting Process

The previous section mentioned the deployable structure configuration using two different fabrics. In this section, a casting process is conducted using these structures to analyze their behavior further and obtain physical outputs. In the first experiment, the system with duck fabric is selected, and the casting is performed without hanging the system. The first attempt serves as an experiment at understanding the casting process. Although it is not fit for the criteria of this study, a cling wrap is utilized only for the first trial, since the focus is the understand the requirements of the casting process. Cling wrap is applied to the surface of the deployable structure after the desired folding angle is achieved and protect the fabric from any deformation of the liquid material.

White cement is selected as the casting material. In the first experiment, a mixture of 650g white cement and 0.5l water (1.3/1.0 ratio) was used (**Figure 15**). The cling wrap helped the cured cement to be removed easily from the mold without any fractures. Due to the smooth surface of the wrapped surface, the texture of the fabric did not affect the cement surface and remained smooth, the same as the bottom part of the cast form. Also, the cling wrap helped the mold remain reusable without any deflections. The water leakage and absorption were prevented, since the fabric's surface did not touch the mixture. Thus, the fabric is not deformed, and the mixture ratio was not affected during the hardening. On the other hand, these properties made the solidification process longer, blocking the porous properties of the fabric. The mixture had to stay in the mold for 22 hours. One of the issues that did not meet the required conditions was the holes on the surface of the finished product caused by not shaking the mixture

to remove air bubbles after it was cast. Additionally, the usage of thick duck fabric caused sharp wrinkles and less stretching from the desired shape.

Figure 15: Casted products photos and details of the first attempt.
(Photograph by the authors)



The second experiment is conducted with the same mixture ratio, but the technique and fabric are changed (**Figure 16**). As of this experiment the use of cling wrap has been eliminated. This experiment aimed to create a product using the combed cotton fabric without the need for a wrap. Still, a protective layer using potash soap is applied to the fabric's surface to allow easy removal of the finished product (**Figure 17**). The water in the mixture is able to get absorbed and leak due to the direct contact between the mixture and the fabric, thus the drying time is shortened from 22 to 13 hours. Although the same mixture ratio is used, the fabric absorbs and leaks water after the mixture is poured. Therefore, the adjacent surfaces become less humid during the first 5 minutes of the pouring process. The soap works while removing the product from the mold efficiently. In this experiment, the cement obtained the surface characteristics of the fabric and the soap and had a texture different from the bottom surface. Due to the color of the soap, the finished product had a slightly colored surface. After the model was removed, the mold was ready to be used again once its cleaned, thus proving reusability without any additional surfaces. The number of surface holes is reduced in this experiment by shaking the casted mixture. The combed cotton fabric proved more suitable for this study than duck fabric since it is possible to provide the desired shape with its high stretch value and continued in the other experiments.



Figure 16: Casted products photos and details of the second attempt.
(Photograph by the authors)



Figure 17: The fabric surface before (with soap) and after the casting process.
(Photograph by the authors)

The following three experiments are conducted with the same techniques as the previous attempts (combed cotton fabric, soap) (**Figure 18**). The same fabric of the second experiment is reused in each subsequent attempt and no extra fabric was needed. The mixture ratio is changed to 1.5/1.0 with 750g white cement to allow more stretching by benefiting from the load. For each experiment, the mixture stayed in the mold for the same amount of time, 13 hours. In each following example, the center points aimed to have a deeper configuration to examine certain levels of asymmetry. After these experiments, it was seen that the water leakage caused the paper tapes to be deformed and allowed the sticks to move. Thus, by creating uneven surfaces, the middle protrusion causes a thin cement layer that can be cracked during mold removal.



Figure 18: Casted products photos and details of the third, fourth and fifth attempts. (Photograph by the authors)

The connections in the pressure points are fixed, and the last experiment is conducted with the same fabric. For this experiment, the center point is left less pressured to allow more stretching in the middle. The same proportion and techniques were used as in the previous experiment (combed cotton fabric, soap, 1.5/1.0 ratio). Since the sixth attempt is the last experiment performed for this study, the mixture stayed in the mold for 22 hours to examine the effects of the time parameter by leaving the concrete in the mold for an extended period. In terms of surface quality, the last experiment gave the best results, and the fabric is still usable if additional experiments are needed (Figure 19).



Figure 19: Casted products photos and details of the sixth attempt. (Photograph by the authors)

4. FINDINGS

There is a total of 6 casting attempts during the course of the study, which is visualized in the chart below (Table 1.).

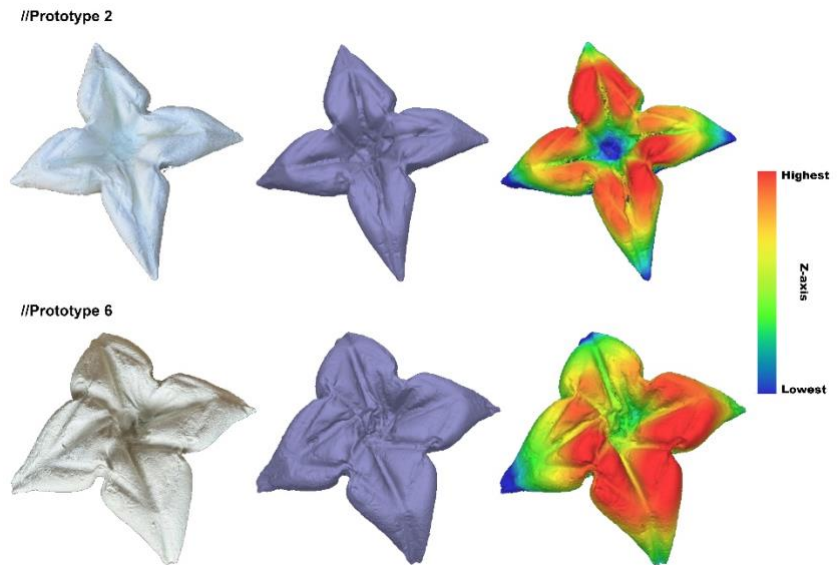
Table 1: Matrix of all the products.

	Mixture Ratio	Fabric Type	Time in the Mold	Technique	Additional Layer	Top View	Results Perspective View	Surface Detail
Prototype 1	650g White Cement: 0.5l Water	Duck Fabric	22h	Without Hanging	Cling Wrap			
Prototype 2	650g White Cement: 0.5l Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup			
Prototype 3	750g White Cement: 0.5l Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup			
Prototype 4	750g White Cement: 0.5l Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup			
Prototype 5	750g White Cement: 0.5l Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup			
Prototype 6	750g White Cement: 0.5l Water	Combed Cotton Fabric	22h	With Hanging	Potash Soup			

4.1 Comparing the Physical Model to Computational Model

Hawkins et al. (2016) suggest that after the form-finding stages, an assessment between model geometries manually or using technologies such as 3D scanning and photogrammetry should be made. The table above displayed the properties of the models and created a criterion focusing on material usage, type, time, and texture to select the optimal variant for the computational comparison. For this stage, the second and sixth prototypes are considered suitable since they are successful examples in texture, shape, fabric stretching, and minimal deformation in the surface. The chosen models are photographed and scanned in the Agisoft Metashape program. This tool assembled a point cloud from colliding points of the model photos. From this point cloud, it is possible to create a mesh model containing the surface qualities of the physical model, including the textures. Also, the program visualizes the point elevations in the point cloud (**Figure 20**). Although the program did not provide any numerical data, it is possible to visualize the height and depth differences of the models through gradient colors and compare them. The point-cloud elevation demonstrates the symmetry of the output products with a display of asymmetry by the sixth prototype. This geometry arises from the stability failure during the casting phase due to the change in mixture weight. Hence, the symmetrical distribution of the point elevations of the second prototype shows system stability. It is seen that the middle recession has a greater depth in the second prototype than in the sixth prototype due to the hanging system remaining stable under the mixture weight. Since the tension in the center is reduced, the fabric stretching is increased.

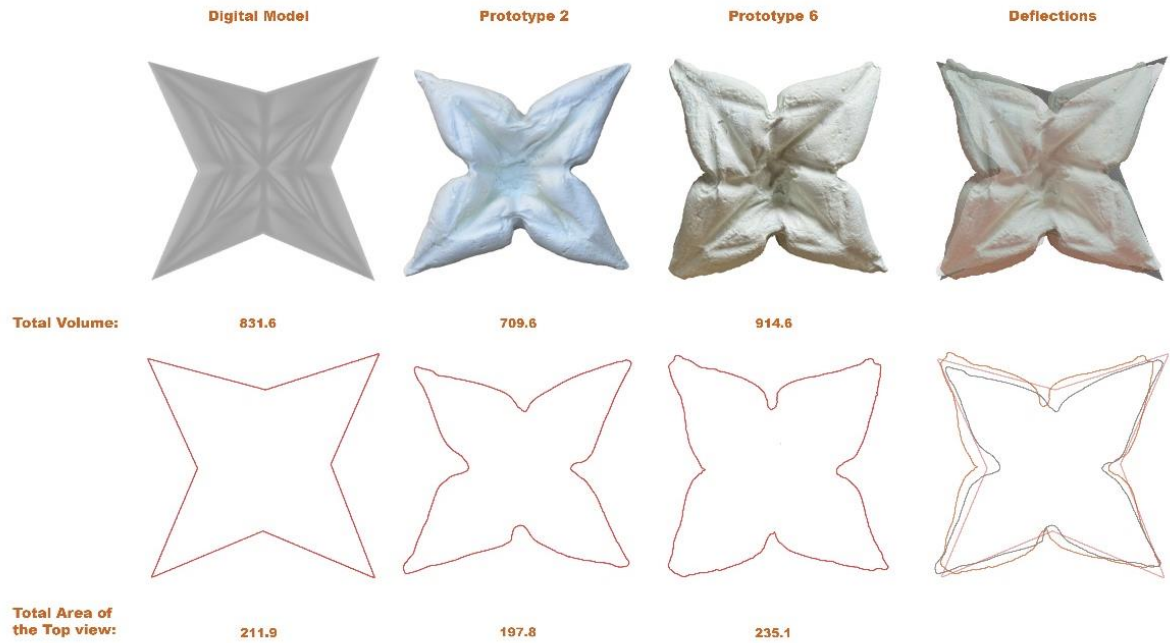
Figure 20: Metashape models using Photogrammetry technique. (Mesh-Textured, Mesh-Solid, Point Cloud-Elevation)



The scanned models are exported to the Rhino7 environment to be examined with the digital model. The figure below (**Figure 21**) shows the sections of each model passing the center. This comparison showed that the sections of the physical model differ from the physical model due to the corresponding skeleton elements not being tied to the hanging system and manipulated from the mixture load. Although the sections provide different results, the models deliver volumetric similarities. Additionally, the outlines of the top views are analyzed for each product, and the sixth prototype is examined to be a more accurate example to the digital model than the second model in terms of volume and area (**Figure 22**). This value difference is caused by material usage. In the second prototype, 650g of cement is used, and in the sixth prototype, 750g is used with the same amount of water. The resulting mixture for the sixth product provided a similar load value used in the algorithm, thus obtaining a closer volume to the digital model.

Figure 21: Sections of the digital model, prototype 2 and prototype 6 and section deflections.





4.2. Exploring the Modular Potential of the Products

After the experimentation period with physical models is concluded, the architectural potentials of the mold units are explored in this section. In this study, fabric formwork is used only for producing a single unit, but the modular nature of the system allows the mold to operate together with numerous units. The modularity of the formwork design holds the potential to create architectural systems, such as wall panels, shading elements, and shell structures. Concrete shell structures are material efficient structural systems, and the usage of fabric formwork eliminates the disadvantages caused by traditional mold examples like cost and structural limits (Tang & Pedreschi, 2015). Within the scope of this study, a preliminary study was presented on the methods of connecting the produced elements to work as an interdependent system.

Three examples are created for the modular system by placing the units into 2D grid and diamond pattern formations. As seen in **Figure 23** the first configuration failed to perform meaningful connections by

Figure 22: Volume and area comparison between the digital model, Prototype 2 and 6 and deflections between models.

providing weaker connection points. Therefore, an angular approach is proposed using the same grid pattern, and a third configuration is obtained (**Figure 23**). It is examined that the connection methods of the second and third configurations offer a stronger connection that holds the potential to build a deployable mold system consisting of several units. The presented usage of such a system with multiple units offers many form variations by adding new parameters to the system, such as the number of units in the system and folding angles of each individual unit, thus improving the flexibility of the fabric formwork.

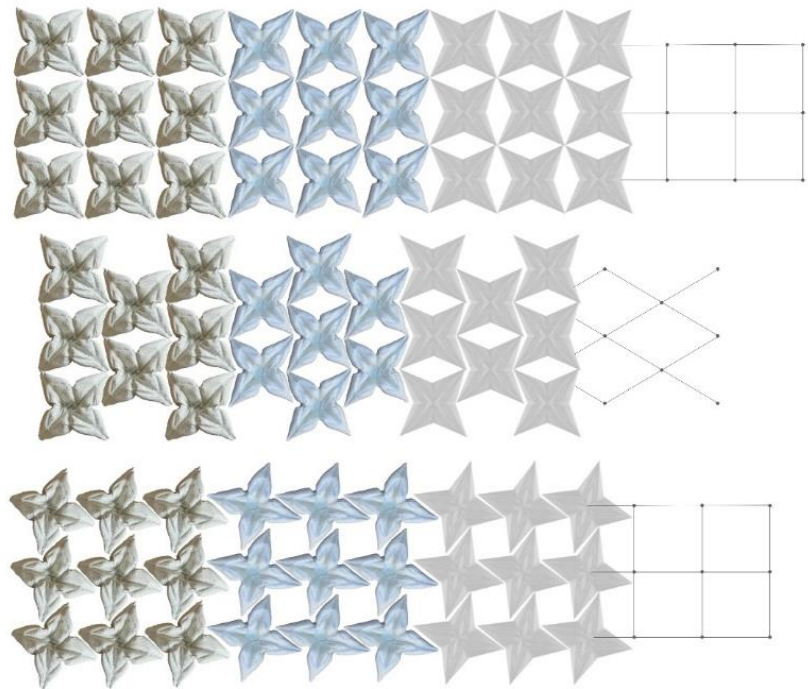


Figure 23: Deployable panel patterns grid, digital pattern, patterns using the physical model. (grid pattern, diamond pattern, grid pattern with angled units).

6. CONCLUSION

This study examines a casting process utilizing a fabric formwork, with the objective of capitalizing on the flexibility and stretching abilities of the fabric. The deployable structure is integrated with the fabric to create a dynamic mold with adjustable parameters, thereby enhancing flexibility. As a preliminary step, a crease pattern is selected as a foundation. The pattern is subjected to analysis, after which a deployable structure is created for purpose of shaping the fabric in accordance with the desired outcome. This research comprises a series of casting attempts utilizing a range of techniques, mixtures, and

materials. In addition to these experiments, Grasshopper simulations are conducted using plugins such as Crane and Kangaroo for folding and simulating cloth behavior. These models are employed to assess the precision of the physical models produced based on specific parameters. Finally, this paper discusses potential applications for these cement units.

In terms of a craft standpoint, the usage of the proposed formwork enhances the inclusion of the hand in the process. While the hand applies a direct intervention by manipulating the mold to the desired direction, it also has the opportunity to affect the mold indirectly by making interventions and additions to the whole casting process (Forren, 2019). While the direct manipulations of mold form, such as geometry selection and deployment angles directly influence the product, the indirect factors that determine the final geometry are influenced by the designer. Applying the mixture transforms the system into a kinetic formation until the concrete reaches its drying point. The system moves and changes with the indirect factors defined by the designers, such as the weight of the mixture according to the mixture ratio, application speed of the mixture, and demolding time.

This project highlights the interconnected relationship between digital mediums and the craft adapted to technological improvements. In the light of the advancements, the role of the hand is not diminished during the craft process but evolved into the development of new methodologies. The utilization of digital mediums helped the craftsman understand complex systems with several parameters, in the case of the study, the dynamic mold.

In this research, the folding units are considered and examined as individual elements. The structural system composed of these elements does not consider the behavior of a continuous system containing a certain number of units. Future research can examine creating a dynamic fabric formwork of a structure possessing more than one unit. Therefore, the system is capable of functioning collectively and being influenced by alterations in each unit. This will provide a greater range of variations and examples of new microstructure. In this paper, the hinges and connection points are assembled from readily available materials, such as straws, tapes, sticks, and wire. Further research could be conducted to enhance the design of these elements

within computational environments. Additionally, the manufacturing process could be optimized through the incorporation of digital tools such as 3D printing, thereby improving the accuracy of the final product. Consequently, the precision between the physical and digital models can be enhanced. Finally, the hanging system is designed to allow asymmetric forms for the casting, despite the project's focus on symmetric results. It is recommended that further studies be conducted to investigate the potential for extending the range of form variations. It is examined that the usage of multiple units to form a flexible mold system holds architectural potential. The system can be utilized in the creation of shading elements, with the openings between each unit reducing with folding according to the direct sunlight values based on the orientation of the building. These patterns can also be used as a wall or ceiling decoration. Future studies are also aimed at examining the possibilities in concrete shell construction using the modular mold system and comparing the efficiency of the deployable fabric formwork to the rigid mold systems.

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Conflict of Interest Statement

The manuscript is entitled "Dynamic Casting: Using Deployable Fabric Formwork" has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Author Contribution

Barış Uzyıldırım: Literature Research, Digital Creation Process, Performing Digital Simulations, Formwork Construction, Performing the Casting Experiments, Writing the Manuscript Draft (50%). Ayşegül Akçay Kavakoğlu: Literature Research, Preparation of the Study Methodology, Contribution to Design, Simulation and Casting Process, Contribution to the Final Manuscript (30%).

Leman Figen Gül: Preparation of the Study Methodology, Contribution to Design, Simulation and Casting Process, Contribution to the Final Manuscript (20%)

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From Mosaic Tiles to Pixels: Reinterpretation of Selected Zeugma Mosaics

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This paper presents a digital art project that reinterprets the rich legacy of Anatolian mosaics using contemporary computational techniques. By converting mosaic tiles into digital pixels, the study creates a link between traditional craftsmanship and modern digital art. The project recreates selected mosaics digitally by assembling them from smaller mosaic images, using an algorithm in the Processing 4 environment. The algorithm divides the main image into a grid and selects smaller images based on color values to reconstruct the mosaic. Several significant Zeugma mosaics from Gaziantep, Türkiye, were successfully regenerated using a modified version of Daniel Shiffman's "Obama Mosaic" algorithm, tailored to fit the project's goals. This work emphasizes the potential of algorithmic art to bridge the gap between tradition and innovation, while showing how digital tools can preserve and transform traditional art forms in the modern age.

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Mozaiklerden Piksellere: Seçilmiş Zeugma Mozaiklerinin Yeniden Yorumlanması

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Bu çalışma, çağdaş hesaplamalı teknikler kullanarak Anadolu mozaiklerinin zengin mirasını yeniden yorumlayan bir dijital sanat projesidir. Mozaik karoları dijital piksellere dönüştürerek, geleneksel zanaatkarlık ile modern dijital sanat arasında bir bağ kurmaktadır. Proje, Processing 4 ortamında bir algoritma ile daha küçük mozaik görüntülerini bir araya getirerek, seçilmiş bazı mozaikleri dijital olarak yeniden oluşturmaktadır. Algoritma ana görüntüyü/ mozaığı karelere bölüp, bu mozaığı yeniden oluşturmak için her karenin renk değerlerine göre daha küçük görüntüleri seçip bu karelere yerleştirerek çalışmaktadır. Algoritma, Daniel Shiffman'ın "Obama Mozaik" algoritmasının değiştirilmiş bir versiyonudur. Projenin hedeflerine göre uyarlanmış bu algoritma ile Türkiye, Gaziantep'ten birkaç önemli Zeugma mozaığı, başarıyla yeniden oluşturulmuştur. Bu çalışma, dijital araçların modern çağda geleneksel sanat biçimlerini nasıl koruyabileceğini ve dönüştürebileceğini gösterirken, algoritmik sanatın gelenek ile yenilik arasındaki boşluğu kapatma potansiyelini de vurgulamaktadır.

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Anahtar Kelimeler: Algoritmik Sanat, Mozaik Sanatı, Piksel Sanatı, Hesaplamalı Tasarım.

1. INTRODUCTION

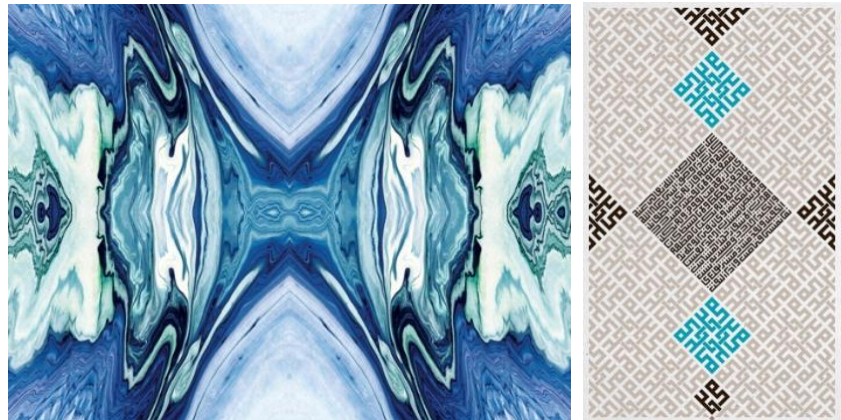
In order to experiment on how traditional mosaic creation can be reimagined through modern computational methods, this paper combines traditional mosaic artistry with contemporary computational techniques, focusing on the transformation of mosaic tiles into digital pixels. This is done by creating images from smaller units resembling pixels, which overlaps traditional mosaic creation. The study includes the use of algorithms to regenerate mosaic art, which situates it in the larger field of algorithmic art, which is the use of code and algorithms by artists to produce visual artworks. The digital regeneration of several Zeugma mosaics from Gaziantep, Türkiye, are focused on, in this study, to contribute the field of digital heritage by using digital tools to preserve and reinterpret cultural material.

1.1. Background

Various studies have looked closely at how traditional art forms might be digitally reinterpreted. Researchers have investigated how digital media, virtual reality, and computer-generated art have affected conventional art forms, emphasizing how these innovations have revolutionized artistic expression and audience participation (Kong et al., 2024). In example, research has investigated the possibilities and difficulties of integrating digital technologies with traditional Turkish arts like calligraphy and marbling, to protect cultural heritage (Kizilaslan & Kozlu, 2021). The authors showed examples of digitally produced artworks, not by algorithms but by graphic design softwares (**Figures 1, 2**).

Figure 1: Digital marbling work by İstanbul Ebru Evi (Kizilaslan & Kozlu, 2021).

Figure 2: Digital Calligraphy work by Erman Yordam (Kizilaslan & Kozlu, 2021).



Vilbrandt et al. (2011), worked on digitally interpreting Norwegian and Japanese traditional crafts by computationally modeling and fabricating them (**Figure 3**). Another study focused on the digital representation of Shan-Shui-Hua, a classic Chinese landscape painting, showing how Eastern aesthetic ideals can be recreated through Western digital approaches (Bolewski, 2008) (**Figure 4**).

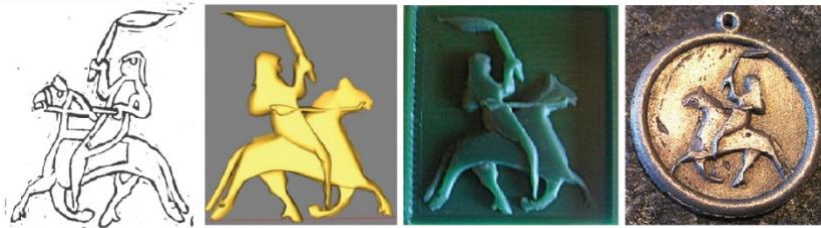


Figure 3: From left to right: An outline of the original wood carving from the Lyngen region of Norway. A 3D model of it. A model made of wax. Final silver jewelry item (Vilbrandt et al., 2011).

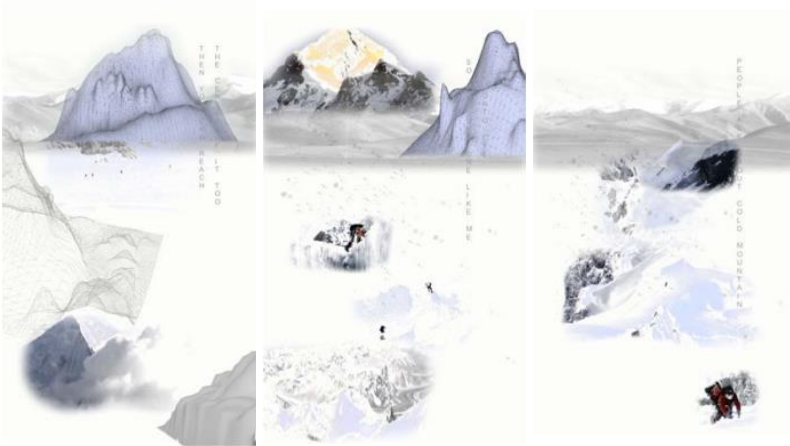


Figure 4: Images from Bolewski's work reinterpreting Shan-Shui-Hua (Bolewski, 2008).

These examples show the variety of ways that digital technology is reinterpreting classic artistic genres. The authors believe that immersive media forms present a chance to protect traditional artworks and make them more relevant to contemporary audiences. However, Holtzman (199,) argued that, with its distinctive features including interactivity and transient nature, the digital medium has been acknowledged as a venue for innovative creative expression with infinite reproduction possibility, but at the expense of temporality.

Studies have also been done focusing on digital reinterpretation of mosaics. Roman mosaics have been rebuilt using virtual restoration techniques (Monti & Maino, 2018) (**Figure 5**). Although there are certain restrictions in reproducing details and preserving consistency,

artificial intelligence -specifically DALL-E2 - has demonstrated potential in reconstructing partial mosaics (Moral-Andr'es et al., 2024) (**Figure 6**).



Figure 5: Original mosaic on the left, virtual restoration on the right (Monti & Maino, 2018).



Figure 6: Original mosaic on the left, reproduction with AI model on the right (Moral-Andr'es et al., 2024)

Elber & Wolberg (2003) present a method for a digital mosaic forming system to convert digital photos into classic renderings that resemble mosaics (**Figure 7**).



Figure 7: Turning an image into a mosaic (Elber & Wolberg, 2003)

1.2. Digital Mosaic Generation Techniques

Puglisi & Battiato (2013) reviewed methods for producing high-quality digital mosaics automatically from raster images. According to authors, the process of generating a digital mosaic from a raster image can be viewed as a mathematical optimization problem. The goal is to take a rectangular region on a plane, a collection of tiles, and a set of specific

rules, and find a set of positions where tiles can be placed. These tiles should be non-overlapping, cover as much area as possible, and follow the given constraints as closely as possible. To address different mosaic generation tasks, four methods are defined: Crystallization Mosaic, Ancient Mosaic, Photo-Mosaic and Puzzle Image Mosaic. The authors also gave visual examples from different researchers.

- Crystallization Mosaic: In this method, tiles are placed in such a way that each tile's color replicates the corresponding portion of the image. While the constraints on edge features are important, they can be relaxed to accommodate a feasible solution (**Figure 8**).
- Ancient Mosaic: The tiles are rectangles aligned based on a vector field influenced by the image's edges. The goal is to place the tiles without overlap, maximizing the area covered while ensuring the tile color matches the image (**Figure 9**).
- Photo-Mosaic: This approach uses a set of small rectangular images and places them on a regular grid. Each tile resembles the section of the image it covers, thus recreating the source image (**Figure 10**).
- Puzzle Image Mosaic: Similar to the Photo-Mosaic, but with an irregular grid and non-rectangular images. The task is to place these irregular tiles so they don't overlap and resemble the part of the image they are covering (**Figure 11**).

The first two techniques break the image into tiles with various colors, sizes, and orientations, while the latter two use pre-existing images to fill the mosaic grid. These last two techniques are referred to as multi-picture mosaics because they rely on fitting multiple small images to form a larger mosaic (Puglisi & Battiato, 2013).



Figure 8: On the left, an example of crystallization mosaic (Mould, 2003).

Figure 9: On the right, an application of the ancient mosaic method (Puglisi & Battiato, 2013).

Figure 10: On the left, an example of photo mosaic, American Gothic (Finkelstein & Range, 1998).

Figure 11: On the right, an example of puzzle image mosaic made by Hausner in 2001 (Puglisi & Battiato, 2013).



1.3. Approach of This Study

This study uses the photo mosaic technique to generate digital mosaics from small images which works as tiles/pixels. For context, the study differs from the others with the approach of using mosaics as tiles to form bigger digital mosaics. Moreover, the focus is on generating several Zeugma mosaics by using Anatolian mosaics as tiles. In order to emphasize the shift from mosaic tiles to digital pixels, this study explores how the Zeugma mosaics might be reinterpreted and recreated in a digital format using contemporary computational techniques and algorithms.

1.4. The Zeugma Mosaics in Gaziantep, Türkiye

The ancient city of Zeugma is renowned for its Roman villas and the extensive mosaics that adorned their floors, covering over 1,000 square meters in area. The ancient city of Zeugma was strategically situated on the banks of the Euphrates River in what is now Gaziantep, Türkiye. It was founded in 300 BCE by Seleucus I Nicator, a general of Alexander the Great, later came under Roman control in the 1st century BCE and was renamed Zeugma. At its peak, Zeugma had a population of around 80.000, making it one of the largest cities of its time, comparable in size to Athens and larger than Pompeii and ancient London. Zeugma became a hub for artists, attracting the finest craftsmen of the time due to its strategic location at the crossroads of trade routes and a military garrison. The city's wealth and safety contributed to its cultural and artistic development, leading to the creation of mosaics, frescoes, and sculptures. The mosaic tradition at Zeugma evolved over time,

beginning with the use of multicolored pebbles and later transitioning to the more refined tesserae technique, where stones were cut into cubes, rectangles, or triangles. This shift allowed for more detailed, picture-like mosaics, a hallmark of the Hellenistic and Roman periods (Zeugma, 2024).

2. METHODOLOGY

This study uses the photo mosaic technique and creative coding to form digital mosaics, in Processing4 IDE. Processing is an open-source program that runs locally on computers and includes a code editor to type code and a canvas that shows the visual outputs of the code (Processing, 2024). It is used mostly for generating visual art pieces. Daniel Shiffman's "Obama Mosaic" Processing4 code which was shared as open-source is taken as a base and manipulated for the purposes of this study (GitHub, 2024). His code uses smaller Barack Obama images as tiles to create selected Obama portraits (Figure 12).



Figure 12: Obama Mosaic Work (Shiffman, 2022).

Pseudocode for Shiffman's "Obama Mosaic" algorithm and the flowchart are as follows (**Figure 13**):

- Initialization:
Load an image (Obama's photo).
Retrieve and store a list of files (image data) from a directory.
Set up variables for processing images (brightness array, smaller images, etc.).
- Image Preprocessing:
Iterate through the list of images:
Load each image file.
Shrink the image to a smaller size (16x16 pixels in example).
Compute and store the average brightness of each shrunk image.
- Assigning Brightness-Closest Images:
For each possible brightness value (0-255):
Compare the brightness of each processed image with the target brightness.
Find the image with the closest matching brightness.
Store the best-matching image for each brightness value.
- Resizing Source Image:
Resize the source image (Obama's image) into a smaller version, based on the predefined scale (16 pixels).
- Main Loop (Drawing):
Iterate over the columns and rows of the smaller source image:
For each pixel in the resized image, get its brightness.
Use the brightness value to find the closest matching image from the array.
Draw the matching image in place of the corresponding pixel.
- Displaying Results:
Display the mosaic of images corresponding to the source image's brightness pattern.
- Stopping the Drawing:
End the draw loop after one iteration.

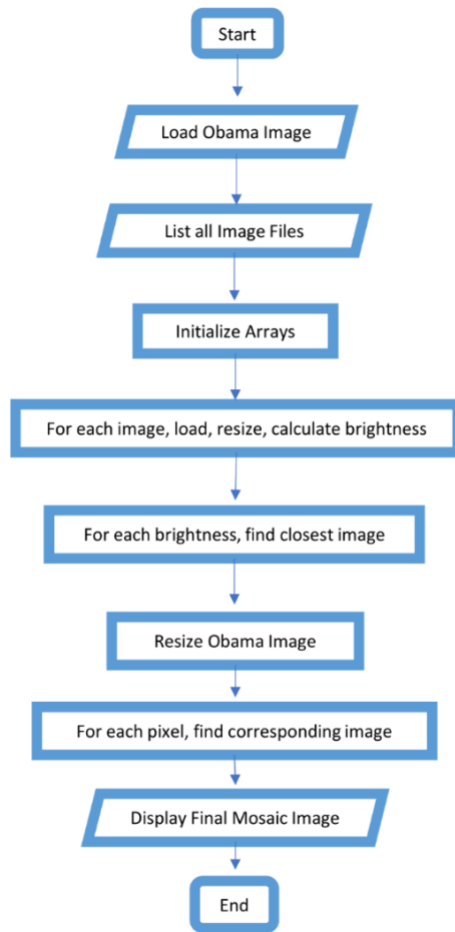


Figure 13: Flowchart of the Shiffman's "Obama Mosaic" algorithm (Author, 2024).

In this study, Daniel Shiffman's code is modified, focusing on color values (red, green, blue) instead of brightness. Therefore, instead of calculating the brightness of images, the code calculates the average red (or green or blue) channel value for each image to match images based on color similarity rather than brightness (**Figure 14**).

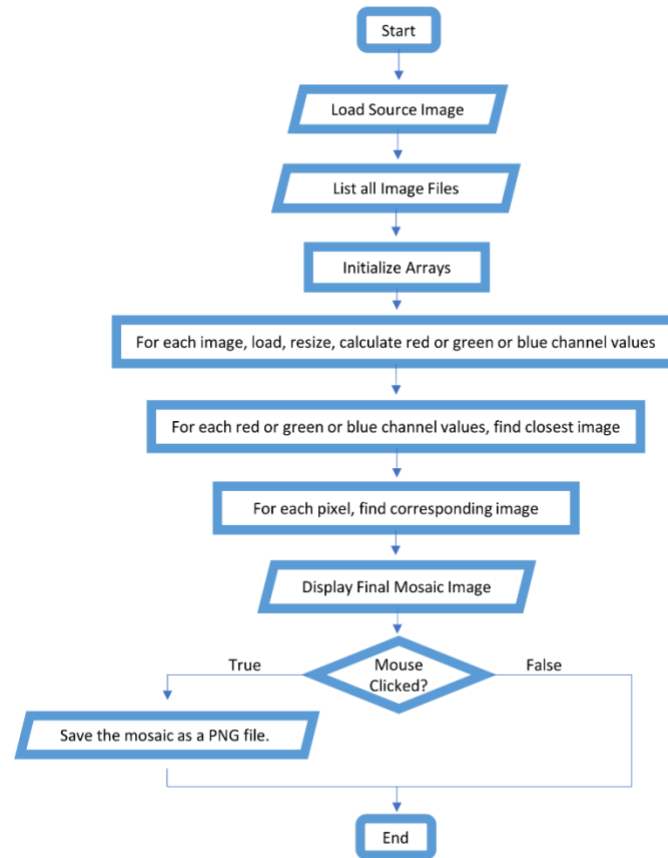


Figure 14: Flowchart of the modified code (Author, 2024).

Six Zeugma mosaic images are selected to be digitally reproduced (Figures 15, 16, 17, 18, 19, 20).



Figure 15: The Gypsy Girl Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd century A.D (Wikimedia, 2024a).



Figure 16: The Dionysos Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd-3rd century AD (Wikimedia, 2024b).

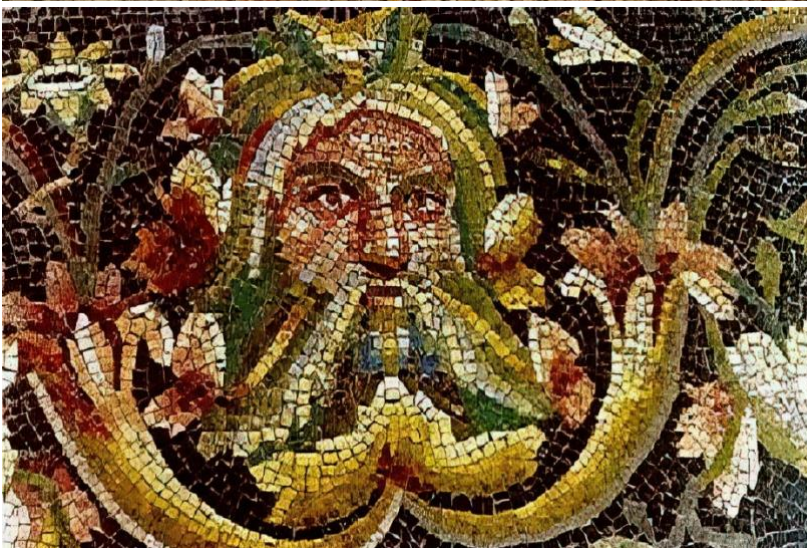


Figure 17: The Acheloos Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd century AD (Wikimedia, 2024c).

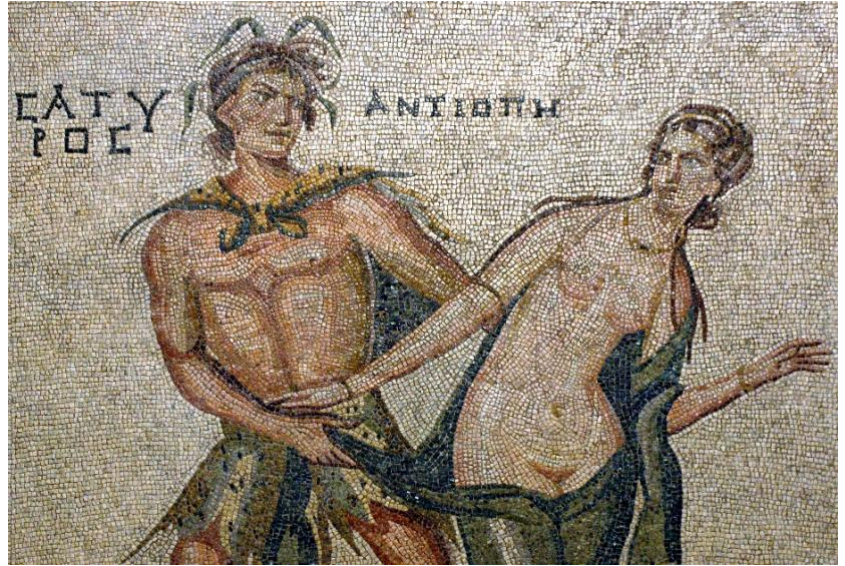


Figure 18: The Euphrates Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd-3rd century AD (Wikimedia, 2024d).

Figure 19: The Oceanus and Tethys Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd - 3rd century AD (Wikimedia, 2024e).



Figure 20: The Antiope and Satyros Mosaic, Zeugma Museum, Gaziantep, Türkiye, 2nd - 3rd century AD (Wikimedia, 2024f).



The algorithm that is used in this study, basically creates a grid system and fills each grid with suitable mosaic images based on their average red/green/blue channel values in order to form a bigger mosaic. For this purpose, while six Zeugma Mosaics were selected, 91 various Anatolian mosaic images (**Figure 21**) were selected from an online source manually to form a vast set for the algorithm, so that suitable brightness and color values can be selected from a wide range (Kültür Portalı, 2024). The images manually turned into square images to fit in the pixel grid without being distorted by the algorithm. The code was run in Processing 4 which is an open-source IDE and java-based language.

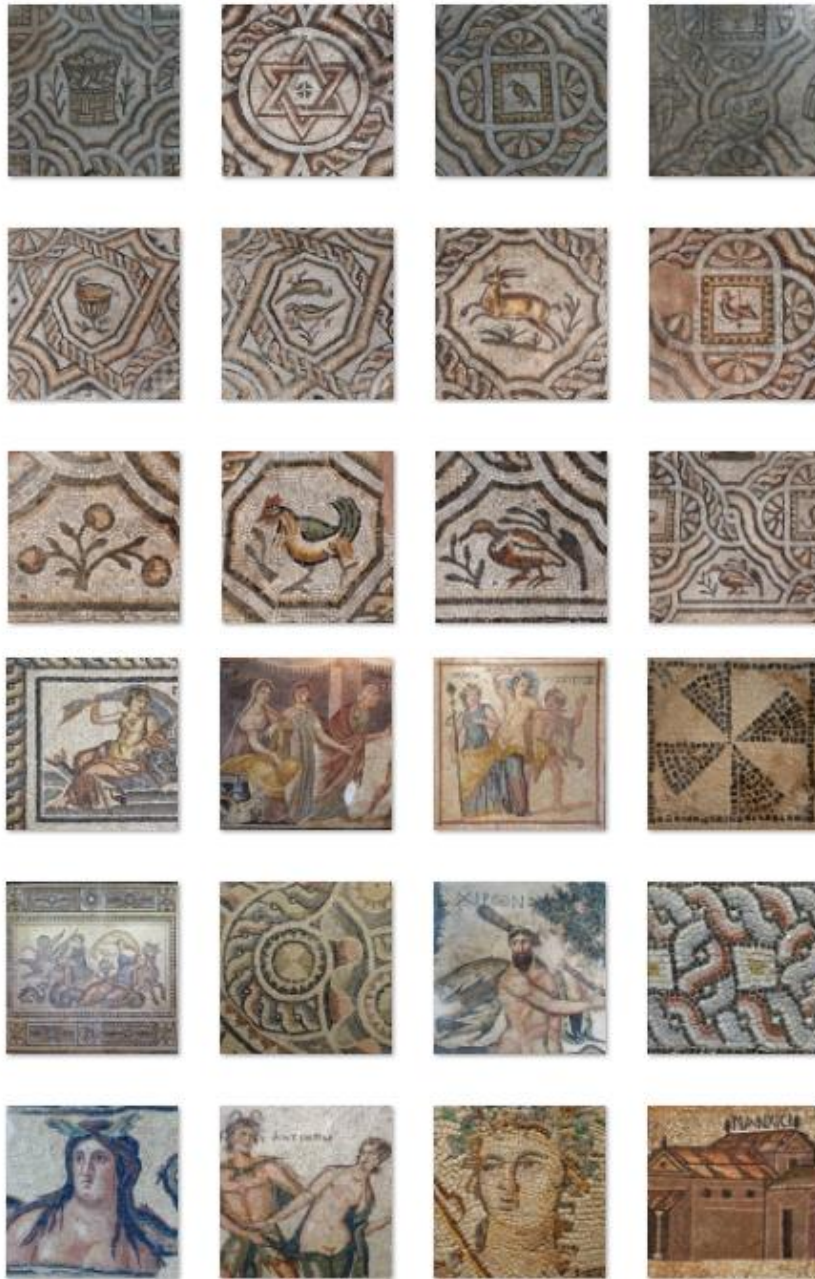


Figure 21: Some images from the Anatolian mosaics image set (Author, 2024).

3. RESULTS

The outcome mosaics that are digitally recreated by using smaller mosaic images as tiles (10*10 px.) based on their average red/green/blue channel values are presented below for each selected mosaic respectively (Figures 22 - 27).

Figure 22a: Digitally recreated the Gypsy Girl Mosaic based on red channel values (Author, 2024).



Figure 22b: Digitally recreated the Gypsy Girl Mosaic based on green channel values (Author, 2024).



Figure 22c: Digitally recreated the Gypsy Girl Mosaic based on blue channel values (Author, 2024).





Figure 23a: Digitally recreated the Dionysos Mosaic based on red channel values (Author, 2024).



Figure 23b: Digitally recreated the Dionysos Mosaic based on green channel values (Author, 2024).



Figure 23c: Digitally recreated the Dionysos Mosaic based on blue channel values (Author, 2024).

Figure 24a: Digitally recreated the Acheloos Mosaic based on red channel values (Author, 2024).



Figure 24b: Digitally recreated the Acheloos Mosaic based on green channel values (Author, 2024).



Figure 24c: Digitally recreated the Acheloos Mosaic based on blue channel values (Author, 2024).





Figure 25a: Digitally recreated the Euphrates Mosaic based on red channel values (Author, 2024).

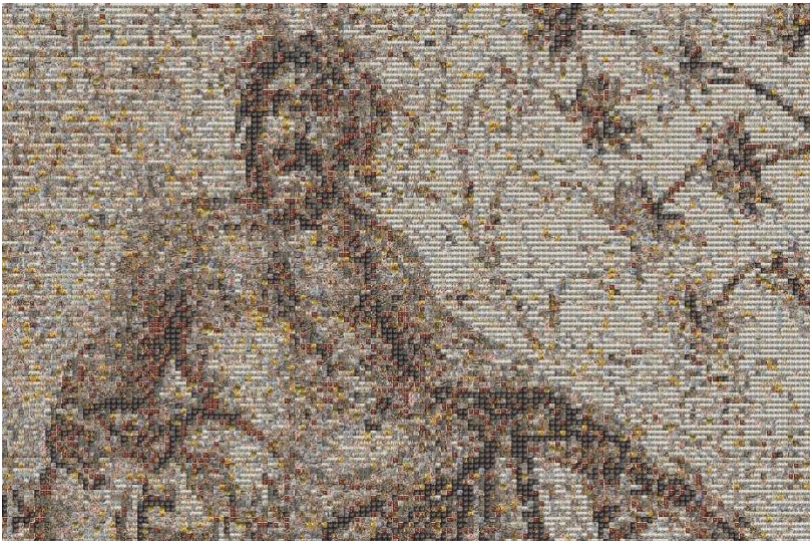


Figure 25b: Digitally recreated the Euphrates Mosaic based on green channel values (Author, 2024).

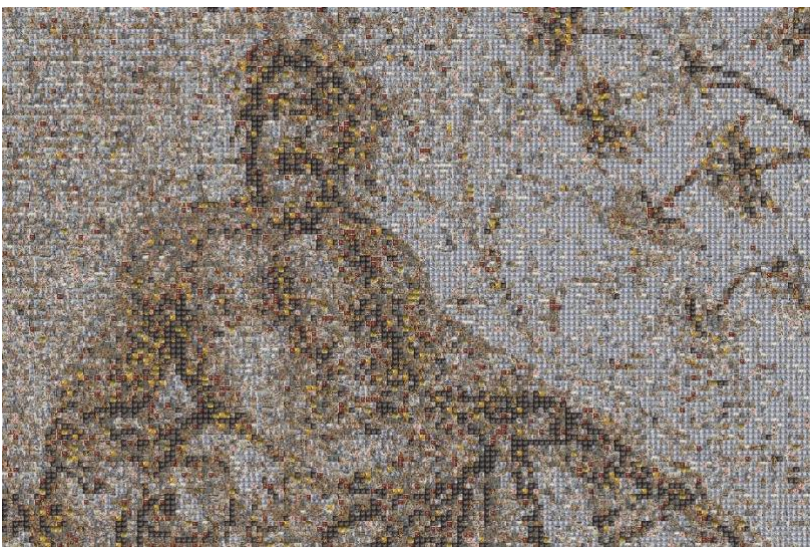


Figure 25c: Digitally recreated the Euphrates Mosaic based on blue channel values (Author, 2024).

Figure 26a: Digitally recreated the Oceanus and Tethys Mosaic based on red channel values (Author, 2024).

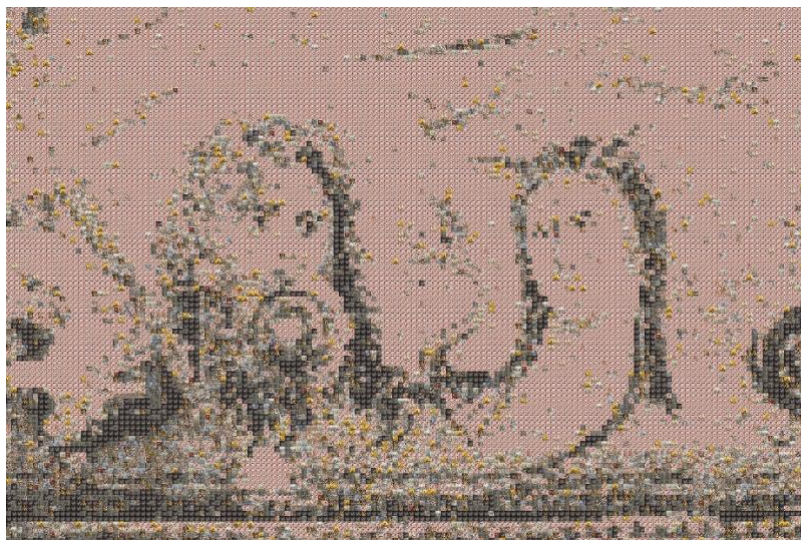


Figure 26b: Digitally recreated the Oceanus and Tethys Mosaic based on green channel values (Author, 2024).



Figure 26c: Digitally recreated the Oceanus and Tethys Mosaic based on blue channel values (Author, 2024).

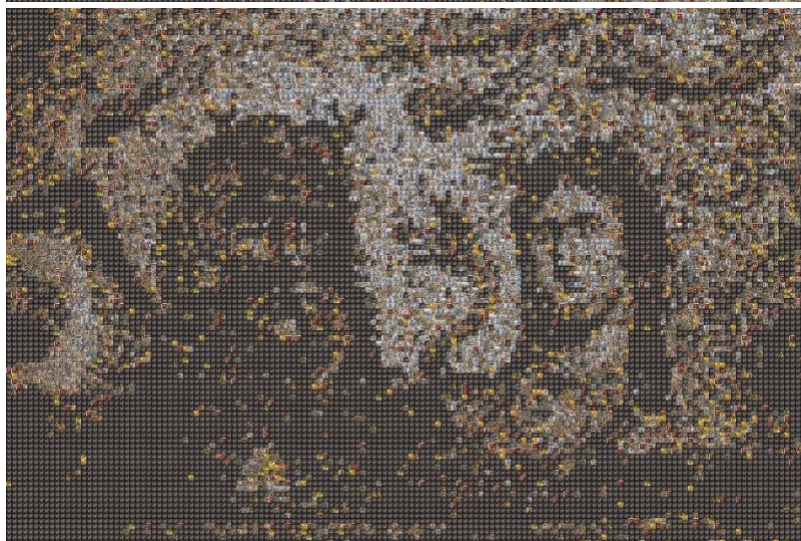




Figure 27a: Digitally recreated the Antiope and Satyros Mosaic based on red channel values (Author, 2024).



Figure 27b: Digitally recreated the Antiope and Satyros Mosaic based on green channel values (Author, 2024).



Figure 27c: Digitally recreated the Antiope and Satyros Mosaic based on blue channel values (Author, 2024).

It is seen that as the grid size increases, details of the main mosaic become less visible, however details of the small images become more visible, as expected (Figures 28, 29).

Figure 28a: Digitally recreated the Gypsy Girl Mosaic based on green channel values, with 10x10 pixel sizes (Author, 2024).



Figure 28b: Digitally recreated the Gypsy Girl Mosaic based on green channel values, with 50x50 pixel sizes (Author, 2024).





Figure 29a: Digitally recreated the Acheloos Mosaic based on red channel values, with 10x10 pixel sizes (Author, 2024).



Figure 29b: Digitally recreated the Acheloos Mosaic based on red channel values, with 50x50 pixel sizes (Author, 2024).

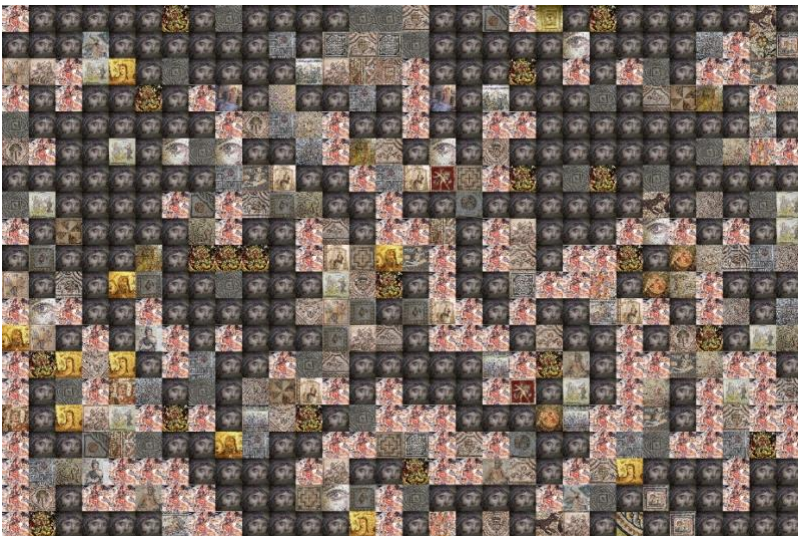


Figure 29c: Digitally recreated the Acheloos Mosaic based on red channel values, with 100x100 pixel sizes (Author, 2024).

Figure 29c: Digitally recreated the Gypsy Girl Mosaic based on green channel values, with 100x100 pixel sizes (Author, 2024).



5. CONCLUSION

Through the use of contemporary computational tools, this study reinterprets a selection of the Zeugma mosaics. The project creates coherent digital artworks that preserve the integrity of traditional mosaic art while introducing modern digital skills. It achieves this by using an algorithm to match the RGB color values of smaller mosaic images with corresponding areas of a larger image. The photo-mosaic method, with the sample algorithm of Daniel Shiffman's 'Obama Mosaic' code, proved effective in generating aesthetically pleasing recreations of the original mosaic photographs. The algorithm mimics the original by dividing the canvas into a grid and selecting suitable mosaic pictures based on RGB values.

This study presents the possibilities of artistic creativity and cultural preservation, reinterpreting mosaics by digitally conserving their features. Furthermore, it merges conventional mosaic techniques with contemporary computational approaches, exploring new potentials for artistic expression. By demonstrating how computational methods can be used to reinterpret ancient art forms, the study contributes to the growing field of digital craftsmanship, showcasing its creative potential.

Looking forward, this approach could be further developed to enhance the precision and variety of mosaic recreations. Additionally, this method could be applied in educational settings, offering students hands-on experience with algorithmic art and cultural heritage

preservation. Beyond mosaics, similar techniques could be adapted to reinterpret other traditional crafts, such as textiles or stained glass, by using computational tools to explore their patterns and colors in new ways. The fusion of digital and traditional techniques opens the door for broader applications in virtual museums, digital conservation efforts, and interactive art exhibits, expanding the role of technology in both preserving and reimagining cultural heritage.

Conflict of Interest Statement

The manuscript is entitled “From Mosaics to Pixels: Reinterpretation of Selected Zeugma Mosaics” has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

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Zoning the Echus Chasma Region on Mars for Settlement Location Selection according to Topographic and Surface

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This study proposes zoning for one of the regions called Echus Chasma on Mars, aiming to open the discussion on selecting the settlement locations for Mars urban planning. The literature on Mars architecture has been an important discussion topic and is increasing in the architecture discipline. On the other hand, planning the Mars areas must be another research focus to understand spatial organization on an urban scale. The Echus Chasma region is selected for the Mars surface's zoning tasks. This selection is because it is considered a past water source region of Mars, and habitable spaces on Mars must also consider the possible water supply. The study applies the Gaussian mixture model algorithm to predict the different zones. The features in clustering for zones are slope, aspect direction, and normalized difference water index. According to AIC and BIC values of clustering nine clusters are obtained, and cluster 2, is the best candidate for settlement zone within the scope of this research. The result of the study can only be hypothetical with its limited number of features; however, the study contributes to the literature and future works with its methodology.

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Mars'taki Echus Chasma Bölgesinin Yerleşim Yeri Seçimi için Topografya ve Yüzey Suyu Özelliklerine Göre Bölgeleme

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Bu çalışma, Mars kent planlamasında yerleşim için konum seçimi konusunu tartışmaya açmak amacıyla, Mars'ta Echus Chasma bölgesinin yerleşime uygun alanlarının tanımlanmasını önerir. Mars mimarisine ilişkin literatür, mimarlık disiplini içinde önemli bir tartışma konusudur. Öte yandan Mars alanlarının planlanması, kentsel ölçekte mekansal organizasyonu anlamak için başka bir araştırma odağı olmalıdır. Echus Chasma Mars'ın geçmişteki su kaynağı olarak tahmin edilen bölgesidir. Mars'taki yaşanabilir alanların konumlanmasında olası su kaynaklarının konumu önemli bir girdi olması nedeniyle Echus Chasma alanı çalışma alanı olarak seçilmiştir. Bu çalışmada, Echus Chasma'nın farklı alt bölgelerini tahmin etmek için Gauss karışım modeli algoritması kullanılır. Bölgelerin tahmini için kümeleme probleminde kullanılan özellikler; eğim, bakı yönü ve normalize edilmiş su indeksi olarak seçilmiştir. Sonuçlar, Echus Chasma bölgesinin verilen özelliklere göre ve kümeleme sürecinde seçilen küme sayısına göre dokuz farklı bölgeye sahip olduğunu ve 2 numaralı kümenin yerleşim için en iyi aday olduğunu göstermektedir. Bu çalışmanın kapsamında eğim, bakı ve normalize edilmiş su indeksi ile bölge tahmini olması nedeniyle, çalışmanın sonucu ancak varsayımsal olabilir. Diğer yandan çalışma metodolojisi ile literatüre ve gelecek çalışmalara katkı sağlamaktadır.

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Anahtar Kelimeler: Mars, Echus Chasma, Yerleşim Yeri, Kümeleme, Bölgeleme.

1. INTRODUCTION

Designing a habitable space on Mars has been a noteworthy research topic, alongside the research on accessing the red planet. Although creating such a big plan remotely without being there has many unpredictable variables, through science, distant planning for habitable space on Mars is possible and has already begun.

Rodrigue (2014) designated the "orders of relief" method to understand the variation on the Mars surface using the Mars Orbiter Laser Altimeter (MOLA) map. Rodrigue proposed five orders: large crustal rocks of Mars, prominent major features, unclear large areas, landscape scale areas, and small details. This classification facilitates the comprehension of the complex terrain of Mars from a systematic perspective. Another study by Rodrigue (2023) focuses on the topographic feature analysis via the software Gridview using MOLA data. In this study, Rodrigue reveals two important discoveries and fault lines in the Terra Cimmeria region on Mars and the geographical depression between the Terra Cimmeria and Terra Sirenum regions. Both studies on the classification and analysis of Mars's surface reveal significant clues of location selection for a possible settlement zone. Precedent examples of Mars settlements show the significance of an urban planning issue for other planets (Hohmann, 1972; Gaviraghi and Caminoa, 2013; Fross & Bielak-Zasadzka, 2019; Hollander, 2022). For lunar tasks, Dalton and Hohmann's (1972)' idea was to design a lunar city system, and they even proposed site plan drawings of the lunar colony. Selenia and SOM's Moon Village are the other examples of the off-world planning proposal in collaboration with the European Space Agency (ESA) (Hollander, 2022). ZA Architects proposes to send the robots to find the most proper location for colonization while designing the system of an underground colony; Foster and Partners propose robots to excavate the suitable region and create habitat modules using the inflatable structures (Fross & Bielak-Zasadzka, 2019, Hollander, 2022). BIG Architects recommends and represents the 3D printable habitat modules for Mars (Hollander, 2022). Besides these attempts, research on Mars colonization has also been growing. On the other hand, different design scales, from architecture to urban design, are necessary to answer the Mars habitat problem consistently. So, issues and solutions of the architectural scale must be combined with urban-scale solutions for the Mars habitation problem.

When considering the current circumstances of Mars habitation, it becomes clear that the problem is about more than just designing a habitable space. Gaviraghi and Caminoa (2013) point to a wider-scope problem in Mars settlement that necessitates a master plan before we can even think about accessing the planet. This problem definition of Mars settlement goes beyond just the architecture of habitable space. It also encompasses the design of the planet's infrastructure, the creation of standard space transportation, and the development of new economic opportunities on the planet. These are all part of the city planning requirements for Mars.

The research gap in the urban planning on Mars's surface is the motivation of this study. This paper first focuses on urban planning on Mars in the literature review, then explains location selection and zoning as the problem statement of the research. In the third chapter, the methodology of the paper is introduced, and finally, the findings and conclusion of the work are presented.

2. URBAN PLANING ON MARS

Urban planning on Mars presents unique challenges, making it a significant issue for scientists, urban planners, and architects. Donoghue (2016) criticizes the research on the Mars settlement problem for its focus on scientific, medical, and economic perspectives, neglecting human-related issues such as environmental psychology and urban planning. Donoghue (2016) proposes five phases of habitation of Mars: exploration, settlement, colonization, urbanization, and terraforming. Dezfouli et al. (2023) identify key physical and environmental components required to design habitable structures on Mars, emphasizing the importance of robust structural designs that can withstand the harsh conditions of Mars. Donoghue (2016) notes that on Earth, a building is a building; however, on Mars, a building must encapsulate all the necessary diverse requirements of a city. Urbanization must be thought of differently than on Earth in terms of its physicality. However, human-related issues, location decisions, and growth scenarios must still parallel Earth-like urbanization. Makanadar (2023) defines the Mars colonization problem as an interplanetary urban planning problem, emphasizing the crucial collaboration between different disciplines, including aerospace, biology,

architecture, and urban planning. This interdisciplinary approach is key to addressing the complex challenges of urban planning on Mars. Despite the existing literature on the urbanization problem on Mars, it remains a significant research topic with many research gaps.

Smirnova (2020) proposes a cyborg city structure that can enhance the autonomous, self-sufficient system for underground urban organizations to protect the inhabitants of Mars from radiation. Łabowska et al. (2020) propose a Mars city organization with one million inhabitants containing social, industrial, residential, and municipality buildings. Detrell et al. (2021) represent a Martian city plan proposal ensuring the usage of local resources to obtain environmental sustainability. Curtò and Zarza (2024) analyze the transportation potentials for intersettlement connectivity.

This study particularly focuses on the zoning issue according to the terrain and water-related features of Mars to understand where to locate. Understanding the topography of Mars is crucial to building a physical habitat space, and understanding the water features is vital for a settlement. Łabowska et al. (2020) state that topography is one of the key components in Mars architecture, and location selection for colonization is a complex task. Fross and Zasadzka (2019) argue the necessity of landscape and terrain decisions for urban and spatial planning on other planets and the collaboration of architects, urban planners, and scientists. Suścicka et al. (2019) emphasize the importance of a plan for the entire infrastructure design on Mars according to the terrain-related inputs for cost-efficient urbanization. This paper proposes a methodology to decide the zones for spatial decisions for habitable surfaces.

3. METHODOLOGY

This study conducts clustering to understand the zones of possible settlement on Mars's surface according to topographic and water features. The study is divided into three phases: dataset preparation, clustering algorithm training, and visualization of the clusters to decide the zones in the selected region of Mars. Dataset preparation includes selecting Mars locations and extracting the topographic and water features from raster images in the planetary data system (PDS). Algorithm training involves choosing the best number of clusters, and

visualization shows the clusters on their coordinates with color labels.

Figure 1 represents the flow of the work.

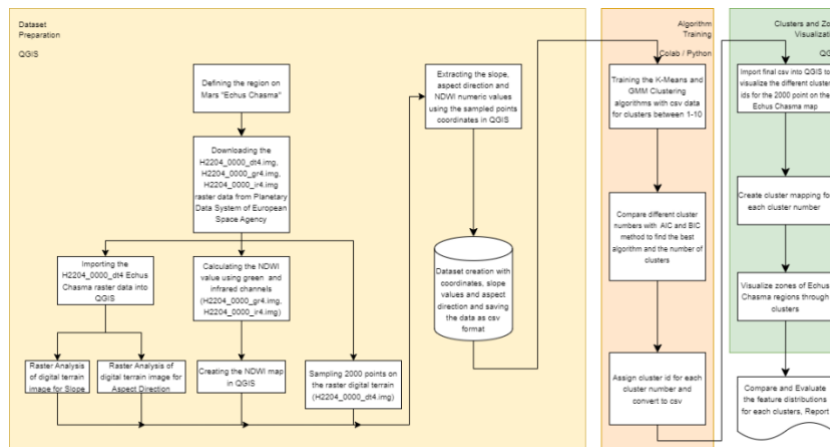
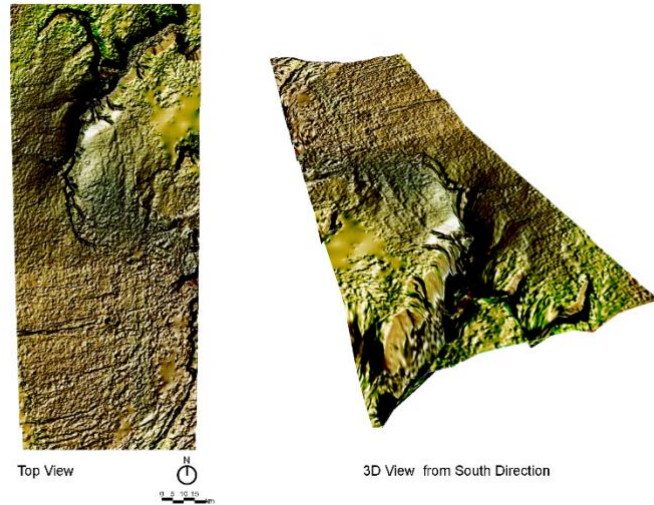


Figure 1: Workflow diagram illustrating the methodology steps

3.1 Region Selection, and Dataset

The Echus Chasma region is selected for the zoning task in this study. The selection criteria are related directly to the National Aeronautics and Space Administration (NASA) criteria and the European Space Agency (ESA) definition of the region. NASA (2021) listed four criteria for selecting the landing location. These are habitable environment evidence, geological analyses that include rock layers, supporting data for water, and secure and stable zones. European Space Agency (2008) defines the Echus Chasma region as 100 km long and 10 km wide, one of Mars's possible largest past water sources. Hollander (2022) represents the suitable locations on Mars for landing and planting and classifies "Valles Marineris" as one of these suitable locations, which Echus Chasma, namely "Grand Canyon of Mars," is located to the north of. Due to the above reasons, the Echus Chasma region is selected for zoning (Figure 2).

Figure 2: Top View and 3D view of Echus Chasma Region



The raster image data of the Echus Chasma region is collected from the planetary data system (PDS) in the European Space Agency (2013). H2204_0000_dt4.img, H2204_0000_gr4.img, H2204_0000_ir4.img raster images are the data for extracting the topographic and water features. "dt" extension stands for digital terrain, "gr" is for the green channel, and "ir" is for the infrared channel of the raster data. All the raster images are in a resolution of 100m/pixel. Although the resolution of the raster images is not enough for a detailed analysis, which is one of the study's limitations, we can use this data for land zoning tasks.

After downloading the raster data, the digital terrain data is imported into QGIS software, and the slope and aspect direction features are extracted using the raster analysis tool for slope and aspect direction. Once the raster analysis was completed, two maps showing the slope and aspect directions were ready. The slope feature denotes the steepness factor of the terrain, while the aspect direction defines the orientation of the slope. Both features are necessary while deciding the location selection to understand the water drainage direction, erosion potentials of the region, the flatness of the area for landing, and solar illumination. These terrain characteristics can help to define the landing and colony positioning zones.

The NDWI method, a remote sensing technique proposed by McFeeters (1996), is a key tool in our research for understanding water features on the surface. According to McFeeters (1996), NDWI is the

ratio between the difference and sum of the green and infrared channels (Figure 3). Using the h2204_0000_ir4.img and h2204_0000_gr4.img raster data, the NDWI value is calculated. These values are converted to a 2D raster image, an NDWI map. Mapping the NDWI value of a region is crucial in understanding the ecological features and deciding the urban planning strategies. Water, the most important factor in life, directly influences the habitability of a region for a colony.

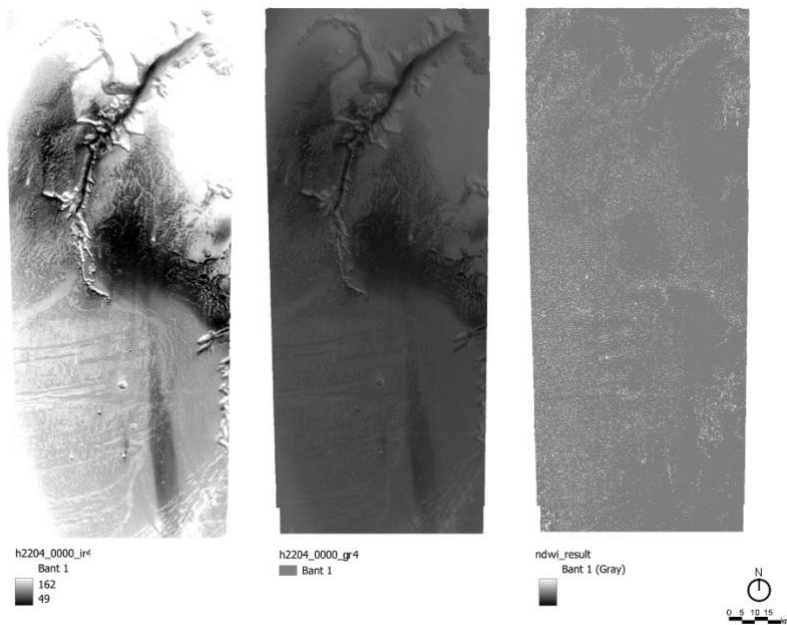
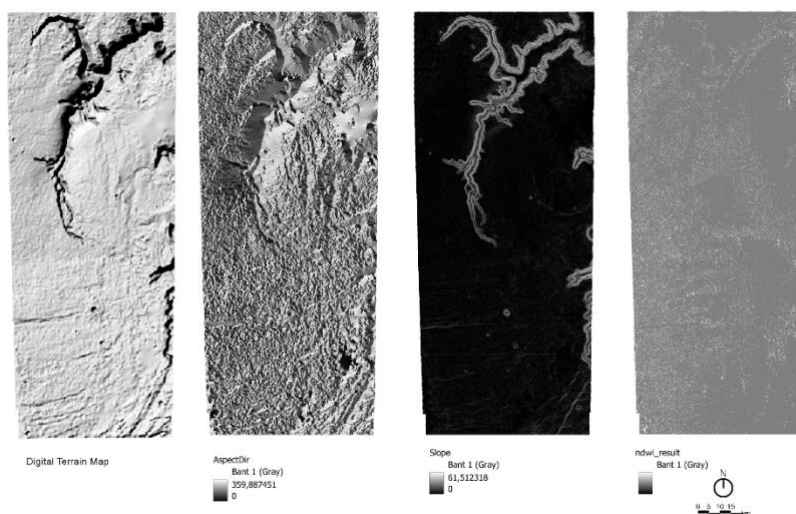


Figure 3: Infrared, green channels of Echus Chasma and NDWI map.

Figure 4 represents the Echus chasma digital terrain, slope, aspect direction, and NDWI maps. After creating the slope, aspect direction, and NDWI maps, 2000 points were sampled on a grid order in QGIS. These points are used to extract the numeric slope, aspect direction, and NDWI values from the sampled point coordinates. Following the assignment of slope, aspect direction, NDWI values to the point coordinates, a comma-separated value (.csv) file is created. This file, which contains the numeric feature values, serves as the dataset for the clustering task.

Figure 4: Echus Chasma region given with digital terrain, aspect direction, slope maps and NDVI values



3.2 Gaussian Mixture Model for Clustering

The task of zoning the Echus Chasma region is decided via the Gaussian mixture models (GMM) clustering method. Clustering is an unsupervised machine learning (ML) method for labeling hypotheses. The algorithm can only predict hypothetical cluster IDs as no label exists in the training sessions. On the other hand, the most important contribution of clustering algorithms is deciding the number of clusters within the dataset, which is previously unknown. So, variability in the dataset can be controlled and clustered according to the dataset's features.

GMM, a prominent clustering method in ML, is a density estimation method that falls under soft clustering methods (Hastie et al., 2009). It represents the feature density in each class and assigns cluster IDs accordingly. Unlike statistical clustering methods, GMM's approach is probabilistic, representing the probability distribution of different clusters rather than creating distinct clusters and efficiently used in complex data. GMM gives a probabilistic decision boundary for the cluster regions. Statistical clustering methods are deterministic and more robust in the simple data—statistical clustering results in discrete sets. Certain decisions on discrete sets can occlude the ambiguous, in-between samples in the dataset contrary to probabilistic models. Therefore, GMM is selected as the clustering method for precisely

defining the ambiguous, in-between values of the selected features on the Echus Chasma region.

Before training the GMM algorithm, the slope aspect and NDWI features in the dataset are scaled between 0-1 to obtain scale compatibility between distinct features; moreover, with scaled data, the algorithm training efficiency can increase, and the interpretability of the results will be easier. After scaling the slope, aspect direction, and NDWI values, the GMM algorithm is trained for cluster numbers between 1 and 10. For each cluster numbers, AIC (Akaike Information Criterion), and BIC (Bayesian Information Criterion), the evaluation metrics for clustering, are calculated. Both metrics measures how well the clustering model fits the data. The better the model, the smaller the result of the AIC and BIC become. Min AIC and BIC scores indicate the optimal number of clusters for the slope and aspect direction datasets.

Figure 5 shows, AIC and BIC values have minimal variations and both showing the same pattern. 9 clusters takes the minimum value of AIC and BIC for the clustering. Hence we can decide the number of clusters as nine. After deciding the number of clusters, CSV file with the slope, aspect direction, NDWI value and coordinates of the points is appended with the related cluster IDs for the visualization task.

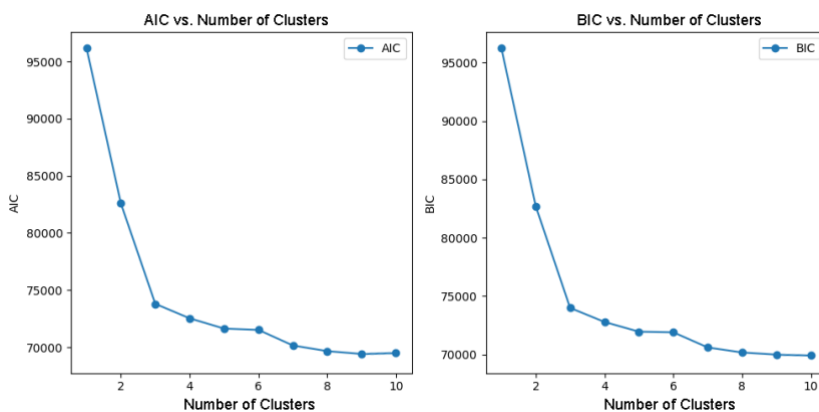


Figure 5: AIC and BIC Scores According to the Number of Clusters in GMM

3.3 Zoning Visualization in QGIS

The visualization process involves assigning cluster IDs to each coordinate in QGIS. After clustering and obtaining the CSV file with cluster IDs, the file is imported into the QGIS software. The imported points initially appear in a single color. The points are classified based on their cluster IDs to create a cluster representation, and different

colors are assigned to each cluster. Once the cluster IDs and colors are assigned to each point, Voronoi diagrams are generated based on the cluster IDs. These diagrams are significant as they help us create clustered surfaces crucial for zoning. Finally, the zoning of the Echus Chasma region is represented in a Voronoi diagram with the assigned cluster IDs (**Figure 6**). All the square cells of the Voronoi diagram have the same size, almost 4 km².

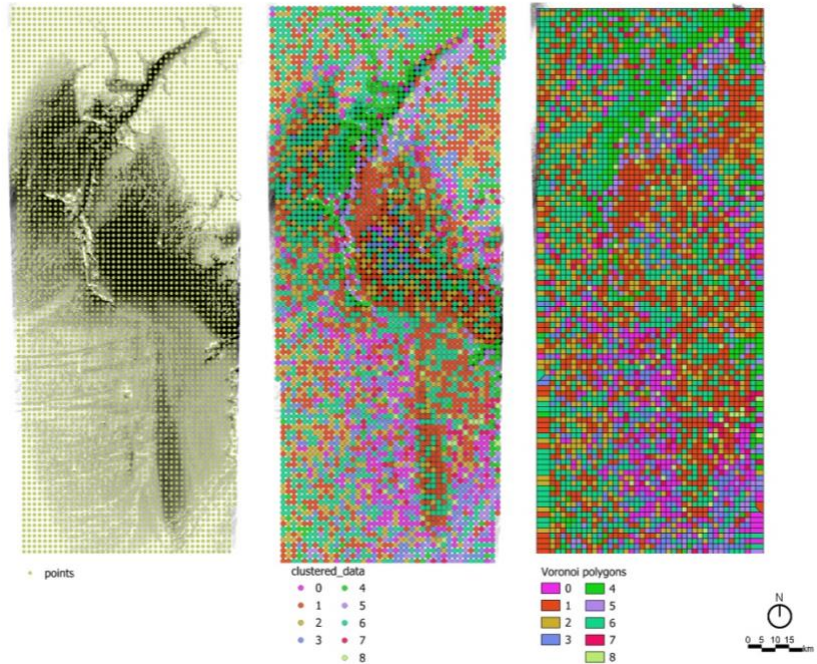


Figure 6: Steps of visualization of zoning decision according to clusters

4. FINDINGS

After deciding the number of clusters as 9, each cluster's feature distributions are represented in **Figure 7** and summarized in **Table 1**. **Figure 7** respectively represents the feature distributions for each cluster.

In slope distribution, cluster 2 is obvious for having mostly the minimum steepness value among all the clusters. Interestingly, two different patterns are obvious: 0, 1, 2, 3, 6, and 7 id clusters create a stack around the slope value 0, and their variance is too small. So, both the steepness value is low, and the terrain is almost flat. On the other hand, clusters 4,5,8 have the biggest variance, having terrain variations that are too

different. The terrain in zones 4, 5, and 8 is rugged and difficult to settle or move.

Aspect direction distribution shows the values between 0-360. The interval between $-45^{\circ}/+45^{\circ}$ demonstrates the Northwest-North-Northeast directions interval. 90° stands for the East, 180° for South, 270° for West cardinal directions. The north direction may help prevent solar radiation while taking the sunlight longer and indirectly, which can benefit site selection and colonization. When we control the densities of the directions, the north direction density is the highest in cluster 2, which makes this region the best candidate for a settlement location according to the aspect direction (**Figure 7**). This can be an advantage in preventing solar radiation and benefit from the longer duration of indirect sunlight. Clusters 4 and 6 have the highest South directional distribution, which can be a crucial problem in terms of solar radiations.

NDWI distribution takes values between $-1/+1$. Between -1 and 0 values show the surfaces without any water features. Values between 0 and $+1$ illustrate the water-related features. Distribution plots show that most values take negative or zero values; however, interpreting the NDWI values directly on the distribution plot is difficult. **Table 1** is describable for NDWI distribution. In the NDWI column of **Table 1**, values show the number of points with values greater than 0 . Cluster 6 shows the highest number of points having values greater than 0 . Cluster 6, 1, 2, and 4 are the first four clusters listed in descending order of the number of points with values greater than 0 .

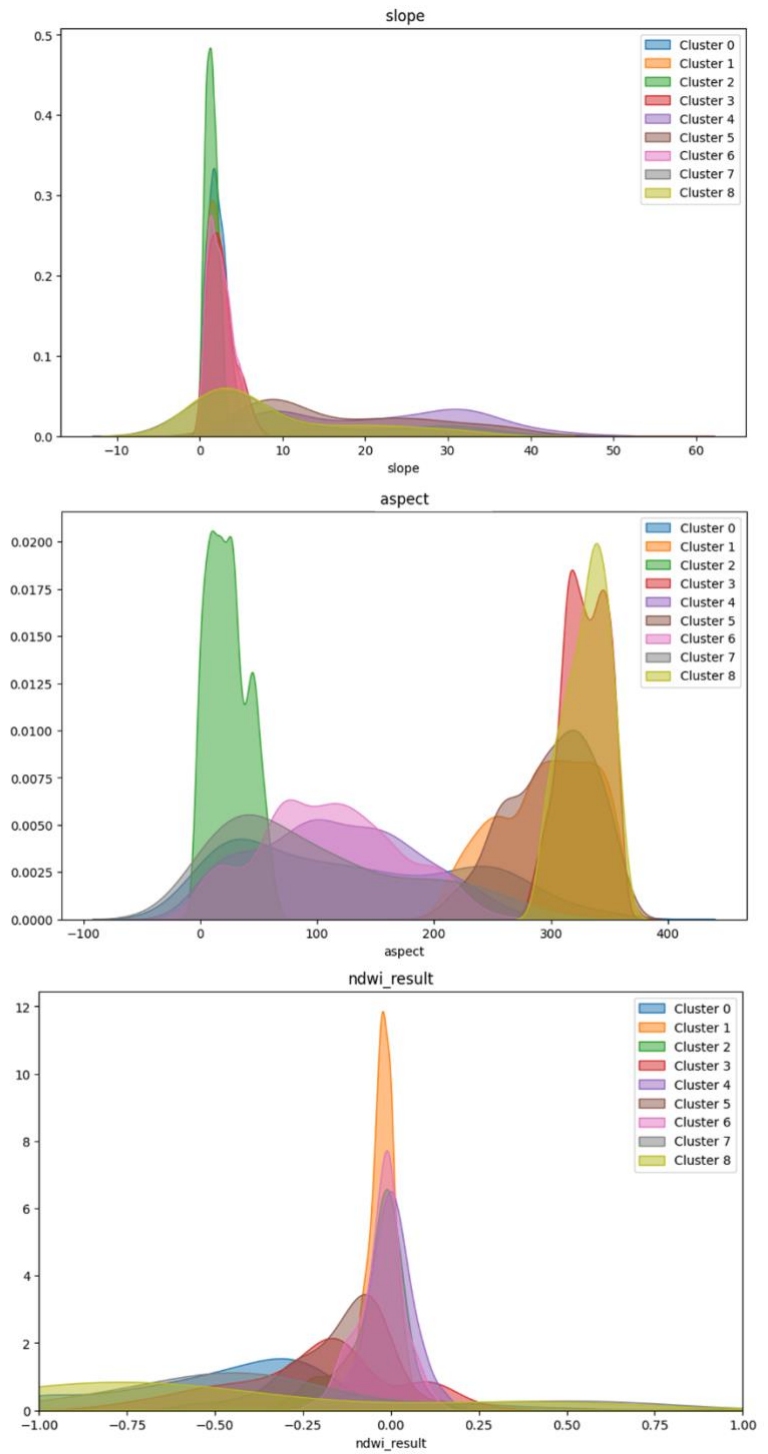


Figure 7: Distribution plots of features for each cluster.

Table 1 represents the best and the worst feature values to understand the best and the worst zones among the clusters. In descending order, northDirection columns list the number of North-directed samples within the related clusters. Zone 2 has the highest number of points oriented in the North direction. Cluster 7 has the smallest number of points oriented in the north direction; hence, this cluster is evaluated as the worst zone with its orientation.

The slope mean column shows the mean values of the slopes within each cluster. The smallest slope mean represents the flattest surface zone. According to this, cluster 2 shows the flattest zone, and cluster 4 is the most rugged zone.

The NDWI column represents the number of points in the dataset with an NDWI value higher than zero. The highest number of NDWI values shows the prevalent presence of water features in the related zone. According to the NDWI column, cluster 6 has the highest number of NDWI values, which is higher than 0. The worst cluster for NDWI value is zone 8.

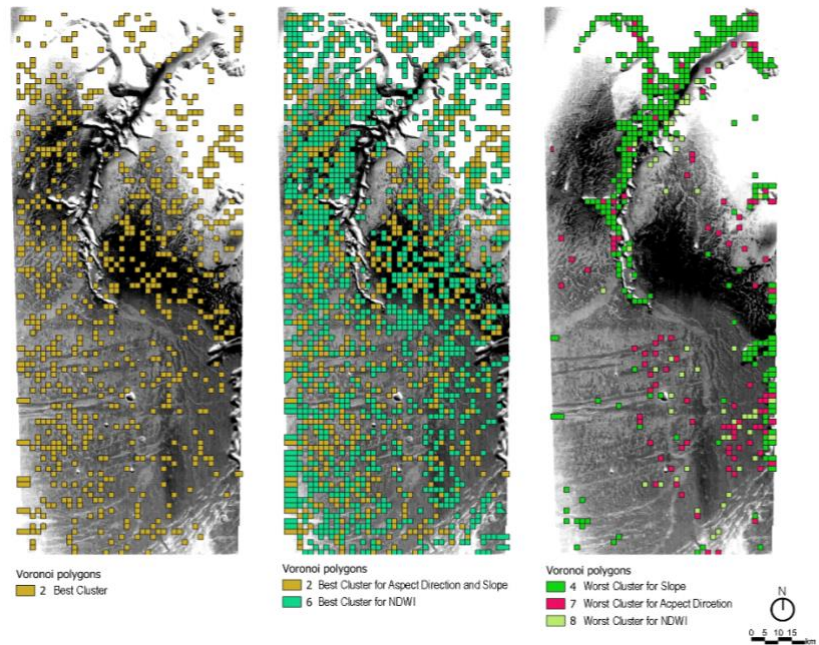
ClusterID	NorthDirection	SlopeMean	NDWI
2	625	1,425124	193
1	380	2,443336	207
3	242	2,646213	67
6	166	2,529766	341
0	119	2,086597	30
5	85	17,63663	16
4	61	22,595386	147
8	40	9,69854	3
7	34	9,883308	13

Table 1: Number of North Direction oriented points, Slope Means, Number of NDWI values which are greater than zero with their corresponding cluster IDs.

Figure 8 illustrates the best zone for settlement, zones with the best features, and zones with the worst features. The best zone is selected as cluster 2, as this cluster has the best value for both slope and aspect direction and takes a considerably high NDWI value, too. However, cluster 2 does not create a connected big region but rather has distributed parts of similar feature zones. Cluster 6 is the best cluster for NDWI but not the best one for both slope and the aspect direction

and shows a similar distribution pattern as cluster 2 on the map without having a connected region. The worst slope zone, cluster 4 is obvious and this zone is located on the canyon part of the Echus Chasma region.

Figure 8: Mapping the best and worst zones on Echus Chasma according to slope, aspect direction and NDWI



4. CONCLUSION

This study proposes a method to decide the zone clusters on Mars according to topographical and water features. This study uses GMM clustering to define habitable zones. The region selected for the zoning task on Mars is the Echus Chasma region. After extracting the slope, aspect, and NDWI data from the Echus Chasma region, the clusters are determined through GMM, and then zones are created through visualization in QGIS. This study aims to subdivide Mars' surface distantly to create a template or starting point for an urban planning task.

Along with this motivation of the study, this research proposes a hypothetical best settlement zone for the selected region, Echus Chasma. The best settlement region in this study is located on the cluster 2.

This study can only propose hypothetical zones based on three features: slope, aspect direction, and NDWI of Echus Chasma, which creates the biggest limitation of the study. On the other hand, since the reliability of the NDWI value cannot be validated, it needs to be controlled carefully. However, the study has a guiding function in creating hypotheses. However, the validity of NDWI also has certain limitations. From a methodological perspective, this study contributes to the literature on Mars architecture and urban planning. It opens new discussion topics for future works about the selection criteria of the settlements on Mars.

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ArchiJury: Exploring the Capabilities of Vision-Language Models to Generate Architectural Critique

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Artificial Intelligence (AI) offers a potent opportunity to rethink architectural critique, in cases such as architectural design competitions. The challenge lies in capturing the interpretive depth required for design evaluation—an inherently human process that connects intuition, reasoning, and contextual sensitivity. Building on this premise, ArchiJury uses a domain-specific dataset, curated and validated by authors as domain experts, architects, to train a context-aware Visual-Language Model (VLM) capable of delivering a nuanced critique. The model development follows two distinct phases: an initial version (v1) explores feasibility through classification of visual architectural attributes, while the second phase (v2) evolves into a structure generating detailed critique texts guided by predefined criteria such as context, form, and programmatic considerations. The proposed model aims to bridge the gap between computational precision and the complexities of architectural judgment, offering a structured yet adaptable framework for utilizing AI in the evaluative aspects of design. Although still in its early stages, this work opens a pathway to complement traditional review processes with reliable, scalable, and context-sensitive feedback, laying a foundation for incorporating the patterns of tacit knowledge in architectural design into the review process.

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Mimar Jüri: Görme-Dil Modelleri ile Mimari Tashih Üzerine bir İnceleme

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Günümüz tasarım pratiğini radikal şekilde dönüştürmeye başlayan üretken Yapay Zeka (YZ) modelleri, tasarım sürecinin derinlemesine değerlendirilmesi ve geliştirilmesi için kritik bir öneme sahip olan mimari eleştiri için önemli bir potansiyel sunmaktadır. Özellikle, mimari tasarım yarışmaları gibi yoğun katılımcı sayısına sahip, kapsamlı ve tutarlı mimari eleştirilerin elzem olduğu çerçevelerde mimari kritiğe ulaşmak büyük bir zorluk oluşturmaktadır. Bu noktada çalışma, Görme Dil Modelleri olarak bilinen bir yapay zeka modeli mimarisini, tasarım problemlerini sorgulayarak, üretilen mimari çözümlere yorum ve mimari eleştiri geliştirmek üzere kullanılmasını önceleyen bir çerçeve önermektedir. Mimari tasarım pratiklerinde YZ araçları daha çok üretim, görsel temsil ve optimizasyon gibi somut çıktılar elde etmek için kullanılsa da, mimari eleştiri gibi sezgisellik, sorgulama ve bağlamsallık gerektiren alanlarda henüz sınırlı bir kullanım alanına sahiptir. Araştırma kapsamında önerilen YZ modelinin mimari eleştirinin sezgisel ve yoruma dayalı, nicel veriler ile ölçülemeyen boyutlarına entegre edilerek, tutarlı ve ölçeklenebilir eleştirilerin geliştirilmesi amaçlanmaktadır. Önerilen model, hem bağlam duyarlılığı hem de mimari değerlere uygunluğu sağlamak adına yazarlar, alan uzmanları, tarafından tasarlanmış bir veri seti ile eğitilmiştir. Modelin geliştirilmesi safhası, iki temel aşamadan oluşmaktadır. İlk aşama olan "v1," görsel mimari özelliklerin (örneğin, geleneksel veya çağdaş, açısız veya organik formlar gibi) ikili sınıflandırmasını inceleyerek, çalışmanın ikinci aşamasında geliştirilen model mimarisinin tanımlanan araştırma problemi karşısında uygulanabilirliğini test etmeyi amaçlamaktadır. İkinci aşama olan "v2"de ise model mimarisi, önceden tanımlanmış değerlendirme kriterlerini (bağlam, ölçek, tasarım stratejileri, programatik ilişkiler vb.) kullanarak kapsamlı ve detaylı metinsel eleştiriler üretmek üzere geliştirilmiştir. İlk aşamada elde edilen sonuçların değerlendirilmesinin ardından; ikinci versiyonda model, genişletilmiş bir görsel veri seti ve uzman değerlendirmesiyle elde edilen mimari yorumlar ile eğitilerek, modelin kapsamlı ve tutarlı eleştiriler üretme kapasitesi artırılmıştır. Bu süreçte, modelin ürettiği her eleştiri, doğruluk ve tutarlılık açısından alan uzmanları tarafından gözden geçirilmiş ve revize edilmiştir. Çalışma kapsamında elde edilen sonuçlar, Görme Dil Modellerinin geleneksel jüri süreçlerini yapılandırılmış, ölçeklenebilir ve bağlam duyarlı eleştirilerle destekleyerek mimari tasarım pratiği ve yapay zeka arasındaki diyalogu geliştirme potansiyeline sahip olduğunun altını çizmektedir.

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1. INTRODUCTION

Architectural critique is the cornerstone of the architectural design practice, opening the discussion space for expanding multi-dimensional aspects of the given design problems, to guide and refine the continuous process of design (Lymer, 2009; Fischer et al., 1993). However, obtaining architectural critique during off-studio hours is often limited by availability and accessibility, making it challenging to integrate consistent feedback into evolving processes of design (Luther et al., 2015). Nowhere is this more evident than in the context of architectural design competitions, which often represent the pinnacle of professional practice. These competitions require rigorous evaluation of entries that are innovative yet feasible and contextual (Rönn, 2011). Given that submissions are often numerous-sometimes in the hundreds, and typically occur within time-constrained competitions, it can be challenging for jurors to provide fair and comprehensive critiques, making it difficult to ensure that strong designs receive the recognition they deserve (Frederickson, 1990).

As artificial intelligence (AI) continues to transform architectural design, its potential to assist in competition review processes presents a compelling area of exploration. While in the current state of the art AI has been employed dominantly in architecture practice for generative design, visualization, and optimization tasks (Salem et al., 2024; Li et al., 2024), its application in the interpretive domain of critique remains underexplored. Because the acknowledgement of AI as a "black box" (Adadi & Berrada, 2018) poses significant challenges when applied to architectural critique since the problem goes beyond simply optimizing or generating output within well-defined parameters and metrics. Rather than the tangible aspects of a design – such as its spatial configuration or structural integrity – architectural critique also requires consideration of the intangible aspects, including cultural context, experiential resonance, and design intent (Güzer, 1994). Since it is a deeply interpretive process, intertwining intuition, reasoning, and contextual sensitivity—qualities that traditionally stem from human expertise, developing an AI model that can provide nuanced critique, these limitations must be addressed by combining computational precision with transparency and interpretive depth.

In light of this discussion, this research introduces an AI-driven architectural critique trained using Vision-Language Models (VLMs) to review architectural designs comprehensively. While the proposed ArchiJury research marks a rigorous initial step, it is only a fragment of the broader challenge of embedding AI in interpretive, intuitive and evaluative aspects of design practice. The main aim of this research presented here is to develop a synthetic architectural review model that can help assess entries in architectural design competitions. We hypothesize that the proposed VLM model trained with domain expert validated architectural image and review datasets, has potential to enhance traditional jury methods with structured, consistent, and scalable critiques of designs based on architectural principles. To this end, the study seeks to explore whether a domain-specific VLM can accurately generate structured critiques for architectural images, particularly by addressing contextual, formal, and programmatic criteria. This guiding question informs the methodological approach and evaluation framework detailed in the subsequent sections.

To draw a theoretical framework for the discussion in Section 1.1., the recent research in the computational design literature that delve into the role of AI in architectural design as evaluator are revisited. In section2, the computational architecture of the Vision Language Models (VLMs) are explained and the related literature that utilizes VLM models in the scope of architectural design are revisited. Starting from the overview of the methodology in Section 3, the development phases of the model are explained regarding two complementary versions. The utilization technique of the VLM architecture in the scope of the research is explained, which enabled us to generate architectural reviews based on architectural images. In Section 3.1 the training process of the initial version of the model is discussed, that focuses on classification tasks to identify key attributes of architectural designs from the provided architectural building photographs, that lays the groundwork for more complex interpretive capabilities. Subsequent iterations during the development phase of the second version of the model are discussed in Section 3.2, in terms of introducing comprehensive critique generation, enabling the model to deliver detailed feedback on contextual relationships, formal qualities, and programmatic considerations. In Section 4, the outputs of both model versions are compared and discussed in terms of the quality of the generated architectural critiques, revealing the limitations of the current model that outlines the further research investigation paths.

1.1. AI models for architectural design evaluation

The integration of Artificial Intelligence (AI) in architectural design evaluation is rapidly gaining traction. While much of the existing research focuses on AI as a design generator, there is a growing interest in exploring its potential as a critical evaluation tool. This section briefly reviews and highlights several key studies that examine computational tools and AI's role in assessing architectural designs, emphasizing their methodologies, limitations, and implications.

One notable study by Guzelci and Sener (2019) introduced an entropy-based model to evaluate projects submitted to architectural design competitions. This model considers various factors such as aesthetics, functionality, context, and innovation, assigning weights to each criterion to create a more objective assessment framework. Similarly, Luther et al. (2015) developed the CrowdCrit platform, a user-driven feedback system designed to gather diverse perspectives during the design process. This approach allows designers to share their projects with a broader audience and receive constructive feedback. Despite its value in democratizing critique, the platform lacks advanced contextual analysis capabilities, restricting its scope to user comments and ratings. Another important contribution comes from Wu et al. (2020), who developed an AI model to classify the visual characteristics of building facades. While this study demonstrated the model's efficacy in evaluating aesthetic properties, it failed to account for broader contextual and user-centric considerations. Its narrow focus on measurable visual elements underscores the need for more comprehensive evaluation approaches. Sanalan (2022) explored the transformative role of AI and big data technologies in architectural design processes. This study highlighted how these technologies are reshaping design workflows, enabling faster decision-making and more efficient collaboration. However, the research also emphasized the necessity of integrating qualitative and human-centric insights into AI-driven evaluations to avoid overly mechanistic assessments.

Despite these advancements, a common limitation of these studies is their dependence on quantifiable parameters. Architectural critique often involves complex, subjective judgments that extend beyond data-driven metrics. For instance, evaluating how a design aligns with its environmental context or enhances user experience requires a combination of intuitive and empirical approaches. To address these

gaps, this paper proposes a context-sensitive Visual-Language Model (VLM) as an alternative framework for architectural evaluation. Building on the strengths of multi-factor approaches like Guzelci and Sener's model (2018) , VLM incorporates the diversity and contextual richness highlighted by Luther et al. while maintaining technical rigor. Unlike existing methods, VLM prioritizes holistic assessments by integrating qualitative feedback with quantitative analysis, offering a more balanced evaluation of architectural projects. By treating AI not merely as a tool for generating designs but as a critical evaluator, VLM opens new possibilities for advancing architectural practice and fostering more nuanced critiques.

2. VISION LANGUAGE MODELS (VLMs)

Vision-Language Models (VLMs) represent a significant advancement in artificial intelligence, integrating visual and textual data to interpret, analyze, and generate context-aware outputs (Ghosh et al., 2024). VLMs function by linking computer vision techniques with natural language processing (NLP) algorithms, enabling systems to process visual inputs and produce textual interpretations (Bordes et al., 2024). Computational architecture of VLM models advanced rapidly, employing transformer architectures and self-attention mechanisms to learn joint representations of text and visual inputs, and are generally categorized into vision-language understanding models, multimodal input to unimodal output models, and multimodal input-output models (Ghosh et al., 2024). Despite these innovations, key challenges in VLM development persist, including data selection, architecture design, and training methods, alongside broader concerns regarding multimodal fusion, interpretability, reasoning, and ethical implications (Laurençon et al., 2024).

The architecture of the proposed VLM follows a modular design to facilitate efficient training and critique generation, incorporating a dual-stream encoder for processing visual and textual inputs, with the visual Vision Transformer (ViT) and the textual encoder employing a transcoder utilizing a pre-trained Transformer-based architecture (Marafioti et al., 2024). A cross-modal attention mechanism aligns visual and textual embeddings, forming the core of the model's interpretive capabilities. For critique generation, a decoder synthesizes structured

textual outputs addressing evaluative dimensions such as contextual relationships, formal characteristics, and programmatic considerations.

2.1. Utilization of VLMs in the Architectural Design Domain

The integration of Vision-Language Models (VLMs) into architectural design represents a novel and evolving research frontier. While generative AI models such as diffusion models and GANs have been widely employed for image generation and visualization tasks, the use of VLMs for interpretive and evaluative purposes in architecture remains relatively underexplored. However, recent scholarly efforts indicate an increasing interest in leveraging the multimodal reasoning capacities of VLMs within the design domain.

One pioneering study by Chen et al. (2024) introduced LLM4DESIGN, an automated multi-modal system that integrates VLMs with multi-agent systems and Retrieval-Augmented Generation (RAG) to facilitate architectural and environmental design processes. The research emphasizes generating coherent, multi-illustrated, and multi-textual design schemes that align with narrative storytelling and objective design presentations. By leveraging VLMs, the system is capable of analyzing design requirements alongside site conditions to produce context-aware architectural outputs, indicating the potential of VLMs for expanding the scope of design automation and critique.

Similarly, Jang and Lee (2023) explored the integration of large pre-trained language models with Building Information Modeling (BIM) systems, highlighting how VLM architectures can mediate the interaction between architectural data and design interpretation. Their approach utilized XML data formatting to translate between textual inputs and BIM models, revealing a pathway for VLMs to dynamically engage with structured architectural information and contribute to iterative design processes. Although the focus remains on system interoperability, the study underscores the capacity of VLMs to interpret and contextualize architectural information within computational frameworks.

Additionally, Galanos et al. (2023) introduced Architext, a language-driven design tool that employs large-scale language models to

generate architectural layouts based on natural language prompts. While primarily focused on conceptual generation rather than critique, the research illustrates the potential of VLMs to mediate between textual design intentions and spatial configurations. The study demonstrated the system's ability to produce valid residential layouts from minimal textual input, suggesting promising avenues for integrating VLMs into early-stage design ideation.

These emerging studies collectively illustrate the gradual incorporation of VLMs into architectural practice, particularly in contexts requiring the translation of complex, multimodal information into actionable design insights. However, the direct application of VLMs for nuanced architectural critique—particularly in assessing the contextual, formal, and programmatic dimensions of architectural proposals—remains largely underdeveloped. Addressing this gap, the present study advances the discourse by proposing a domain-specific VLM framework explicitly tailored for architectural critique. Unlike prior applications that primarily focus on generative design or descriptive tasks, this research emphasizes the interpretive and evaluative capacities of VLMs. The model is designed to generate structured critiques that engage with the contextual relationships, formal qualities, and programmatic considerations inherent in architectural proposals.

3. TRAINING THE MODELS FOR ARCHITECTURAL CRITIQUE: OVERVIEW

This section revisits the research's overarching aim of using Vision-Language Models (VLMs) as synthetic jury members in architectural critique. It provides an overview of the research workflow while addressing the rationale for training a domain-specific AI model.

The rationale for developing a domain-specific AI model lies in the inherent limitations of general-purpose language models when applied to architectural critique. General-purpose language models often suffer from hallucinations—producing plausible yet incorrect outputs—due to their training on broad, multi-domain datasets (Zhang et al., 2023). This issue, exacerbated by computational parameters such as temperature, underscores the need for a targeted approach (Mittal et

al., 2024). Furthermore, generic models have limited ability to understand contextual sensitivity and nuanced concepts such as spatial relationships (Gokhale et al., 2022), cultural relevance (Shen et al., 2024), and design intent for architectural critique. Besides, these models also contain biases from their datasets which are unreliable in special contexts (Mehrabi et al., 2021). To overcome these biases, this proposed methodology adopts a comprehensive strategy: training the model on a domain-specific, context-aware dataset validated by six architects with a minimum of five years of experience; embedding architectural standards and principles are embedded into the dataset annotations; and a targeted task framework is defined to guarantee precise, structured outputs. This integrated approach not only mitigates hallucinations and biases but also ensures consistent, scalable, and professionally relevant critiques.

The research methodology is presented in two main phases of the developmental process, each with its own objectives and the sets of data used for training the goals (**Figure 1**). The first version, v1, takes an initial approach with classification tasks to sort out architectural images into different categories based on certain formal and stylistic characteristics. As the initial step validated the feasibility of the proposed AI-driven critique framework, the subsequent version, v2, aims to train a more advanced model that generates comprehensive textual critiques based on the pre-defined evaluation criteria with the specific task definition.

The VLM employed in this study was developed as a domain-specific model tailored for architectural critique, leveraging a curated dataset validated by architectural domain experts to ensure reliable and context-sensitive outputs. For this purpose, the SmolVLM framework developed by Huggingface was chosen due to its lightweight architecture, open-source licensing, high performance-to-size ratio, and low training cost. SmolVLM builds upon the Ldefics3 architecture, introducing enhancements such as a compact SmolLM2 1.7B language model and a visual processing layer employing a pixel shuffle strategy that compresses visual information ninefold, significantly improving efficiency compared to prior models. This strategy optimizes visual inputs of 384x384 pixels with 14x14 internal patches, reducing memory usage while maintaining high performance (Huggingface, 2024). The

model's tailored design aligns with the resource constraints of this study, allowing it to be fine-tuned effectively using a single RTX 4090 GPU. Techniques like Quantized LoRA (QLoRA) further optimized training efficiency (Dettmers et al., 2023), making SmolVLM particularly suitable for this application.

The training workflow involved two iterative phases: Version 1 focused on classification tasks using a dataset of 1,589 architectural images, supplemented by synthetic images generated through text-to-image diffusion models, and Version 2 expanded this approach with a dataset of 12,320 textual critiques linked to architectural images, transitioning the model to generate detailed, multi-dimensional architectural reviews.

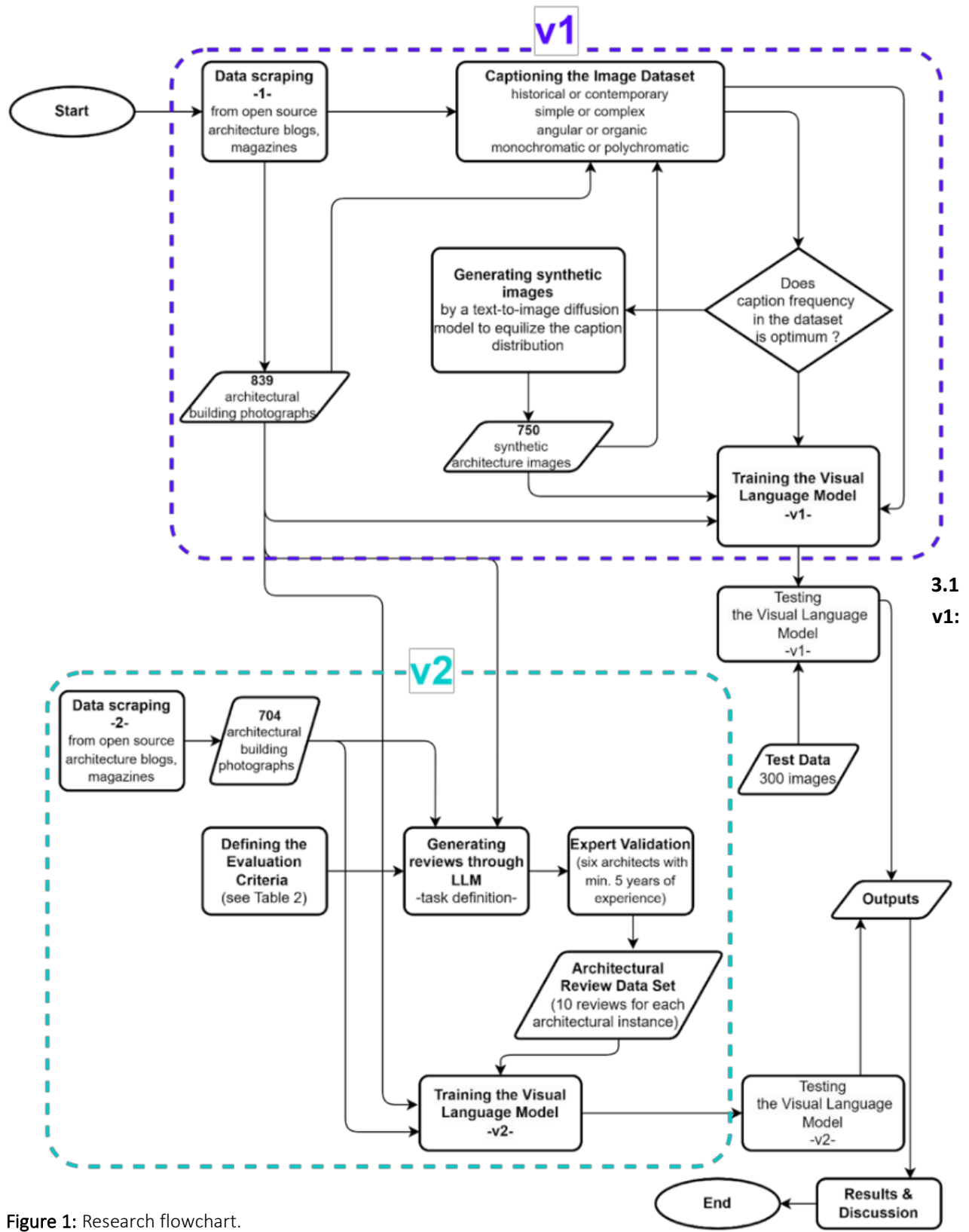


Figure 1: Research flowchart.

Classification Based Descriptive Model

The initial version of the model, v1, was designed as a simple prototype to see the feasibility of the concept. Thus, a simple tagging system was utilized, concentrating on ease of implementation and evaluation. The goal was to determine whether the approach would be effective enough to warrant more sophisticated techniques being developed.

The v1 dataset consisted of 839 architectural images collected from a combination of international and local architectural websites. Well-known architecture blogs i.e. ArchDaily, Dezeen and Architectural Digest made up the international segment, while the Turkish platform Arkitera provided the local content. The data collection process was a combination of automated and manual efforts. Although a small portion of the dataset was curated manually, the vast majority of the images were collected through custom data scraping scripts, with a focus on Arkitera's massive project archives. For consistency, the first two images in each project's page were retrieved as the visual representatives of that specific architectural project. After the initial scraping, we removed images containing architectural drawings, presentation boards, noisy, deformed, ultra-wide perspective, and aerial perspective images to guarantee that the dataset contained only proper visuals of architectural structures. **Figure 2** displays the collected dataset instances partially.

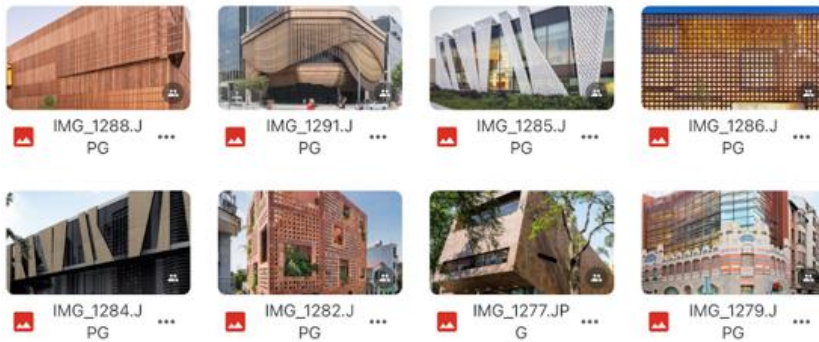


Figure 2: Examples from collected image dataset that contains architectural building photographs.

After the scraping and gathering processes, the images were subjected to a structured captioning process. Six domain experts, also architects, evaluated and captioned each image. The captioning was done based on visual characteristics of the images alone, without considering the context of the architectural design. (**Figure 3**)

The primary objective was to assess the baseline capabilities of the Vision-Language Model (VLM) in classifying architectural images based on simple, yet fundamental, visual characteristics. To ensure clarity and minimize interpretive complexity, we designed a controlled training approach using predefined caption categories that are visually discernible and fundamental to architectural analysis.

The selected classification criteria were based on four core visual attributes:

Form: Categorized as angular or organic, reflecting the geometric nature of the architectural form.

Style: Defined as contemporary or historic, indicating the temporal and stylistic context of the design.

Color Palette: Distinguished as monochromatic or polychromatic, referring to the visual character of the facade's color composition.

Spatial Organization: Classified as simple or complex, capturing the arrangement and complexity of spatial elements observable in the facade composition.

These categories were chosen for their clarity, objectivity, and relevance to architectural discourse. Each attribute represents a fundamental aspect of visual analysis that can be consistently identified from single images. For a single image of a building, the 16-class multi-class captions, formed by combinations of whether historical or contemporary, simple or complex, angular or organic, and monochromatic or polychromatic, were chosen for their ability to capture core architectural characteristics while being straightforward to differentiate.

Although the v1 dataset was technically suitable for training the model, there were problems with the distribution of captions in the data. As images were obtained from contemporary architectural blogs, the dataset was highly concentrated on contemporary buildings as expected. In addition to the single-caption imbalances, certain caption combinations also appeared disproportionately often. For instance, the most frequent combination was contemporary, complex, organic, monochromatic, while the least frequent combination was historical, complex, organic, polychromatic. (Figure 4)

A	B	C	D	E
NO	Contemporary-Historical	Simple-Complex	Angular-Organic	Monochromatic-Polychromatic
	Is the design contemporary or historical?	Does the structure appear simple or complex?	Does the design feature angular lines or organic curves?	Does the design use a monochromatic or polychromatic color palette?
	Contemporary	Simple	Angular	Monochromatic
0	Contemporary	Complex	Angular	Monochromatic
1	Contemporary	Simple	Angular	Monochromatic
2	Contemporary	Complex	Angular	Monochromatic
3	Contemporary	Complex	Organic	Monochromatic
4	Contemporary	Simple	Angular	Monochromatic
5	Contemporary	Simple	Angular	Monochromatic
6	Contemporary	Complex	Organic	Monochromatic
7	Contemporary	Complex	Angular	Monochromatic
8	Contemporary	Complex	Angular	Monochromatic
10	Contemporary	Simple	Organic	Monochromatic
12	Contemporary	Simple	Angular	Polychromatic
13	Contemporary	Complex	Organic	Monochromatic
14	Contemporary	Complex	Angular	Monochromatic
15	Contemporary	Simple	Angular	Monochromatic

Figure 3: The spreadsheet used by the domain experts for the captioning the architectural instances in the dataset.

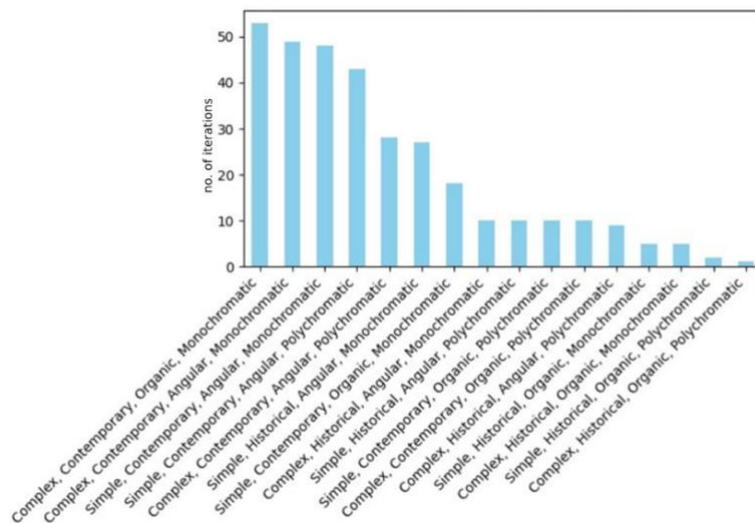




Figure 4: The distribution graph of the captions combinations in the initial version of the dataset.

This imbalance posed a risk of having a biased model, as certain architectural captions and combinations would dominate during training. To address this issue, we enhanced our dataset through a synthetic data generation method. Using text-to-image diffusion models, we created architectural building images with the less frequent caption combinations by incorporating these combinations into the prompts given to the text-to-image diffusion models. While the generated images were synthetic and do not exist in the real world, they increased the diversity of the dataset and provided the caption frequency and combinations balance.

Table 1: Exemplary selection of the synthetic data included in the architectural images dataset.

In total, 750 synthetic images were generated, specifically from the underrepresented caption combinations. **Table 1** displays an exemplary selection of the synthetic architectural images and their text prompts generated by using accessible text-to-image diffusion models i.e. Midjourney, Prome AI. After generation, the synthetic images were also captioned correspondingly to maintain consistency. These synthetic images were then combined with the original scraped data to create a final v1 dataset of 1,589 images. The following comprehensive dataset provided a more balanced and representative foundation for training the first version of our model.

Text-prompts	Generated Images
A simple, historical cultural pavilion with sharp, angular geometry and a vibrant polychromatic façade. The design features bold, triangular rooflines and color panels that shift from deep reds to soft blues, contrasting with the historical stonework. The angular shapes create a dynamic interplay of light and shadow, emphasizing the modern use of color within a historical context.	
Exterior architectural photography, Contemporary organic architecture with fluid, seamless forms, monochromatic material palette of raw concrete and warm-toned wood, natural stone accents, minimal yet bold design, soft transitions between surfaces, open and expansive spaces, calm and earthy aesthetic.	

During the training process of version 1, the pre-trained SmolVLM model was utilized. This decision was primarily driven by the high costs associated with training large-scale Vision-Language Models (VLMs) from scratch. Instead, a strategy was adopted to select pre-trained models suited to the target task and specialize them through fine-tuning with customized datasets. One of the primary challenges encountered during the training process stemmed from the dataset's classification-based structure, which relied on predefined categories. While the input images encompassed significant diversity and varied data types, the insufficient representation of labels (categories) to match this diversity posed difficulties for the model's learning process. The test results of the initial version of the model, v1 are displayed in **Figure 5** partially. The results of these experiments ultimately highlighted the need for a transition to version 2, accompanied by the preparation of a more comprehensive and balanced dataset, leading to concrete steps in this direction.

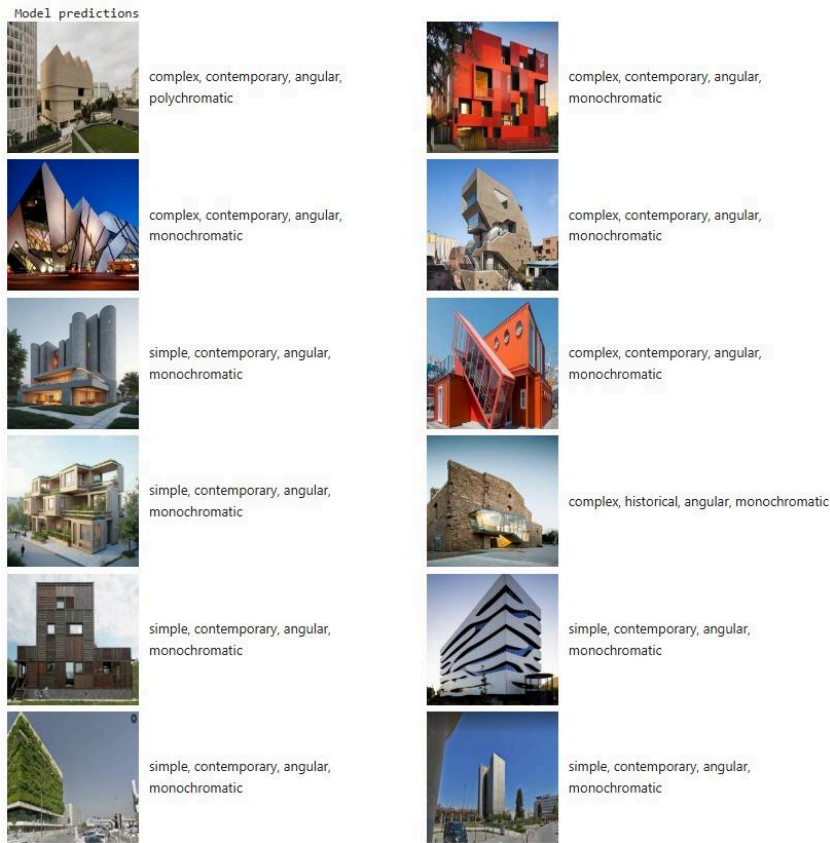


Figure 5: The distribution graph of the captions combinations in the initial version of the dataset.

3.2. v2: VLM based Comprehensive Review Model

After confirming the feasibility of our approach with v1, to improve the performance of the model, computational architecture of the VLM model is altered from generating multi-class captions to comprehensive and descriptive architectural review structures. This improvement required both a larger dataset and a new approach for captioning. To achieve this, the initial image data set is extended by using data scraping and acquisition techniques. Approximately 15,000 images from over 2,400 architectural projects are scraped from Arkitera's archives using scripts. To ensure the quality and relevance of the images a multi-step filtering process is implemented. First, script-based methods to eliminate images containing technical drawings, presentation boards, and infographics were used. After, a manual screening was conducted to remove noisy or deformed images, ultra-wide perspectives, and aerial perspectives. After these rigorous preparation steps, 704 new high-quality images were added to the dataset. These were combined with real-world architectural images from the initial dataset used in v1. However, synthetic generated

images from v1 were excluded, as the need to balance captions was no longer relevant in this version. As a result, the second dataset contains a total of 1,232 architectural images.

Unlike v1, where multi-class captions were employed, v2 adopted a text-based captioning approach. Every image in the dataset was captioned with textual descriptions to address various architectural evaluation criteria. These criteria included context, form, architectural style, design principles, scale, program, and structural system etc. **(Table 2)**. The captions were created synthetically with the help of large language models (LLMs). For each image, the language model was prompted to review the architectural features based on these specific criteria, producing detailed review comments. To improve diversity and the ability of the model to learn, ten alternative captions are generated for each image instance.

Table 2: Defined evaluation criteria to generate architectural reviews.


Evaluation Criteria	
Context	Relationship with surroundings, Urban density, Urban texture
Form	Angular, Orthogonal
Design Principles	Rhythm, Balance, Contrast, Integrity, Hierarchy, Symmetry Datum, Harmony, Repetition
Architectural Style	Traditional, Modern, Post-modern, Parametric, Brutalist, Minimal, Eclectic, Classic, Neo-classic, Futuristic, Deconstructivist, Gothic, Baroque, Art Nouveau ,Renaissance
Height	Low-rise (1-4 floors), Mid-rise (5-12 floors), High-rise (13+ floors)
Program	Residential, Commercial, Public, Mixed-use, Industrial, Institutional , Religious
Construction Strategy	Additive, Masonry, Frame
Architectural Scale	Pavilion, Building, Urban
Construction System	Reinforced Concrete, Steel Frame, Wooden Frame

To generate detailed textual captions for the dataset, a specialized task definition is tailored to have comprehensive architectural reviews from the large language model: “As an expert architect, provide a one-paragraph critique on the depicted architectural design, considering its relationship with the context, form, design strategy, style, scale, construction strategy, structural system, and sustainable approach.” The task definition in the text prompt structure was important to make sure LLM to mention all the given architectural evaluation criteria, without enabling the model to hallucinate.

After generating synthetic architectural review comments utilizing the large language model, all the 12,320 reviews went through manual examination by a team of six domain experts, all of whom were architects with a minimum five years of experience. This step was important to validate the quality and reliability of the dataset

annotations. Poorly constructed, insufficient, or unclear comments were manually revised and improved. This meticulous process guaranteed that the textual annotations maintained a high standard of accuracy and relevance, aligning with the expectations of professional architectural review. The whole process created an annotated dataset that v2 was trained on, enabling it to generate comprehensive architectural review comments. **Table 3** illustrates the dataset that is used to train the VLM model over one of the examples. The reviews displayed in the table are initially generated by an LLM and revised and validated by the experts of the study in terms of the review structure regarding the given task definition and evaluation criteria.

Table 3: Example of validated review alternatives generated through LLM from the input architectural image dataset.

Provided Image	Review 1	Review 2
	<p>The building makes a bold visual statement in the natural coastal landscape, with its vertical, monolithic form standing in stark contrast to the rugged rocks around it. Its form is streamlined, with smooth, layered panels that create a sense of rhythm and flow, despite its height. Design principles of contrast and emphasis are evident, as the white structure rises dramatically from the rock. The futuristic style complements its unique setting, offering an iconic addition to the coastline. The large-scale, vertical design appears to serve a residential or hospitality purpose. Likely utilizing a steel or concrete core for stability, the building is designed to withstand its exposed cliffside environment.</p>	<p>Rising sharply from the cliffside, this building's smooth, vertical layers create a striking dialogue with the rocky landscape. Its form is bold and sleek, with a flowing façade that enhances the sense of height and elegance. Design principles of emphasis and contrast are evident, with the bright white color and modern aesthetic standing out against the natural terrain. Its futuristic style gives it a unique character, aligning with themes of innovation. Towering in scale, it seems suited for high-end residential or hotel use. Reinforced concrete likely forms the core structure, while smooth cladding materials create the layered, monolithic effect, making it both visually striking and durable.</p>

Training the model by implementing SmolVLM’s fine-tuning process, enables AI to preserve the original architecture while adapting it to the specific task using a specialized dataset. This approach was cost-effective and leveraged pre-existing capabilities of the model in visual understanding and interpretation. A consistent task prompt—“Evaluate the building architecturally in terms of its context, form, design principles, style, scale, architectural size, architectural program, construction strategy, structural system, sustainability, and green architecture”—ensured focus on architectural critique. Fine-tuning was performed over 375 steps with a loss plateau observed at step 250, indicating optimal training convergence. **(Figure 6)**

Using QLoRA, the fine-tuning process was efficient, requiring only a single GPU with 24 GB VRAM, which reduced computational costs and allowed broader accessibility. Loss values, while indicative of the

model's learning process, are not the sole measure of performance for large generative models like VLMs; practical evaluation often involves direct interaction with the model. In this study, we tested the model using architectural images it had not encountered before, demonstrating its ability to generate coherent and nuanced critiques. The checkpoint at step 250 was selected as the optimal stopping point based on loss stabilization and evaluation results on diverse architectural examples, yielding positive outcomes.

Figure 6: Plot of the loss values during training of the VLM model.

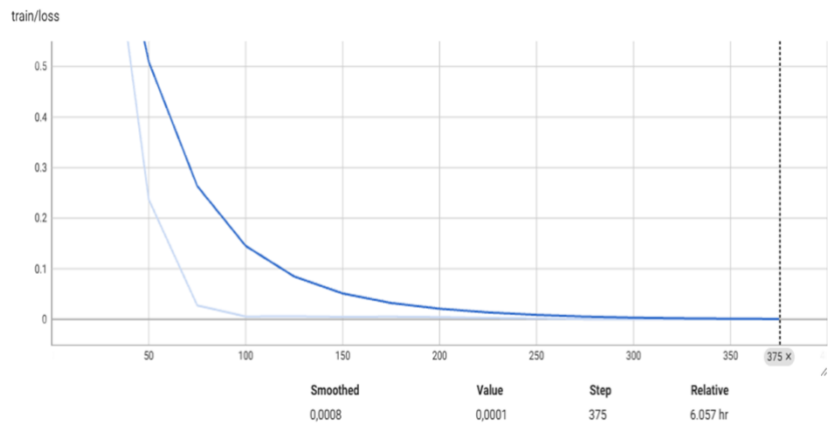


Table 4: Test results of the second version of the model, v2.

Table 4 displays two instance from the test results in terms of the architectural building photographs as input and the generated architectural review as output.



	Image (Input)	Review (Output)
(a)		<p>This striking public building combines modern transparency with an organic design ethos, evident in its undulating roofline that mimics natural forms while framing the expansive glass façade below. The structure's scale and open interior suggest a civic or institutional function, likely a library or cultural center, where light and openness foster community interaction and knowledge sharing. The rhythmic arrangement of slender columns enhances verticality while maintaining an elegant balance and unity with the horizontal roof profile. The use of glass maximizes natural light and visual connection between the interior and exterior, emphasizing transparency and accessibility. The landscaped surroundings integrate seamlessly with the architecture, softening the formal grid of the plaza and creating a welcoming approach. The design’s sustainable intent is evident in the thoughtful interaction with natural light and potential energy efficiency measures. Overall, this project masterfully blends form, function, and environmental sensitivity into a contemporary architectural landmark.</p>

Table 4 (continued): Test results of the second version of the model, v2.

(b)		<p>This building’s form and context respond effectively to its waterside location, where the sweeping wooden roof adds a natural, organic contrast to the reflective glass facade. The curvilinear roof creates rhythm and movement, while the orthogonal black facade elements offer balance and contrast. Modern in style, the building embodies contemporary architectural principles with a bold, sculptural form that commands the site without overpowering it. Its low-rise scale aligns with the surrounding waterfront structures, promoting cohesion. Likely designed as a public or mixed-use space, it fosters engagement and interaction. The construction seems to involve a steel frame supporting the expansive wooden canopy, illustrating advanced construction techniques.</p>
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5. DISCUSSION AND INTERPRETATION OF GENERATED CRITIQUES

The initial v1 model demonstrated success in accurately identifying and categorizing architectural images based on predefined attributes, as reflected in the examples provided. By classifying images into clear categories such as "complex," "contemporary," "angular," or "monochromatic," the model established a reliable framework for recognizing architectural characteristics. However, this classification approach, while useful, simplifies architectural critique into distinct categories, limiting its capacity to engage with the interpretive and subjective aspects of design evaluation. While this approach offered a foundational structure for the critique process, it inadvertently stripped away the nuanced layers that define architectural judgment. Architectural critique extends beyond dichotomous classifications; it is an iterative and interpretive process that intertwines subjective and objective considerations.

By reducing architectural critique to classification labels, we risk overlooking the interconnected relationships between form, context, and experiential resonance. This simplification fails to account for the dynamic potentials and emergent qualities within a design that often defy clear categorization. The v2 model addresses this limitation by shifting from a multi-class framework to a more holistic and descriptive critique, capturing the complexities of architectural design within a context-sensitive structure.

As displayed by **Table 4**, the v2 model test results demonstrate that generated reviews effectively highlight the contextual relationships between the architectural design and its environment. For instance, in the example “b” of the waterside structure, the critique captures the dialogue between the sweeping wooden roof and the reflective glass façade. This insight demonstrates the model's capacity to recognize and articulate the interplay between form and site, a critical aspect of architectural evaluation. The integration with the natural environment and the mention of cohesion with surrounding waterfront structures further reflect the nuanced understanding embedded in the model.

Both reviews in the table show the ability to evaluate design principles like rhythm, balance, and contrast. For example in instance “a”, the undulating roofline in the public building example is noted for mimicking natural forms, creating a visual rhythm. This analysis aligns with key architectural critique practices where dynamic forms are evaluated for their aesthetic and functional implications. Similarly in instance “b”, the contrast between the bright white structure and the rugged natural terrain in another example exemplifies the model's capacity to assess formal relationships within the architectural composition.

Both generated reviews in **Table 4** also briefly touch on sustainability and structural systems, which are critical components of modern architectural evaluation. In the example “b”, the use of a steel frame supporting the wooden canopy is identified, emphasizing the construction strategy and its alignment with advanced building techniques. Similarly in example “a” the maximization of natural light and the potential for energy-efficient measures in the public building further underline the model's capacity to evaluate sustainability features.

5.1. Limitations

While the proposed model marks an important step toward automating architectural critique, certain limitations in its current implementation warrant further discussion. At its core, the model functions as a descriptive tool, adept at analysing and articulating specific attributes of architectural images. This descriptive capability is valuable in identifying design qualities; however, it does not fully meet the requirements of an effective architectural critique. Critique in architectural practice is not confined to describing existing features but

also involves uncovering shortcomings and offering constructive suggestions for improvement.

Another significant limitation lies in the model's dependence on single-image inputs to generate critiques. Architectural evaluation, by its nature, is a holistic process that encompasses multiple dimensions of design. Reducing a complex architectural work to a single image oversimplifies its intricacies and omits vital information necessary for comprehensive critique. Evaluations based solely on façade images neglect critical aspects such as spatial organization, structural systems, material use, and functional programming. Plans, sections, elevations, and site analysis provide essential layers of information that reveal how a design functions and interacts with its context. Without these additional perspectives, the current model cannot fully capture the multidimensional nature of architecture, which significantly limits the depth and reliability of its critiques.

One critical aspect that remains unaddressed is the absence of scoring mechanisms in the current model. Human juries often evaluate architectural designs not only through qualitative critique but also by assigning quantitative scores to specific criteria, such as context, functionality, aesthetics, and innovation. These scores serve as an objective framework for comparing and ranking submissions, especially in design competitions. Without a scoring system, the model lacks the capability to quantify its assessments or offer a structured basis for comparison. Integrating a scoring mechanism would align the model more closely with real-world jury practices and enhance its utility as a decision-support tool in competitive settings.

5.2. Future Research Directions

As a future research plan of efforts to integrate AI-driven insights into architectural evaluation, we plan to develop a model that focuses on providing quantitative measures of an architectural image. The proposed model would utilize the existing framework of deep learning architecture and estimates and provides scores for four parameters: style, context, design principles, and total.

The proposed aesthetic model may utilize a ResNet-18 backbone which has been pre-trained in large datasets for effective feature extraction.

The architecture's last few layers are augmented with fully-connected layers fixed to output scores for different dimensions of scores. The model is trained end-to-end using a dataset annotated with ground-truth scores for each attribute. The predictions against the ground-truth are optimized by a mean squared error (MSE) loss function for increasing scoring accuracy.

To enhance explainability, the model is also required to include a Grad-CAM based explanation methodology that generates heatmaps for each predicted attribute. These heatmaps can indicate the parts of the image that influence the scoring decision the most and thus give various components of the model an understanding of how the model scores different aesthetic components. This explainability would offer us the opportunity to combine computational scoring with a more nuanced opinion of a human-like critique and therefore makes the model suitable for real-life and academic applications.

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Author Contributions

All authors contributed equally to this article.

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Generative Adversarial Networks (GANs), and Architecture: Investigating Quality in Architectural Plan Generation

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Artificial intelligence (AI) finds extensive applications in architecture, alongside various other domains of daily life. Recent years have witnessed a surge in visual processing, analysis, and production, primarily propelled by deep learning algorithms. Among these algorithms, Generative Adversarial Networks (GANs) stand out as exemplary tools for image generation. Within architecture, GANs are utilized across various domains including facade design, interior layout, and generation of perspectives and architectural plans. Notably, GANs have emerged as prominent tools in architectural plan generation. However, unlike other image synthesis tasks, architectural plan generation places greater emphasis on plan quality over image fidelity. Consequently, evaluating the quality of plans generated through AI poses a novel and contemporary challenge. While some studies touch upon quality issues in GAN-generated outputs, a comprehensive exploration of quality-related concerns remains lacking. The study analyses the plans generated by GAN and assesses the capacity of GAN in ensuring architectural quality. To this purpose, a study is undertaken to analyze existing architectural plan generation studies utilizing GANs and to interpret the notion of architectural quality. The studies analyzed that the experiments with GANs are preliminary and there is a lack of studies on the production of higher quality plans using GANs. However, these studies seem to be due to the limitations of GAN itself. This study concludes by underlining the limited capacity of the GANs to enhance the quality of architectural plans, and provides comments and reviews on this matter.

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Çekişmeli Üretken Ağlar (ÇÜA) ve Mimarlık: Mimari Plan Üretiminde Nitelik Araştırılması

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Yapay zekâ, günümüzde yaşamımızın her alanına nüfuz eden bir araştırma alanına dönüşmüştür. Bilgisayarların karmaşık sorunları insanlar gibi ele alıp çözmelerini hedefleyen yapay zekâ; sayısız alanda daha önce çözülmemiş zorluklara araçlar ve yöntemler getirmektedir. Yapay zekâ uygulamaları mimarlık alanında da aktif olarak kullanılmaktadır. Mimarlıktaki akıl yürütme sürecine benzer bir sistemin yapay zekâ teknolojileri ile oluşturulabileceği birçok araştırmacı tarafından öngörülmektedir. Bu anlamda birçok araştırmacı Yapay zekâyı, mimarlık alanında ortaya çıkan "Sıradaki Büyük Şey" olarak görmektedir.

Günümüzde özellikle derin öğrenme algoritmaları yardımıyla mimarlıkta görsel işleme, analiz ve üretimlerine dair uygulamalar artmıştır. Derin öğrenmenin bir türü olan, ÇÜA (Çekişmeli Üretken Ağ) görsel üretimi üzerine en iyi örnekler veren algoritmalarından biridir. Görsel tabanlı bir algoritma olan ÇÜA'nın başta görsel üretimi olmak üzere, görüntüden görüntüye, metinden görüntüye, fotoğraflardan çizime gibi birçok uygulaması bulunmaktadır. Mimarlık alanında ise, cephe, iç mekân, perspektif ve plan üretimleri gibi birçok alana yayılan bir kullanımı vardır. Mimarlık alanında ÇÜA yardımıyla yapılan çalışmalar incelendiğinde özellikle mimari plan üretiminin öne çıktığı görülmektedir. Mimari plan üretimi, özellikle erken aşamalarında alternatif plan çözümlerinin şekillenmesi ve ortaya çıkması gibi tekrarlanan işlemlerin olduğu bir süreç olması sebebiyle yapay zekânın araştırma alanına girmektedir. Bu sebeple mimari plan şeması üretimi, tasarımı ve mekân kurgusu üzerine yapılan çalışmalar, yeni bir araştırma alanı olarak karsımıza çıkmaktadır. Mimari plan üretimi konusunda yapay zekâ yardımıyla son yıllarda öncü çalışmalar yapılsa da, mimari plan üretiminin diğer görsel üretiminden farkı görselin kalitesinden daha önemli olan üretilen görselin niteliğidir. Bu nedenle de üretilen plan şemalarının niteliğinin değerlendirilmesi yeni ve güncel bir problemidir.

Çalışma kapsamında ÇÜA algoritmasının mimari plana dair nitelik problemlerine ne ölçüde cevap verebileceğinin araştırılması hedeflenmiştir. Bu kapsamda öncelikle ÇÜA algoritması kullanılarak üretilen mimari plan üretim çalışmaları incelenmiştir. Kullanılan ÇÜA algoritmalar ve özellikleri kısaca değerlendirilmiştir. Mimari nitelik kavramı araştırılmıştır. Mimari niteliğe dair incelenen literatürde niteliğin katmanlı bir kavram olduğu, nesnel ve öznel farklı gereksinimlerin göz önüne alınması gerektiği görülmüştür. Çalışma sonucunda niteliğin ve plan üretiminin çok katmanlı bir süreç ile elde edildiği sonucuna varılmıştır. Bu sebeple de çalışmada plan üretiminin doğası ile ÇÜA algoritmaları arasındaki çeşitli tutarsızlıklar vurgulanmıştır. ÇÜA algoritmasının mimari plan niteliğini arttırmak konusunda potansiyelleri tartışılmış ve değerlendirilmiştir.

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Anahtar Kelimeler: ÇÜA, Mimari Plan Üretimi, Mimari Planda Nitelik, Yapay Zekâ.

1. INTRODUCTION

Artificial intelligence (AI) has emerged as a widespread area of research with substantial effects in many sectors of the modern world. With the objective of replicating human cognitive processes, AI provides a variety of tools and methodologies to address previously unresolved problems in many fields.

Architecture, along with many other sectors, commonly uses AI. AI can utilize processes similar to architectural design, enhance design tools, generate valuable design information, and stimulate the development of new models and methodologies. Through learning processes based on predefined tasks or undefined inputs, AI can produce practical solutions customized to meet individual needs (As & Basu, 2021). AI in architecture is expected to optimize processes, facilitate extensive cooperation, and improve the intuitive and creative abilities of architects. Contemporary research trends indicate a shifting ground in traditional design methodologies, with a notable increase in AI-focused investigations in the field of architecture (Özerol & Arslan Selçuk, 2022). Primary research on AI in architecture has mostly concentrated on areas including design, performance, conservation-restoration and education. Architectural plan generation is an essential element of architectural design and has an important role in the architectural project and implementation phases. In the last few years, there has been a significant increase in the use of AI for the purpose of creating architectural plan diagrams. It is crucial to build networks that can efficiently and consistently identify and generate architectural plan diagrams. By relieving architects of repetitive duties, this will facilitate the investigation of innovative possibilities for design (Zheng & Huang, 2018).

Architectural plan generation using AI is a current research topic in the architectural literature that has been investigated using various approaches and technologies. Different techniques, such as evolutionary algorithms, expert systems, constraint-based models, decision trees, machine learning methods, recurrent neural networks (RNN), convolutional neural networks (CNN), and recently generative adversarial network (GAN) algorithms, have been used to generate architectural plans (Uzun, 2020b).

GAN (Generative Adversarial Network) algorithm has become prominent among these strategies. GAN is a type of deep learning and is considered one of the most effective machine learning algorithms for creating visual content (Goodfellow et al., 2014). Some of the applications of GANs are creating samples for image datasets, creating realistic photos, image rendering, image-to-image, text-to-image, photo-to-emoji's, photo editing, photo blending, super resolution, video prediction, 3D object creation. Although GANs have achieved great success in several domains of image generation, the process of plan generation is different. It is insufficient for the visuals produced during plan generation to merely resemble plans. They have to create rational relationships that are practical and meet the needs of their users. Plan generation is a complex procedure. GANs are only image-generation algorithms. The contradictory nature that exists in these two situations gives rise to a conflict in the assessment of the proposed strategies. Although the GAN algorithm can analyze the production output in terms of resolution, clarity, realism, and similarity to the target image (Shmelkov et al., 2018), resolution and clarity are not properties of the architectural plan, but rather define the quality of the architectural visualization (Uzun, 2020a).

The main goal of this study is to systematically analyze the quality of plan generation and assess the potential of the GAN algorithm in this regard. This investigation is based on plan generation studies with GANs. The distinctive feature of this study is its discussion and evaluation of the characteristic features of the GANs in the generation of plans. The study first discusses the concept of plan generation, the meaning of a quality plan, and then examines the GAN algorithm and plan generation studies. After that, using case studies, it offers an assessment and goes over the benefits and drawbacks of using GANs for plan generations. The study concludes by assessing the GAN algorithm's capacity to enhance architectural quality in comparison to previous research. This evaluation will provide a deeper understanding of the GAN algorithm and its impact on plan generation, while also providing crucial data for future investigations.

2. METHOD

This study conducted a literature review to assess the relationship between GANs, architectural plan generation, and the concept of quality in architecture.

This study first assesses the concept of architectural quality and establishes its relationship with the architectural plan. Afterwards, studies on plan generation with the GAN algorithm are evaluated. The selection of papers was conducted by manually examining the reference lists of the retrieved items from the electronic journal databases; Scopus, Google Scholar, and the National Thesis Center (YöKTez). The search query consisted of the following keywords: Artificial intelligent, GAN, architecture plan generation, floor plan generation, and site plan generation.

The selected studies are expected to generate architectural plans using GAN. As a result, architectural plan generation studies that did not use the GAN algorithm were excluded. As a result, 16 unique papers were included in this study. **Figure 1** shows the literature and years.

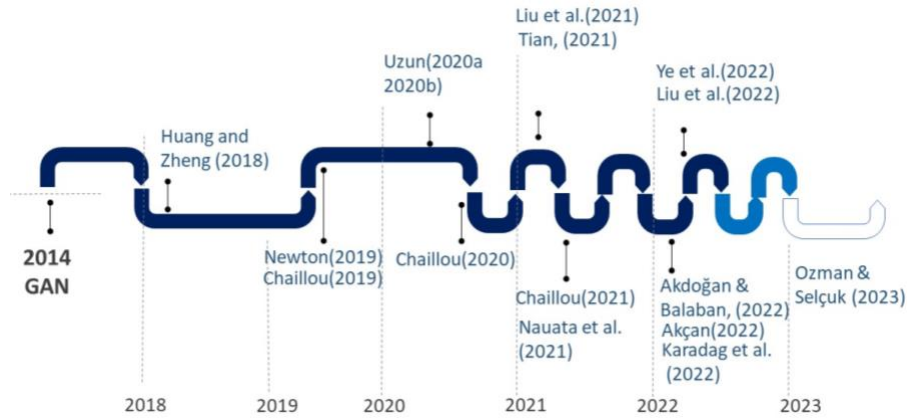


Figure 1: Number and year of studies (Figure prepared by author)

The first study on GAN and architectural plan generation was carried out in 2018. Studies have significantly increased after 2020. The studies were examined in two categories: site plans and floor plans. This literature part reviewed the generated plan diagrams, the size of the data set, and the kind of GANs.

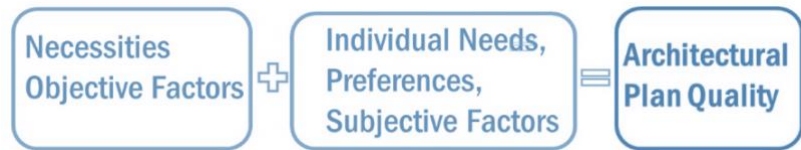
3. THE CONCEPT OF QUALITY IN ARCHITECTURE

The concept of 'Quality' is intricate and multifaceted, making it challenging to describe. Quality can be described using adjectives like 'feature, qualification, quality, character, essence, smoothness' (Kul, 2019). Due to its difficult-to-define nature, quality is a concept that requires to be defined with adjectives and requires adjectival descriptions such as the words 'good, beautiful, excellent' (Nelson, 2017).

Nelson defines architectural quality as the degree to which a set of inherent characteristics meets specified criteria, with 'requirement' denoting a stated, inferred, or imperative need. Collectively, these definitions encapsulate the notion of 'the extent to which specific expressed, implicit, or obligatory requirements or expectations are fulfilled.' The term 'obligatory' pertains to adherence to all legal and regulatory frameworks, while 'expectations' denotes that criteria are influenced by individual perspectives (Nelson, 2017). Quality serves as an evaluative criterion based on the fulfillment of needs and expectations. Consequently, higher levels of fulfillment in architecture correlate with higher quality, rendering it both comparable and quantifiable. Nonetheless, the quality of architecture is influenced by various factors, resulting in complex needs and expectations.

The quality of the architectural cannot be considered independent of the user in this framework. Quality emerges through the user's experience of it, and therefore every experience allows quality to emerge. For this reason, although quality includes compliance with mandatory rules, laws and regulations, it is basically every 'becoming' rather than being a static value (Akin, 2006). For this reason, it is a value that reappears in different users, situations and experiences. Due to the relationship between experience and value, quality can vary from person to person, from society to society and over time. When we evaluate the definitions of quality, we can say that architectural quality should be handled in a layered framework. In **Figure 2**, the layering of architectural quality is shown diagrammatically. First of all, it must meet the requirements; it must be in compliance with statutes, decisions and regulations, and then it must meet the expectations of the user in the relationship it establishes with the user, and it must be able to receive "positive evaluations" in every encounter with the user.

Figure 2: Defining themes of Architectural Quality (Figure prepared by author)



A similar layered approach is applied to assess quality in plan generation. Architectural plan generation is primarily subject to many regulations and rules. We can assert that the most challenging aspect of architectural projects is the creation of plans. At the beginning, compliance with established protocols for plan generation is the most important element. However, complete compliance with these rules is not enough to qualify the plan. This is followed by meeting user preferences and expectations.

Therefore, the generation of architectural plans by any artificial intelligence system necessitates the consideration of these qualitative variables. Consequently, the following part of the study focuses on investigating how these qualitative criteria were approached, and to what degree the experiments with GAN were acceptable in terms of the quality of plans for architecture.

4. GANS AND ARCHITECTURE PLAN GENERATION

Computer-generated image, known as image synthesis, has experienced significant advancements in the past several years. GAN is a deep learning technique that offers exemplary results in the field of machine learning.

GAN consists of two models based on artificial neural networks. In this model, which learns through a contested process, the structure of the model consists of a generative model (Generator) that captures the distribution of the data and a discriminative model (Discriminator) that predicts the actual and generated data. The generative model enhances the interpretability of random noise data through the use of filters (kernels) and training. The discriminator evaluates the output it receives. The data is refreshed with the assessed image. The producer is moving towards generating visuals that are increasingly capable of deceiving the discriminator. The discriminative model is trained by

examining both the authentic dataset and images produced by the generator. It calculates a loss value for the actual data set and a loss value for the counterfeit images provided by the generator. It assesses these values and conveys the loss value to the generator. **Figure 3** shows the working principle of the GAN algorithm (Park et al., 2021).

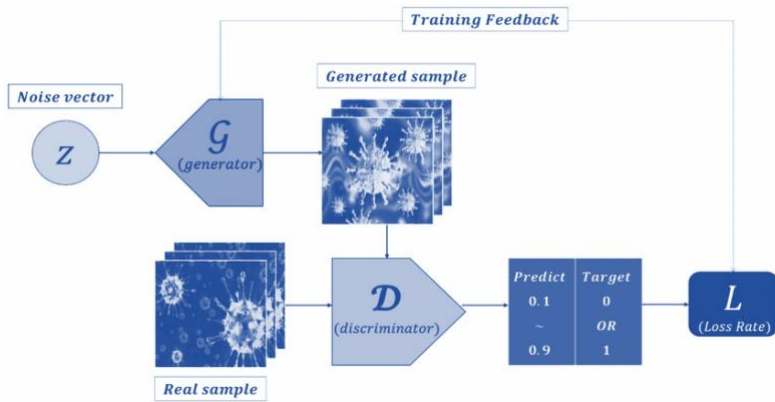


Figure 3: Working principle of the GAN algorithm (Park et al., 2021).

GAN's visual production has been widely utilized in architecture studies since its introduction in 2014 due to its success. GAN is utilized in various fields including facade design research, interior design, urban landscape, and the creation and characterization of various architectural styles through visual generation. Plan generation is also an important area studied with GAN algorithms. The study focused on examining architectural plan generating studies utilizing GAN algorithms.

4.1. Architectural Plan Generation with GANs

The majority of research on artificial intelligence and architectural plan generation is centered on autonomous plan generation. GAN is mostly utilized in various studies, such as site planning and floor plans. The studies that produce floor plans and site plans visually and pixel-based are pioneering Ai in plan generation.

In site plans, Liu et al. utilized GAN algorithms and a restricted data set to create campus site plans in the experiments on site plan generation (Liu et al., 2021). The study favored the Pix2Pix model, which is a type of GAN algorithm. The work investigates the application of deep learning on a small data set for campus layout generation, demonstrating successful outcomes despite the data limitation.

Urban design includes several factors including building layout, street block organization, orientation, density, and green space distribution. In Tian's study, they aimed to develop a model that can produce plan references for architects, landscape architects and urban designers and create a framework for design with a model that learns from the existing built environment (Tian, 2021). In their study using Pix2PixHD, GAN algorithm, 4400 different site plans were used. Visual representations were generated using Rhinoceros and Grasshopper software to interactively generate site plans. The research can be applied in concept design, rapid prototype creation, and can generate more detailed building data by utilizing numerous GAN models within the extensible framework.

Labeling during GAN training aids the algorithm in comprehending the logical connections among elements and boundaries. Liu et al. examined the design of private gardens in the southern Yangtze region in a separate study (Liu et al., 2022). The study utilized 125 unique garden layouts as a dataset. The algorithm was trained on examples of traditional Chinese private gardens, leading to the generation of private garden plans. The Pix2Pix algorithm has been developed to generate a separate garden design based on specific conditions provided in a site plan. The study is expected to assist the designer in creating concepts and developing sample schemes (Liu et al., 2022).

Developing a prototype for autonomous site plan generation is the most comprehensive initiative in the field of site plan generation. Ye et al. developed a prototype for the autonomous generation of site plans (Ye et al., 2022). Around 5000 site plans were extracted from Pinterest to develop a model named MasterplanGAN. The primary algorithm of the new model is CycleGAN. The MasterplanGAN algorithm is meant to transform monochromatic site plans into colored site plan visualizations. This study can be a valuable resource for urban designers and planners to simplify real projects and advance the automation of subjective and experience-driven processes (Ye et al., 2022).

Upon reviewing studies utilizing GAN algorithms for generating house floor plan diagrams, Zheng and Huang's research reveals as significant. In their study the Pix2PixHD algorithm was utilized, with residential housing floor plan as the dataset. The study focuses on recognizing and

generating architectural drawings through machine learning. In their study, they first used machine learning to recognize and label architectural drawings and then to generate plans. Initially, a dataset of 115 plans was generated. They used 100 plans for training, whereas 15 layouts were for testing. The study investigated at how machine learning slowly learned about the features of architectural plans. The features in the graph also became clearer and more concise as the networks got deeper and the training times got longer (Zheng & Huang, 2018).

Newton's research predominantly utilizes Le Corbusier plans as the dataset, considering both limited and specialized plan-specific datasets. The main objective of the project is to comprehensively explore the use of GAN in the creation and analysis of architectural plans, particularly in connection to the works of individual architects (Newton, 2019). The study with the use of the WGAN algorithm in production did not achieve the anticipated standard of production quality. In this study shows how various dataset expansion approaches can be useful for architects dealing with small datasets (Newton, 2019).

Another comprehensive study on architectural plan generation is Chaillou's thesis. The researcher used Pix2Pix, a type of GAN algorithm, and floor plans and studied with a large data set (Chaillou, 2019). In this study, he first focused on identifying and labeling the plans. Afterwards, he diversified the plan schemes he produced in Baroque, Manhattan, Row House and Victorian styles. With the inclusion of different styles in the plan production, it was seen that production in different criteria is possible with GANs. In addition, a research was conducted to prepare the way for plan production in an interactive design environment (Chaillou, 2019, 2021). Based on the various experiments conducted in the investigations, which have advanced the study field, it has been concluded that the models examined have the capacity to be used in more intricate programs with difficult limitations. As the number of studies and examples in plan generation continues to grow, the possibility for developing practical plan generation models is also expanding steadily (Chaillou, 2019, 2021, 2022).

Uzun's studies are also one of the important studies in the field of plan generation. It was selected the DCGAN approach, a specific variant of the GAN algorithm, to undertake the task of designing and assessing

architectural plans. The study conducted by Uzun et al. utilized a dataset consisting of pixel-based Andrea Palladio plans for testing purposes (Uzun et al., 2020). This paper highlights the need of comprehending the learning mechanism of the algorithm, carefully preparing the dataset, and critically assessing the outcomes generated by the Ai. This study involved the analysis of plans using qualitative and quantitative evaluations, specifically employing techniques such as space syntax, "Frechet Inception Distance" and "Fast Scene Classification" (Uzun, 2020b, 2020a; Uzun et al., 2020).

In Nauata et al.'s study, which is a comprehensive study on architectural plan generation and the quantitative and qualitative evaluation of these plans, a large data set was used (Nauata et al., 2021). In the study using the RPLAN dataset, which includes sixty thousand different plans, the room connections in the plan are shown in the form of a bubbled diagram, the rooms are color coded in the dataset and the production is expected to be done using these color codes. Afterwards, three criteria for qualitative and quantitative evaluation were determined as realism, diversity and compatibility. To assess the realism factor, both professional and beginner architects were questioned about the level of realism shown in the plans. Considering diversity, the FID score was considered, and compatibility was assessed by analyzing the graphic arrangement distances between the predicted plan and the generated plan. As a result of the study, it was stated that the study has the potential to improve an incomplete design, incorporate user input, and create alternative designs(Nauata et al., 2021).

A study by Akdoğan and Balaban explores the use of Palladian plan schemes in architectural plans (Akdoğan & Balaban, 2022). They conducted an experiment where they translated Haeckel's microorganism drawings into Palladian plan schematics. The research employing the CycleGAN algorithm can be viewed as an experiment that may stimulate next studies. Akçan utilized 150 distinct housing plans from the Ataşehir area of Istanbul as the dataset in his thesis. The dataset was categorized based on the number of rooms in the floor plans. The study revealed that data sets belonging to a specific category yielded more consistent findings. The study highlights the significance of developing datasets and the challenges involved. It suggests that local and administrative governments should adapt their databases to facilitate AI research and enhance its effectiveness (Akçan, 2022).

Karadag et al. created a machine learning model named EDU-AI using the GAN. The study also utilized the Pix2Pix algorithm. 144 classroom plans were reviewed, a structure for utilizing GAN was established, and a two-layer learning model was created (Karadag et al., 2022).

Study	Data set -type	GANs
Liu vd.,(2021)	Campus plans (387 examples)	Pix2Pix
Tian, (2021)	Site plan (4400 data, 4000 training and 400 validation)	Pix2PixHD
Liu vd.,(2022)	Garden plans (125 data 120 training and 5 validation)	Pix2pix
Ye vd.,(2022)	Site plans (5000 data)	CycleGAN
Huang and Zheng (2018)	Housing floor plans (115 data, 100 training, 15 validation)	Pix2PixHD
Newton(2019)	Le Corbusier plans (45, 135 ve 180 data)	WGAN
Chaillou(2019,2021,2022)	Housing floor plans (more than 800 data)	Pix2Pix
Uzun(2020a, 2020b)	Paladian Plans (125 data)	DCGAN
Nauata vd.(2021)	Housing floor plans (60.000 data)	CGAN
Akdoğan & Balaban, (2022)	Paladian Plans (100 data) Haeckel's drawings (105 data)	CycleGAN
Akçan(2022)	Housing floor plans (150 data)	Pix2Pix
Karadag vd. (2022)	Classroom plans (162 data, 144 training 18 validation)	Pix2pix
Ozman & Selçuk (2023)	TOKI plan typologies (157 data)	DCGAN

Table 1: Studies on floor plan and site plan generation using GANs.

Ozman and Selçuk (2023) utilized 21 TOKI plan typologies as a dataset in their investigation. The dataset was augmented into 157 plans and DCGAN was utilized. Visual results were not achieved after 500 epochs in the DCGAN. The study also tested a larger dataset, HouseGAN LIFULL HOMES. The study highlighted the significance of dataset size, stating that with a significant dataset, plans can be utilized more systematically and functionally (Ozman & Selçuk, 2023). The studies on site plan and floor plan generation using the GAN algorithm are summarized in the

table (**Table 1**) above, taking into account the methods used, data set and year.

In 2018, the initial instances of planned generations emerged, and they are already seeing significant growth. This study offers a brief assessment and identification of issues regarding the plans generated using GANs.

4.2. Brief Evaluation of Plans Generation with GANs

Over the past five years, a multitude of studies have been conducted on plan generation within controlled settings, significantly advancing the capabilities of GAN algorithms and plan generation methodologies. Many studies on plan generation prioritize the selection of residential plans due to the relative ease of obtaining datasets compared to other plan typologies.

In the light of the reviewed literature, it is seen that Pix2Pix, DCGAN and CycleGAN algorithms are the most prominent algorithms in plan generations. The increased prevalence of these algorithms can be attributed to their enhanced usability and compatibility with architectural plans.

The process of generating the dataset is a pivotal stage in GAN-based research. Enhanced accessibility to datasets facilitates progress in subsequent stages of investigation. Expansion of the small dataset, among other tasks, is a crucial aspect of research based on GANs. Due to its nature as an image and dataset-based generation method, the quality of the outputs is directly influenced by the dataset it is provided.

Most of the studies analysed included the generation of the plan up to the point of acquiring the image. While the possible applications of the plan are acknowledged, the majority of the studies fail to address the quality or usability of the plans (Chaillou, 2019; Newton, 2019; Ozman & Selçuk, 2023; Zheng & Huang, 2018). The quality of the generated plan is more crucial than the quality of the image. Research on architectural plan creation highlights the necessity for novel assessment methods for assessing the GAN algorithm for architectural plan generation (Chaillou, 2022; Nauata et al., 2021; Uzun, 2020b). Research indicates that quantitative evaluation methods in GAN assessment prioritize visual quality and lack the necessary depth for

generating plans. There is limited research on qualitative evaluation methods for designs created by GANs. The research primarily investigate the authenticity of plans created by participants, aiming to differentiate between plans generated by GANs and those created by humans (Nauata et al., 2021; Uzun, 2020a).

This study posits that the determination of authenticity hinges on specific criteria, which necessitates further exploration through research on architectural quality. The dependence of GANs on a dataset, as well as the fact that their production is only visually based and unstructured, creates a conflict with the plan generation process.

5. DISCUSSION

The quality of plan generation is derived from a multi-layered procedure. This study highlights various inconsistencies between the nature of plan generation and the GAN algorithms.

- Plan generation facilitated by GANs yields visual outputs without adhering to a layered framework. While visuals may suffice in certain contexts, they fall short in addressing legal compliance, user expectations, and spatial coherence, all of which are crucial in plan preparation. The primary objective of plan production extends beyond mere visual representation. Thus, rule-based productions, in which the GAN generates only a portion of a plan rather than its entirety, are regarded as more effective (As et al., 2018; Karadag et al., 2022; Wu et al., 2019). For instance, Wu et al. show a rule-based progress. The living room is the first to be positioned with the learning network that has been built, based on the observation that the living room is present in nearly all floor plans. It then continues by generating other rooms. The study performs better than current methods since it is layered and rule-based (Wu et al., 2019).
- Due to the hallucinogenic nature of the creations in the GAN, it is not feasible to apply specific criteria across the areas as the productions rely on the dataset's properties. Most studies on plan generation using GANs have mostly concentrated on the plan-generating stage. Exploring or modifying the nature of

plan generation has become less of a priority. However, as technology and algorithms continue to improve and their boundaries are being investigated, it is increasingly probable that plan quality will become a central area of study in the next few years.

- A significant drawback lies in the pixel-based nature of GAN-produced images. Pixel-based outputs have yet to gain traction in architectural practice due to the reliance on extensive datasets and limitations in post-production utility (Deprez et al., 2023). This presents a major drawback of GANs in plan generation. Due to the fact that architectural designs are rarely implemented and developed on a pixel-by-pixel basis.
- Another disadvantage is the requirement for extensive data sets. Research with GANs has shown that an increase in the number of samples in the dataset leads to more sophisticated outputs (Zheng & Huang, 2018). Plan generation does not consistently follow same criteria in all locations. For instance, regional contributions can vary because of climate or cultural influences. Accessing large data sets is not always possible.

In architecture, plan generation is expected to meet both quantitative and qualitative standards. Architectural plan generation is a complex process that involves considering various criteria such as spatial organizations, technical limits, and consumers' perception, ultimately relying on creativity. Considering the layered structure of quality for future studies, it is thought that the productions made with AI should also model this layered framework. A thorough examination of quality in the architectural plan generation is necessary to enhance AI applications and represent qualitative attributes. This research should be conducted using a comprehensive methodology that incorporates both qualitative and quantitative research methods.

6. CONCLUSION

Generating architectural plans using artificial intelligence presents a contemporary challenge. This study underscores the limitations of the GAN algorithm, which has gained prominence in plan generation in recent years, particularly in terms of quality. The GAN algorithm is

known for its effectiveness in image-generating tasks, but its actual implementation in plan generation is still limited. Although studies on plan generation with GANs are crucial, only the GAN algorithm is insufficient. Artificial intelligence is widely recognized as pivotal for the future of architecture. In the coming years, inquiries such as "Can machines be taught architecture?" "To what extent can machines acquire architectural knowledge?" and "To what degree can machines produce high-quality architectural design?" will be revisited and further investigated. To advance research in this field, the development of a comprehensive methodological framework that evaluates both qualitative and quantitative capabilities is imperative.

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Conflict of Interest Statement

The authors of the study declare that there is no financial or other substantive conflict of interest that could influence the results or interpretations of this work.

Author Contribution

Author Contribution The authors declare that they have contributed equally to the manuscript

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