ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

MODELING BRICK SURFACES IN HISTORIC BUILDINGS WITH DESIGN COMPUTATION METHODS

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

TARİHİ YAPILARDA TUĞLA YÜZEYLERİN HESAPLAMALI TASARIM YÖNTEMLERİYLE MODELLENMESİ

YÜKSEK LİSANS TEZİ

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Sevgi ALTUN, a M.Sc. student of İTU Graduate School student ID 523191012, successfully defended the thesis entitled "MODELING BRICK SURFACES IN HISTORIC BUILDINGS WITH DESIGN COMPUTATION METHODS", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To Bilge,

FOREWORD

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February 2023

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Architect

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ABBREVIATIONS

BIM: **:** Building Information Modeling
HBIM **:** Heritage Building Information Modeling

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MODELING BRICK SURFACES IN HISTORIC BUILDINGS WITH DESIGN COMPUTATION METHODS

SUMMARY

Studies in computational design have increasingly turned to architectural heritage in recent years, and this interest has helped the advancement of both disciplines. This thesis aims to contribute to the field by exploring examples of brickwork from Medieval Anatolia and modeling the correlation between the material construction of brick surfaces and the design geometry.

Medieval Anatolia saw a flourishing of brick-built structures with the effect of Iranian bricklaying tradition, a testament to the skill and artistry of the craftsmen who built them. However, the preservation and restoration of these historic buildings present challenges. Traditional methods and techniques for building with bricks are insufficiently documented or existing documentation is not shared in a common platform. The lack of documentation combined with the difficulty of access to information makes it challenging to restore architectural heritage elements accurately, and the know-how gets lost through time.

This thesis proposes a method for bridging the knowledge from the disciplines of architectural history and building technology by developing grammars that enable the production of selected samples of brick elements in monumental architecture in Anatolia. The design reasoning behind historical brick structures is externalized and transferred to the digital environment. This approach intends to preserve and transfer the construction techniques and materials used in these historic buildings while utilizing contemporary tools and fabrication technology. We aim to use computational design tools as a medium to assist architectural heritage studies by providing a common ground for studies that understand the architectural design process as a whole with making.

The first chapter of the thesis presents a discussion of the use of digital tools in heritage studies for surveying and modeling purposes, heritage building information models (HBIM), and the importance of preserving the know-how in heritage studies, relating construction techniques and materials to the design process. We use shape and making grammars as computational approaches for our formalization. Shape grammars are developed to formalize the visual thinking and reasoning of design as well as generative processes with shapes. Their extension, making grammars that formalize the design and making process, are discussed with their applications. Making grammars have the potential to contribute to heritage studies by providing a more comprehensive understanding of historical buildings and structures by documenting not just the geometry and form but also the know-how and intangible qualities of the construction process. However, there is still a need for further research and development to integrate these methods into the architectural heritage field and make them more accessible and useful to historians and conservation specialists. In the second chapter, the literature review addresses the importance of geometry in architectural design in the early Islamic period, with a particular focus on Medieval

Anatolia, and provides an overview of the use of digital tools to analyze, design, and produce brick surfaces.

The first step of the method of the research involves modeling, analyzing, and reconstructing selected cases of brickworks with complex geometric patterns, aesthetic appeal, and different curvatures that are also used as decorations in addition to their structural function (single-curved surfaces, domes, and corniches below minaret balconies). The cases were chosen due to their unique characteristics and the challenges they present in terms of analysis and documentation. The similarity in the period, geographical region, function, and materialization of abstract geometric patterns through the bricklaying is considered.

The analysis includes the examination of historical documents and archival sources, as well as the physical analysis of brickwork samples from medieval buildings in Anatolia. Through this multi-faceted approach, we combine information from various sources to model the parts and wholes of the sample cases. The formal features of the selected cases are analyzed using digital modeling tools to uncover the underlying geometrical compositions.

The second step is the synthesis of the information, which will involve the definition of parameters and the development of grammars that capture the know-how of traditional design and construction techniques, formalizing information on the tectonics of existing surfaces. A modular approach has been used that takes into account the types of bricks used, their sizes, and the sequential and spatial stages followed in the traditional construction of brick surfaces. The potential use of practical geometry is discussed and demonstrated through the method. The research focuses on the flexibility in the perceiving of parts and wholes and the analysis of patterns as a result of constructional relations between three-dimensional units rather than two-dimensional arrangements. The parts of these compositions are obtained through a specific material application and bricklaying technique. The production parameters can change the visual characteristics of the results without altering the overall order. Different surface types are associated with each other through analysis based on the geometrical layout and the units. The constructional logic and order of bricklaying behind complex patterns on different surfaces are examined, as are the three-dimensional qualities of brick muqarnas on corniches below minaret balconies. The third step involves the definition of the least number of rules required for the recreation of the analyzed surfaces. There are two types of bricklaying rules namely, the brick rules and the pattern rules. Brick rules define the three-dimensional relation between two adjacent bricks and the shapes and dimensions of the bricks through the use of parameters. Pattern rules define the geometrical order of the emerging pattern due to bricklaying.

The final step is the conversion of the bricklaying generated with the grammars into robotic fabrication codes and fabrication using a 6-axis robotic arm, KUKA KRC2, to lay bricks in a specific pattern. The KUKA PRC programming language is used in Grasshopper in Rhinoceros to generate G-code commands and toolpaths for the robotic arm. The process involves picking up individual bricks with specialized gripping equipment, called an end-effector, and placing them in the desired layout. Robotic fabrication can potentially complete tasks more quickly and accurately than human workers. However, it also has several limitations, including restricted working space, the selection of stand-in materials for the bricks, the age of the software and hardware, and the differences between manual and robotic bricklaying processes. Despite these limitations, the research suggests that robotic fabrication can be part of the workflow used to document and transfer knowledge about historical bricklaying techniques and can be integrated with conservation and restoration efforts. Although the pick-and-place application of a brick with a robotic arm mimics the movements of a craftsman, the construction parameters are different from analog production methods. Through the production trials, the importance of material properties, tools, and the actions of the maker and their differences with robotic production are discussed.

We suggest that the proposed method can assist in the documentation of architectural heritage and can be integrated with conservation and restoration efforts through the use of heritage building information models (HBIM). Further studies include the improvement of the grammar with more examples, the robotic fabrication process with the use of different materials, and the implementation of different brick designs.

TARİHİ YAPILARDA TUĞLA YÜZEYLERİN HESAPLAMALI TASARIM YÖNTEMLERİYLE MODELLENMESİ

ÖZET

Hesaplamalı tasarım çalışmalarının son yıllarda artan bir şekilde mimari mirasa odaklanması her iki disiplinde ilerlemeleri beraberinde getirmektedir. Bu ilerlemelere katkı sunmak amacıyla tez çalışmasında Ortaçağ Anadolu'sunda tuğla duvar yapımının incelenerecek tuğla yüzeylerin malzeme yapısı ile tasarım geometrisi arasındaki ilişkiyi modellenmesi için bir yöntem önerilmiştir.

Ortaçağ Anadolu'sunda, İran'dan gelen zanaatkarların çıplak tuğla yüzeyler ile ilgili bilgi ve becerilerinin etkisi ile anıtsal mimaride tuğlanın yalnızca yapısal değil süsleme amaçlı kullanımında da gelişme görülmüştür. Geometri bilgisi ile birleşen yapım teknikleri kubbe, duvar, geçiş elemanları, tonoz, kemer, minare gibi çeşitli mimari elemanların tasarım ve üretiminde kullanılarak, aynı türde veya farklı türlerde tuğlaların çeşitli uzamsal ilişkiler ile bir araya gelmesi sonucunda geometrik düzene sahip bezemeler üretilmiştir.

Literatür taraması bezemelerin geometrik düzenini ele alan birçok çalışma olmasına rağmen tuğla ile inşa etmeye yönelik geleneksel yöntem ve tekniklerin belgelenmesi konusunda eksiklikler olduğunu göstermiştir. Bu durum tarihi binaların korunması ve restorasyonu konusunda zorluklara yol açmaktadır. Tuğla yüzeylerin tasarım sürecinin bu yüzeylerin yapımlarında kullanılan malzeme ve tekniklerle ile bir arada ele alındığı kısıtlı çalışma olduğu, var olan mimari miras araştırmalarının bir araya getirilmesi ve yapıma odaklanarak detaylandırılması gerektiği görülmüştür. Ayrıca yapıların rölöve çizimleri ve restorasyon çalışmaları ile edinilen bilgilerin toplandığı ve paylaşıldığı bir ortam bulunmamaktadır. Bilgiye erişimin zorluğuyla birleşen belgeleme eksikliği bilgi birikiminin zaman içinde kaybolmasına sebep olmaktadır. Bu nedenle, biçim bilgisine ek olarak yapma bilgisini aktarmak, bilginin analizi, korunması ve uygulaması için bütünsel bir anlayış geliştirmek için önemlidir.

Bu tez, Anadolu'daki anıtsal mimari yapılarda bulunan tuğla yüzeyler arasından seçilmiş örneklerin tasarım ve üretimini sağlayan gramerleri geliştirerek mimarlık tarihi ve yapı teknolojisi alanlarındaki engin bilgi birikimini bir araya getiren bir yöntem önermektedir. Tarihi tuğla yapıların tasarım prensiplerini malzeme ile inşa teknikleri ile birlikte dışsallaştırmayı, dijital ortama aktarmayı ve belgelemeyi hedefleyen bu yaklaşım, çağdaş araçlardan ve üretim teknolojisinden yararlanmaktadır. Tez kapsamında hesaplamalı tasarım araçları mimari tasarım sürecini yapım ile bir bütün olarak anlayan çalışmalar için ortak bir zemin sağlayarak mimari miras çalışmalarına yardımcı olacak bir araç olarak kullanılmaktadır.

Tezin ilk bölümü, mimari miras araştırmalarında ölçme ve modelleme amaçlı dijital araçların kullanımına ve tarihi yapı bilgi modellerine değinmektedir. Çağdaş yöntem ve araçların mimari miras araştırmalarında yapıma dair bilgi birikimini koruma ve tasarımla ilişkilendirme amacıyla kullanılma potansiyeli tartışılmaktadır. Araştırma için hesaplamalı yöntem olarak biçim ve yapım gramerleri kullanılmıştır. Biçim

gramerleri tasarlama eylemini şekiller aracılığı ile görsel düşünme ve akıl yürütme süreci olarak modelleyen üretken bir yöntemdir. Biçim gramerlerinin tasarım ve yapım sürecini bir bütün olarak ele alan uzantısı olan yapım gramerleri sadece geometri ve formu değil, aynı zamanda yapım sürecine dair bilgileri ve soyut nitelikleri de belgeleyerek, tarihi bina ve yapıların daha kapsamlı bir şekilde anlaşılmasını sağlama, böylelikle mimari miras çalışmalarına katkı sunma potansiyeline sahiptir. Ancak, yöntemi mimari miras alanına entegre etmek ve tarihçiler ve koruma uzmanları için daha erişilebilir ve kullanışlı hale getirmek için daha fazla araştırma ve geliştirmeye ihtiyaç duyulmaktadır. İkinci bölümde, literatür taraması özellikle Ortaçağ Anadolu'suna odaklanarak geometrinin o dönem mimari tasarımındaki önemine değinmekte, tuğla yüzeyleri analiz etmek, tasarlamak ve üretmek için dijital araçların kullanımına ilişkin daha ayrıntılı bir genel bakış sunmaktadır.

Üçüncü bölümde sunulan araştırma yönteminin ilk adımı, dönem, coğrafi konum,ve fonksiyon olarak benzerlik gösteren yapılarda bulunan tuğla yapı elemanlarının modellenmesini, analiz edilmesini ve dijital ortamda yeniden inşa edilmesini içerir. Örnekler, tuğla örgü ve örüntüsüne dair özgün özellikleri ile analiz ve belgeleme açısından ortaya koydukları zorluklar nedeniyle seçilmiştir. Örneklemi oluşturan elemanlar farklı renk ve şekillerdeki çıplak ve sırlı tuğlaların üç boyutlu ilişkileri sonucu ortaya çıkan soyut geometrik desenlere sahiptir. Yatay veya düşey-yatay örgü ile inşa edilmiş farklı eğriliklere sahip elemanlar seçilerek yapım bilgisinin yüzeyler arasında aktarılabilirliği tartışılmıştır.

Yüzeylerin analizi amacıyla tarihi belgelerin ve arşiv kaynaklarının incelenmesinin yanı sıra Anadolu'daki Ortaçağ binalarında saha çalışması yapılarak ölçüm yapılmış ve fotogrametrik veriye dayalı nokta bulutu ve mesh modelleri oluşturularak fiziksel analiz yapılmıştır. Bu amaçla tek eğrili yüzey örnekleri olarak Harput Ulu Camisi (1144-1167) ve Erzurum Tepsi Minareli Cami'nin (12. yy sonları) minare gövdeleri ile Amasya Gök Medrese (1266-1267) ve Malatya Ulu Camisi'nde (1224) bulunan tonozların iç yüzlerini oluşturan tuğla örgüler seçilmiştir. Tek eğrili yüzey örnekleri mevcut literatüre ve yapı rölöve çizimlerine dayanarak analiz edilmiş ve modellenmiştir. İnce Minareli Medrese (1258-1265), Sahip Ata Hankahı (1269-1270) ve Beyşehir Eşrefoğlu Camisi (1297-1299) kubbelerinden oluşan ikinci örneklem grubunun analizi ve modellenmesi için fotoğraflardan, mevcut literatürden, yapı rölöve çizimlerinden ve fotogrametrik veriye dayalı nokta bulutu modellerinden faydalanılmıştır. Son olarak minare şerefesi örnekleri olan Akşehir Güdük Minareli Cami (1227), Akşehir Ulu Camisi (1213), Afyon Ulu Cami (1272-1277), Konya Sahip Ata Camisi (1277), ve Afyon Kuyulu Cami (yaklaşık 1250-1300) fotogrametrik veriye dayalı mesh modellerden ve saha çalışmasından elde edilen veriden faydalanılarak incelenmiştir. Bu çok yönlü yaklaşım sayesinde, örneklemde bulunan yüzeylerin parça ve bütün ilişkilerini modellemek için çeşitli kaynaklardan gelen bilgiler bir araya getirilmiştir. Seçilen örneklerin biçimsel özellikleri, tasarımın temelini oluşturan geometrik kompozisyonları ortaya çıkarmak için dijital modelleme araçları kullanılarak analiz edilmiştir.

İkinci adım, parametrelerin tanımlanmasını içerir. Parametreler, mevcut yüzeylerin tektoniği hakkında bilgiler derlenerek geleneksel tasarım ve inşaat yöntemlerinin teknik bilgisini belgeleyen gramerlerin geliştirilmesini sağlayacak olan bilginin sentezi için ilk adımdır. Bu adımda kullanılan tuğla türlerini, boyutlarını ve tuğla yüzeylerin geleneksel yöntemler ile yapımında izlenen sıralı ve uzamsal aşamaları dikkate alan modüler bir yaklaşım kullanılmış ve yöntem aracılığıyla uygulamalı geometrinin potansiyel kullanımı tartışılmıştır.

Araştırma, gözün farklı parça ve bütünleri algılama esnekliğini göz önüne alarak tek tek tuğlaların yanı sıra ve tuğla gruplarının oluşturduğu geometrik örüntü desenlerinin analizine iki boyutlu düzenlemelerden ziyade üç boyutlu birimler arasındaki yapısal ilişkilerin bir sonucu olarak odaklanmaktadır. Hem örüntünün biçimsel tasarımı, hem de yapım aşamasında uygulanan örgü için bir hesaplama ele alınmıştır. Örüntü birimleri tuğla ve harcın belirli örme teknikleri ile bir araya gelmesi ile elde edilen biçimler ile tanımlanmıştır. Aynı zamanda farklı yüzey türleri, geometrik düzen ve birimler bazında yapılan analizlerle birbiriyle ilişkilendirilmiştir. Böylece farklı yüzeylerdeki karmaşık desenlerin ardındaki tuğla örgü ve örüntüsünün yapısal düzeni ile minare şerefelerinin altındaki kornişlerdeki tuğla mukarnasların üç boyutlu nitelikleri incelenmiştir.

Üçüncü adımda parametreler kullanılarak analiz edilen yüzeylerin yeniden oluşturulması için gerekli olan en az sayıda kural tanımlanmıştır. Kurallar analiz sürecine paralel şekilde örgü ve örüntü kuralları olarak ikiye ayrılır. Örgü kuralları tuğlaların uzamsal ilişkisini gösterirken örüntü kuralları, örgü sonucunda ortaya çıkan desenin geometrik düzenini tanımlar. Tanımlanan kural seti ile örgü ve örüntü birbiriyle ilişkili olarak üretilebilmektedir. Örgü kuralları ile birlikte örüntü kurallarının uygulanması sonuçlarda çeşitlilik olasılığını artırmaktadır.Yapım parametreleri, yüzeylerin genel düzeni değiştirmeden sonucun görsel özelliklerini değiştirebilmektedir.

Son adım, gramerlerle oluşturulan tuğla örgü örneklerinin robotik fabrikasyon kodlarına dönüştürülmesi ve tuğlaların belirli bir düzende dizilmesi için 6 eksenli KUKA KRC2 robotik kol kullanılarak üretim denemeleri yapılmasıdır. Rhinoceros 3D programı içinde Grasshopper eklentisi olan KUKA PRC programlama dili kullanılarak robot kol için G-kodu komutları ve robotun izleyeceği yol oluşturulmuştur. İşlem kavrama özellikli uç ekipmanıyla tek tek tuğlaların alınmasını ve istenen düzende yerleştirilmesini içerir. Robotik fabrikasyon, potansiyel olarak yapılacak işi insan işçilerden daha hızlı ve doğru bir şekilde tamamlayabilir. Bununla birlikte, araştırma kapsamında kısıtlı çalışma alanı, tuğlalar için malzeme seçimi, yazılım ve donanımın eskiliği ve geleneksel ve robotik tuğla örme süreçleri arasındaki farklar gibi çeşitli kısıtlar vardır. Bu kısıtlara rağmen tez çalışması, robotik fabrikasyonun tarihi tuğla örgü teknikleri ve örüntüleri hakkındaki bilgileri belgelemek ve aktarmak için kullanılan iş akışının bir parçası olabileceğini ve koruma ve restorasyon çalışmalarıyla entegre edilebileceğini göstermektedir. Robotun tuğlayı alması ve yerleştirmesi ustanın hareketleri taklit etse de, yapım parametreleri analog üretim yöntemlerinden farklıdır. Üretim denemeleri aracılığı ile malzeme özelliklerinin, araçların ve üretimi yapan kişinin eylemleri ve bunun robot ile üretim ile benzerlikleri ve farklılıkları tartışılmıştır.

Araştırma, önerilen yöntemin mimari mirasın belgelenmesine yardımcı olabileceğini ve tarihi yapı bilgi modellerine (HBIM) aktarılan bilgilerin koruma ve restorasyon çalışmaları ile bütünleştirilmesine katkı koyulabileceğini varsaymaktadır. Gelecek çalışmalar, gramerlerin daha fazla örneğin incelenmesi ile iyileştirilmesini, farklı malzemelerin kullanımı, üretim süreci planlaması ve daha fazla örneğin üretilmesi ile robotik üretim sürecinin geliştirilmesini içermektedir.

1. INTRODUCTION

Studies on architectural heritage preservation fundamentally depend on the documentation of historical structures including any deterioration and interventions over the years and to its materials. Conventional methods of architectural heritage surveying typically involve the use of physical tools and techniques to create records and representations of historical buildings and structures. Surveying involves the systematic and detailed measurement of a building or site, including its physical dimensions, materials, and construction techniques. This can include methods such as text-based descriptions, measuring and drawing by hand, using photography and other forms of visual documentation, and creating physical models or replicas. Measured drawing involves using a ruler or other measuring device to create a detailed and precise two-dimensional representation of a building or structure.

While traditional survey methods include measurements and detailed drawings on-site, with digital developments, experts have access to tools such as total station measurements, digital photogrammetry, and laser scanning that provide more accurate and detailed results (Smars, 2008). The hybrid use of these tools allows fast and detailed modeling of the architectural elements three-dimensionally. Digital design tools allow for a level of precision and accuracy that would be difficult to achieve using traditional methods. For example, 3D modeling software can capture the exact dimensions and three-dimensional geometrical characteristics of a historical building, which can be useful for preservation efforts. Building information models (BIM), which cover a wide variety of components of architectural design knowledge, such as building system, time, and cost, are recently developed to include built heritage as Heritage Building Information Models (HBIM). The aim is to provide a ground for interdisciplinary works on sustainable understanding and management of built heritage. HBIM approaches still need to evolve and develop to respond to the needs of architectural heritage studies (Ewart & Zuecco, 2018).

Architectural heritage reconstruction often makes use of parametric modeling. Such applications are usually at the building scale and with regards to style. Examples include the parametric reconstruction of Indian pavilions based on the descriptions from the Mayamatam text (Garg and Das, 2013), the parametric rule set for ancient Chinese buildings based on the Chinese design rule book named Yingzao Fashi and the data collected from existing historical structures (Li et al., 2013), the parametric models of the American Second Empire architecture (Kramer and Akleman, 2020), and the regeneration of New Zealand's 19th-century timber churches based on parametric definitions derived from architectural heritage studies (McLennan and Brown, 2021). On the other hand, there is a need to incorporate the pre-production of the material and construction information as a design component to provide a comprehensive and sustainable understanding of the built heritage. Despite advances in the documentation processes, contemporary approaches in architectural heritage studies reveal the need to include other layers of information beyond geometry and form that cannot be documented solely by drawing and modeling the existing situation. Additional layers could include an expert's know-how, the tools, materials, and intangible qualities such as semantic information combined with the existing survey methods. The lack of analysis and documentation without including the parts and how they are related physically and semantically leads to an incomplete understanding and expression, possibly leading to poorly made restoration applications at the site.

The conservation processes can benefit from the inclusion of the skills and creative knowledge in relation to the architectural heritage since, in traditional production methods, design and making are integrated, with master builders being both the designer and the maker (Kolarevic, 2005). The fabrication process was part of the design generation through craftsmanship and materials, and the transfer of knowledge of making to the practitioners in the field was tacit through making within the master-apprentice relationship. The introduction of architectural representations made design and making processes independent of each other, putting a distance between them. The development of digital modeling and fabrication tools enabled users to engage in the entire process simultaneously from drafting to production again. The separation between design and making has disappeared, just as in artisanal times (Carpo, 2011). With digital tools, end-users can model the process, and interfere during the fabrication, only restrained by the software's capacity. However, the need to document the know-how that developed and accumulated over the years and how to make use of it still needs to be addressed. Contemporary interdisciplinary studies from the computational design perspective still develop methods to learn from existing crafts, externalize and incorporate the know-how to offer projections to novel designs.

Shape grammars is a method to formalize the visual thinking and reasoning of design and generative processes in art and design (Stiny & Gips, 1972), which has been intensively discussed in style studies. In shape rules, what we see is shapes whose parts fuse in infinitely different ways, regardless of their pre-set definition, resulting in the emergence of shapes to compute with and ambiguity (Stiny, 2006). The intention is not to analyze the end product but to decipher the design process as a generative system. In this respect, they provide the potential to examine historical buildings comprehensively, yet the researches conducted with a focus on heritage are carried out are not yet used by historians or conservation specialists. From a more technical point of view, parametric shape rules as tools vital to understanding and exposing the three-dimensional relations between units and the development of its generative system, have been a research problem for the design of interpreters (Grasl and Economou, 2018; Yue et al., 2009).

An extension of shape grammars is making grammars that investigate the process of design and production as a whole through acts of making and physical factors, which are mostly reduced to visual representations as materials, tools, actions, and senses with abstract shapes and their visual relationships (Knight & Stiny, 2015). It has become a field of research that considers all aspects of the making process to integrate formal rules between shapes, tools, and actions, formalizing materials and tools as stuff and things; and actions as doing and sensing. Aspects that are complex to represent visually, such as material interaction, time, and non-visual senses, are generally represented with labels. Stiny and Gips (1972) laid out the foundation to include material aspects to the shape grammars by including the mixing of different colored paints.

Muslimin (2010) examines the traditional craft of interweaving with parametric shape rules while considering material properties such as dimension, strength, and elasticity. The research shows that the method is applicable to generate novel patterns and analyze existing ones, with experiments of three different materials; brick, beam, and plates. The outcomes provide insights into the potential of human-machine collaboration in traditional crafts. MacLahlan and Jowers (2014) use weighted shapes to formalize the material properties such as color, softness, and flexibility of multi-material objects produced by 3D printing. The weight functions are defined with algebras as vectors or numbers to compute complicated behaviors of combinations of the materials. The research forms a basis for future explorations of additive manufacturing and material behavior. Gürsoy and Özkar (2015) formalize the making of dukta patterns with the spatial displacement of the material. The drawing and cutting of the material are abstracted using the shapes. Photographs are incorporated into grammars to indicate materials, and the labels indicate orientation for physical material manipulations. The research aims to externalize the design process by representing material interactions through the acts of making.

Using shape rules, Harrison et al. (2015) formalized the motions and material explorations of kinematic designs and the folding of paper models. Labels and weights are used to formalize different actions. They explore the successful and unsuccessful results to understand crucial relations and possibilities of variations. El-Zanfaly (2015) redefines making as a process that includes a conversation between the maker, the material, the tools, and the object in the making. The importance of learning through doing is emphasized to create opportunities for improvisation and creation. Bidgoli and Cardoso-Llach (2015) define a machine-specific motion grammar for robotic stereotomy for hot wire cutting, slicing, and carving. They define two sets of rules for motions of the tools for hot wire-cutting that show the sequential and composite procedures and their effect on the physical manipulation of the material. Noel (2015) defines the Bailey-Derek Grammar as the traditional craft of wire-bending in the Trinidad Carnival using rules. Materials such as wire, aluminum rods and flats, fiberglass rods and tape, PVC rods, and cable ties with the connection details are formalized with symbols, shapes, colors, line thickness, texture, and text. The application of rules is formalized on a different scale than the rules, which include the connection details. Materials other than wires are not included in the visuals of the overall structure. The significance of the study is the consultation process with the experts and the observation of the transfer of know-how between them and other practitioners and students.

Hamzaoğlu and Özkar (2018) analyze the relationship between design geometry and its transformation during fabrication with the parameters of making in the stone-carved ornament of the Anatolian Seljuk period with a 3-Axis CNC machine. Knight (2018) integrates sensory aspects of making into traditional kolam pattern-making grammars.

Aspects such as gestures and actions of makers, time, and amount of material are discussed with each other. On the other hand, the formalization shows the movement and the resulting shapes instead of aspects. Krstic (2019) elaborates on the formalization of the physical transformations emphasizing the importance of reflecting the making process accurately. Kamath (2020) develops a making grammar to formalize the hands-on making of thin-tile vaults. With a series of non-deterministic rules, the whole process, from the material interactions to the laying of the tiles. The tools and materials of making are formalized with symbols and hatches in the identification rules. Material interaction rules are used to show the complex behavior of materials when combined, and the building rules show the vault's construction. The grammar is noteworthy for the formalization of the interaction of multiple materials in various ways and the process of making independently from designing through drawing. Even though researchers are focusing on traditional crafts or fabrication with digital tools separately, except for the work of Hamzaoğlu and Özkar (2015), making grammars are not considered at the intersection of cultural heritage and digital fabrication. The potential of shape grammars to be used in heritage studies is enhanced with making rules. The integration of the artisan’s know-how with all aspects of making and the formal analysis offers an opportunity to fill the gaps in documentation and examination of built heritage.

This thesis aims to make a methodological contribution to bring the vast knowledge of architectural history and building technology together while developing the codes that enable the production of selected samples of brick elements in the monumental architecture in Anatolia. We externalize the relations between parts and wholes that enable the making of said structure, which depends on the period and geography specific historical design and construction knowledge. Transformation of the relations into parametric digital fabrication codes with digital tools to carry out robotic fabrication experiments will provide a method to preserve construction techniques with contemporary information and fabrication technology.

The method of research consists of three steps. First is an analysis elucidating the correlation of the material construction of brick surfaces with the design geometry in the selected cases of single-curved surfaces, domes, and corniches below minaret balconies with a computational approach, based on the survey drawings, photogrammetry-based three-dimensional models, and existing literature. The following synthesis involves the definition of the parameters and development of a grammar of the know-how of design by associating surface types within themselves and with each other. Considering the types of bricks and the relation between their dimensions, we take a modular approach in modeling and in the definition of the parameters regarding the sequential and spatial procedures that are followed in the manual building of a brick panel. Each type of brick, the bricklaying, and the pattern are interdependent. The final step is the conversion of the bricklaying generated with the grammars to robotic fabrication codes. The production is carried out with a 6-axis robotic arm and focuses on the corniches and the single curved brick surfaces with brick rows horizontal to the ground since the production in the scope of this research does not involve the use of adhesives, scaffold, or specially designed bricks. The architectural element cases subject to the study are limited in terms of time, geography, brick types, bricklaying, and curvilinearity. The accuracy of production and feasibility of the proposed method is tested in this context. The three-dimensional modeling and simulations are carried out in the Grasshopper environment in Rhinoceros 3D to combine the visual making rules with the control of the robotic arm in a parametric model. The integration of the geometric model with fabrication parameters is followed by production and testing.

The formal features of the selected cases from a certain period and geography with similarities in the materialization of abstract geometric patterns through the bricklaying and difference in the curvilinearity are analyzed to expose the underlying geometrical compositions. The parts of these compositions are obtained with a particular material application and bricklaying. The parameters of production change the visual characteristic of the end result without changing the overall order. Similar patterns can be carved into stone or constructed with bricklaying. The thickness of the curves defining the pattern, their interactions with each other, and last but not least, the structural features of the surfaces depend on the process of making. In the case of brick surfaces, this relation is reciprocal between the geometrical pattern and the unit based on the material properties. The distances between the pattern units are strictly restricted by the number of brick units, their dimensions, and the mortar spacings. On the other hand, the placement and the orientation of brick units are based on the geometrical design.

2. LITERATURE REVIEW

2.1 Architectural Heritage of Medieval Anatolia and Design Computing

The practice of architectural design in Medieval Anatolia is strongly related to artistry, knowledge of geometry, and materials. The problems of the design and construction of complex geometrical patterns are known to be solved through the communication between mathematicians and master builders in the Islamic era (Özdural, 2000). The written sources of explanations of practical geometrical applications to craftsmen, such as Abu al-Wafa' Buzjani's, confirms the connection (Sarhangi, 2008; Necipoğlu, 1995). The geometric constructions of basic forms are explained with simple drawings making them comprehensible and applicable for the artisans. The example drawing from the writings of Abu al-Wafa' Buzjani in Figure 2.1 shows the connection between geometry and design by addressing the artisans on the division of squares with the use of applied geometry which constitutes the basis of many complex construction methods. The outcomes of this communication and the integration between design and making over practical geometry are most observed in the geometrical ornamentations of architectural surfaces, making them the subject of interest for many interdisciplinary studies over the decades.

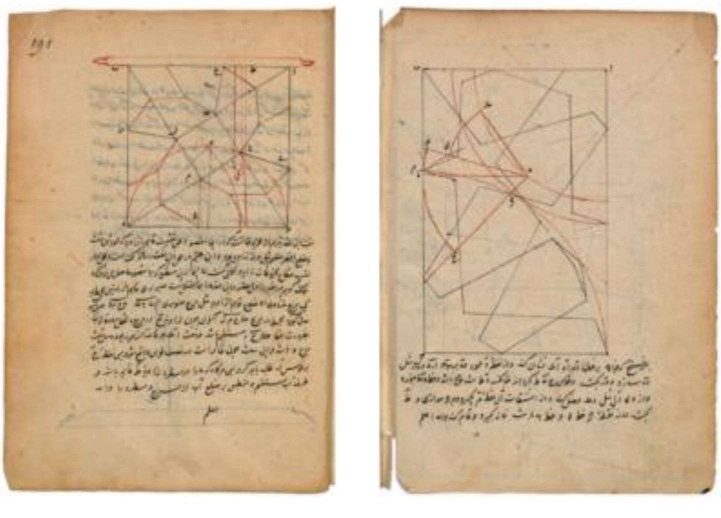

Figure 2.1 : Drawings from the writings of Abu al-Wafa' Buzjani, showing division of a square (Buzjani, 10th century, Bibliotheque Nationale de France, MS Persan 169, sec. 23, fols. 141v– 179v).

Researchers have studied the use of geometric ornaments in Islamic art and architecture for a variety of reasons, including to better understand the historical and cultural significance of these ornaments, to explore the mathematical principles underlying their design, and to investigate the ways in which they were created and used.

The majority of the studies focus on deciphering the generation of geometric compositions of the ornaments based on two-dimensional analysis. Various studies explain the use of practical geometry with a compass and a straightedge to draw interlaced circles that are the base of the girih patterns with the use of symmetry and repetition (Hankin, 1925; Critchlow, 1976; Bakırer, 1981; Lee, 1987; Lu & Steinhardt, 2007; Al Ajlouni, 2012; 2017). Kaplan (2000; 2005; 2017) developed an algorithm of two-dimensional star-shaped motifs and their patterns in three-dimensional interlocking layers to create sculptural polyhedral forms. Cenani and Çağdaş (2006) and Ulu (2009) apply shape grammars to develop generative systems for the two-dimensional geometric Islamic patterns. Colakoğlu et al. (2008) use the geometrical design of Islamic star patterns and their potential to be constructed parametrically with computational design tools to utilize them for educational purposes.

The division of spheres geometrically and the analysis of curved surfaces including domes also have been the subject of various research. Kaplan & Salesin (2004) developed an algorithm to divide curved surfaces with star patterns and produce the results with digital fabrication tools. Sarhangi (1999) examines the geometrical division of Persian domes with a focus on the division of a circle on plans without commentary on three-dimensional construction. Kasraei et al. (2015) relate drawing Girih patterns on the surfaces of domes to the curvature of the surface, yet do not indicate an insight into the on-site drawing and the construction process. Özgan & Özkar (2020) investigate the construction of patterns on domes of Medieval Anatolia using latitudes and longitudes, vertical segments, and spherical polyhedrons. They dwell on the relationship between surface division methods and craftsmanship.

The two-dimensional geometrical layouts were also used to design and produce more complex three-dimensional units and compositions. Muqarnas, which is an element that has been of interest among scholars for decades, is an important outcome of experiments with more complex units. It is a three-dimensional ornamental element that provides a smooth transition between shapes that are different in size, form, and position in Islamic architecture (Imani, 2017). Similar to other architectural elements and ornaments, the studies on muqarnas take a two-dimensional approach and examine the geometric layout of the plan. The traces on the stone surface points out that the construction is based on the two-dimensional plan scheme drawing (Harb, 1978). Visual representation is one of the methods used to understand muqarnas (Tabba, 1985; Özdural, 1990) Cromwell (2009) uses subdivision to analyze the geometric pattern, while Dold-Samplinous (1992) and Yaghan (2000;2003) evaluate the geometric relations of cells. Harmsen (2006), Hensel (2008), and Gökmen et al. (2022) use a graph-based approach. Even though muqarnas provides a ground to evaluate the formation of the design three-dimensionally, there is a lack of focus on constructing three-dimensional cells, raising the design from the plan. Additionally, even though both stone and brick are used as a material for muqarnas, studies on the effect of the material and production method used for the application of design on the surface are limited.

There is limited research with a computational design approach focusing on the patterns emerging from the bricklaying. Panahi (2012) reviews the geometric background of the ornamental naked brick patterns with an emphasis on the effect of mathematics and geometry in Islamic architecture. The review concludes that the layout and pattern creation are based on a set of circles and their divisions from intersections to define other geometric shapes. Similarly, Kharazmi (2016) analyzes the two-dimensional geometric layout of the Iranian Islamic brick decorations with polygons. Another research by Al Ajlouni & Justa (2011) documents the existing cut brick ornament on a flat surface of a minaret using digital tools and reconstructs the two-dimensional pattern (Figure 2.2). The study is significant since it proposes a method to analyze and reconstruct the geometrical composition of a deteriorated historical surface based on the geometrical and constructional know-how of the period and geography. However, beyond the design of the surface it is not clear how the geometry will be transferred to the material. Safaeianpour & Valibeig (2022) study the geometric brick patterns of cut bricks and unit bricks on the minarets in Isfahan by projecting the patterns. Their conclusion includes practical solutions such as tapering the bricks to prevent overlaps, using smaller bricks, and reducing mortar spacings to make geometric compositions more visible. The research by Özen Yavuz & Sağıroğlu

(2016) approaches bricks as three-dimensional entities with a shape grammar method, yet neither the order of bricklaying involved nor the related parts that emerge through the application of rules are disclosed in the study.

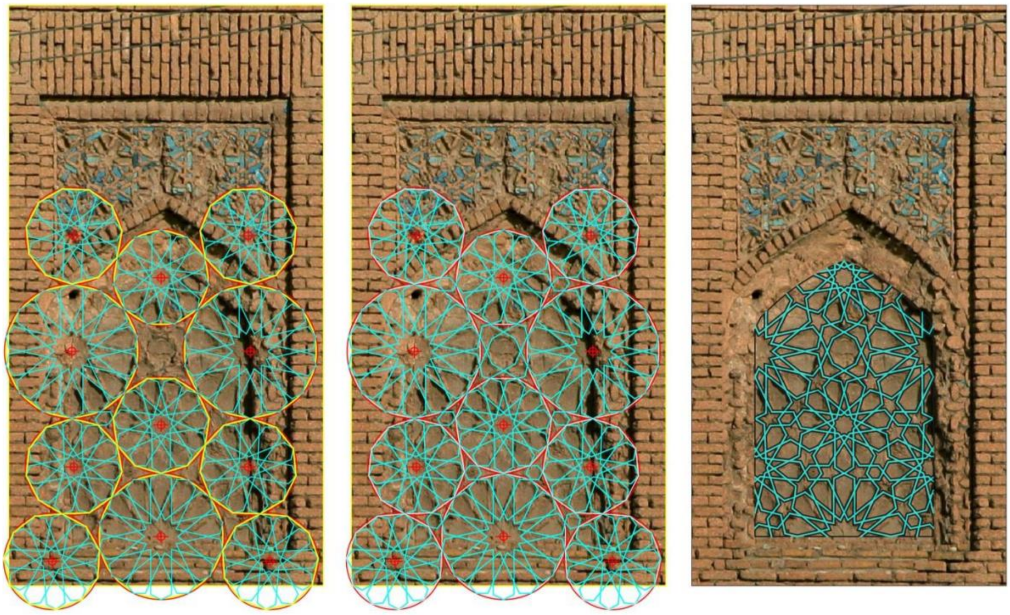

Figure 2.2 : The use of two-dimensional geometrical layout for the reconstruction of an eroded surface (Al Ajlouni & Justa, 2011).

2.2 Digital Applications on Brick

Due to its repetitive nature and identical parts, there are multiple studies on algorithmic and robotic production of masonry surfaces with a unit building element such as brick. Bonwetsch (2015) distinguished between top-down and bottom-up representations for the automation of brickwork. Top-down representation reconstructs a predefined surface with bricks, while bottom-up representation constructs the surface with bricks without regarding the overall structure.

Some studies approach surface construction with bricks as a problem of dividing a surface. Lachauer et al. (2010) propose a fully digital design process starting with modeling a surface with form-finding methods, which is materialized with tessellating with reference to a given plan geometry. CNC fabrication techniques are used to produce customized units. Afsari et al. (2014) define corbelling and yaw rotation using Processing and Rhinoceros 3D to design a parametric bricklaying pattern based on interactive 2D sketch input. Rajabzadeh & Sassone (2017) experimented with arranging bricks on a free-form curved surface with regular-sized bricks with stretcher and herringbone brick bonds. The use of bricks and the patterns are mainly structural, and their ornamental quality is out of scope. They developed a plug-in for Grasshopper in Rhinoceros 3D, calculated the alignments of brick units to define the targeted surface aiming to create curvilinear surfaces by masonry, and tested the performance with hands-on application. An existing surface can be redefined and reconstructed with bricks using two-dimensional brick masonry visuals to train machine learning algorithms (Zandavali Andrade & Jimenez Garcia, 2020). The training data is also generated with a filling algorithm. While the brick bond types are accurate, the dimensions of the bricks are not yet sufficient. These studies ignore the contribution of the part whole relation and construction knowledge to the creative design process. Imbern (2014) redesigns brick to deploy digital tools to design brick surfaces, yet the fabrication tools are not integrated into the bricklaying process. Unlike these approaches, Vazquez et al. (2020) implement shape grammars to design the perforated brick walls, further emphasizing parts. However, direct production from these grammatical models has not been realized.

Robotic assembly in construction sites for bricklaying has been researched since the 1990s (Anliker, 1988). Automated construction and the possible contributions of robotic fabrication to the process have been subject to many studies. Mousavian & Gentry (2014) propose a workflow with parametric tools and structural analysis to model and construct masonry vaults. Sousa et al. (2015) compare manual and robotic assembly of identical surfaces to analyze the possible contributions of robotic automation in brick construction. Bruzl et al. (2017) propose a complete process starting from modeling the architectural element in BIM of the surface to production with a robotic arm. Their workflow focuses on the optimization of the process and increasing the efficiency of production. Ariza et al. (2017) have designed local joining details for freeform shell surfaces made of stone masonry using robotic fabrication. In another experiment, Piskorec et al. (2019) have worked with a dry stacking method to lay bricks with multiple robotic arms and custom-developed brick magazines. They calculate the structural performance of the unit, whole, and the structural relations between units. The research is part of an educational process to integrate the design of the structural system and production into the design process. Brunn et al. (2021) have conducted experiments on eliminating the need for scaffolding with the simultaneous operation of multiple robotic arms to construct complex surfaces with interlocking units.

Simulation of the bricklaying process with augmented reality for optimizing robotic production (Mitterberger et al., 2020) and planning through building information models (Ding et al., 2020) are also discussed. Wu et al. (2018) implement a simulation-based approach for designing, analyzing, and constructing a brick surface with a cable-driven construction robot. Fingrut et al. (2019) use structural models and cable-driven construction robots to test irregular stacking conditions. Dörfler et al. (2016) experiment with a location-aware mobile robotic arm with real-time computation to reduce human intervention and inaccuracies.

The possibilites for interactive bricklaying have also been addressed. A tool was developed to precisely determine the positions where the units will be placed in the sequence of manual bricklaying to produce a brick masonry surface designed in a digital environment that can be used by the maker in the field (Fazel et al., 2022). Robotic production is combined with the design process and has been made interactive using computer vision (Das et al., 2020). On the other hand, Tish et al. (2020) propose automated close-loop bricklaying with computer vision that could be improved to include designer and robot interaction. In studies where a single robot arm is used for stacking, solutions for the application of mortar must be produced. Oliveira and Sousa (2015), learning from the architect Raúl Hestnes Ferreira's works and conducted a brick column production experiment, propose a model that the brick unit has taken with the robotic gripper and moved to the area where the adhesive was sprayed and left by taking it to its place.

Various pieces of research concerning producing brickworks with robotic fabrication, reviewed by Eldemir Kara (2021), show the effect of traditional production methods. However, in the current studies, it is seen that the aim is the optimization of production. Learning from traditional methods is limited to the production of units or intermediate products. No study has been found that integrates an approach that examines the relationship between traditional bricklaying methods and design with robotic production.

2.3 Brick Masonry in Medieval Anatolia

The use of brick, one of the earliest materials used in construction, started from the earlier periods in Anatolia, and brick structures were generally covered by revetments, unlike the exposed brick applications and ornamentations in Iran and Syria. Even though the stone was the primary construction material of the period, brick has been one of the important traditional building materials in Anatolia (Kahya, 1992). The exposed brick style was carried to Anatolia during the Seljuk period by the immigration of Seljuk Turks (Bakırer, 2017). The brick-built structures after this period were under Iranian influence. McClary (2017) explains the constructional and aesthetic relationship between Anatolian and Iranian bricklaying tradition in brick sizes, shapes, and types, as well as the formal and decorative features of ornamental brick surfaces with the mobility of craftsmen and material (Figure 2.3).

Brick was mainly used in small-scale structures and on the upper structures of larger edifices built of stone (Bakırer, 1981). It was mainly used in structural systems combined with other materials such as cut stone, rubble stone, wood, and marble in most of the examples instead of structures built entirely from brick (Aktaş Yasa, 2016). Both Bakırer (1981) and Aktaş Yasa (2016) point out that İplikçi Mosque in Konya is the only monumental structure built entirely of brick.

Figure 2.3 : Examples of brickworks from the period. (Konya Sahip Ata Hanikah and Mosque, Konya Sırçalı Madrasa, and Konya İnce Minareli Madrasa)

2.3.1 Characteristics of bricks of the period

There are detailed studies on the dimensions and classifications of bricks used in Medieval Anatolia. There are two types of bricks in the Anatolian Seljuk period based on their application on the construction site, and these are respectively called unit bricks and cut bricks (Bakırer, 1981). Brick units are premade and laid on the construction site as they are, while cut bricks are generally produced as large elements and shaped on-site according to the applied pattern. Bakırer (1981) divides the unit bricks into four types based on their shapes: square-shaped whole bricks, rectangular-shaped half bricks, small square-shaped quarter bricks, and radial-shaped tapered minaret bricks (Figure 2.4).

Hejazi & Mehdizadeh (2014) illustrate other types of fired bricks, such as triangular bricks used in Persian architecture in the thirteenth and fourteenth centuries. Types of bricks are used by themselves or combined with others, except for the quarter bricks, which are never used alone. The types form subgroups according to their sizes. The dimensions of different types of bricks used to construct an architectural element are interrelated with each other and mortar spacings to ensure the legibility of the pattern with vertical and horizontal order in the borders between brick and mortar in the pattern.

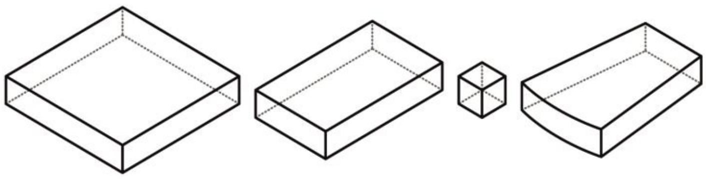

Figure 2.4 : Brick types (from left to right: whole brick, half brick, quarter brick, minaret brick).

Another classification is based on the front surface finish of the brick as glazed and unglazed (Bakırer, 1981). The implementation of glazed brick is a critical feature of the Anatolian brickworks (McClary, 2017) (Figure 2.5). In the Anatolian Seljuk period, turquoise was the most used color compared to the rarer use of navy blue and brown-purple in the glazed bricks, a common material of the era (Özkul, 2020). The glazed bricks are mainly used vertically and define the pattern, while naked bricks are laid horizontally to provide a neutral background.

Figure 2.5 : An example composition of naked and glazed bricks; Side panel of entrance iwan of Konya Sırçalı Madrasah.

2.3.2 Characteristics of bricklaying of the period

The composition of bricks is another classification criterion. The pattern created by structural bricklaying is called a brick bond. There are three types of brick bonds in the Anatolian Seljuk period; horizontal bond, vertical-horizontal bond, and herringbone bond (Figure 2.6) (Bakırer, 1981; Yasa, 2016).

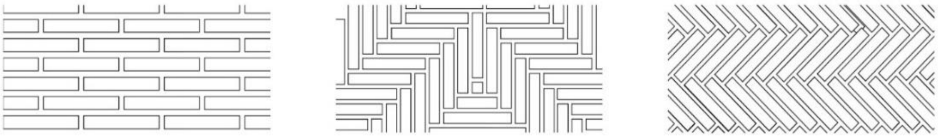

Figure 2.6 : Brick bond types (from left to right: horizontal bond, horizontal/vertical bond, diagonal bond).

In horizontal bonds that can be applied with all brick types, bricks are set flat as stretchers (Figure 2.7). The stride can be 1/2, 1/4, or 1/5 of the brick length. In brickworks with 1/4 and 1/5 stride, the vertical mortar spacings can rise in one direction or opposite directions. The arrangement of rising directions could be used to visually form evenly spaced parallel lines with an angle, V shapes, or rhombus. The rhombus pattern requires a quarter brick. There are some special applications with changes in mortar spacings and additional materials, such as glazed tiles and tile strips, support these patterns.

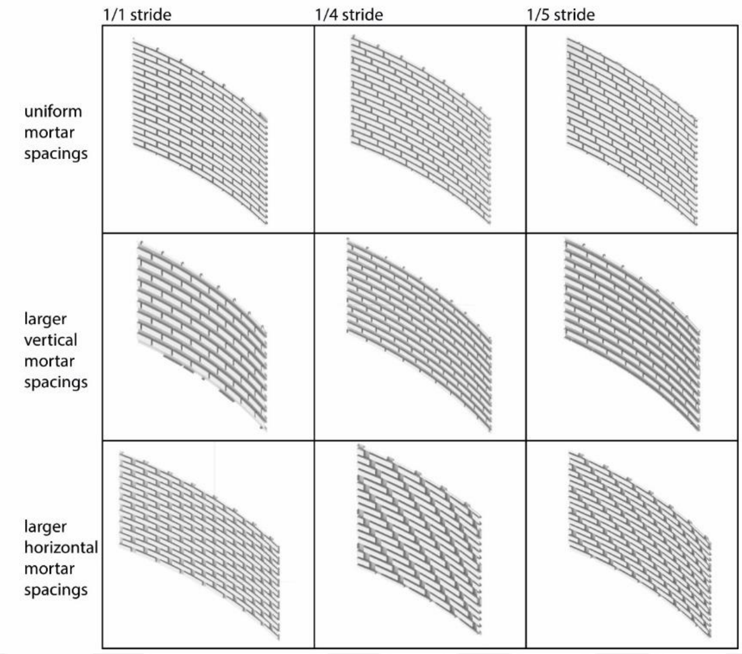

Figure 2.7 : Examples of horizontal brick bonds.

In vertical-horizontal bonds, bricks are set as stretchers and headers alternatingly. Since the borders between mortar and bricks are visually continuous on a line, the dimensions of bricks and mortar spacings show a careful calculation during bricklaying. Similar to the rising of mortar spacings in horizontal bonds, the rising of vertical bricks visually forms patterns on the surfaces (Figure 2.8). Half bricks are placed in different orientations, creating an impression of two different types of bricks. Section drawings by Bakırer (1981) show that the level difference resulting from this type of layout is compensated at the back of the brick surfaces, potentially with the use of mortar.

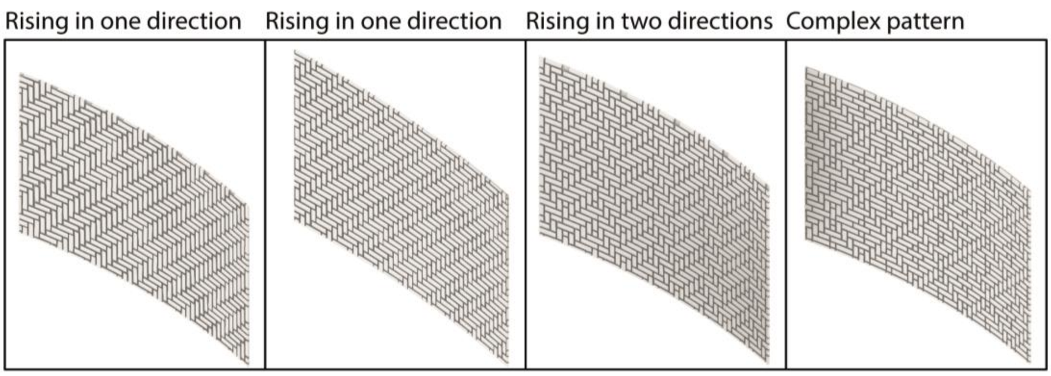

Figure 2.8 : Examples of vertical brick bonds.

Finally, bricks are set with an angle of 45 degrees to horizontal in the diagonal bond, also called the herringbone bond. Herringbone bond improves structural performance on brick structures by preventing vertical compression and horizontal shear (Rajabzadeh & Sassone, 2017). Visually, the herringbone pattern is very similar to vertical-horizontal brick bonds through euclidean transformations. On the other hand, in herringbone bonds, there are no complex patterns but inclined bricks placed with 90 degrees of rotation alternatingly.

The last two brick bonds are not applied with minaret bricks (Bakırer, 1981); the tapered form would not allow the balance of rotated bricks. There are subgroups of all three brick bond types based on various qualities; the variations in the surface finishings of the brick units, the wideness of the vertical and horizontal mortar gaps, and the special treatments of the mortar spacings (Bakırer, 1981). The use of bricks with different dimensions and variations of mortar spacings is observed on minarets to maintain the relationship between the curved surface and the bricklaying. Bakırer's (1981) work includes the assortment of the Anatolian Seljuk brick structures based on these classifications. Aktaş Yasa (2016) also points out that different types of mortars are used for different purposes of bricklaying; lime mortar is commonly used in plain applications, while gypsum mortar is preferred for decorative geometric applications.

2.3.3 Tools and methods of making

There are limited sources from the period that discuss historic construction techniques. McClary (2017) carried out comprehensive research on the working methods and mobility of the craftsmen in Anatolia between the late twelfth and early thirteenth centuries, focusing on the primary construction materials of the said era and geography are stone and brick. He explains the details of the tools used for on-site measurement of brickworks based on the dimensions and proportions of the human body, such as "shibr" (span of a human hand) and "işba'maftüh" (length of a finger) with reference to the historical written engineering sources such as. The calculation of the dimension of a brick in relation to the human hand is related to the workflow's optimization since the bricks were carried and placed with human hands without the need for additional tools. The availability of the other hand for the laying of mortar and alignment of the placed brick with a trowel is also essential for the manual bricklaying process.

Brick was produced with primitive methods, with the knowledge transferred from the master to the apprentice until the industrial revolution (Kahya, 1992). The main ingredients are clay and water. The production has four stages; extraction of clay and making dough, shaping, drying, and baking. The bricks are predicted to be mostly baked on the construction site (Dalkılıç & Nabikoğlu, 2017).

It is known that the makers of the period made on-site calculations with tools such as ropes (Ousterhout, 2008; Docci & Migliari, 1989) (Figure 2.9). A rope is used to lay aligned rows of bricks with the help of gravity, align the bricks in a row on a line when fixed at the corner of the surface, and enable builders to lay the bricks and define the curve when fixed at the center of surfaces. A variety of artisans, brick masons, mortar makers, and carpenters worked in the construction of the structures of the period. Scaffolding is used to keep the surface stable during the production process or allow builders to move and access high levels. The masons combined experience and practical geometry (Prak, 2011).

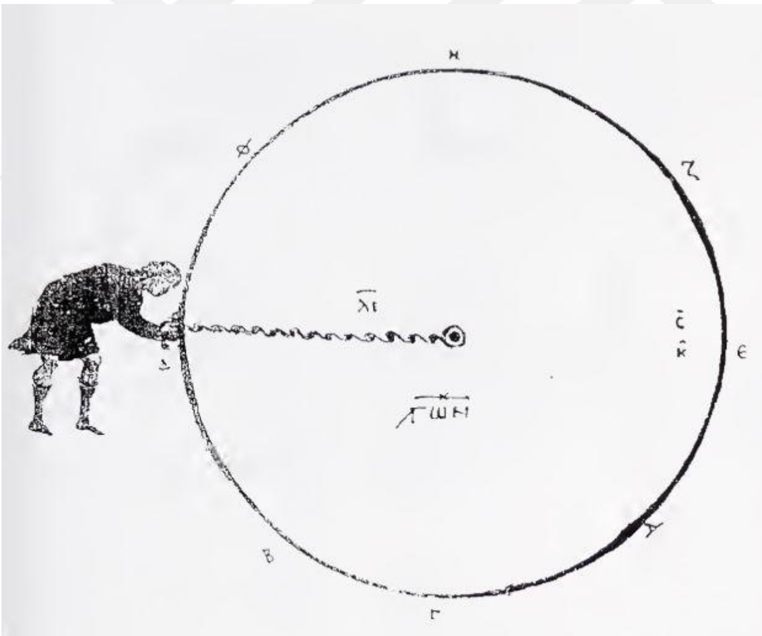

Figure 2.9 : The procedure for measuring a circle. Vatican Library, Rome (MS. 1605) (Ousterhout, 2008)

The only source for constructing the herringbone on domes is the drawings of Brunelleschi and the experiments carried out based on said drawings (Pizzigoni et al., 2018). Pizzigoni (2015) also mentions a "gualandrino" tool with three mobile arms for three directions of alignment. He explains that the definition of the tool is complicated, and there is no reconstruction of it. The research and experiment of Jones et al. (2010)

show no single center point for the construction of Brunelleschi's dome but a central platform. Our model shows that a system of ropes connected to a platform at the center of the dome may have been used to follow up the path of the spiral over the dome as the bricks are laid in the analyzed domes. If the azimuth angle between two ropes is kept constant with a tool, the horizontal placement of the glazed bricks can be carried out accordingly. The vertical angle is directly related to the brick height, so there is no need for a secondary control tool for vertical calculation. A similar system could be utilized for cornices and single curved surfaces.

3. ANALYSIS OF PARTS AND WHOLES

The design of the brick surfaces depends on the relation of parts on different levels. The first layer can be defined with the different types of construction units, which are discrete parts of singular bricks and mortar spacings in between. While these make up the constructional basis of the surfaces, they define other layers of parts which can be identified by the boundaries of abstract geometric patterns formed through the bricklaying. These parts unite and be perceived in many ways. The design knowledge, which enables craftsmen to bring these levels together to create the whole, constitutes the richness and cultural value of these architectural elements.

In order to analyze the parts and wholes of bricklaying, we modeled the surfaces brick-by-brick using the data acquired from existing literature, photographs, and photogrammetry-based mesh models in Rhinoceros 3D and Grasshopper. To estimate the dimensions of the surfaces and the brick sizes, we referred to survey drawings and the mesh models. Bricklaying is an additive production method; by its nature, the making units correspond to well-defined shapes. At the same time, the mortar gaps are modeled as null spaces, which can be redefined in further studies to include material properties to use in HBIM models.

Prior research which established a starting point for this thesis was an analysis of a single brick panel from the period that contains both naked and differently colored glazed bricks in a vertical-horizontal bond (Altun & Özkar, 2021) and its improvement with parametric shape rules and inclusion of more examples (Altun & Özkar, 2022). In works of this genre, visual reasoning, with flexibility in perceiving different parts and wholes, delivers the constructional relations between individual bricks and the geometric patterns formed by groups of bricks. This thesis expands the research to include curved surfaces, the development of robotic production codes, and production. Birkett & Jurgenson (2001) also stated that the modules and proportions were the tools of craftsmen in a historical context; they used practical geometry instead of complex algebraic methods based on numerical calculation. In our research, a modular approach is used to analyze and model the cases by referring to the dimensional relations of the units. The modular approach also ensures that the dimensions of the glazed bricks and the levels of bricks on rows are constant, and the proportional relations are not disturbed in surfaces with different curvatures. Different brick types are a combination of one or more modules with mortar spacings. The bricks are modeled as ideal rectangular prisms, and the rows of bricks are modeled as perfectly aligned, as intended in the design of the existing surfaces. The local deformations, minor divergences, and irregularities due to workmanship and deterioration are disregarded to make holistic inferences.

In our study, we aim to understand if the instrumental role of geometry, the knowledge of pattern design, and of construction can be translated between surfaces of different curvatures. The cases are analyzed one by one with a focus on individual brick relations and the patterns formed by these relations to expose underlying geometric relations of laying bricks to form various surfaces to develop the grammar with the least number of rules that enables the making of the brickworks. The convertibility of the rules between different types of architectural elements with the use of parameters is detected. The corniches below the minaret balconies differ from other samples by using particular types of bricks, their three-dimensional qualities, and the definition of the pattern.

We used the Sortal GI interpreter developed by Rudi Stouffs (2018) to test and validate the syntactic accuracy of the non-parametric rules and the grammar and Wasp developed by Andrea Rossi to test and validate the parametric grammars in the Grasshopper environment of Rhinoceros 3D. The models shown in this chapter are generated with the generative system explained in Chapter 4.

The images of domes are collected within the site surveys of the project supported by TÜBİTAK (The Scientific and Technological Research Council of Turkey) (Project number: 119K896) and the images of minarets are collected within the site surveys of the project supported by Research Fund of Istanbul Technical University (Project Number: 43337). Mustafa Cem Güneş collected the images of the dome of İnce Minareli Mosque and Sahip Ata Hanikah and processed the images to export point-

cloud models in Meshroom Software using the computing sources provided by the National Center for High Performance Computing of Turkey (UHeM) under grant number 1010152021. The images of minarets are processed in RealityCapture Software.

3.1 Selection of Cases

For the scope of the study, twelve brick surface samples are selected based on their variances in curvilinearity in terms of being formed with horizontal or vertical-horizontal bonds, patterns, and structural aspects. The thesis develops a method that can be applied in the analysis and documentation process of different architectural elements, which have architectural value, depend on know-how, and consist of units that come together in a defined manner, so we focus on the physical aspects and reduce the historical and semantic interpretation. The scope of the thesis is limited to the examples of single curved surfaces, domes, and corniches below minaret balconies of monumental structures, which are similar in terms of period, geographical region, and function. Pattern diversity is another selection criterion to cover different levels of complexity. The selected single curved surfaces and domes are formed of naked and glazed bricks of different shapes and dimensions, forming abstract patterns through the bricklaying in horizontal and vertical-horizontal bonds. The rows of bricks in the single curved surfaces settle at different angles with the ground, while the bricks in the domes face the center of the dome. The corniches below minaret balconies are formed of both minaret bricks and triangular bricks with varying three-dimensional spatial arrangements, in which the rows of bricks are horizontal to the ground. The existing section drawings do not provide information about the underlying structure of the analyzed surfaces, especially in the cases of domes and corniches; it is unclear what is between the outer shell and the brick surface. Thus, this study focuses on brick surfaces.

3.2 Single-Curved Surfaces

The brick units and the patterns on four single-curved surfaces are analyzed using modules and proportions. The single curved surfaces analyzed in the scope of the thesis are inside surfaces of vaults and minaret bodies. The elements are the minaret body of Harput Ulu Mosque (1144-1167) and Erzurum Tepsi Minaret (ends of 12th century), inside the surfaces of vaults of the Amasya Gök Madrasah (1266-1267) and Malatya Ulu Mosque (1224), from here on abbreviated as HUM, ETM, AGoM, MUM respectively. Figure 3.1 shows that each element is composed of plain and/or glazed bricks, forming abstract patterns through the bricklaying.

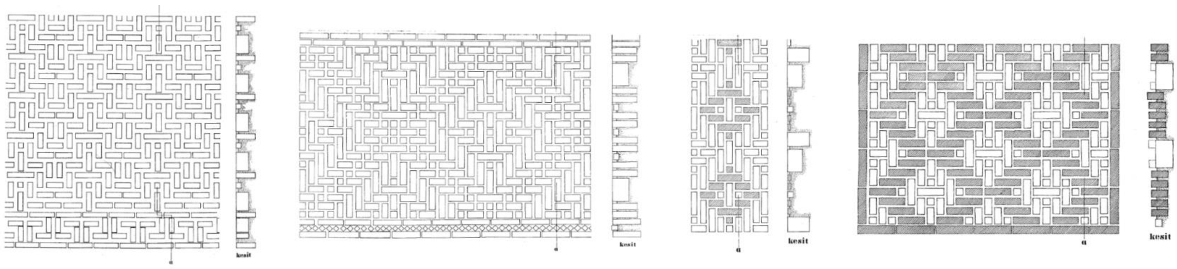

Figure 3.1 : Front view and section drawings of Bakırer for case surfaces (Bakırer, 1981) (From left to right: HUM, ETM, AGoM, and MUM).

We referred to Bakırer’s (1981) drawings for the modeling and analysis of surfaces.The bricks used for the minaret bodies with the horizontal bond are minaret bricks, while the ones in vertical-horizontal bonds are generally half and quarter bricks. While the use of minaret bricks helps makers to lay bricks closely, the tapered sides do not allow vertical bricklaying. In horizontal bonds with minaret bricks, the patterns are emphasized with glazed tiles that could be placed in the mortar spacings.

There are two bricklaying directions for single curved surfaces with reference to the ground (Figure 3.2). In the first one, the rows of bricks parallel the ground surface. The bricklaying in minarets, drums, and corbelled domes are in this order; the surface rises row by row, as on flat surfaces. This type of bricklaying defines spaces with circular plan layouts and can be constructed without scaffolding. The rows of bricks are perpendicular to the ground surface for the second type of bricklaying. In this type of bricklaying, where a side of the surface rests on a vertical surface, scaffolding may not be required, yet there is a need for scaffolding in freestanding ones. Especially the use of quarter bricks decreases the stability during construction.

The production starts from both ends of the arc, the curved surface section as the rows of bricks revolve around the arc's center, and bricks meet at the top. The methods and tools of making different surfaces are similar yet different due to gravity. For both situations, a rope tied to the center could be used to lay the bricks around the arc. Ropes hanging down with a weight at the end maintain the flatness of brickwork during construction for bricklaying with rows horizontal to the ground, and a rope tied at both ends of the horizontal surface could be used for the rotating surfaces.

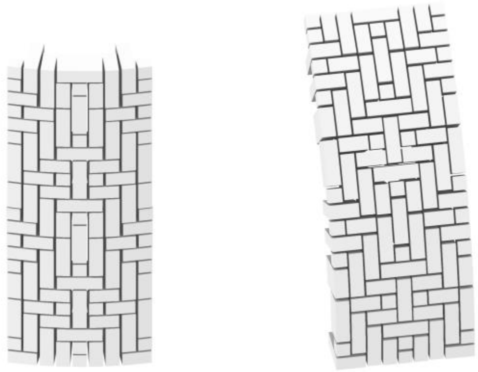

Figure 3.2 : Directions of bricklaying in single-curved surfaces: brick rows parallel to the ground, brick rows are rotating around the center.

The surfaces are modeled using modules and proportions based on the rotation of bricks around the center of the arc defined at one plane and translation in the other direction. The bricks are placed ideally with perfect geometries and alignments. The vertical and horizontal mortar spacings are calculated based on the size and proportions of the bricks and vice versa. The drawings of Bakırer (1981) provided the basis of the models. The brick types and dimensions for single-curved surface cases are given in Table 3.1.

Table 3.1 : Table of brick types and dimensions in centimeters for single-curved surfaces.

Surface	Whole Brick	Half Brick	Quarter Brick	Mortar Spacing
HUM	14x12.5x4	20-21x12.5x4	4x4x4	3.5-4
ETM		19.5-20x12-13x5-5	5x5x5	1.5-3
AGoM		15x9.5x4	4x4x4	1.5
MUM		14-15x9-9.5x4.5	4.5x4.5x4.5	1.5

The unit dimension is the short side of a brick, and this unit dimension is also the height of a circular brick row. When adding up the units, the thickness of the mortar in between is also considered, and the vertical mortar thickness is taken as constant

(Figure 3.3). The largest side of the half brick equals the sum of three units and vertical mortar spacings between them, while the other side equals the sum of two units and the vertical mortar spacing. The central angle that corresponds to the horizontal arc between two aligned corners of a brick on the surface (α) approximately results from the unit brick, and β and γ approximately result from the longest and the shorter sides of the half brick, respectively, as in equation 3.1.

$$\left(\beta \cong \left(a \times 2 \pm \delta\right)\right) \wedge \left(\gamma \cong a \times 3 \pm \delta \times 2\right) \tag{3.1}$$

The horizontal mortar spacing is calculated with the angles between the unit bricks. The calculation of mortar spacings in vertical-horizontal bond brickwork on a single-curved surface can be done by placing unit of bricks on the surface and combining them for the placement of half bricks while repeating their relations.

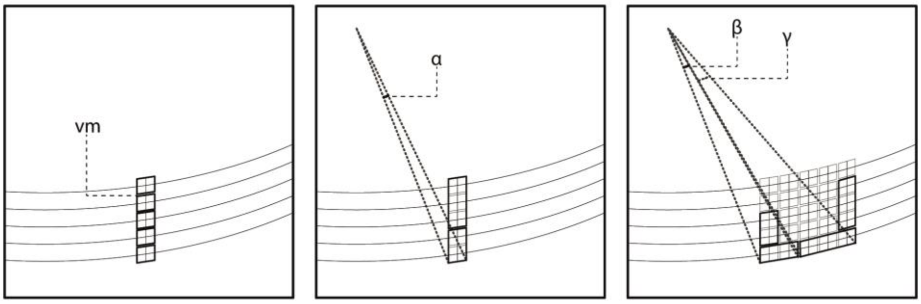

Figure 3.3 : Placement of bricks: (a) unit bricks with vertical mortar (vm), (b) half brick placement, (c) horizontal mortar angles calculation.

Hypothetical lines between the center of the surface and the edges of the long side of a radially positioned whole or half brick that faces to the center coincide with the outer edges of three quarter bricks, which are placed radially on a row, and the middle one shares a center with the longer brick. During manual bricklaying, the corners of the quarter and half bricks could be aligned or surfaces could be overlapped. This helps us to calculate the angles of vertical mortar spacing.

All three types of naked bricks, including minaret bricks, are used in HUM. Vertical units are laid in each row with a stride equal to the combination of a mortar gap and a length of a quarter brick to form the pattern of inclined with 45 degrees curves that change their directions in a zig-zag order parallel to the ground surface. These curves repeat seven times vertically and continue through the surface of the minaret and quarter bricks, emphasizing the change of direction (Bakırer, 1981). The minaret bricks are placed horizontally at the top of quarter bricks, separating curves.

In ETM, the surface is constructed with naked bricks of different shapes and sizes. The bricks are laid in each row with a stride equal to the combination of a mortar gap and a length of a quarter brick to form the interlocked squares, which are rotated horizontally to cover the surface and are translated with a half stride vertically. The pattern is emphasized by placing quarter bricks deeper than other bricks to separate the adjacent edges of square patterns from each other and create a three-dimensional visual effect (Bakırer, 1981). The long sides of the larger half bricks are laid vertically, while the short sides of the smaller half bricks are laid horizontally. Dimensions of all four types of bricks are proportional to each other, and the edges are aligned in the order of bricklaying. This surface has two different half bricks, different from the other.

The bricklaying in AGoM consists of half, and quarter bricks, which are both naked and glazed. The glazed bricks are placed horizontally, while naked bricks are placed vertically. The naked bricks were laid in each row with a stride equal to the combination of a mortar gap and a length of a quarter brick to form the pattern of squares. The glazed bricks protrude from the surface, gradually increasing from the bottom level of the arch to the keystone. These bricks surround the square patterns, enhancing the three-dimensional quality of the surface. Bakırer (1981) states that this method, frequently used in Iran, is seen in Anatolia only in samples where glazed and naked bricks are used together.

In MUM, both long and short sides of the naked half bricks are laid vertically with a stride equal to the combination of a mortar gap and a length of a quarter brick, while the glazed bricks are laid horizontally, forming a pattern of squares. The pattern is visually similar to AGoM and ETM.

The bricklaying techniques used in HUM, ETM, AGoM, and MUM involve using bricks in various shapes, sizes, and finishings combined with mortar to create distinct surface patterns (Figure 3.4). The orientation and depth of brick placement and the differentiation of brick surfaces play a role in highlighting and emphasizing these patterns. Overall, the bricklaying techniques described in this analysis demonstrate the importance of mortar spacing in achieving curvilinearity and the versatility of naked bricks in creating various visual effects on a surface.

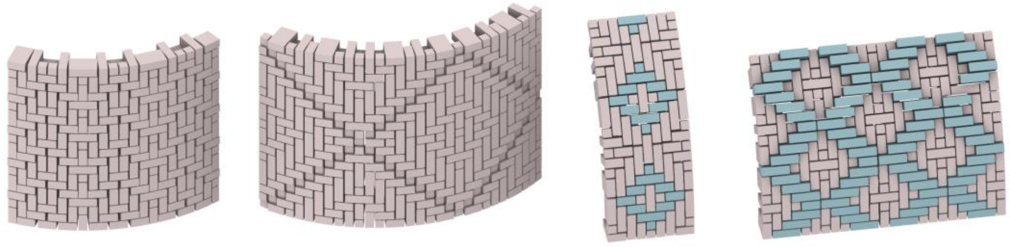

Figure 3.4 : Three-dimensional models of the single curved surfaces (From left to right: HUM, ETM, AGoM, and MUM).

3.3 Domes

The division and construction of a sphere is a research area that has been the subject of many studies of various disciplines. Latitudes and longitudes were abstract tools for the geometric calculation of brick patterns in Medieval Anatolia (Özgan & Özkar, 2020). For this thesis, the brick units and the patterns on three brick domes are analyzed using modules and proportions. The buildings are the İnce Minareli Madrasa (1258-1265), the Sahib Ata Hankah (1269-1270), and the Beyşehir Eşrefoğlu Mosque (1297-1299) from here on, abbreviated as IMM, SAH, and BEM respectively. Figure 3.5 shows that each dome is composed of both plain and glazed bricks, forming abstract patterns through the bricklaying. The domes in Anatolia are generally half spheres (Aktuğ Kolay, 1999).

There are limited studies on brick domes. One of the most researched, the herringbone bricklaying in the cupola (dome) of Santa Maria del Fiore in Florence by Brunelleschi, is often studied with a focus on its structural capacity. Pizzigoni (2015) suggests that non-traditional bricks are used for the construction of the dome, while Paris et al. (2020) and Beatini et al. (2019) analyze the structural role of the herringbone of the dome showing the constructional purpose. Cross-herringbone bricklaying can also be seen in but not extensively studied in detail for eleventh-century brick masonry domes in Iran.

Figure 3.5 : Selected domes, from left to right: İnce Minareli Madrasah (IMM), Sahip Ata Hankah (SAH), and Beyşehir Eşrefoğlu Mosque (BEM)

There are limited sources about the structure of the domes that this research focuses on. Bricks were mainly used on the upper structures in the period and the historical pictures of collapsed domes from the same period show there is an underlying brick structure. Thus, we can conclude that these domes are entirely built of bricks. However, there is no written information on whether the brick surfaces analyzed here are structural elements or ornamental veneerings. Unlike Brunelleschi's dome, the herringbone patterns of the analyzed domes are not physically continuous. The structural importance of herringbone might not be valid for these domes due to these interruptions. The continuity is visual in the case of IMM, where there are naked bricks in between the parts of spirals, and we do not have any documentation of whether the parts are connected behind the brick surface. On the other hand, the section drawings of the dome show that the lead plates surrounding the domes have breaking points that coincide with the patterns implying structural use. In SAH, spirals are independent of each other and limited in slices. The rings of nine-pointed stars formed by the intersecting spirals might be associated with the structural capacity of the dome. In BEM, the visual continuity is there, yet the angle changes. There are rings of six-pointed and twelve-pointed star-like patterns.

Data acquired through existing architecture and construction history literature, photographs, and photogrammetry-based mesh models are used to model the domes, brick by brick using modules and proportions based on a division by latitude and longitude curves, ideally with perfect symmetries. There are two types of geometric patterns applied on the non-Euclidean surfaces of domes in Islamic architecture, which are the ones repeating radial gore segments and the ones repeating polyhedra (Bonner, 2017). All domes have radial symmetries, so we divided them into slices concerning symmetry axes and accepted the slices as identical to others. The ratio of the radius of the dome base to the height is approximately 1 for IMM and 1.03 for SAH, and 0.9 for BEM. We model the domes as perfectly spherical and the bricks as perfect rectangular prisms to reduce variables since we are after a generalizable understanding of brick construction patterns.

Table 3.2 : Table of dimensions of glazed bricks and mortar spacings used in domes in centimeters.

Dome	Quarter Brick	Mortar Spacing
IMM	14-15x12x4	1.5-2
SAH	20-22x10-10.5x4-4.5	1.5-2
BEM	4x4x4	2

The dimensions of the glazed bricks used in IMM are 14-15x12x4 centimeters with 1,5-2 centimeters mortar spacing, 20-22x 10-10.5x 4-4.5 centimeters with 1,5-2 centimeters mortar spacing in SAH, and 4x4x4 centimeters with 2 centimeters mortar spacing in BEM (Table 3.2) (Aktaş Yasa, 2016). All three domes have an oculus at the center which play a part in cosmological representations along with the domes and the pools underneath them (Peker, 1998)

In each of the three domes, color-glazed bricks create patterns amidst rows of plain bricks. In IMM and SAH, the glazed bricks are placed only vertically in contrast to the horizontally laid plain bricks. In BEM, the glazed bricks are only little squares amidst plain bricks, again laid horizontally. The vertically laid glazed tiles consistently follow a unit dimension in all cases. In IMM, the height of a vertically-laid glazed brick matches the total height of three rows of plain bricks with mortar spacing. In SAH, this is two rows, and in BEM, just one. The unit dimension is the short side of a brick, and this unit dimension is also the height of a circular brick row corresponding to a hypothetical latitude. When adding up the units, the thickness of the mortar in between is also considered, and the vertical mortar thickness is taken as constant (Figure 3.6). The central angle that corresponds to the vertical arc in between two aligned corners of a brick on the dome (α) results from the height of a brick.

The product of the number of latitudes (x) and α gives the total elevation angle of the dome (δ), which determines the height of the dome (h) with radius (r) or vice versa, the height of the dome and its radius determine the elevation angle, or the number of brick rows, etc. We designate the first and last bricks of a hypothetical spiral and draw longitudes through these bricks, as shown. Then we measure the azimuth angle between the longitudes for each latitude (β). We divide β into the number of latitudes on the spiral (z) to get the azimuth angle between two unit bricks (γ), i.e., the central angle between the longitudes. The inclined curves of the pattern connect the intersections of latitudes and longitudes and the center points of the bricks. The analyzed domes are true domes rather than corbelled, and the bricks face the center (Cowan, 1977). In our model, square units with normals coincident with those of the dome join vertically for glazed bricks and horizontally for plain bricks. Since the arc length defined on the dome with the angle γ shortens towards the top of the dome and the brick size is constant, the horizontal mortar gap decreases.

$$(x \in N) \wedge (.y \in N) \Rightarrow (\delta = (a \times x)) \wedge (\beta = (z \times y)) \wedge (h = \sin(\delta) \times r) \qquad (3.2)$$

These calculations in equation (3.2) help us place the bricks and see the overall order as well as the relations and symmetries. We accepted each slice of a dome as identical to others with the same brick counts for this method.

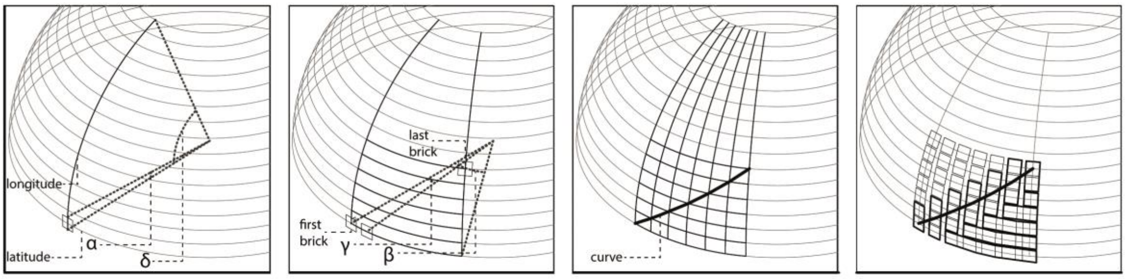

Figure 3.6 : Placement of bricks: (a) latitude calculation, (b) longitude calculation , (c) spiral calculation, (d) brick placement

In the dome of IMM, turquoise, brown-purple and navy blue glazed bricks are laid vertically, forming the pattern as shown in Figure 3.7. The diameter of the dome is 11 meters (Akok, 1070; Erdemir, 2009). The plain bricks are laid horizontally and filled between the motifs. The height of each vertical glazed brick corresponds to the combination of three rows of plain bricks and two mortar spacings in-between. The pattern repeats in nine vertical slices in an alternating fashion that is a-b-a-b-... The slices of the dome are asymmetrical in themselves. Yet the ninth slice that is different from others has mirror symmetry—the irregularity results from the odd numbers of slices without internal symmetries. The model shows that the symmetrical half of the ninth slice is almost symmetrical to the half of the slices on both sides. There are fifty-four left-handed and fifty-four right-handed spirals. Each spiral intersects with the others seventeen times, including the intersections at the topmost and the bottommost latitudes. There are sixty-four rows of horizontal plain bricks. The number of longitude curves intersecting a latitude curve; thus, the order of spirals changes at the thirty-third row from the bottom. While there are nine bricks between two intersections up to this level, there are eight bricks after, which compensate for the change in the lengths of spiral parts between intersections while keeping the lengths of the horizontal plain bricks and their numbers per row consistent with the existing situation as rows go up. It is worth noting that there is also flexibility in the design concerning the varying sizes of the horizontal plain bricks. The very thin mortar spacing between them makes the creases barely visible, rendering the use of same-size bricks trivial. This contrasts the wider and easily perceivable creases between the glazed and plain bricks. The dome has a complex pattern of whole and half squares rotated forty-five degrees, nested, translated, or interlocking.

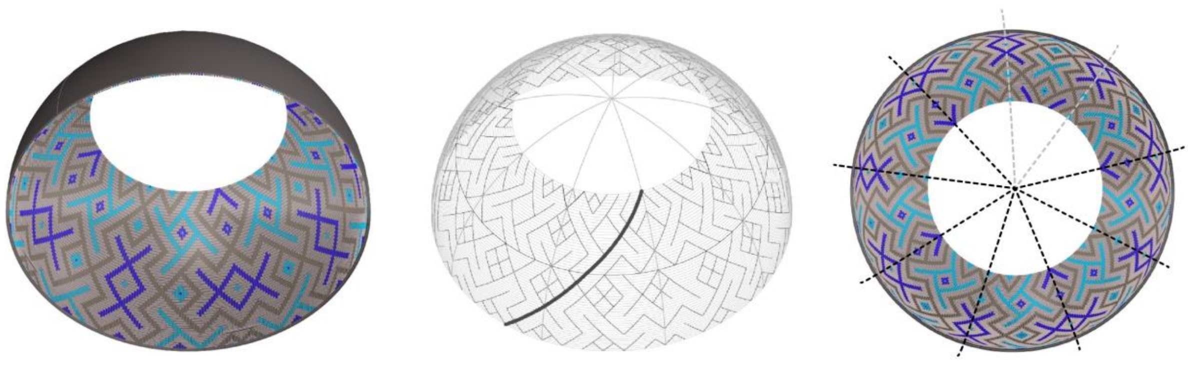

Figure 3.7 : Three dimensional model of IMM: bricks, pattern, and symmetry axes.

The dome of SAH consists of vertically laid turquoise and navy blue glazed bricks and horizontal plain bricks, shown in Figure 3.8. The diameter of the dome is 8 meters

(Akok, 1970). The height of the glazed bricks equals the sum of the height of two horizontal plain bricks and a mortar spacing. There are eighteen vertically symmetrical parts of the pattern. The spirals are not continuous between the slices. The pattern creates intertwined nine-pointed concentric stars with altering colors. For each star, nine right-handed and nine left-handed spirals intersect at two latitudes for the inner and outer corners. There are fifty-nine rows of horizontal plain bricks. The bricklaying of the domes has a simple pattern of inclined curves parallel and mirroring. The order of the spiral changes for each star, a total of nine times, as it goes up to the dome. The size and number of plain bricks vary depending on the spacing between glazed bricks. The horizontal mortar spacing between two plain bricks is smaller than the one between glazed and plain bricks.

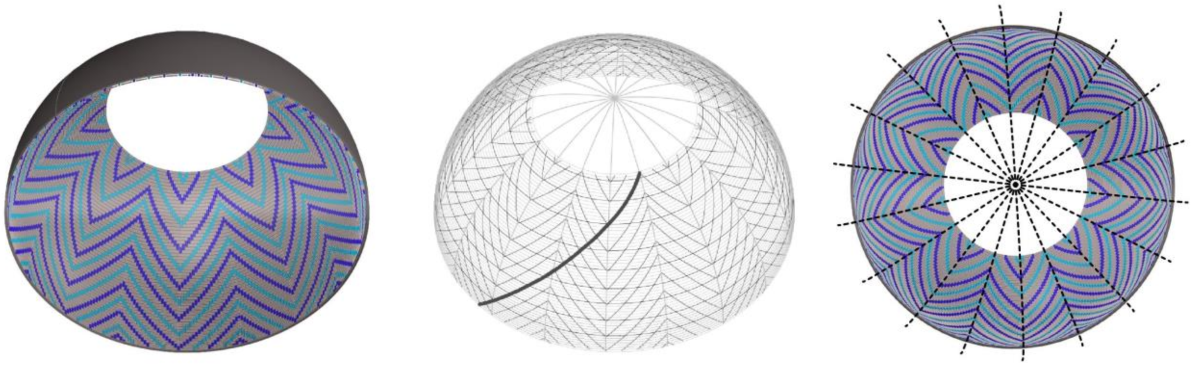

Figure 3.8 : Three dimensional model of SAH: bricks, pattern, and symmetry axes.

The dome of BEM consists of navy blue square-shaped glazed tiles and horizontally laid plain bricks, shown in Figure 3.9. The dome diameter is approximately 5.60 meters (Akok, 1976). There are forty rows of bricks. The pattern that the glazed tiles form has a twelve-fold symmetry until the twentieth row, and it switches to a six-fold symmetry from there to the top. The order of the spirals varies for different horizontal rings of the dome, and there are ten different spiral orders. The vertical mortar spacings are equal to half the height of bricks and are filled with turquoise tiles. The horizontal spacings between the plain bricks are larger on the spirals, and the navy blue glazed tiles fill these gaps. Turquoise glazed tiles also surround the navy blue glazed tiles. The horizontal mortar spacings between two plain bricks are very small and serve their perception as one long brick. The dome has a combination of inclined curves parallel and mirroring with a complex pattern of distorted squares that are rotated forty-five degrees, nested, translated, or interlocking.

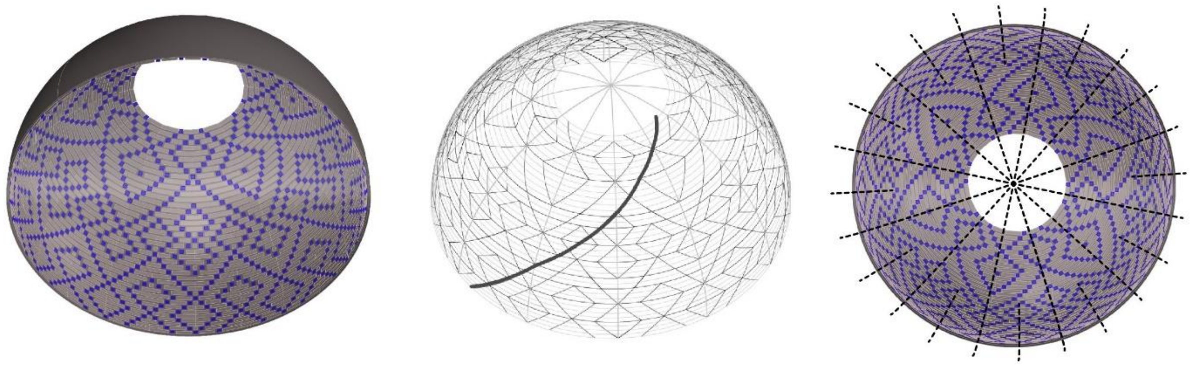

Figure 3.9 : Three dimensional model of BEM: bricks, pattern, and symmetry axes.

Further analysis of the photogrammetry-based mesh models of IMM and SAH reveals several variations and inconsistencies from the idealized models. While the proportions of the heights of naked and glazed bricks are still present, the rows of bricks do not form a continuous latitude. This may be the result of the manual labor of bricklaying, the small changes in the horizontal mortal spacing, and the deformations through time. Additionally, the vertical distance covered by a segment between intersections of spirals changes in relation to these deformations. While the bricks are placed on the segment, the difference between the total height of glazed bricks and the vertical distance they need to cover is compensated with the variations in mortar spacings. These irregularities are not easy to detect by the eye.

The intersecting spirals in the domes correspond to the inclined curves in the flat and single-curved surfaces. The patterns can be seen as parts of these spirals or the deformed equilaterals that are the projections of squares to the spherical surface.

3.4 Corniches below Minaret Balconies

Corniches below minaret balconies are a type of muqarnas, and they are architectural elements that can be constructed without using scaffolds. They provide the transition from the body of the minaret to the balcony -from circle to circle and carry the weight of the balcony. Various debates exist about the origin of muqarnas, varying from Iran, Morocco, India, Egypt, and Algeria (Ödekan, 1977). Iranian Seljuks commonly used brick and plaster to build muqarnas, yet in Anatolia, they are majorly built in stone. The brick examples are thought to be works of craftsmen from Iran. There are limited examples of brick muqarnas, which are most likely the contribution of craftsmen from Iran, which can be divided into three functional categories; brackets, cornices below minaret balconies, and hoods at the top of niches (McClary, 2014).

In the brick muqarnas of the selected cases, the horizontal rows of brick units are laid with a slide away from the center. The diameter of the corniche rows is wider than the radius of the minaret body and gets larger as the rows go up. The center of gravity of the units and the whole structure are both critical in this pattern, in which bricklaying needs to be applied with precision. The brick muqarnas are smaller architectural elements with fewer units than the walls, minaret bodies, or domes. So the customized shape and dimensions of the bricks are affordable. There are two main types of bricks with variations; minaret bricks with long tapered sides and triangular bricks with a triangular form pointing forward. The vertical and horizontal mortar spacings in case of the corniches are independent from each other.

The buildings are the Akşehir Güdük Minareli Mosque (1227), the Akşehir Ulu Mosque (1213), the Afyon Ulu Mosque (1272-1277), the Konya Sahip Ata Mosque (1277), and the Afyon Kuyulu Mosque (approximately 1250-1300) from here on, abbreviated as AGuM, AUM, AfUM, SAM, and AKM respectively.

Figure 3.10 : The photogrammetry-based mesh models of the minarets (From left to right: AGuM, AUM, AfUM, SAM, and AKM).

In the selected examples, the three-dimensional character of the pattern is emphasized with the triangular extension outward from the center of the minaret at the front ends of bricks and the rotation of the units around their centers, both making a V-shaped projection. Similar to the ones used in the minaret body, the bricks used in the corniches are tapered to enable the bricklaying and the rotations, preventing them from overlapping at the inner parts of the minaret.

The rows of bricks with the same radius and brick types repeat multiple times for many examples, enhancing the pattern. The rows of triangular bricks are numbered 1, while the rows of minaret bricks and minaret bricks rotated around their centers are numbered 0 and 2, respectively. In many examples, rows of minaret bricks follow the rows of triangular bricks with the same radius, highlighting the triangular protrusions.

Due to limited literature on the corniches, the photogrammetry-based mesh models of the minarets are used as references. We cropped the mesh models to draw the plans and sections, counted the bricks, and placed them ideally with perfect geometries. We divided the circles of the plan equally and perfectly aligned the bricks facing away from the center of the minaret. The horizontal mortar spacings are calculated based on the plans, while the vertical mortar spacings are calculated based on the sections.

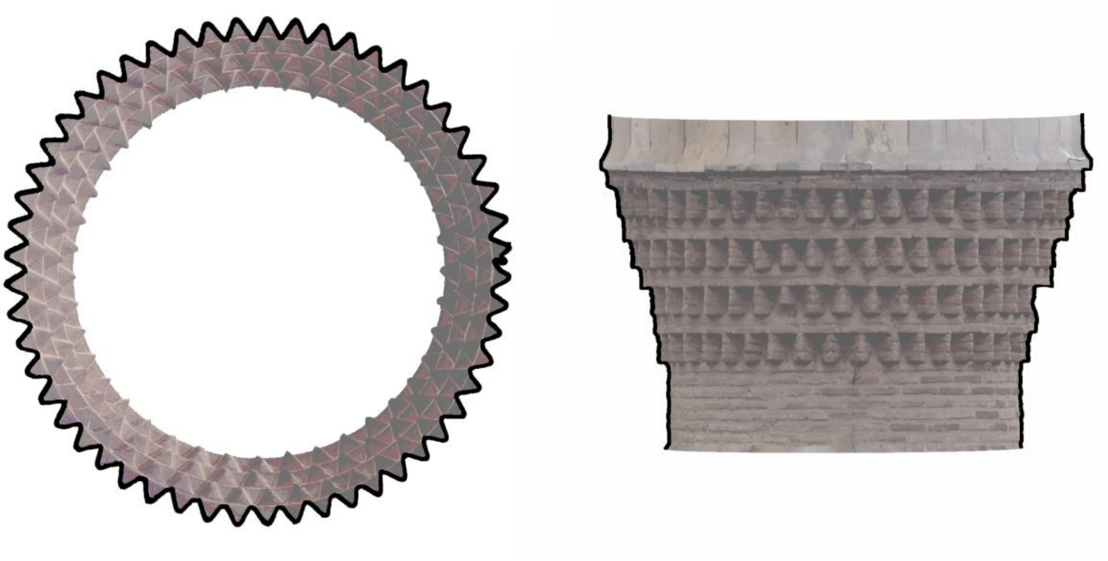

Figure 3.11 : The exterior contours of the plan and section of AGuM taken from the photogrammetry-based mesh model.

In the corniche of AGuM, three rows of overlapping triangular bricks are followed by two rows of minaret bricks repeating in twenty rows in an alternating fashion that is 111-00-111-00… Brick fronts face away from the center of the minaret in this example. The corniche of AUM, which is visually very similar to AGuM, consists of two rows of overlapping triangular bricks and a row of minaret bricks repeating in alternating fashion 11-0-11-0…

The corniche of AfUM consists of rows of bricks that are rotated thirty degrees clockwise around their centers in the same direction. There are twelve rows of bricks in four groups of repeating bricklaying, and each group has three rows of the same bricklaying. The count of bricks in every row is equal, and the angle between two adjacent bricks is constant. Groups are rotated half of this angle around the center of the minaret going up, resulting in a half stride. So, the brick groups have similar layouts in an alternating fashion 222-222... other than the translation away from the center. Due to the rotational layout, the axes extending from the brick center to the center of the minaret overlap in the first and third rows and the second and fourth rows, and horizontal mortar spacing gets larger as the bricklaying goes up with the increased radius.

The corniche of SAM consists of rows of bricks that rotate around their centers both clockwise and anticlockwise in different rows. The brick rows can be grouped into three with rows of minaret bricks as transition groups. In the first group of rows, the triangular bricks and the minaret bricks are used alternatingly in the same row, differently from the other examples. The minaret bricks are translated away from the center at the second row of the group, enhancing the three-dimensional quality of the bricklaying. The transition in the third row is the only example that breaks the repetition of the same rows twice or three times in selected cases. The other two pattern groups, separated by minaret bricks, consist of bricks that rotate clockwise (+) and counterclockwise (-) around their centers, respectively. These rows of bricks follow the order 0/1-0/1-0-22(+)-000-22(-). The width of the minaret bricks is almost half of the previous cases in the rows with rotations, resulting in an increase in the number of bricks in a row and extrusions.

In the corniche of AKM, the brick pattern changes between each row. This example has the most complex bricklaying, distinctive pattern, and unique brick types. Triangular bricks divided from the center through the front and back surfaces create a three-dimensional pattern. The corniche has a twelve-fold symmetry which creates a potential to analyze it in slices like the domes.

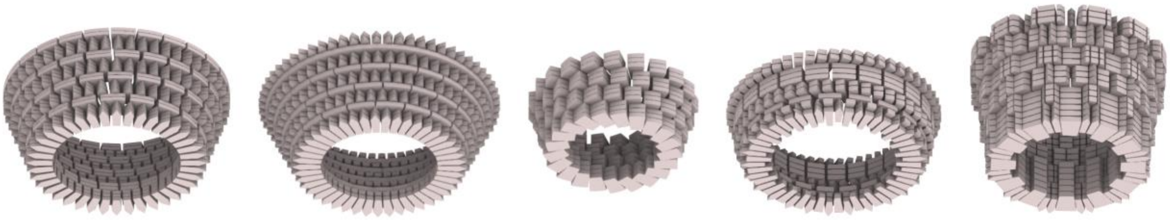

Figure 3.12 : Three dimensional models of the corniches (From left to right: AGuM, AUM, AfUM, SAM, and AKM).

Cornices below minaret balconies of bricks are primarily constructed using minaret bricks and triangular bricks. These bricks are rotated around their centers to create a three-dimensional pattern that helps transition from the minaret's body to the balcony. The selected examples of brick muqarnas in AGuM, AfUM, SAM, and AKM demonstrate the versatility of this technique, with variations in the orientation and arrangement of the bricks used to create unique visual effects. Overall, brick muqarnas serve as essential decorative and structural elements in these buildings and showcase the skilled craftsmanship of the makers.

4. THE GENERATIVE SYSTEM FOR HISTORICAL BRICK SURFACES

The information gathered through analysis is utilized to develop generative system for producing the brick surfaces used for robotic fabrication (Figure 4.1). The development of the generative system consists of two steps; the definition of the parameters and the rules of bricklaying. The bricklaying parameters are divided into three groups for all surfaces. These are the parameters of individual bricks, the relation between two bricks, and the pattern. Based on the spatial and constructional relations identified with the parameters, shape rules are defined either as pattern or brick rules. These rules respectively correspond to the design and construction of historic structures. The sequential application of sets of pattern and brick rules simulates the reconstruction of existing and novel brickworks in the said genre to serve the purpose of integrating cultural-historical knowledge and the making from a computational approach.

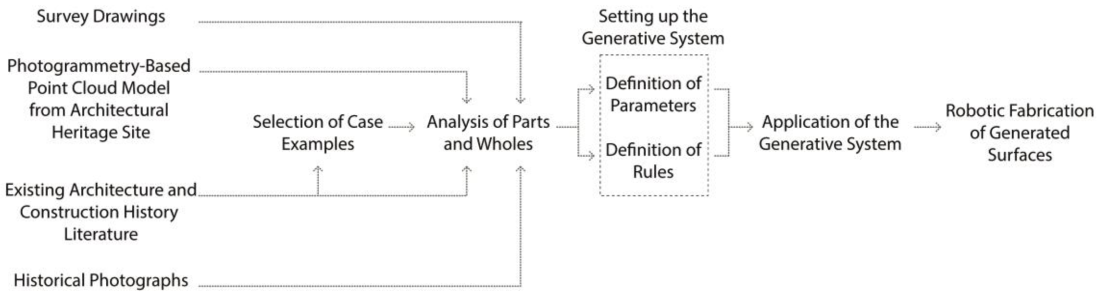

Figure 4.1 : Workflow of the method.

This chapter comprises developed versions of previous research (Altun & Özkar, 2021; Altun & Özkar, 2022), and the development of both parameters and rules are developed by examining the transformations of the bricklaying and patterns on flat panels to be applied to surfaces with different curvatures. The similarities and differences of patterns, regarding both design and making with historical tools and methods, are discussed.

4.1 Setting up the Generative System

The synthesis phase comprises the definition of the parameters of bricklaying and the sequential and spatial procedures followed in the manual building of brickworks of the era. Studying historical photographs, photogrammetry-based models, and survey drawings, we identify the parameters of historical bricklaying in Anatolia and define the smallest number of spatial relations between bricks required for recreating the brickworks.

4.1.1 Parameters of brick

The parameters of the bricks are related to the shape and size of the bricks. The typical dimensions for the brick types in the cases of single curved surfaces and domes studied are the determinants of these parameters: the width, height, and depth for whole, half, and quarter bricks. The width of a whole brick is equal to the width of a half brick, but while the whole brick is a low square prism with equal depth, the half brick is a smaller rectangular prism. In the horizontal position, the total height of three bricks on top of each other and the mortars between them, likewise, the total of a short side of the one half brick and the height of one brick with the mortar between them is equal to the long side of one whole brick or a half brick. The depth of a half brick equals the total height of two bricks lying on top of each other in the horizontal position and the mortar between them. In comparison, the quarter brick is a much smaller cube with dimensions equal to the heights of the whole and half bricks. Half bricks with different orientations and quarter bricks are used in most vertical-horizontal bonds.

The bricks for the corniches under the balconies of the minarets have additional parameters that differentiate them from these rectangular prism-shaped ones (Figure 4.2). The additional parameters for the curved minaret bricks are the radius of the curve (r) and the proportion of cut parts on the back surface to the depth of the brick (d1/d, d2/d). Similarly, the parameters for triangular bricks are the proportion of cut parts on the back surface to the depth of the brick (d1/d, d2/d) and the angle of the isosceles triangular front end or the proportion of cut parts on the back of the surface to width (w2/w). The cut parts are not necessarily symmetrical and identical to each other, considering the cutting is done with manual tools by hand, thus d1 and d2 can potentially have different values. The shape and dimensions of bricks in corniches are independent of the mortar spacings, but are related to the radius of the minaret.

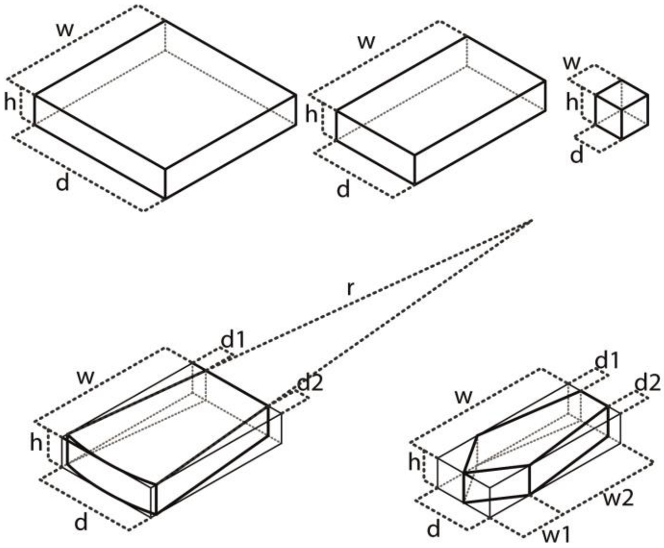

Figure 4.2 : Shape and dimension parameters of brick.

The secondary parameters of bricks are the surface finishings (Figure 4.3). The bricks are labeled with letters to identify the naked bricks (a), turquoise-colored glazed bricks (b), brown-colored glazed bricks (c), and purple-colored glazed bricks (d). The labels indicate not only surface finishings but also the direction of bricklaying through the use of numbering of the front edges of the front surface of bricks. Labels are also used to identify minaret bricks (e) and triangular bricks (f) to make the definition and application of the rules easier.

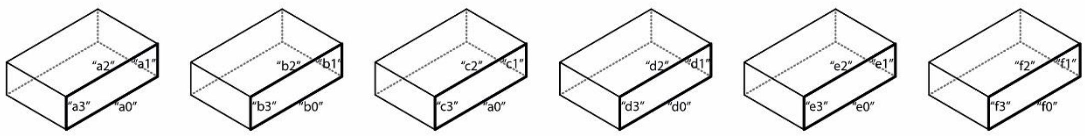

Figure 4.3 : Labels at the edges of the front face of the brick indicating surface finishings of rectangular bricks and brick types for minaret bricks.

In most cases of vertical-horizontal brick bonds, such as the panel from Sırçalı Madrasah (Altun & Özkar, 2021) and the case surfaces in this thesis, visually, there are three different brick dimensions. However, two are half bricks with different orientations, and the other is a quarter brick. Generally, the long side of the half bricks is used horizontally, while the short side is used vertically. The short sides of the front-facing half bricks are generally glazed in different colors (turquoise, navy blue, and purple-brown) to emphasize the pattern, while the long sides can be both glazed or naked. The quarter bricks define the corners and rotation centers of the square-based patterns and can be glazed or naked. Another method that is used by craftsment to emphasize the pattern is the shift in alignments of the front surfaces of bricks.

4.1.2 Parameters of spatial relations between bricks

The parameters of the relations between bricks are crucial for defining the three-dimensional spatial relations between two consecutive bricks. There are many possible relations between the half bricks of different orientations and the quarter bricks. The position of the bricks, the stride, and the mortar spacings are the parameters of the brick relations. In a vertical-horizontal bond, the stride is generally constant and equals a horizontal dimension of a brick and a vertical mortar spacing (Bakırer, 1981). Based on the proportion of the height of the brick to the long side of a brick, the vertical mortal spacing is 1/3, 1/4, or 1/5 rising.

The vertical and horizontal mortar spacings are not interdependent in the horizontal bond. There are examples of various combinations in existing historical brickworks with combinations of wide and narrow mortar spacings in different directions. On the other hand, in vertical-horizontal bonds, the mortar spacings are constant as distance or angle in each direction for flat and spherical surfaces respectively. The equality of mortar spacings is visual in the single-curved surfaces where vertical and horizontal spacings are not required to be equal yet still dependent on each other and the radius of the surface..

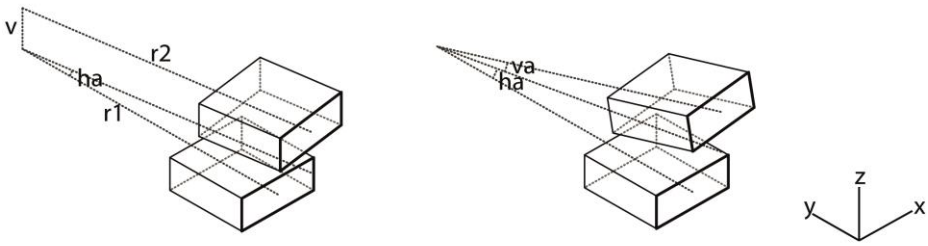

Figure 4.4 : Parameters of spatial relations between the bricks for single-curved surfaces and corniches; and spherical surfaces.

Figure 4.4 shows the difference between the calculation of vertical and horizontal mortar spacings and parameters of spatial relations between bricks on different surfaces. In single-curved surfaces, horizontal mortar spacing equals angle (ha), while vertical mortar spacing is a direction vector. The height difference between two vertically adjacent bricks (v) is the combination of a brick height with vertical mortar spacing. The only difference between single-curved surfaces and corniches is between the radius of rows of bricks (r-r2). Corbelled domes have the same relation as corniches. Both mortar spacings are expressed with angles (va-ha) and equal to each other in true domes on spherical surfaces.

4.1.3 Parameters of pattern

What we refer to as the pattern units in the scope of this analysis in the complex bricklaying examples cases of flat, single-curved, and spherical surfaces are the squares and rhombuses rotated forty-five degrees, nested, translated, or interlocking, emerging from the relation of the intersecting inclined lines parallel to or mirroring each other. In both horizontal and vertical-horizontal brick bonds, the rising of vertical mortar spacings defines intersecting inclined lines parallel to or mirroring each other. The inclination is related to the stride of bricklaying, and the distance between the lines is related to the dimensions of the bricks. For the simpler bricklaying patterns, the unit of the patterns is inclined curves parallel and mirroring each other. The stride is strictly related to the brick dimensions in the complex vertical-horizontal bond examples, and thus the inclination is constant and alike for different examples.

In complex patterns, their intersections define the square pattern units. The squares are distorted with the curvature of the surface. In single curved surfaces, the distortion is in one direction and visually not very disruptive, while in domes and narrows at the top due to the scaling down of horizontal rows of bricks to define the surface curve, which is compensated through the change of brick count on the curves. The distortion of the squares and curves does not visibly change the overall effect of the bricklaying but adapts the geometrical order of design to the curvature of the surface.

Pattern parameters are closely related to brick parameters since the patterns consist of multiple bricks laid together to define a whole (Figure 4.5). The placement of the squares depends on units of the bricklaying. The offset distance between horizontally aligned corners of nested squares (p2) or the stride between two squares (p4) equals the width or the depth of a half brick, depending on the bricklaying pattern.

The pattern units are more ambiguous for the corniches below the minarets than for the other surfaces. The rows of bricks and the circular boundry they define in the plan are the units of the pattern repeating at different levels with changing the number of brick units and different brick types (Figure 4.5). The parameters of the pattern units are the radius of the rows and the vertical distance between them as well as the types of bricks. The vertical distance is equals the height of one brick and a vertical mortar gap. The vertical difference between the rows is flexible as horizontal and vertical mortar gaps are not dependent on each other, and increasing the horizontal mortar spaces creates steeper surfaces. Labels express the type of brick used to lay the circular rows; minaret brick (m0), triangular brick (m1), and rotated minaret brick rotated around its center (m2), respectively. Another parameter is the radius of the circle, which gets larger going up and effect the structural performance of the architectural element.

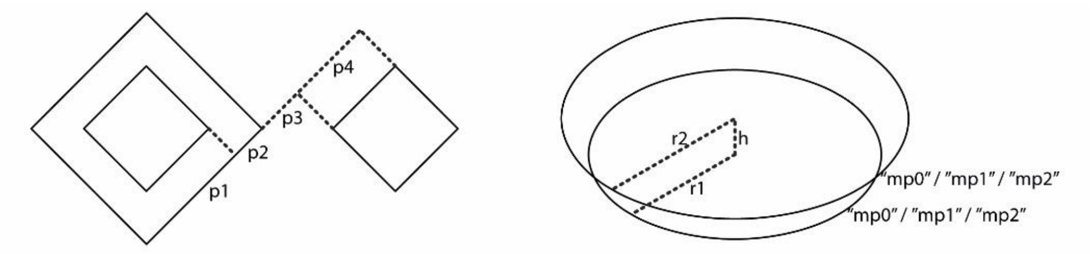

Figure 4.5 : Parameters of pattern.

These are only some of the pattern systems perceivable on the brickworks. However, they are general enough to match the shapes that horizontal and vertical-horizontal brick lays used to achieve brickworks in this genre. The pattern units in domes and some corniches which resemble brick muqarnas, such as AKM, can also be perceived as slices of a circular form.

4.2 Bricklaying Rules

Bricklaying rules are the least number of rules required for the recreation of the analyzed surfaces. There are two types of bricklaying rules namely, the brick rules and the pattern rules. Brick rules define the three-dimensional relation between two adjacent bricks and the shapes and dimensions of the bricks through the use of parameters. Pattern rules define the geometrical order of the emerging pattern due to bricklaying.

4.2.1 Brick rules

In flat surfaces and domes, there are twelve spatial relations between any two bricks (Figure 4.6), while bricks come together in the order of laying. In the single-curves surfaces, the visual effect of the relations are the same, yet the count of the spatial relations is doubled due to surface characteristic.

For each brick relation, there are two possible reciprocal shape rules except the first three, which are spatially symmetric. The rules are named based on the relation they define and the order of the bricks added to the right-hand side. For instance, Rule 4.1 and Rule 4.2 represent two alternatives to achieve Relation 4. In rules, we use labels to indicate the front-facing borders of the bricks to indicate their type and colors, which are used to define the parameters used to calculate dimensions and distances between bricks. For different interpreters, the labels are associated with tags or types.

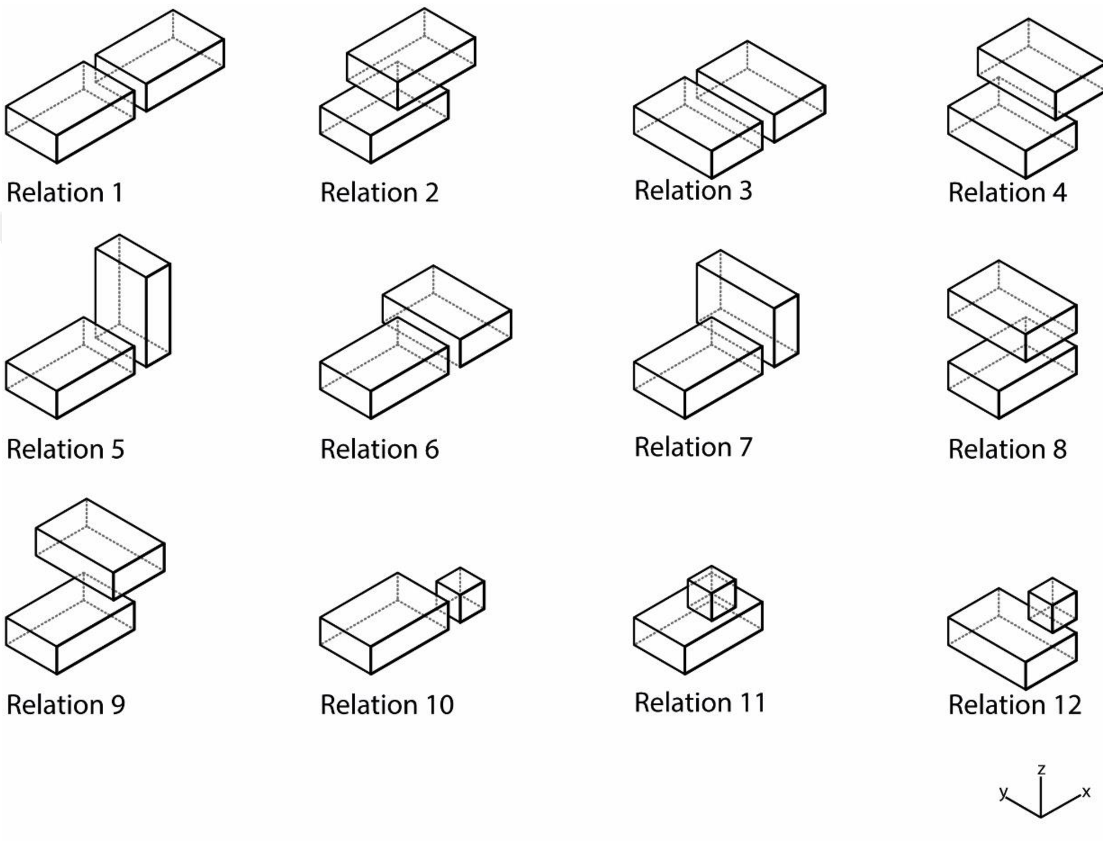

Figure 4.6 : Spatial relations between individual bricks. Adapted from (Altun & Özkar, 2022).

The first four rules define the relation of bricks placed with the same orientation regarding their front-facing surfaces and are the most commonly used ones. They show the addition of bricks in a row and the laying of additional rows with a stride. The second and fourth rules also show the definition of the borders of square pattern units. Horizontal bonds of whole bricks without quarter bricks can be reconstructed with the first two rules or the third and fourth rules. In the fifth rule, the long faces of the bricks face to the front or the center of the surface, but one is rotated around the plane the brick sits on. The following four rules include bricks laid in different orientations regarding their front-facing surfaces. Rules 10, 11, and 12 are for relationships between quarter and larger bricks.

The difference between the brick rules for flat and spherical surfaces is the definition of distance and direction. The directions are defined with X, Y, and Z axes in flat surfaces, corresponding the width, depth, and height of a brick, and the distances are numerical values of vectors in that direction. On spherical surfaces, directions and distances are defined with angles between the bricks placed tangentially to the spherical surface. These are the horizontal angle (ha) in XY plane and the vertical angle (va) in the YZ plane. These relations in spherical surfaces and flat surfaces do not require variations based on the order of the left-hand brick and the brick added on the right-hand side since both cases would be the same with euclidean transformations. The symmetry is disturbed in cases of single curved surfaces where the three-dimensional relation between two adjacent bricks in the same row is different from the ones in adjacent rows. The number of rules doubles up by describing the visually similar relationship with vectors and angles.

We specify the color of the bricks with the letters a, b, and c in labels which correspond to naked brick, turquoise colored glazed brick, and navy blue colored glazed brick, respectively. The rules can be applied for bricks of the same color or for transition, in which case the color of the brick on the left is the same as the newly added brick on the right. They can also be used for the transition between bricks of different colors. The labels of bricks are constant and do not change during application.

Similarly the special types of bricks in corniches below minarets balconies are specified with letters e and f which correspond to minaret brick and triangular brick respectively. The bricklaying of the corniches could be reconstructed with the first two relations with reference to the parameters that determine the dimensions of the rectangular prism framing the bricks and the related labels, but there are three additional rules (Figure 4.7). First two special rule for the corniches below minaret balconies transform the bricks into the cut brick. The thirteenth rule is only applied to minaret bricks (e) for the rows of bricks rotated around their centers. For the bricks that are cut half such as the ones in AKM, we use subletters.

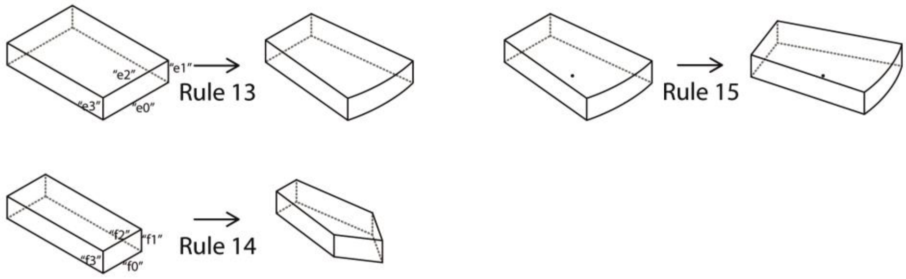

Figure 4.7 : Special rules for corniches below minaret balconies.

The parameters that express the directions and distances between the front-facing borders of bricks define the brick dimensions, shapes, subtle shifts in the placement of bricks in Y direction due to craftsmanship or the change of radius between rows in corniches, and mortar spacings for both directions.

Labels are used to formalize the relations and parametrically restrict the distances and angles between labeled curves for application of the rules. The labels are not removed after the application of a rule since the same brick could be the left hand shape for two different applications. After the creation of brickworks with shape rules, the curves can be used to transform the model into robotic fabrication codes, converting the rules into making rules.

To formalize material transformation in making with a brick and mortar, the settlement of bricks in the mortar can be represented with a post processing brick rule showing three-dimensional rotation of prisms representing bricks around their centers. This rule would require a change in the labels to select and rotate the bricks without a direction restriction.

4.2.2 Pattern rules

In brick surface designs where the bricklaying is a horizontal bond or a vertical-horizontal bond, glazed bricks are utilized to overlay additional layers of patterning. The groups of glazed bricks form certain shapes, i.e., rotated squarish ones, and the geometrical arrangement of these shapes forms a pattern, i.e., one with interlocking rotated squares. The complex brickworks of horizontal and horizontal-horizontal bonds are fundamentally based on inclined lines and an arrangement of squares. There are interlocking squares of different sizes for each brickwork. The arrangement of squares in the surfaces can be repeated with three rules (Figure 4.8).

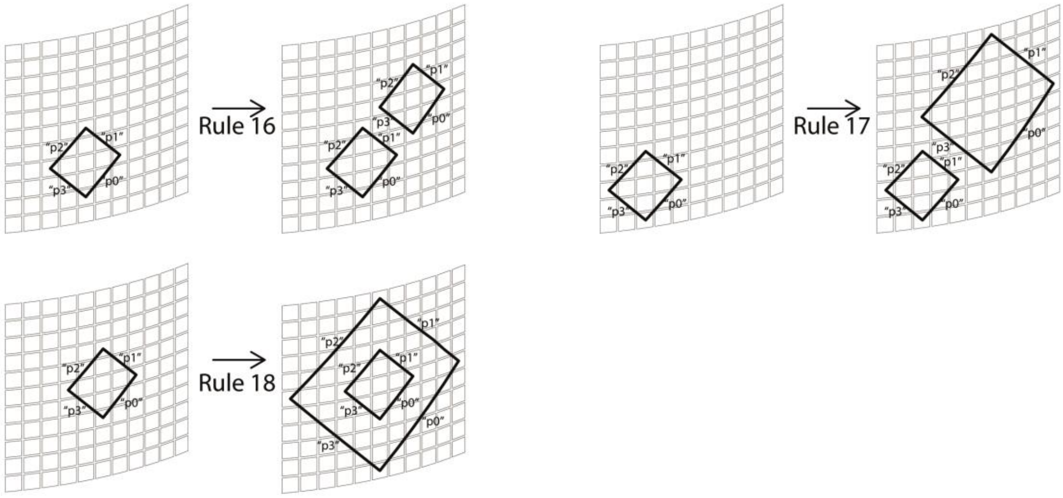

Figure 4.8 : Pattern rules for single-curved and spherical surfaces. Adapted from (Altun & Özkar, 2022).

The modular approach is utilized to project squares of the pattern onto the curved surfaces. The borders of the squares are the curves connecting the centers of the modules, and the bricks are the modules or the vertical or horizontal combination of the modules. The relationship of the inner squares defines the overall arrangement of the model as well as the intersections between the other squares.

The first pattern rule shows the translation of the same-sized squares, while the second shows the relation between two different-sized squares. These two rules can be used to set up the layout. The third rule is for the placement of nested squares. The distance between the squares is directly related to the dimension, count, and orientation of the bricks that fill them as well as the mortar spacings.

Squares and the areas between nested squares are filled with different bricklaying rules (Figure 4.9). For all pattern rules, the format on the left side of the rule is the same, regardless of the size. The right size of the rules shows the vertical placement of bricks, which can be rotated for horizontal placement in flat or spherical surfaces.

The number of pattern rules is doubled in the case of single-curved surfaces, in which the vertical or horizontal alignment of the bricks in pattern-filling rules is essential. With the rule set, the bricklaying and pattern on different surfaces can be produced in relation to one another, while the squares that form the basis of the geometric layout of the brickwork turn into a bricklaying pattern with the brick rules.

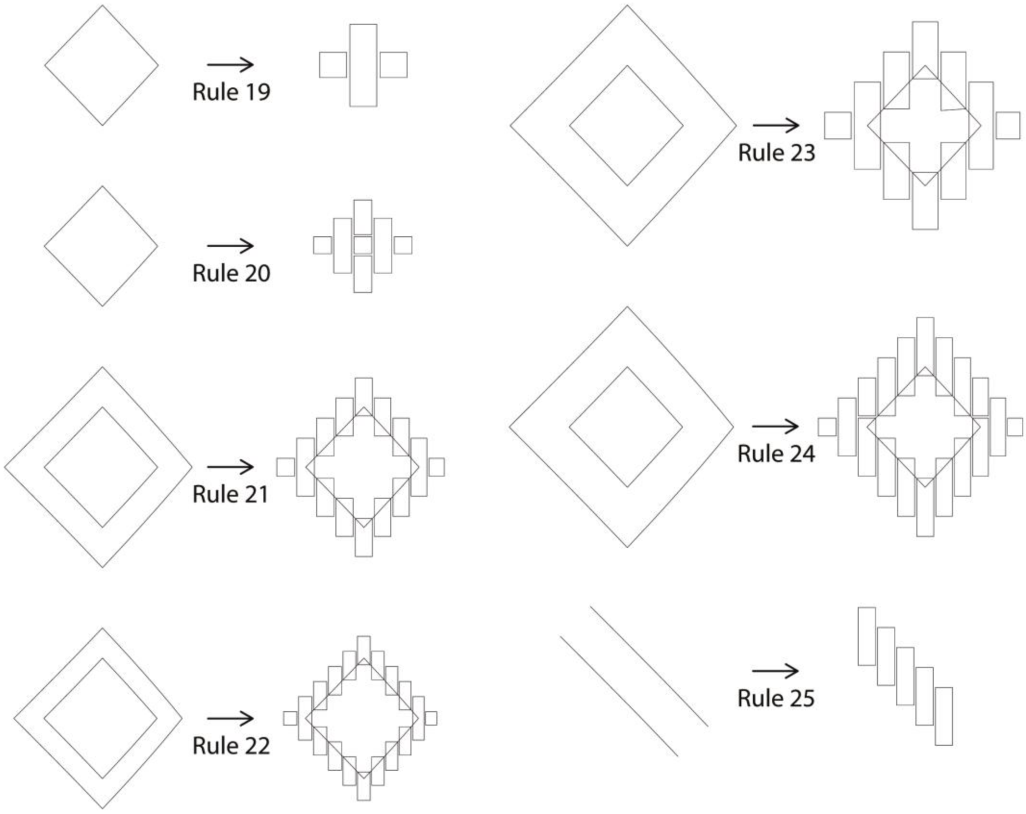

Figure 4.9 : Pattern filling rules. Adapted from (Altun & Özkar, 2022).

The pattern rules for the corniches below minaret balconies are related to the coming together rows of bricks aligned from the center with varying radii and brick types (Figure 4.10). Three different pattern units are repeated in rows of bricks. The first one is the stellate plan that emerges with the laying of triangular bricks (mp1). The second one is the circular pattern of horizontally laid minaret bricks facing away from the center of the minaret (mp0). Finally, the third is the windmill pattern of minaret bricks rotated around their centers (mp2). The pattern units in corniches usually repeat two or three times without a change in parameters to make the pattern easy to grasp from the perspective of a human from the ground.

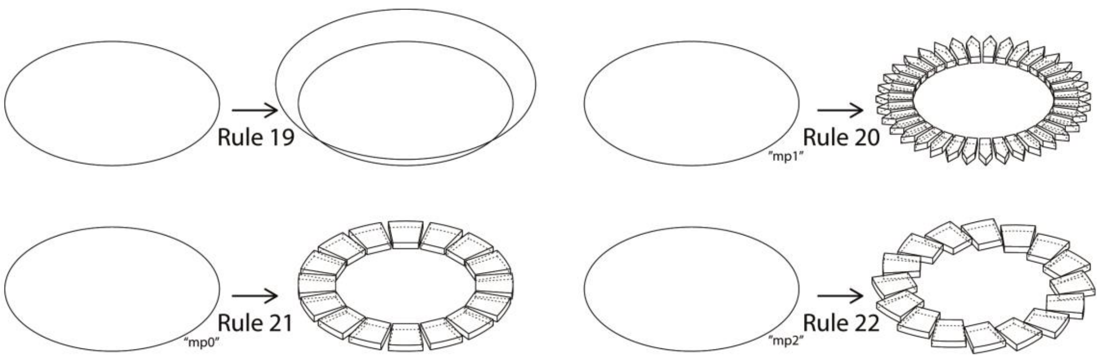

Figure 4.10 : Pattern rules for the corniches below minaret balconies.

The sequence of pattern units in corniches can be repeated using Rule 19. The radius of the circle left-hand side and the radius of the circle added on the right-hand side can be equal or different. Generally, after rows of triangular bricks or rotated minaret bricks, at least a row of minaret bricks is used as a transition. The circles that make up the geometrical order of the corniches turn into patterns with the brick rules. The number of bricks to be placed in each circle is calculated in the parametric model using the radius of the circle, the brick dimensions, and the horizontal mortar gap. The balcony of Afyon Kuyulu Mosque is an exception to this rule set. Unlike other examples, this brickwork has rotational symmetry similar to the domes; the pattern unit can be considered a slice of a conical surface. In order to examine this pattern in detail, it may be considered to increase the samples in future studies.

For validating the grammar on designs of the same genre, we apply the parametric rules to recreate selected existing brick surfaces from the same period and geography. We have reconstructed simple vertical-horizontal brick bonds from the period implementing brick rules which are HUM and SAH; and more complex patterns with both brick and pattern rules. For the latter, we also have recreated brick bonds from the ETM, AGoM, MUM, IMM, and BEM.

4.3 Application of the Generative System

We use Sortal GI and Wasp to test and validate the syntactic accuracy of the grammars. We defined the bricks with the borders in Sortal GI and labeled the front-facing borders, and used tags related to these labels. The tags enabled us to define distance and angle directives to set specific constraints. The labels indicate the different edges of the bricks and the define type of the bricks with their colors or shapes.

We used Wasp in the Grasshopper environment for the parametric implementation of the rules. We defined the relationships that enable the bricks to come together parametrically and form surfaces with different curvatures. For this purpose, the parameters of bricks and the parameters of the relation between bricks were used. In Wasp, the surfaces of the geometries must be in contact, so each brick is defined with a geometry including mortar gaps. The exact geometries of bricks are defined as attributes that reveal the bricks after units come together. We used the connection from the direction component while defining the parameters of relations between the bricks and determined the points and direction of the junctions. As in the brick definition in the rules, front-facing surfaces are used as references.

Even if the brick unit is the same, bricks with different orientations in the XY plane are defined separately to prevent undesirable combinations when used with different orientations, as the use of labels indicates in the rules. Similarly, since the side and top/bottom connections of the bricks are different on single curved surfaces, bricks with varying orientations in the XZ plane had to be defined separately. Connection surfaces are divided with type input as side connections and bottom/top connections.

We used Graph-Grammar Aggregation to enable the sequential application of the rules. Each unit is given a name in this laying method, and the two units are brought together by specifying the number of points they connect to. Separation of the connection surfaces by type creates confusion in the numbers; thus, type inputs are not used in this method as the manual selection is made among the possible results of the application of rules. This method defines sequentially combined brick units as pattern groups by obtaining geometry and connection points information via the deconstruct part component. Thus, we can apply the pattern rules. To set the parameter values, we refer to the existing literature.

The brick surfaces generated through the application of rule sets via the tools mentioned above are used as inputs for robotic fabrication. In order to create models for production without the use of adhesives, the vertical mortar gap parameter is set to zero, horizontal gaps are enlarged to enable the fabrication of scaled models, and the planes on the upper surfaces of the geometry representing the bricks are defined in the Grasshopper model. These planes are aligned with the plane defined at the center of the bore of the gripper, creating production codes.

5. THE MAKING OF BRICK SURFACES WITH A ROBOTIC ARM

Robotic fabrication is the process of using robots to build architectural elements. For automatic bricklaying, a robotic arm is necessary to lay the bricks to construct a surface with specialized gripping equipment as an end-effector to pick up individual bricks and place them in a specific pattern or design. This common task is called pick and place. The toolpath for the robotic fabrication is programmed with the desired layout using G-code, a standardized numerical control programming language that tells the robot arm where to move and what actions to perform. Using G-code the robot arm is able to lay the bricks automatically, potentially completing the task more quickly and accurately than a human worker.

The G-code commands are typically generated by Computer-Aided Manufacturing (CAM) software that automates and optimizes the manufacturing process by generating instructions for machine tools based on digital models. These tools provide simulations of the process, enabling the designer/maker to quickly and easily test different design configurations and make changes as needed. In this study, a KUKA KRC2 robotic arm with 6-axis is used to fabricate the reconstructed surfaces of selected cases to test whether the generative rule system for the bricks informs actual production processes as well. To define a complete and integrated workflow with a holistic understanding of the bricklaying of the period, we used the KUKA PRC programming language developed by KUKA in Grasshopper in Rhinoceros.

A pneumatic parallel gripper with a 15 cm open and 11 cm closed bore size is used as an end effector. The bore size is reduced with 3D-printed extensions, and soft materials that are easily compressed are placed at both sides of the inside surfaces to prevent the gripper from crushing triangular ends of bricks made of XPS. Since the thickness of the gripper ends are greater than the mortar gaps between the bricks, the bricks were held from their front and back surfaces and placed according to this axis (Figure 5.1). For HUM, to pick bricks of different sizes, soft materials with different thicknesses are used during bricklaying.

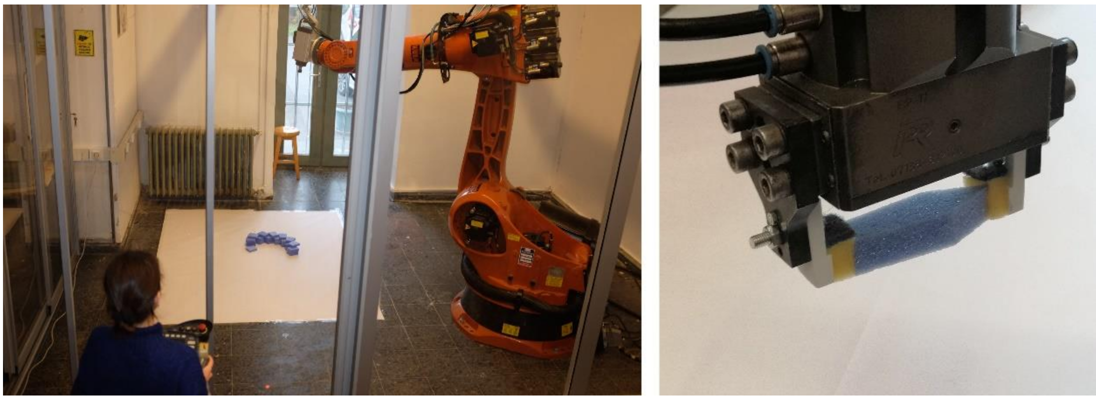

Figure 5.1 : Working space for robotic fabrication and the gripping of the bricks.

The generative process outputs that use the rules of developed grammar are scaled, moved to the working space of the robotic arm in the Grasshopper, and directly connected as inputs to generate the toolpath as 3D polygons. The planes for gripping the bricks are placed at the center of a line connecting the front and back of the brick geometries at the top surfaces. These planes are aligned with the gripper plane, which is placed in the middle of a line connecting the centers of the fingers of the gripper. Thus, there is no need to alternate the definition for the pick locations of the bricks with different shapes but the same depth, especially in corniches. The movements between the origin point of bricks in pick and place locations are created with "linear movement" between the planes placed in these points. To eliminate possible collisions between the already laid bricks and the robotic arm, we defined the movements as “hover over the brick to be picked, go down, pick up the brick, go up, hover over the coordinate where the brick will be dropped, go down, drop the brick, go up, and repeat” as shown in Figure 5.2 with the toolpath curve. The lists of the linear movements and the digital outputs for the gripper are divided, merged, and weaved with the use of Grasshopper components. The digital outputs of the pneumatic gripper involve two commands for an action. To open a closed gripper, first, the boolean value of a closed valve is turned to false, and then the open valve is turned to true. We divided the list into two as pick and place lists and weaved them separately with gripper open and close commands. Then these two lists are weaved together. The initial and final movement is different from others since it involves the home position of the robot, and they are handled separately. Finally, these commands are merged with other commands.

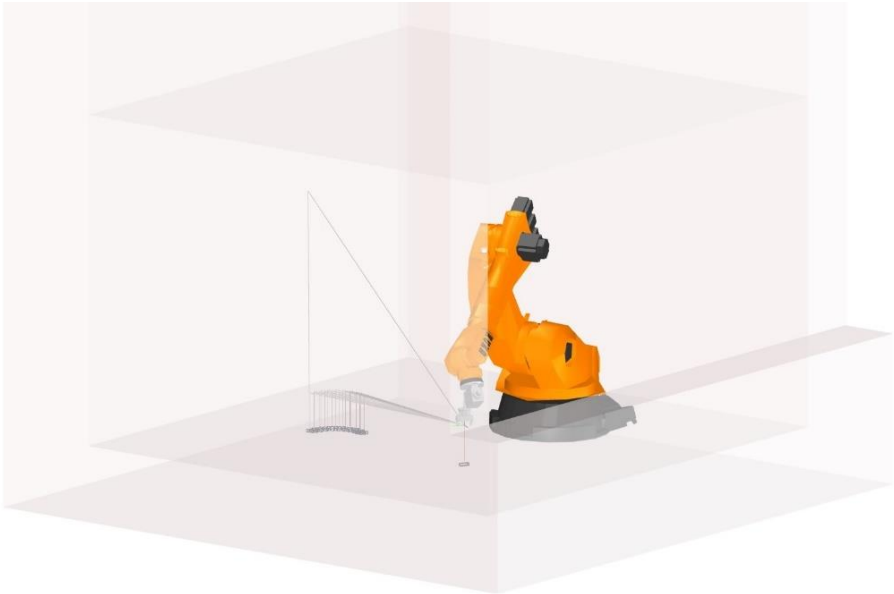

Figure 5.2 : Simulation of toolpath with curves and the working space in KUKA PRC.

One limitation of robotic fabrication is the restricted working space around the robot. The scales of the partial models are determined as 1:2 for HUM shown in Figure 5.3 and 1:5 for corniches (AGuM, AUM, AfUM, and SAM) to enable production and have sufficient space to move and operate inside the confined space of the safety cage. Considering the mortar gaps become very small when working with scaled models, minor deformations on the brick surface or small shifts in the placement cause friction between bricks and disruption of the order. We ensured that the mortar gaps were more than 3 mm to prevent friction.

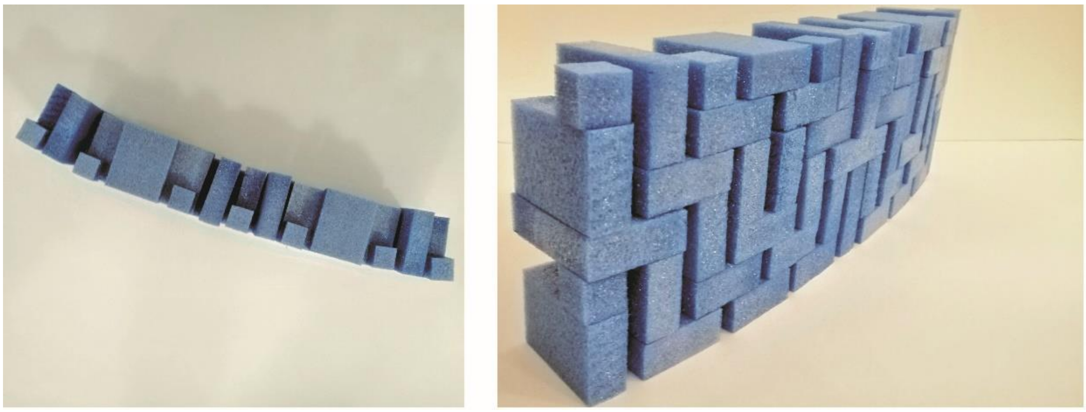

Figure 5.3 : Results of robotic production (HUM).

Separate production codes were created for each row of bricks, taking into account the limit of the number of lines of code that the existing robot arm can run at once and the control of the production stages (Figure 5.4). Even though the pick and place tasks would potentially mimic the movements of a maker, the making parameters are different from the manual bricklaying process. For example, the displacements of bricks due to friction, air flows, or gravity would be corrected immediately by the maker in analog bricklaying. Robotic fabrication requires human intervention to remove the disruptions and repeat the process.

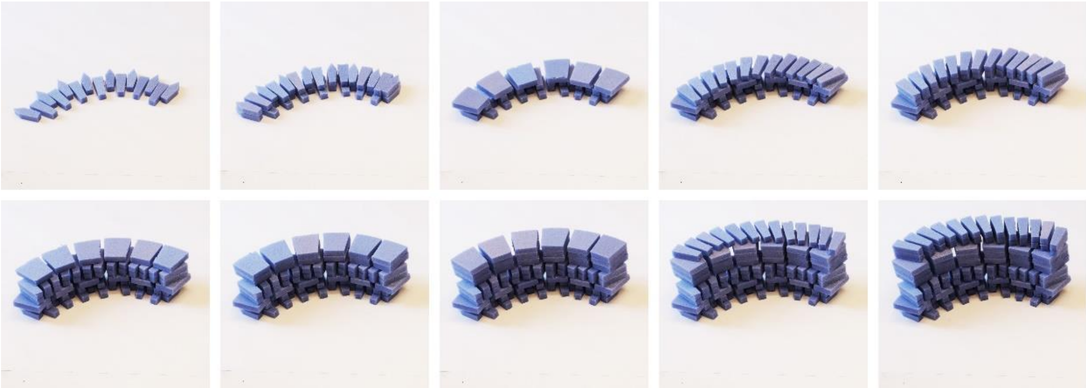

Figure 5.4 : Laying the rows of bricks for the case of SAC.

Another limitation is the selection of materials for the bricks. Expanded Polystyrene, XPS, is used in this study to produce bricks due to financial limitations and the workability and ease of cut of the material. It is a very lightweight material that the slightest impact would displace, limiting the range of applications and precision of surfaces that can be produced using robotic fabrication. To produce the bricks, we used stencils that are 3D-printed based on the generative model and hot wire cutter to cut the material. Adhesives or mortar are not used in the fabrication, and the surfaces are laid with the dry-stacking method, enabling the re-use of the material for different experiments. The vertical mortar spacing parameter is adjusted as zero to generate the models for robotic fabrication. The lack of mortar spacing resulted in the change of proportions in the bricklaying. We also carefully adjusted the speed of the robot not to cause air flows that would affect the fabrication.

Due to stability issues, the dry-stacking application of surfaces with numerous quarter bricks is not rational. With the scaled models, the intersecting surface between bricks is reduced, and the small deformations on the surface become critical. Similarly, the surface collapses when the loads cannot be transferred due to the inclination of the surface in corniches; the design is revised with the change of parameters. The density of brick material and the use of adhesives are effective in the static stability of the surfaces. Generated surfaces could be simulated, and the optimum inclination could be calculated with the help of digital design tools, such as Kangaroo Physics, in the Grasshopper environment integrating the material properties into the model.

The placement of the bricks at the exact height they are supposed to be causes pressure on the brickwork at the highest rows, so the placement height needs to be redefined for different rows. Additionally, the ground surface is not entirely flat, and there are millimetric height differences at the upper surfaces of bricks in the same row. The bricks in the upper rows were placed by lowering them from a height of 5mm while aligning the gripper with the upper surface of the brick, unlike the ones in the lower rows, to prevent these problems from negatively affecting production by applying pressure during placement. For this reason, small shifts due to the dropping were observed in the bricklaying.

The age of the software and hardware of the robot was another limitation for the fabrication. It resulted in slower processing speeds, caused problems during the implementation, and reduced the number and variety of experiments, thus limiting the efficiency and effectiveness of the robotic fabrication process.

The experiments (Figure 5.4) can be further improved with the involvement of mortar or adhesives, different materials, and ground with more friction. The use of mortar would require an additional robotic arm or a change in end effectors for each brick. The robot can be programmed to dispense the appropriate amount of mortar and apply it to the bricks in the desired pattern, ensuring that the bricks are properly bonded together. Additional solutions could be needed to remove excess mortar materials from the surfaces. On the other hand, adhesives could be incorporated into the toolpath with related periphery units. These improvements would enable laying steeper surfaces or surfaces with numerous quarter bricks while increasing the accuracy of dimensions and proportions of the brickwork.

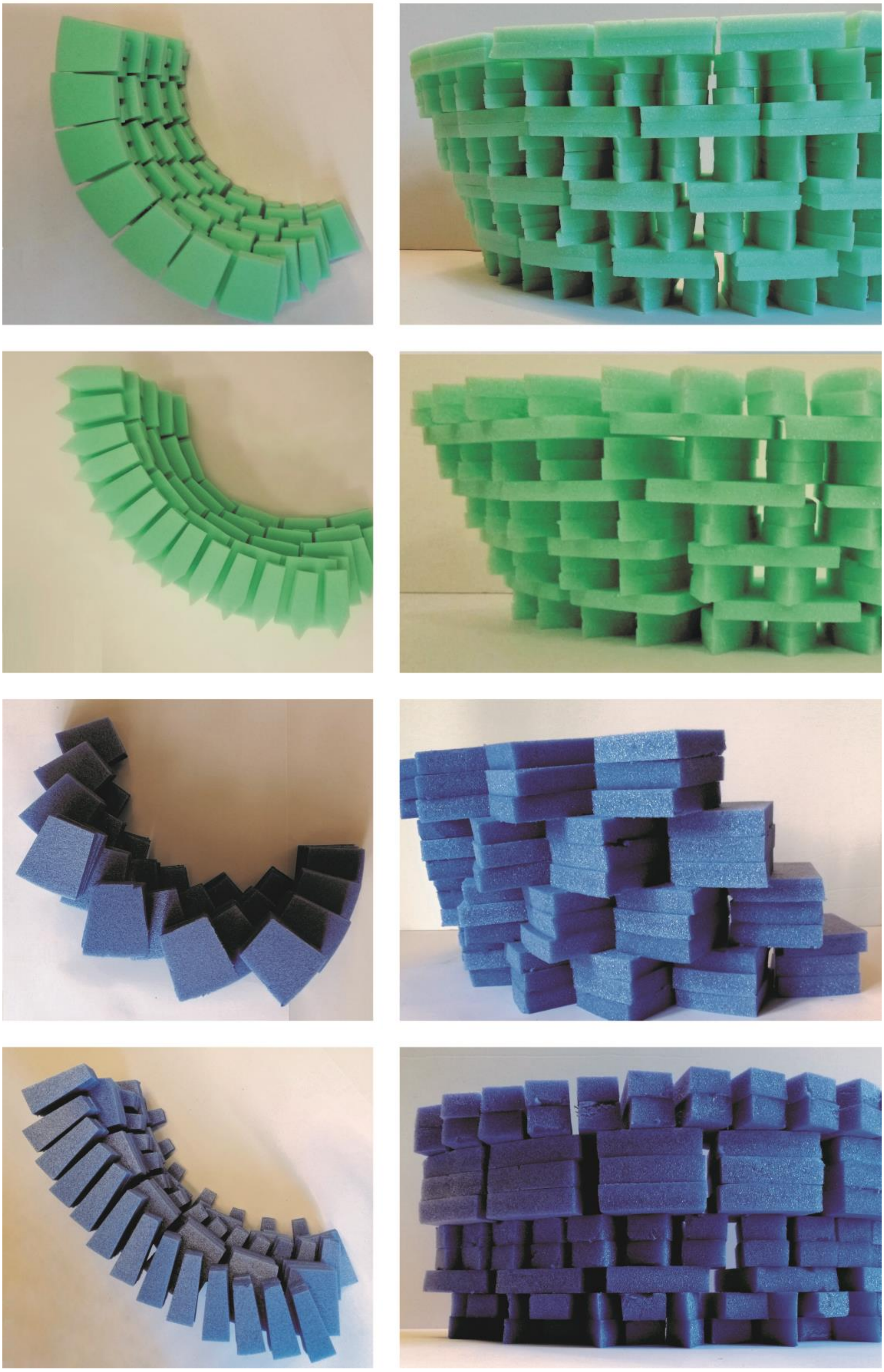

Figure 5.5 : Results of robotic production (From top to bottom: AGuM, AUM, AfUM, SAM).

6. CONCLUSIONS

The primary aim of this thesis has been to propose a methodology to serve in bridging the knowledge from the disciplines of architectural history and building technology by modeling brick surfaces in historic buildings with design computation methods. To demonstrate the correlation between the design of the surface pattern and material in historical bricklaying, brickworks with different curvatures and three-dimensional qualities are modeled, analyzed, reconstructed both digitally and physically, and compared. The information about the tectonics of existing surfaces is formalized through the development of grammars which helps us to externalize design reasoning behind historical brick structures based on the know-how of making. The models produced and fabricated with digital tools show that the method can be applied to transfer the implicit design knowledge of the case studies and transfer it to a digital environment aiming to provide a holistic transfer of the knowledge to future generations. The importance of this study is that the flexibility in parts and wholes are taken into consideration, and the patterns are analyzed as a result of constructional relations between three-dimensional units instead of two-dimensional arrangements. The design of the patterns with the arrangements of squares are combined with the sequential repetitions of individual brick relations for single-curved surfaces and domes. The analysis revealed that the constructional logic and order of bricklaying that lies behind the complex patterns on different surfaces share some fundamental principles. The construction of brick muqarnas and its three-dimensional qualities related to individual relations between bricks are also discussed through the examples of corniches below minaret balconies.

The research points out the use of practical geometry and modules for bricklaying. However, to propose a more comprehensive grammar, further studies needs to include many examples and other bricklaying architectural elements, such as transition elements and brick muqarnas that provide a transition from point to rectangle or rectangle to rectangle would be necessary.

The experiments of robotic production show that the reconstruction of a surface can be completed in a single model from the analysis to production. The importance of material properties, tools, and the actions of the maker is revealed. The unexpected results due to all these aspects and limitations implied the need for intervention by the designer. Future studies to improve the robotic fabrication part of the research include solutions to eliminate inaccuracies and minor deviations created by the incorrect holding of the brick by the gripper. These inaccuracies would have a negative impact on surface quality. A possible solution would be the development of an end effector and some changes in the brick design. Another improvement would be using different materials or bricks as a unit.

Having valued a historical perspective, the research focus has mostly been a technical one. This thesis does not propose a generalization for Medieval Anatolian brick patterns but instead proposes a method to document formal and material design attributes belonging to the field of architectural and cultural heritage. The examples constitute a case. The proposed method has the potential to assist in the documentation of architectural heritage, with improvements with more resources and collaborations with experts in architectural history. It can add another layer of information to heritage building information models (HBIM) by identifying the parts separately and in relation to each other, with the design and construction logic required to reconstruct the surfaces with digital fabrication tools. One of the difficulties in HBIM applications is that the architectural heritage elements do not match the ones in a library of typical software (Dore & Murphy, 2012). While HBIM models mainly focus on the structural information, and the building components of historical structures are assumed to match those already in libraries (Garagnani & Manferdini, 2013), this study proposes to integrate the semantic part-whole relations and a generative tool to model components as they are in the scale of construction units. This method can integrate HBIM studies with conservation and restoration applications to transfer knowledge from experts to digital fabrication tools and help protect architectural and cultural heritage. Additionally, integrating digital tools to document architectural heritage allows a broad audience to share and access information quickly. The know-how could be incorporated into HBIM models, which could provide a common ground for discussions and enable the production of accurate and efficient models that include multiple layers of information in different scales.

The results imply that the combination of computational modeling, geometrical analysis, and historical research with robotic fabrication could provide new insights into the relationship between geometry, materials, and design. While the analysis and modeling based on the architectural construction history contribute to the documentation efforts, the application with the robotic arm shows that the generative model could provide the basis for transferring the understanding of material relations and their influences on the design into the design and production of novel brickworks. The workflow and the experiments of the thesis present the importance and potential of transdisciplinary works for preserving knowledge of architectural heritage. Information from different disciplines gains value when associated with each other, providing a deeper understanding of the subject. The research shows that combining information from different sources can be essential for a more comprehensive understanding of a subject. For example, the analysis of the domes shows that a photogrammetry-based point cloud model can provide detailed, three-dimensional information, while text-based descriptions from the existing literature provide additional context and background information about the materials, tools, and making. Additionally, the survey drawings help to clarify and visualize the exact shapes and dimensions and be used as a reference to measure the accuracy and scale of the point cloud model. Combining these different sources makes it possible to gain a more well-rounded understanding and propose a more informed model. Using multiple sources of information can also help to verify and validate the accuracy of the information being gathered. The research shows a need for increased collaboration and partnerships between organizations working to document cultural heritage and those with expertise in digital design. By working together, these groups can share knowledge and resources and develop more effective approaches to using digital tools for cultural heritage documentation.

Another opportunity the method presents is integrating digitally processed real-world data into the parametric model to create a site-specific model of the constructional parts and wholes. The combinations of discrete parts, which are the parts of the design, can also be detected and documented as other layers of design elements. As Altun et al. (2022) discussed, the data collected from the site could be processed with deep learning and digital modeling tools to be used as input for the stochastic parameters of spatial relations and the rules of designs with repetitive units.

Last but not least, the developed model has the potential to be used as a generative model to produce a synthetic dataset. Future studies include the creation of a dataset that can be the training data for a deep learning model, which may be used for semantic segmentation of real-world data from existing historical structures. The application has the potential to contribute to the SCAN-to-BIM applications by automation of documentation in a level of detail of a construction unit that needs to be more considered.

REFERENCES

Afsari, K., Swarts M.E., & Gentry R. (2014). Integrated generative technique for interactive design of brickworks. *Journal of Information Technology in Construction (ITcon), 19*, 225-247.

Aktaş Yasa, A. (2016). Anadolu Selçuklu ve Beylikler Dönemi Konya yapılarında malzeme kullanımı ve yapım teknikleri. *Vakıflar Dergisi, 45,* 143–176.

Akok, M. (1970). Konya'da İnce Minareli Medresenin rölöve ve mimarisi. *Türk Arkeoloji Dergisi, 31*, 5-36.

Akok, M. (1970). Konya'da Sahib-ata Hanikah, Camiinin rölöve ve mimarisi. *Türk Arkeoloji Dergisi, 19(2),* 5-38.

Akok, M. (1976). Konya Beyşehir Eşrefoğlu Camii ve Türbesi. *Türk Etnografya Dergisi, 15,* 5–34.

Aktuğ Kolay, İ. (1999). *Batı Anadolu 14. Yüzyıl Beylikler mimarisinde yapım teknikleri*, Atatürk Kültür Merkezi, Ankara.

Al Ajlouni, R. (2012). The forbidden symmetries. In *ACADIA 12: Synthetic Digital Ecologies. Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture* (pp: 391-400), San Francisco, 18-21 October.

Al Ajlouni, R. (2017). An ancient rule for constructing dodecagonal quasiperiodic patterns. *Journal of Physics: Conference Series, 809 (1),* Retrieved December 21, 2022 from https://iopscience.iop.org/article/10.1088/1742-6596/809/1/012028.

Al Ajlouni, R. & Justa, P. (2011). Reconstruction of eroded and visually complicated archaeological geometric patterns: Minaret Choli, Iraq. *Geoinformatics FCE CTU, 6*, 18-24.

Altun, S. & Özkar, M. (2021): Formal studies on the relationship between the brick bond and the pattern in Anatolian Seljuk Architecture. In G. Çağdaş, M. Özkar, L. F. Gül, S. Alaçam, E. Gürer, S. Yazıcı, B. Delikanlı, Ö. Çavuş, S. Altun & G. Kırdar (Eds.). Computational Design in Architecture, 15th National Symposium (pp. 205-213).

Altun, S. & Özkar, M. (2022): Formal studies on the parts and wholes of historical bricklay designs. Paper presented at the 6th International Symposium Formal Methods in Architecture, A Coruna, Spain.

Anliker, F. J. (1988). Needs for robots and advanced machines at construction site. social aspects of robotics. In *Proceedings of the 5th International Symposium on Automation and Robotics in Construction (IAARC*) (pp: 145-150). Tokyo, Japan.

Ariza, I., Sutherland, T. S., Durham, J. B., Mueller, C. T., McGee, W., & Clifford, B. (2017). Robotic fabrication of stone assembly details. In A. Menges, B. Sheil, R. Glynn, M. Skavara (Eds.), *Fabricate 2017*, 106–113. London: UCL Press.

Bakırer, Ö. (1981). *Selçuklu Öncesi ve Selçuklu Dönemi Anadolu Mimarisinde Tuğla Kullanımı*. ODTÜ Mimarlık Fakültesi Baskı Atölyesi, Ankara.

Bakırer, Ö. (2017). Reflections of the "naked brick style" in Seljuk Anatolia. *Selçuklu Medeniyeti Araştırmaları Dergisi, (2),* 193-225.

Beatini V., Royer-Carfagni, G., & Tasora, A. (2019). A non-smooth-contact-dynamics analysis of Brunelleschi's cupola: an octagonal vault or a circular dome? *Meccanica, 54,* 525-547.

Bidgoli, A. & Cardoso-Llasch, D. (2015). Towards a motion grammar for robotic stereotomy. In Y. Ikeda, C. M. Herr, D. Holzer, S. Kaijima, M. J. Kim. M, A, Schnabel (Eds.), *Emerging Experience in Past, Present and Future of Digital Architecture, Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2015* (723 -732), The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

Birkett, S. & Jurgenson, W. (2001). Why didn't historical makers need drawings? Part I -Practical geometry and proportion. *The Galpin Society Journal 54,* 242–284.

Bonner, J. (2017). *Islamic Geometric Patterns: Their Historical Development and Traditional Methods of Construction*. Springer Publishing. 10.1007/978-1-4419-0217-7.

Bonwetsch, T. (2015). *Robotically assembled brickwork, Manipulating assembly processes of discrete elements* (Doctoral dissertation). Retrieved from https://www.research-collection.ethz.ch/handle/20.500.11850/113633

Bruun, E. P. G., Pastrana, R., Paris, V., Beghini, A., Pizzigoni, A., Parascho, S., & Adriaenssens, S. (2021). Three cooperative robotic fabrication methods for the scaffold-free construction of a masonry arch. *Automation in Construction, 129,* 103803.

Bruzl, M., Usmanov, V., Svoboda, P., & Šulc, R. (2017). Modelling of industrial robotic brick system. *In ISARC 2017 Proceedings of the 34th International Symposium on Automation and Robotics in Construction* (pp: 1013–1021), 3, Taipei, Taiwan.

Carpo, M. (2011). *The Alphabet and the Algorithm (Writing Architecture)* (Illustrated). The MIT Press.

Cenani, S., & Cagdas, G. (2006). Shape grammar of geometric Islamic ornaments. In: Bourdakis, V. And Charitos, D. (Eds), *eCAADe 24 Conference Proceedings: Communicating Space(s)* (pp: 290-297). Volos: eCAADe.

Colakoglu, B., Yazar, T., & Uysal, S. (2008). Educational experiment on generative tool development in architecture. In *Proceedings of the 26th International Conference on Education and Research in Computer*

Aided Architectural Design in Europe (ECAADe). https://doi.org/10.52842/conf.ecaade.2008.685

Cowan, H. J. (1977). A history of masonry and concrete domes in building construction. *Building and Environment, 12(1),* 1–24.

Critchlow, K. (1976). *Islamic Patterns: An Analytical and Cosmological Approach*. Schocken Books.

Cromwell, P. R. & Beltrami, E. (2011). The whirling kites of Isfahan: Geometric variations on a theme. *The Mathematical Intelligencer, 33(3),* 84-93.

Dalkılıç, N. & Nabikoğlu, Ad. (2017). Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). *Frontiers of Architectural Research. 6.* 346-359.

Das, A., Foged, I.W., & Jensen, M.B. (2020). Designing with a robot interactive methods for brick wall design using computer vision. *Anthropologic: Architecture and Fabrication in the Cognitive Age - Proceedings of the 38th ECAADe Conference, (2).* 605–612.

Ding, L., Jiang, W., Zhou, Y., Zhou, C., & Liu, S. (2020). BIM-based task-level planning for robotic brick assembly through image-based 3D modeling. *Advanced Engineering Informatics*, *43,* doi: 10.1016/j.aei.2019.100993.

Docci, M. & Migliari, R. (1989). La costruzione della spinapesce Nella Copertura Della Sala Ottagonale Di Simon Mago Nella Fabbrica Di San Pietro. *Palladio, 3,* 61–72.

Dold-Samplonius, Y. (1992). Practical Arabic mathematics: measuring the muqarnas by al-K¯ash¯i. *Centaurus, 35(3),* 193–242. https://doi.org/10.1111/j.1600-0498.1992.tb00699.x.

Dore, C. & Murphy, M. (2012), Integration of historic building information modeling and 3D GIS for recording and managing cultural heritage sites, In 18th International Conference on Virtual Systems and Multimedia: "Virtual Systems in the Information Society", 2-5 September, 2012, Milan, Italy, 369-376. doi:10.21427/e7sy-rt81.

Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M., Buchli, J. (2016). Mobile robotic brickwork. In: Reinhardt, D., Saunders, R., Burry, J. (eds) *Robotic Fabrication in Architecture, Art and Design 2016*. Springer, Cham. https://doi.org/10.1007/978-3-319-26378-6_15

Eldemir Kara, C. (2021). Evolution of brick architecture through digital tools and technologies. *Gazi University Journal of Science Part B: Art Humanities Design and Planning, 9 (4),* 329-344. Retrieved from https://dergipark.org.tr/tr/pub/gujsb/issue/67705/1014697

Ewart, I. J. & Zuecco, V. (2018). Heritage Building Information Modelling (HBIM): A review of published case studies. *Advances in Informatics and Computing in Civil and Construction Engineering*, 35–41.

Fazel, A., Fayaz, R., Mostaghni, A., & Matini, M. R. (2022). Optical tool for additive construction of complex brick structures. *Automation in Construction, 140(8),* 104330, doi: 10.1016/j.autcon.2022.104330.

Fingrut, A., Crolla, K., & Lau, D. (2019). Automation complexity - Brick by brick. In *Intelligent and Informed - Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA, 1*, 93–102.

Garagnani, S. & Manferdini, A. M. (2013). Parametric accuracy: Building Information Modeling process applied to the cultural heritage preservation. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL5*, 87–92, doi:10.5194/isprsarchives-XL-5-W1-87-2013.

Garg, Y. K. & Das, V. M. (2013). Generating 3 dimensional pavilions described in Mayamatam; A traditional Indian architecture treatise. *International Journal of Architectural Computing*, *11(1)*, 105–134.

Grasl, T., & Economou, A. (2018). From shapes to topologies and back: an introduction to a general parametric shape grammar interpreter. *AIEDAM, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 32(2),* 208-224.

Gürsoy, B. & Özkar, M. (2015). Visualizing making: Shapes, materials and actions. In Knight, T. Ve Vardouli, T. (Eds.), *Design Studies, 41(A),* 29-50.

Gokmen, S., Basik, A., Aykin, Y., & Alacam, S., (2022). Computational modeling and analysis of Seljukid muqarnas in Kayseri, *Journal on Computing and Cultural Heritage (JOCCH), 15(2),* 1 - 19.

Hamzaoğlu, B. & Özkar, M. (2018). Digitizing caft: Making of carved stone patterns from Seljuk-era using digital fabrication tools. In Ö. Karakul, & A. Dalkıran (Eds.), *CRAFTARCH'18 International Art Craft Space Congress, Revitalizing Art Craft Space Relations: Proceedings Book*. (pp: 44-51) Konya: Eğitim Yayınevi.

Hankin, E. H. (1925). *The Drawing of Geometric Patterns in Saracenic Art*. India: Government of India Central Publications Branch.

Harb, U. (1978). *Ilkhandische stalaktitengewölbe: beiträge zu entwurf Und bautechnik, archäologische mitteilungen aus iran* (Vol. 4). Berlin: Dietrich Reimer.

Harmsen, S. (2006). *Algorithmic computer reconstructions of stalactite vaults-muqarnas-in Islamic architecture* (Doctoral dissertation), Heidelberg University, Heidelberg.

Harrison, L., Earl C., & Eckert, C. (2015). Exploratory making: Shape, structure and motion. Knight, T. Ve Vardouli, T. (Ed.), *Design Studies, 41(A),* 51- 78.

Hejazi, M. & Mehdizadeh Saradj, F. (2014). *Persian Architectural Heritage: Structure.* WIT Press / Computational Mechanics.

Hensel, M. (2008). Performance-orientated design precursors and potentials. *Architectural Design, 78(2),* 48-53.

Imani, E. (2017). *Historical and geometrical analysis of muqarnas and prospect of its reflection on today's architecture* (Masters Thesis). Middle East Technical University, Ankara.

Imbern, M. (2014). (RE)Thinking the brick: Digital tectonic masonry systems. In N. Gu, S. Watanabe, H. Erhan, M. Hank Haeusler, W. Huang, R. Sosa (Eds.), *Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia*. (pp: 211-220). Kyoto: CAADRIA.

Jones, B., Sereni, A., & Ricci, M. (2010). Building Brunelleschi's dome: A practical methodology verified by experiment. *Journal of the Society of Architectural Historians*. *69(1).* 39–61.

Kahya, Y. (1992). İstanbul Bizans Mimarisinde Kullanılan Tuğlanın Fiziksel ve Mekanik Özellikleri (Doctoral dissertation), İstanbul Technical University, İstanbul.

Kamath, A. V. (2020). Making grammars for material and tectonic complexity: An example of a thin-tile vault. *Design Studies*, *69*, 100944. https://doi.org/10.1016/j.destud.2020.05.001

Kaplan, C. S. (2000). Computer generated Islamic star patterns. In *Proceedings of Bridges 2000: Mathematical Connections in Art, Music and Science,* 105-112.

Kaplan, C. S. (2005). Islamic star patterns from polygons in contact. In *Proceedings of graphics interface 2005*. 177-185.

Kaplan, C. S. (2017). Interwoven Islamic geometric patterns. In D. Swart, C. H. Sequin & K. Fenyvesi (Eds.), *Proceedings of Bridges 2017: Mathematics, Art, Music, Architecture, Education, Culture* (pp 71-78). Waterloo: Tessellations Publishing.

Kaplan, C. S. & Salesin, D. H. (2004). Islamic star patterns in absolute geometry. *ACM Transactions on Graphics (TOG), 23(2),* 97-119.

Kasraei, M. H., Nourian, Y., & Mahdavinejad, M. (2016). Girih for domes: Analysis of three Iranian domes. *Nexus Network Journal*, *18(1),* Springer Basel, 311–321.

Kharazmi, M. (2016). A study on geometric constructions on brickwork decorations in Iranian architecture. In E. Torrence, B. Torrence, C. H. Sequin, D. McKenna, K. Fenyvesi & R. Sarhangi (Eds.), *Bridges 2016: Mathematics, Music, Art, Architecture, Education, Culture* (pp. 301–308). Jyvaskyla: Tessellations Publishing.

Knight, T. (2015). Shapes and other things. In Ozkar, M. (Ed.), *Nexus Network Journal*, *17(3),* 963-980.

Knight, T. (2018). Craft, performance, and grammars. *Computational Studies on Cultural Variation and Heredity*, 205–224.

Knight, T., Stiny, G. (2015). Making grammars: from computing with shapes to computing with things. In Knight, T. & Vardouli, T. (Eds.), *Design Studies, 41(A),* 8-28.

Kolarevic, B. (2005). Information master builders. In B. Kolarevic (Ed.), *Architecture in the Digital Age: Design and Manufacturing*, 55-62. Taylor and Francis.

Kramer, M., & Akleman, E. (2020). A procedural approach to creating American Second Empire Houses. *Journal on Computing and Cultural Heritage (JOCCH), 13(1),* 1-19

Krstic, D. (2019). Grammars for making revisited. *Design Computing and Cognition '18*, 479–496.

Lachauer, L., Rippmann, M., & Block, P. (2010). Form finding to fabrication: A digital design process for masonry vaults. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010*, Shanghai, China.

Lee, A. J. (1987). Islamic star patterns. *Muqarnas*, *4*, 182–197. https://doi.org/10.2307/1523103

Li, D., Knight, M., & Brown, A. (2013). A parametric creation of traditional Chinese Architecture. In R. Stouffs, S, Sariyildiz (Eds.), Computation and Performance - *Proceedings of the 31st eCAADe Conference*, 2, (pp. 697-703). Brussels: Education and research in Computer Aided Architectural Design in Europe; Delft: Faculty of Architecture, Delft University of Technology.

Lu, P. J., & Steinhardt, P. J. (2007). Decagonal and quasi-crystalline tilings in medieval Islamic architecture. *Science* (New York, N.Y.), *315(581*5), 1106–1110. https://doi.org/10.1126/science.1135491.

MacLachlan, L., & Jowers, I. (2014). Formalising flexible multi-material surfaces as weighted shapes. In *SIGGRAPH Asia 2014 Creative Shape Modeling and Design (SA '14)* (pp. 1-7). Association for Computing Machinery, New York. https://doi.org/10.1145/2669043.2669046

McClary, R. P. (2014). Brick muqarnas on Rūm Saljuq buildings - The introduction of an Iranian decorative technique into the architecture of Anatolia. *Transkulturelle Perspektiven, 3,* Retrieved from https://journals.ub.uni-heidelberg.de/index.php/kunsttexte/article/view/88327/82800.

McClary, R. P. (2017). Craftsmen in Medieval Anatolia: Methods and materials. In Blessing, P. & Gashgorian, R. (Eds.), *Architecture and Landscape in Medieval Anatolia* (pp. 1100-1500). Edinburgh University Press, Edinburgh.

McLennan, S., and Brown, A. (2021). A smart heritage system to re-generate New Zealand's 19th century timber churches. *Heritage, 4(4),* 4040-4055.

Mitterberger D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F., & Kohler, M. (2020). Augmented bricklaying. *Construction Robotics*, *4*, 151–161 (2020). https://doi.org/10.1007/s41693-020-00035-8

Muslimin, R. (2010). Learning from weaving for digital fabrication in architecture. *Leonardo, 43(4),* 340-349.

Mousavian, E. & Gentry, R. (2014). Digital tools for automated generation of vaulted brick assemblies for construction and structural analysis. *9th International Masonry Conference 2014,* Guimarães.

Necipoğlu, G. (1995). *The Topkapı Scroll – Geometry and Ornament in Islamic Architecture*. The Getty Center for the History and the Humanities, Santa Monica, CA.

Noel, V. (2015). The Bailey-Derek Grammar: Recording the craft of wire-bending in the Trinidad Carnival. *Leonardo*, *48(4)*, 357-365.

Oliveira, R. & Sousa, J.P. (2015). Building traditions with digital research reviewing the brick architecture of Raúl Hestnes Ferreira through robotic. *Proceedings of the eCAADe, 1(34)*, 123–31.

Ousterhout, R. (2008). *Master Builders of Byzantium*. University of Pennsylvania Museum of Archaeology and Anthropology.

Ödekan, A. (1977). *Osmanlı Öncesi Anadolu Türk Mimarisinde Mukarnaslı Portal Örtüleri*. İ.T.Ü. Mimarlık Fakültesi Baskı Atölyesi, İstanbul.

Özdural, A. (1990). Gıyaseddin Jemshid El-Kashi and stalactites. *METU Journal of the Faculty of Architecture*. *10(1-2).* 31-49.

Özdural, A. (2000). Mathematics and arts: Connections between theory and practice in the Medieval Islamic World. *Historia Mathematica*, *27*, 171-201.

Özen Yavuz, A, & Sağıroğlu Ö. (2016). Reviewing the bricks used in the traditional architecture with the shape grammar method. *Gazi University Journal of Science*, *29(4)*, 741– 749.

Özgan, S.Y., & Özkar, M. (2017). A thirteenth-century dodecahedron in Central Anatolia: Geometric patterns and polyhedral geometry. *Nexus Network Journal*, *19*, 455–471.

Özkul, K. (2020). Anadolu Selçuklu Dönemi mimari yapılarında turkuaz. *International Journal of Humanities and Education (IJHE), 6 (13)*, 291–318. Retrieved from https://dergipark.org.tr/tr/pub/ijhe/issue/54071/652750.

Prak, M. (2011). Mega-structures of the Middle Ages: The construction of religious buildings in Europe and Asia, c.1000–1500. *Journal of Global History*, *6(3)*, 381-406. doi:10.1017/S1740022811000386.

Panahi, A. (2012). Application of geometry in brick decoration of Islamic architecture of Iran in Seljuk period. *Journal of American Science*, *8(6).* 814-821.

Paris, V., Attilio P., & Giuseppe R. (2017). Brunelleschi's herringbone hidden reciprocal structure and the form finding of its self-supporting bricks. In *Interfaces: Architecture, Engineering, Science, Annual Meeting of the International Association of Shell & Spatial Structures (IASS)* (pp: 1-10). Hamburg.

Peker, A. U. (1998). Orta Çağ Anadolu mimarisinde anlam. *Arkeoloji ve Sanat*, *85*, 29-39.

Piskorec, L. et al. (2019) *Brick Labyrinth.* (n.d.). Masdfab. https://www.masdfab.com/work-1617-bricklabyrinth.

Pizzigoni, A. (2015). Brunelleschi's bricks. *IASS Journal*, *56(184)*, 137-148.

Pizzigoni, A., Paris, V., & Ruscica, G. (2018). Herringbone technique: truth and history of a cutting-edge technology. In C. Mueller, S. Adriaenssens (Eds.) *Proceedings of the IASS Symposium 2018 Creativity in Structural Design*. MIT, Boston, USA.

Rajabzadeh, S., & M. Sassone. (2017). Brick patterning on free-form surfaces. *Nexus Network Journal. 19.* 5–25.

Safaeianpour, A., & Valibeig, N. (2022). A study on the construction technology of the Seljuk Minarets in Isfahan with focus on their geometric brick pattern. *Curved and Layered Structures, 9(1),* 13–24.

Sarhangi, R. (1999). The sky within: Mathematical aesthetics of Persian Dome interiors. *Nexus Network Journal, 1 (2),* 87–98.

Sarhangi, R. (2008). Illustrating Abu al-Wafā' Būzjānī: Flat images, spherical constructions. *Iranian Studies. 41 (4).* 511–523.

Smars, P. (2008). Documenting architectural heritage, looking for a balance between automation and control. *Journal of Cultural Conservation Science, 1(2),* 3–10. http://smars.yuntech.edu.tw/papers/jccs0.pdf.

Stiny, G. (2006). *Shape: Talking about Seeing and Doing*. Cambridge, Massachusetts: The MIT Press.

Stiny, G., & Gips, J. (1972). Shape grammars and the generative specification of painting and sculpture. In O. R. Petrocelli (Ed.), *Proceedings of IFIP Congress'71*. Amsterdam: North Holland publishing Co. Also in the best computer papers of 1971. Philadelphia: Auerbach.

Stouffs, R. (2018). Where associative and rule-based approaches meet a shape grammar plug-in for Grasshopper. In T. Fukuda, W. Huang, P. Janssen, K. Crolla, & S. Alhadidi (Eds*). 23rd International Conference on Computer-Aided Architectural Design Research in Asia: Learning, Prototyping and Adapting* (pp. 453-462). Beijing, CAADRIA.

Sousa, J. P., Varela, P. A., & Martins, P. F. (2015). Between manual and robotic approaches to brick construction in architecture. *Proceedings of the 33th International Conference on Education and Research in Computer Aided Architectural Design in Europe (ECAADe). 2.* 361-370. https://doi.org/10.52842/conf.ecaade.2015.2.361.

Tabbaa, Y. (1985). The muqarnas dome: its origin and meaning. *Muqarnas. 3,* 61–74.

Tish, D., King, N., & Cote, N. (2020). Highly accessible platform technologies for vision-guided, closed-loop robotic assembly of unitized enclosure systems. *Construction Robotics, 4,* 19–29. https://doi.org/10.1007/s41693-020-00030-z.

Ulu, E. (2009). *İslami Geometrik Örüntü Türetimi Amaçlı Bir Biçim Grameri Modeli* (Masters Thesis). İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü.

Vazquez, E., Duarte, J., & Poerschke, U. (2020). Masonry screen walls: A digital framework for design generation and environmental performance optimization. *Architectural Science Review. 64(3),* 262-274.

Wu, Y., Cheng, H. H., Fingrut, A. Crolla, K., Yam, Y., & Lau, D. (2018). CU-Brick cable-driven robot for automated construction of complex brick structures: From simulation to hardware realisation. *IEEE International Conference on Simulation, Modeling, and Programming for Autonomous Robots,* 166–173, doi:10.1109/SIMPAR.2018.8376287.

Yaghan, M. A. J. (2000). Decoding the two-dimensional pattern found at Takht-I Sulayman into three-dimensional muqarnas forms. *Iran*, *38(1)*, 77-95.

Yaghan, M. A. J. (2003). Gadrooned-Dome's muqarnas-corbel: Analysis and decoding historical drawings. *Architectural Science Review*. *46(1)*. 69-88.

Yaghan, M. A. J. (2010). The evolution of architectural forms through computer visualisation: Muqarnas example. In A. G. Seal, J. P. Bowen, & K. Ng (Eds). *Electronic Visualisation and the Arts* (EVA 2010) (pp. 113-120). London: BCS.

Yue, K., Krishnamurti, R., & Grobler, F. (2009). Computation-friendly shape grammars: Detailed by a sub-framework over parametric 2D rectangular shapes. In T. Tidafi and T. Dorta (Eds), *Joining Languages, Cultures and Visions: CAADFutures 2009*, (pp. 757- 770). Montreal: PUM.

Zandavali Andrade, B. ve Jimenez Garcia, M. (2020). Automated brick pattern generator for robotic assembly using machine learning and images. *37th eCAADe 23th and SIgraDi Joint Conference*, *1(79)*, 217-226, doi:10.5151/proceedings-ecaadesigradi2019_605

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- **Altun, S.** & Özkar, M. **(**2022): Formal studies on the parts and wholes of historical bricklay designs. Paper presented at the 6th International Symposium Formal Methods in Architecture, A Coruna, Spain.
- **Altun, S.** & Özkar, M. (2021): Formal studies on the relationship between the brick bond and the pattern in Anatolian Seljuk Architecture. In G. Çağdaş, M. Özkar, L. F. Gül, S. Alaçam, E. Gürer, S. Yazıcı, B. Delikanlı, Ö. Çavuş, S. Altun & G. Kırdar (Eds.). *Computational Design in Architecture, 15th National Symposium* (pp. 205-213).

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- **Altun, S.** & Güneş, M. C. **(**2021): Classification of historic ornaments with CNN, *JCoDe: Journal of Computational Design, 1(3),* 115-130