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

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This study explores the evolution of crafting and fabrication techniques, particularly focusing on the intersection between analogue and digital methods in the field of bricklaying. The inquiry seeks to address how digital advancements have influenced the way we build, comparing historical, conventional, and digital processes to highlight their similarities and differences. By using masonry, one of the oldest and most widespread construction methods, the study aims to trace the transformation of craftsmanship from fully analogue methods to digitally enriched practices.
The methodology is threefold: First, a literature review is conducted to identify contemporary fabrication approaches that blend digital and analogue techniques. This review helps categorize and analyze recent tendencies in digital fabrication, focusing on the integration of real-life data, feedback loops, and geometrical investigations. Secondly, a case study investigates different bricklaying fabrication methods to analyze how these digital-analogue interactions manifest in actual practice. Finally, a focused strategy based on four workflows is presented to compare different crafting processes, ranging from fully historical to highly digitized methods.
Consequently the study explores the evolving relationship between physical craft and digital environments via bricklaying techniques. Typical-conventional and semi-digitized practices seem to reduce the craftsman's intuitive decision-making role. On the other hand, the resemblance between completely digital and historical fabrication, in terms of allowing the craftsman to make intuitive decisions during crafting, is significant. The study suggests that future fabrication methods may continue to blend digital precision with human creativity, potentially leading to an archaic revival of traditional craft approaches in a contemporary context. Further research could expand into more complex volumetric structures to better understand this evolution.

Keywords: Craft, Computational Design, Digital Fabrication, Masonry.

Received: 28.06.2024
Accepted: 22.11.2024

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Taşcı, H. & Yazıcı, S. (2025). An Inquiry on Analogue and Digital Making Processes in Architecture: Craft and Fabrication within the Scope of Masonry Structures, JCoDe: Journal of Computational Design, 6(1), 37-66. https://doi.org/10.53710/jcode.1506394

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

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

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

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

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

Teslim Tarihi: xx.xx.xxxx
Kabul Tarihi: xx.xx.xxxx

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Taşçı, H. & Yazıcı, S. (2025). An Inquiry on Analogue and Digital Making Processes in Architecture: Craft and Fabrication within the Scope of Masonry Structures, JCoDe: Journal of Computational Design, 6(1), 37-66. https://doi.org/10.53710/jcode.1506394

1. I 'THING,' THEREFORE I AM

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

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

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

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

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

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

Kwinter (2011, p. 91) proposes a more radical approach to overcome both disamenities (loss of personality and representation of reality) with the concept of the *archaic revival*, which implies "a new regime of subjection”, by returning to “matter, complexity, and free development” using digital fabrication methods.

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

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

2. WAYS TO MAKE IN THE DIGITAL ERA

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

However, Leach (2018) points out that the computational paradigm shift is not yet complete even though computers are already widely used. What one now calls digital fabrication is actually “an analogue process that is merely digitally controlled” (Leach, 2018, p. 26); computers are not creatively involved. Therefore, in the context of this research, it is crucial to trace the evolution of making, from craft to fabrication, and to explore the transformation of realization from the pre-digital era to the computerized world.

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

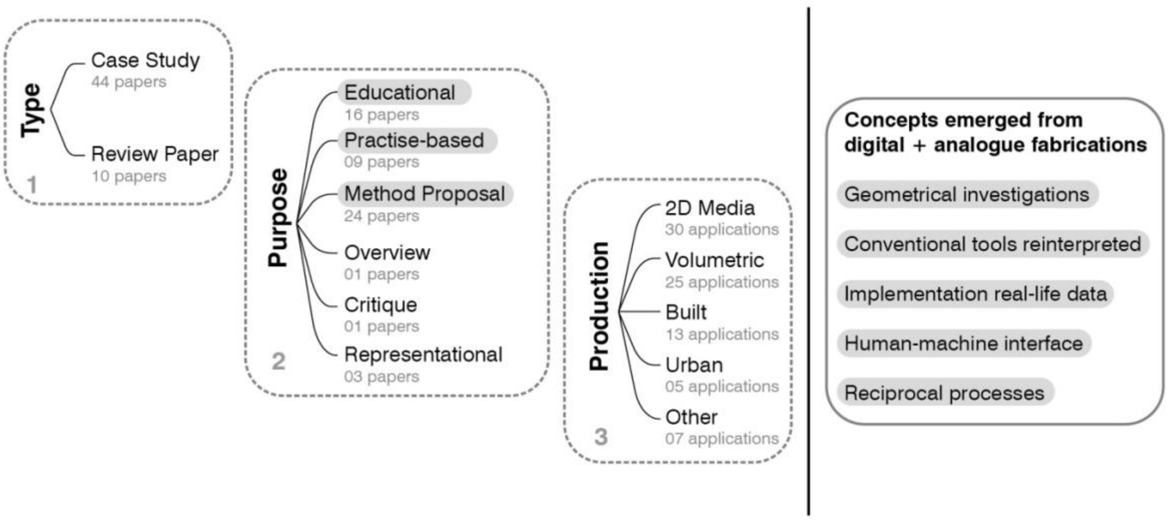

Figure 1: Categorization of 54 papers from the CumInCAD database on exploring conventional ways to make

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

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

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

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

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

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

(1) Geometrical investigations aim to tesselate or reinterpret the form by manipulating the surface (Cheng, 2012; Stavrić, et. al 2012; Forren & Nicholas, 2018), or volume (Jabi, 2004; Griffiths, 2011; Anderson & Tang, 2014; Lanham, et. al. 2017; Suzuki & Knippers, 2018). The results are mostly variations rather than an ultimate geometrical solution, and these results are generated by complex outputs starting from an extremely basic level. However, all these studies focus on digital fabrication methods rather than creating a common ground with analogue methods.

(2) The studies aimed at implementing real-life data into digital manufacturing processes implement many different data sets – including structural, material, performative, haptic, gestural, etc.– and their modification after being confronted with real-life constraints. These studies examine the behaviour of the materials

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

(3) Studies that investigate the human-machine interface introduce a gadget or tool that allows additional inputs into the design and fabrication process, such as Augmented Reality/Virtual Reality (AR/VR) (Dorta, 2006; Poustinchi, et. al. 2018; Fong, et. al., 2020; Bevilacqua, 2021) or Artificial Intelligence (AI) (Cudzik & Radziszewski, 2018). However, it is not straightforward to define the boundaries of this theme since the 'human-machine interface' will encompass every profession after digitalization.

(4) Some studies are aimed at reinterpreting conventional tools and propose a novel understanding of already existing tools. The focus of these studies is diverse, whether based on a pre-digital method (Dritsas & Becker, 2007; Voordouw, 2015; Jaminet et. al, 2021; Hamzaoğlu, et. al., 2022); a digital method (Serriano, 2003; Parthenios, 2008; Kenzari, 2010; Asanowicz, 2012; Dounas & Spaeth, 2016); or preliminary examples aimed to find implementations of digital tools for design studies (Neiman & Bermudez, 1998; Donath et. al., 2001).

(5) Studies that analyze reciprocal processes include collaborative (Schubert et. al., 2011) and responsive processes (Burry, et. al., 2010; Davis, et. al., 2011; Zandavali, et. al., 2020) which include feedback data (Ahlquist & Fleischmann, 2008). Some studies may incorporate cybernetic/bio-cybernetic theories (Viscardi, 2002; Wójcik & Strumiłło, 2017). These studies aim to consistently transfer analogue data to the digital environment and by mostly using hybrid techniques such as file-to-factory processes (Dunn, 2012) Reciprocity is clearly associated with the two previous themes, as feedback loops are crucial for cybernetics and systems theory and reciprocity makes it possible to implement real-life data into the digital environment.

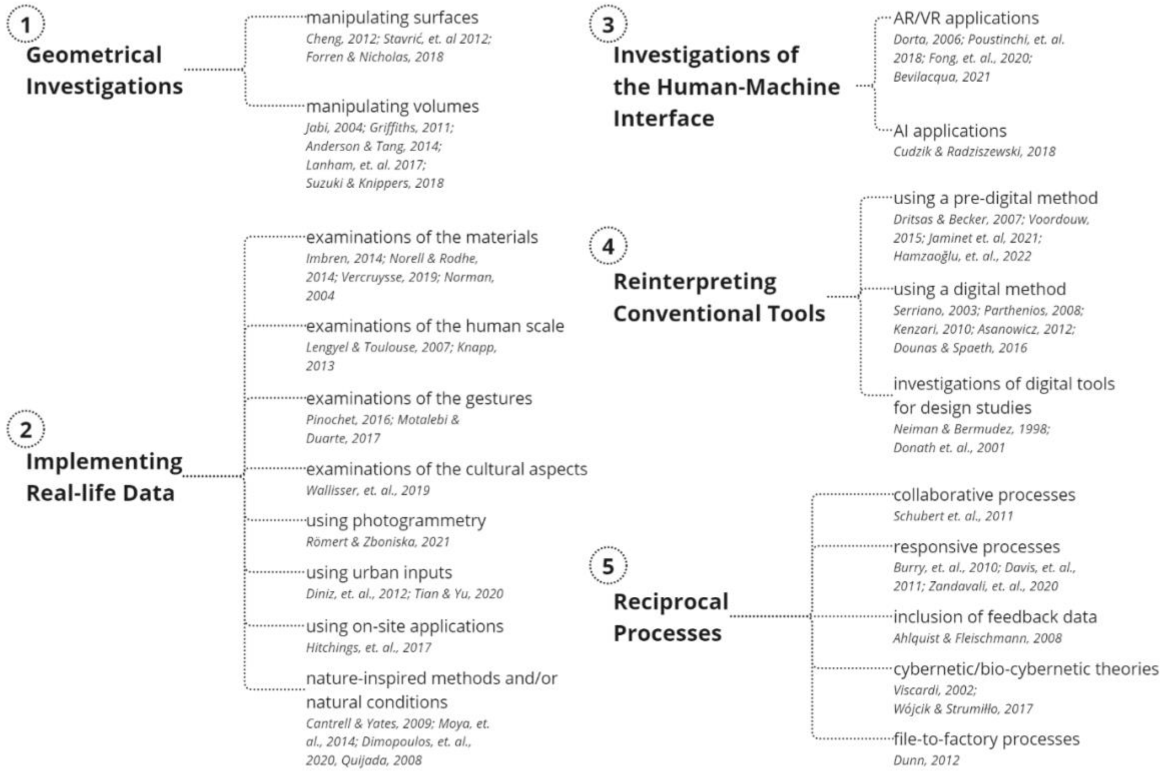

Figure 2: Classification of the reviewed papers.

2.2 Interpretation of the Review Results

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

For hybrid methods, some approaches primarily use analogue techniques, with digital tools providing supplementary data. In these cases, the origin of the design process is completely analogue and the crafting process can be enriched by digital data. Other methods rely on digital fabrication, though the process is bred by physical constraints, particularly in terms of material and form. Rationalization plays a crucial role when the design process starts entirely within a digital medium. These thresholds determined the classification of fabrication methods and the focused research area, as represented in **Figure 4**, along the fabrication method axis.

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

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

The main hypothesis of this inquiry is that, throughout the evolution of architectural fabrication, improvisation or the realm of creativity that used to manifest itself during making was initially completely normal at first, then highly undesirable, and then relocated to different phases of the process. But has not 'evaporated' as modernity or orthodox computational designers might postulate.
To trace the relocation and involvement of intuitive and creative knowledge in the design and fabrication phases, brickwork serves as an excellent research area for the following reasons:

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

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

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

3. MASONRY AS A REALM OF INVESTIGATION

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

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

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

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

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

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

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

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

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

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

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

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

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

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

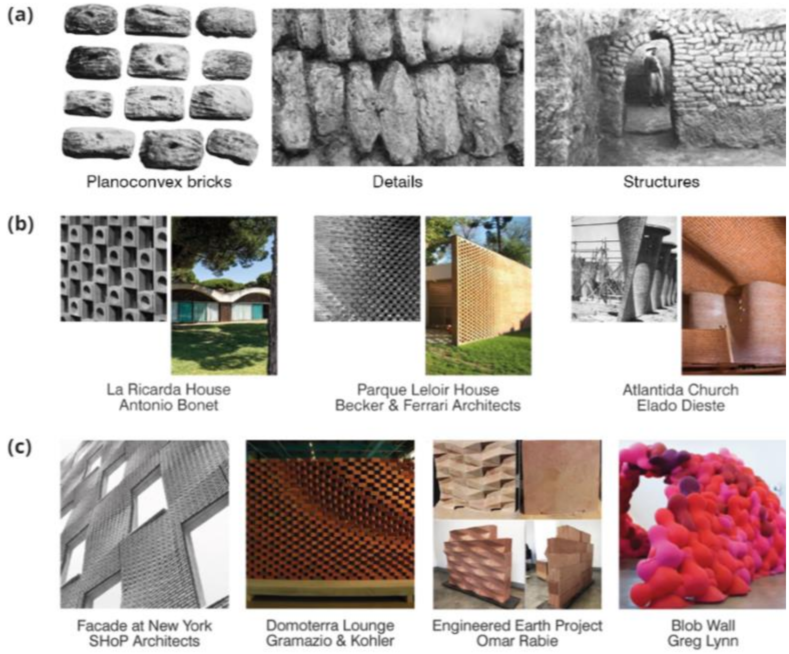

Figure 3: Examples of (a) historical, (b) conventional, and (c) digital brickwork

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

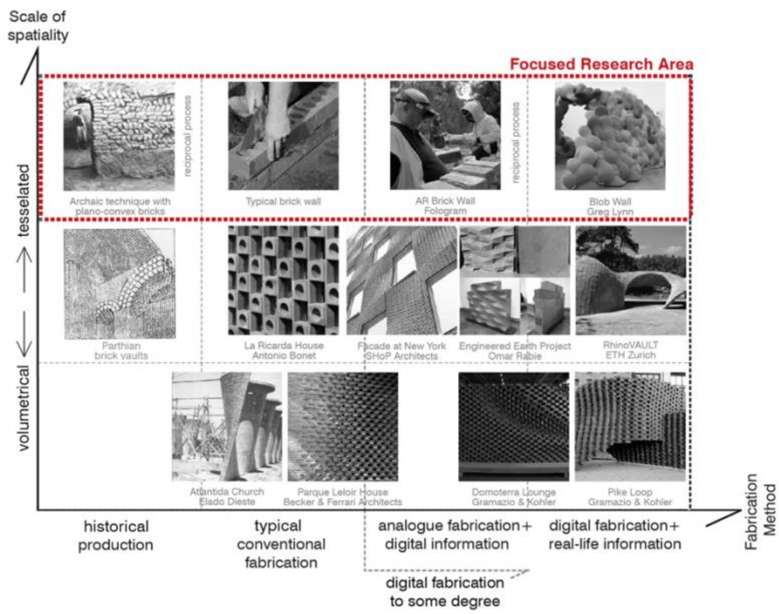

Figure 4: An attempt to categorize the brickwork projects

4. COMPARISON OF DIFFERENT WAYS TO MAKE

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

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

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

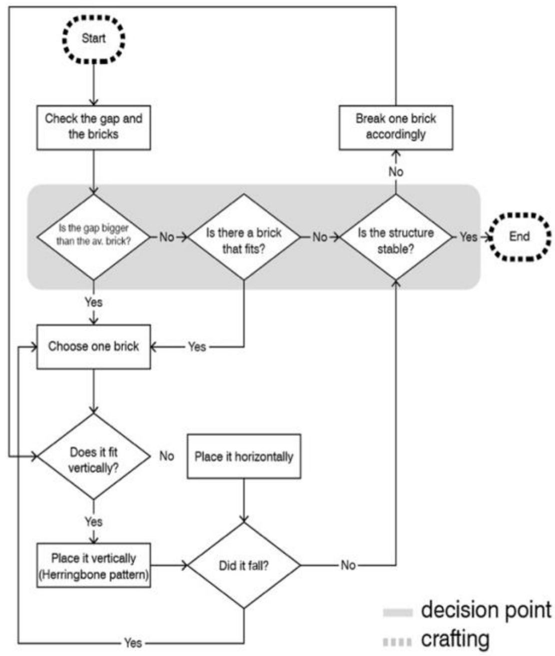

Figure 5: Workflow of historical brick wall fabrication with plano-convex bricks.

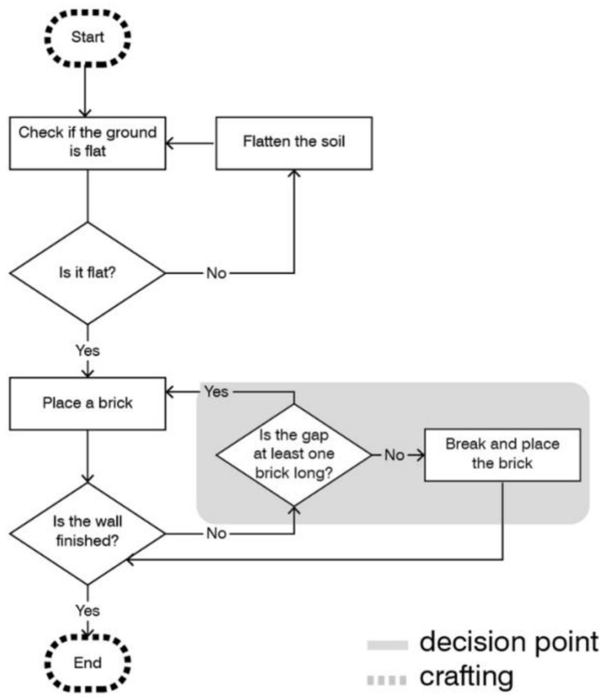

Figure 6: Workflow of conventional brick wall fabrication.

The most significant feature of the typical conventional way of fabricating a brick wall is that it requires manipulation of real-life circumstances to produce a well-defined, predetermined result, whereas in the first example of historical craft, real-life data directly influences the result; real-life is not just a to be controlled as in the typical procedure, but rather a companion of the process. The workflow in **Figure 6** shows that in the typical procedure, the process is comparatively scarce, the key points are very few and descriptive; the feedback loops are limited and isolated, unlike the other examples.

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

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

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

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

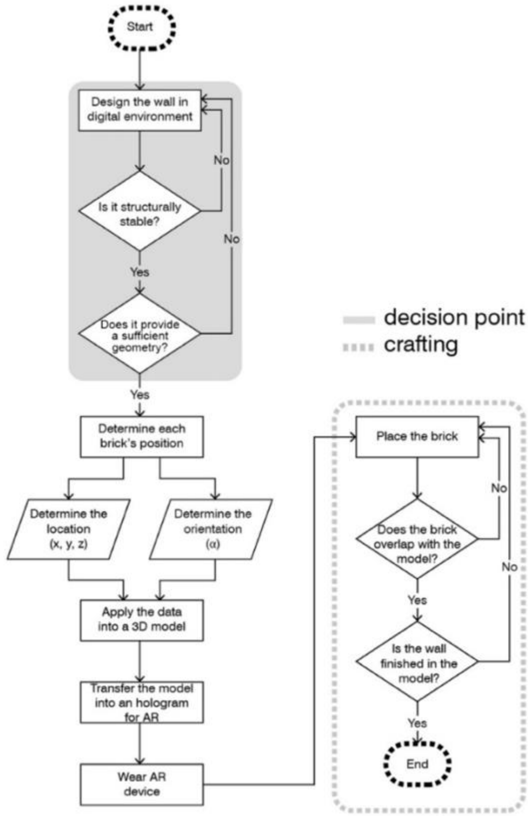

Figure 7: Workflow of AR-Implemented brick wall fabrication.

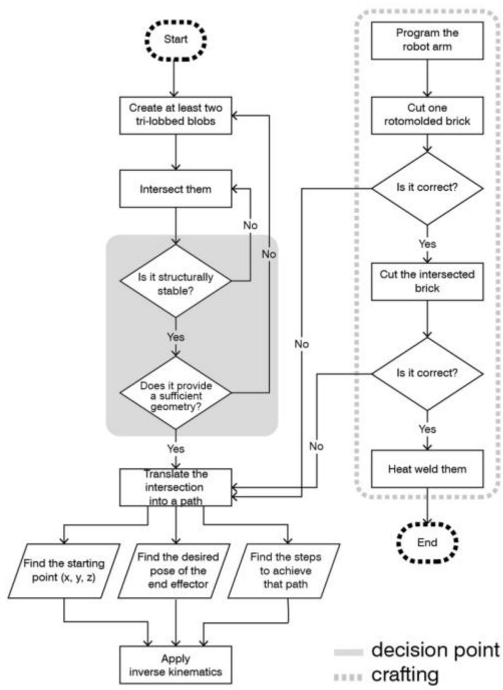

Figure 8: Workflow of the Blobwall fabrication.

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

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

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

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

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

5. EPILOGUE

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

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

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

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

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

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

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

Acknowledgments

This paper is an outcome of a postgraduate course entitled "Architectural Design Synthesis: Form, Material and Performance" conducted by Assoc. Prof. Sevil Yazıcı at İstanbul Tecnical University, Faculty of Architecture, Architectural Design Programme.

Statement

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

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

Author Contribution Statement

All authors contributed equally to this article.

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