A Stereotomic Approach to Regional Digital Architecture

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Declaration

I, the undersigned, declare that this thesis is my original work, and has not been presented in fulfilment of other course requirements at the University of Malta or any other university.

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Abstract

Maltese traditional cultural landscape emerged from three dominant contextual realities: limited resources, the limestone as the single available building material, and a geographic discontinuity. The recently increased geopolitical connectivity has negated Malta's geographic isolation and instigated an unprecedented influx of investments, clients, users, and services. Due to high urbanisation, Malta can be equated with a small European city, yet its operations have neither environs nor a surrounding region to rely on. The result is a persistent speculative building boom dependent on imported technology and materials that are uncritically streamlined towards the economy of design and production. The established limited material palette and fixed, Modernist-like construction procedures bound the contemporary architectural practice within a highly restrictive design space, directly opposite to the long-lasting ability of vernacular and traditional architectural practices to continuously expand through assimilations of the tangible and intangible goods.

Stereotomy, the initial point of the research, is recognised as a historical reference that offers a way to expand limitations of the current dominant design thinking towards more contextually responsive architecture. Stereotomy is approached beyond its immediate definition as the stonecutting discipline for executing geometrically complex masonry assemblies that ties it to specific material and construction choices. Instead, it is recognised as a material system formulated through a systemic approach to the context that establishes bottom-up, computational processes that discretise and externalise its multiple constraints as a material system of interdependent geometric. In short, the research exposes the stereotomic design process as contextual structuring and stereotomy as a digital architecture.

From this theoretical perspective, the research theorises the notion of regional digital architectural practice as an architectural practice grounded in a systemic approach to the context that guides its thinking, design, and production. The notion becomes the theoretical framework of Maltese contextual analysis that recognises the traditional cultural landscape as a material system and its contextual authenticity as derived from the architectural formation of structuring the context. Finally, regional digital architectural practice lends itself as an open-ended methodology for teaching architecture, tested within several study-unit seminars and research projects and Design Workshops tutorials. Here, the context is approached not as a collection of forms but topologically continuous capacities and constraints.

Key Words

Stereotomy, digital architecture, Malta, regional context, computational thinking

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1. Research Background

1.1. Practising and Teaching Architecture in Malta

“I’ve been practising architecture for the past fifty years …. I say 'practising' since I rarely get it right.”
(Cullinan 2008, paraphrased)

Malta's small scale and high urban density make apparent the stark contrast between traditional and contemporary architectures (Figure 1). The traditional architecture, based on limestone, established a tectonically coherent cultural landscape of different yet similar forms equated with the Maltese contextual authenticity. On the other hand, contemporary architecture consists of generic, universally bland built forms that are synonymous with the global, unremitting crisis of architecture (Cuff 2012). The schism is also present between the connected performances of the topologically continuous traditional cultural landscape and the individual, segmented, utilitarian contemporary architectural typologies.

While practising architecture in Malta, from a student intern up to a senior architect/project leader, I continuously confronted these contradictions within the built environment and their widely apparent impact on its quality. I found that developing design processes and architectural proposals that narrowed this gap was not a straightforward approach. When I became an assistant lecturer at the Faculty for the Built Environment, University of Malta, teaching and tutoring architectural design further exposed

Figure 1: View of the Sliema seafront.
The townscape is typical one of Malta, consisting of multi-story apartment blocks continuously replacing the traditional architecture.
Source: Bothe, F. 2014, Montage of various landmarks in Sliema, Malta, digital image, Wikimedia Commons, viewed 22 January 2019, https://commons.wikimedia.org/wiki/File:Sliema_montage.png

the difficulty to establish confident architectural thinking without understanding these contradictions.

As a result, a strong personal interest developed to assess built forms beyond their immediate appearances and performances towards differentiating architectural practices that actualised them. More specifically, my interest became to understand the underlying design thinking, methods of working, and contextual constraints that instigated the built forms.

1.2. Traditional Architectural Practice

"Malta is a small [316 km[1]], densely populated [1,448 inhabitants/km[2]] island country that is located in the central Mediterranean Sea, 100 kilometers (km) south of Italy and 290km north of Libya. The three inhabited islands of Malta, Gozo, and Comino host few mineral resources except for clay, limestone, and salt, and no indigenous mineral fuel resources."
(Hastorun 2014, page 29.1)

Malta's traditional architectural practice emerged from three dominant contextual constraints: the limestone as the single available building material, limited resources, and a geographic discontinuity.

For most of its history, Malta's geographic discontinuity made large-scale imports of tangible goods, like building materials and technology, unfeasible. The resultant lack of material variation established the traditional architectural practice grounded in design thinking and methods of working that were fully subservient to limestone.

The limestone is brittle, heavy, and "remarkable for its softness; it is sawed more easily than wood […] Hence, it is worked easily, but it is not strong enough against moistures and the sea-breezes; and […] it is not strong enough for mortar and cements [either]" (Quintin d'Autin, cited in Cassar 2010). Its heterogeneous lithology generates highly inconsistent performances necessitated proficient tacit material knowledge that formulated the traditional design thinking and methods of working (Mallia 2018). Since the production and the dissemination of the tacit knowledge were determined by contextual constraints (Heynen, Wright 2012), the advancements

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[1] GOVERNMENT SERVICES AND INFORMATION, 2019-last update, About Malta [Homepage of government services and information], [Online]. Available:
https://www.gov.mt/en/About%20Malta/Pages/The%20Maltese%20Islands.aspx [01/23, 2019]
[2] NATIONAL STATISTICS OFFICE MALTA, 2016b. *Trends in Malta 2016.* Malta: National Statistics Office Malta.

within the traditional architectural practice were slow yet persistent.

Further, the lack of material variation and limited technology tied the traditional methods of working to manual labour and minimal use, and extensive reuse, of non-local materials. The established traditional architectural practice was, thus, based on simple tools, techniques, and details yet encompassed high technical skills. Similarly, due to the laborious processes of extraction, transport, dressing, and assembly of limestone ashlars, they were never discarded but were continuously reused and re-engaged, either in their originally capacity or as gravel. In short, the traditional architectural practice was on an economy of means. Its design thinking and methods of working were grounded in self-reliance, frugality, and careful husbandry of Malta's limited resources (Tonna 1971).

In the hinterland contexts, different materials were engaged to comply with architectural forms' intended performance, typology, and style. It reflected in forms' distinct visual appearances and clear differentiation between architectural typologies. For examples, there is a clear visual distinction between the vernacular and the traditional, the secular and the religious, and the anonymous and the monumental architectures and their forms. In Malta, the lack of material variation, the limestone, and its strict constraints had to respond to all architectural concerns. In short, any pursued design intents were subservient, and thus secondary, to the design thinking and methods of working formulated by the limestone. As a result, the Maltese traditional architectural practice actualised built forms that did not comply to stylistic classifications and taxonomies of the hinterland context, albeit in the treatment of their surface ornamentation.

On the other hand, Malta's strategic position in the Mediterranean region instigated a continuously increasing geopolitical connectivity that prompted an increased influx of intangible goods. Since the intangible goods, like knowledge, skills, ideas, and influences were susceptible to contextual assimilations, they continuously expanded the design thinking and methods of working with the limestone. As a result, the Maltese traditional architectural practice emerged as at once rigid and robust, consistent and fluid (Tonna 1971). It was subservient to strict contextual constraints yet grounded in continuously increasing material knowledge that unveiled novel material affordances. It became proficient in engaging the single building material to fit diverse building performances and derive architectural responses to multiple design constraints of climate, structure, utility, and socio-cultural concerns.

In conclusion, the material-based, Maltese traditional architectural practice was a bottom-up and process-driven, rather than aesthetics-driven, architectural practice.

1.3. Contemporary Architectural Practice

"And in architecture, what could be more emotional than [stone] masonry? [...] It is the artistic characteristic of [stone] masonry that provides the ethical and aesthetic resonance that legitimises may things."

(Moravanszky 2008, page 22)

In recent decades, Malta's global geopolitical connectedness has negated its geographic isolation and enabled an unprecedented influx of tangible [3] and intangible goods. The abundance of investments[4], clients, and users[5] on a limited available footprint guarantees profitable returns for the building industry[6] and has instigated a persistent speculative building boom[7]. Due to the high population and urban density, Malta can be equated with a small European city, yet its operations have neither environs nor a surrounding region to rely on. Instead, the building industry achieves the economy of design and production through fixed procedures and high-volume imports of a limited number of semi-finished materials.

Firstly, architecture and engineering are approached as binary practises. Engineering has gained dominance with the increasing need to address technical requirements of the unprecedented complexity of building services and technologies. The concerns of the contemporary architectural practice have reduced to endowing the built form with unique sensorial qualities and the production of

[3] Between 2010 and 2015, imports increased steadily reaching €4.4 billion in 2015 (National Statistics Office Malta 2016b).

[4] In 2017, the foreign direct investment in Malta has registered an increase of almost 5 per cent over the corresponding period of the previous year (National Statistics Office Malta 2018a).

[5] Between 2001 and 2015, an increase of 55.6 per cent in inbound tourists was recorded. The trend continued in 2016, the number of in inbound tourists stood at 1, 965, 928, an increase of 10.2 per cent when compared to 2015. In terms of long-term residency, in 2017, with 46 immigrants per 1,000 inhabitants, Malta recorded the highest rate of immigration in the EU (National Statistics Office Malta 2016b, National Statistics Office Malta 2017, Bonnici 2019).

[6] In 2015, the largest increase in Gross Value Added (GVA) at basic price was recorded in the real estate industry, 15.1 per cent and assumed a contribution of 5.2 per cent to total GVA (National Statistics Office Malta 2017)

[7] In 2015, building permits increased by 34.4 per cent, the highest increase registered in the past years and considerably higher than the average increase of 7.2 per cent registered at EU level. Similarly, the amount of useful floor area registered in 2015 increased by over 19 per cent when compared to 2014. It is the highest increase registered in the past years and more pronounced than the increase registered at EU level of 6.6 per cent (National Statistics Office Malta 2016b). The trend continued in 2016 and 2017 with the number of building permits registering the second highest in Europe (Eurostat 2019).

documents to accurately describe them (Moussavi, López 2009, Carpo 2011).

Next, to respond feasibly to construction's low volumes yet varied demands, the contemporary architectural production uncritically streamlines pre-set affordances of imported, semi-finished materials[8]. Due to its performative versatility, ease of construction, and affordability, concrete has become the dominant building material. The methods of working in concrete have established a limited number of standardised building elements that supplanted the labour-intensive masonry configurations. More specifically, the precast concrete block for vertical surfaces and the cast-in-situ concrete for horizontal ones have become the norm (Figure 2 a).

Further, the current tax incentives and the low price of limestone resulted in quarries being more profitable as landfill sites for construction and demolition waste than to be used for the limestone extraction[9] (MaltaToday, 2017). Today, the limestone is solely used for its phenomenological characteristics of colour, mass, and permanence equated with the 'Maltese-ness' of the Maltese architecture. Engaged as a surface material, the limestone has become a tool of cultural mediation, to instigate familiarity, and to mimic the context, like an expected Mediterranean feel in touristic developments and expression of national identification in civic buildings (Figure 2 b).

In conclusion, although the contemporary Maltese context continuously complexifies, the Maltese contemporary architectural practice responds to a specific, limited set of its constraints. As a result, the architectural practice operates within a restricted design space bound by universal solutions, a limited material palette, and fixed, pre-set design thinking and methods of working. Visually, its built forms have ambiguous expressions of modernity, authenticity, and contextuality. Economically, the architectural practice is fully dependant on the non-local resources at every scale and each step of forms' actualisation[10].

[8] Import of salt, sulphur, earths, plastering materials, and cement increased by 39% from 2006 to 2018. Import of iron and steel increased by 20% from 2005 to 2017 (National Statistics Office Malta 2007, National Statistics Office Malta 2008, National Statistics Office Malta 2016a, National Statistics Office Malta 2018b, National Statistics Office Malta 2019)

[9] Between 2010 and 2014, mineral production from quarries decreased by 21 per cent as quarries closed down or temporarily suspended activities (National Statistics Office Malta 2016b).

[10] The non-local resources referrer to, among others, the non-renewable fuels used for the production of fresh water and electricity, materials used for building construction and building finishes, building services and technology, the building industry's work force, and the final users.

Figure 2: The Maltese Contemporary Architectural Practice
a) The dominant construction procedure uses the concrete block for horizontal surfaces and cast reinforced concrete for the horizontal ones.
Source: Author, 2019, Typical Construction in Malta, digital image
b) The New Parliament Building, completed in 2015, was designed by Renzo Piano Building Workshop (RPBW). Although the building is primarily a steel frame structure, the limestone is engaged as the façade cladding and interior finish to instigate familiarity.
Source: Vincentz, F. 2013, Parliament House under construction, with both the steel frame and limestone facade visible, digital image, Wiki Media, viewed on 12 January 2019 https://en.wikipedia.org/wiki/Parliament_House_(Malta)#/media/File: Malta_-_Valletta_-_Triq_ir-Repubblika_-_New_Parliament_Building_(St._John%27s_Bastion)_01_ies.jpg

In short, the contemporary Maltese architectural practice is fully subservient to the global contextual constraints and susceptible to their inevitable, volatile shifts yet, rigid and inflexible, it has neither ability nor adaptability to respond to them.

1.4. Divergent Materiality

"The acritical acceptance of design paradigms, prevalently developed in Northern Europe or North America, had let to an increasing use of solutions that bear no connection with [Mediterranean] tectonic research, and are often in blatant contrast with it …"
(D'Amato Guerrieri, cited in Etlin, Fallacara, et al. 2008, page 11)

The contractions between the traditional and the contemporary architectural practice stem from a fundamentally different approach to materiality. More specifically, they originate from divergent ways through which the material's virtual affordances are understood, and construction processes developed that actualise these affordances (De Landa 1995, Menges 2015).

The approach to the materiality of the traditional architectural practice was bottom-up. The traditional architectural practice continuously explored limestone properties to expand its capacities and overcome its constraints. In short, it sought to unveil novel affordances intrinsically embedded in the limestone to optimise and diversify its performances. The bottom-up approach made the traditional architectural practice susceptible to knowledge assimilations and appropriations that fortified its ability to actualise a web of multiple contextual forces as context-specific architectural solutions.

On the other hand, the approach to the materiality of contemporary architectural practice is top-down. The contemporary architectural practice produces specific formal and performative design intents with pre-set, synthesised material properties that are activated through fix construction procedures. The results are universal architectural solutions applicable to any context.

1.5. Research Motivation

> *"…positive values [of the traditional architectural practice] are being unnecessarily thrown away in the process of change, [and] the least we can do is draw on what remains of the past [to] project guidelines for the future"*
> *(Tonna 1971, page 6).*

The research motivation is to expand the current restricted and restrictive design space by assimilating the traditional, bottom-up, process-based approach to materiality within the contemporary architectural practice, its design thinking, and methods of working.

More specifically, the research motivation is to theorise the design thinking driven by neither technological imports nor romantic returns to precedents but by the continuously changing context. In this way, the design thinking lends itself as a theoretical framework for an architectural practice that establishes the economic robustness of methods of working and contextual authenticity of built forms. Both are derived from and for the transiency and indeterminacy of the contemporary Maltese contextual constraints [11]. The research motivation is, thus, to pursue an architectural practice that embodies architectural analysis, design, production, and teaching grounded in exploring, evaluating, and engaging of shifting contextual constraints.

Finally, in theorising the design thinking, the notion of materiality becomes pivotal, and the research motivation is to instigate its systematic rethink. Within the research, the notion of materiality encompasses both material and material knowledge. Similarly,

[11] The most obvious and immediate contextual shifts being the depletion of limestone reserves by the year 2036 (Cromie, Cole 2002), the limited access to sand for aggregates by the year 2020 (Thorns 2018), the exhaustion of landfill spaces for construction and demolition waste disposal by the year 2020 (Debono 2010), and the depletion of fresh water aquifers by the year 2100 (McGrath, 2007).

material knowledge encompasses both the understanding of the material's affordance and the proficiency of the methods of working that activate it.

1.6. Contemporary Stone Masonry Research

“[A] critical recognition of the current potential of stone masonry culture, intended not only as a continuity with traditional [architecture and its] construction techniques but also as their radical [assessment and] renewal.”

(D'Amato Guerrieri 2006, page 20)

During the twentieth century, stone masonry construction almost disappeared from the architecture of the hinterland regions. As a way to achieve contemporary insulations standards in an economically viable way, stone masonry reduces to the cladding of composite ‘sandwich’ walls (Dambacher, Elsener, et al. 2008).

During the past decade, there has been a renewed interest in the stone masonry discipline of stereotomy. The interest was instigated by the advancements of digital tools that enabled the design and representation of the complexity of conceived forms and their transformation into physical construction assemblages (Picon 2010). The contemporary stereotomic research [12] diversifies its traditional formal repertoire and seeks to reinstate stereotomy as a viable contemporary construction technique.

Throughout its history, stereotomy was grounded in exploring stone's affordances to resolve multiple design constraints as geometrically complex masonry assemblies. The contemporary stereotomic research pursuits engage digital tools to reinstate masonry construction technique's intrinsic bottom-up approach to materiality (Figure 3).

In conclusion, as at once a historical and a contemporary reference model of an architectural practice grounded in the bottom-up approach to materiality, stereotomy becomes the initial point of the research.

[12] The reference is made to the research by Mark Burry on the Sagrada Familia project, Giuseppe Fallacara at the University of Bari, The Block Research Group (BRG) at ETH Zurich, Pedro de Azambuja Varela and José Pedro at the University of Porto, Brandon Clifford at Matter Design, the AAU ANASTAS Studio, and Shayani Fernando at the University of Sydney.

Figure 3: Examples of Contemporary Stereotomy
a) The Armadillo Vault, The 15th International Architecture Exhibition, La Biennale di Venezia, Venice, Italy, 2016, by The Block Research Group (BRG).
Source: Baan, I. 2016, Armadillo Vault, digital image, dezeen, viewed on 1 April 2019, https://www.dezeen.com/2016/05/31/armadillo-vault-block-research-group-eth-zurich-beyond-the-bending-limestone-structure-without-glue-venice-architecture-biennale-2016/bbb
b) Stone Matters, Jericho, Palestine, 2017, by AAU ANASTAS.
Source: Burtstow, M. 2017, Stone Matters, digital image, ArchDaily, viewed on 14 March 2019, https://www.archdaily.com/870512/stone-matters-aau-anastas/590a1a4ee58ece2d8a000053-stone-matters-aau-anastas-photo

1.7. Research Methodology for Analysing Stereotomy

“Stereotomy was at the very edge of architecture [...] of mathematical geometry, […] of technical drawing, of structural theory, practical masonry, and military engineering [...] it is impossible to periodize [it] for the same reason. It was on the edge of classicism and every other stylistic category – baroque, rococo, neoclassical, Gothic, and even modern [...] It flourished only where definitions blurred, where one thing began to glide off into others; where structural theory met technical drawing, where neoclassical blended with rococo, where mathematical geometry came into contact with architectural composition, […] being peripheral to each, it was shared by all, […] joining many diverse regions”

(Evans 2000, pages 179 and 180).

The research methodology is based on assessing stereotomy's relevance for the research motivation. More specifically, the research methodology aims to assess stereotomy's relevance as a theoretical model to guide the evaluation of the two dominant Maltese architectural practices and the formulation of their contemporary, contextually responsive variants.

Firstly, the research focuses on the study of literature, primarily monographs and conference proceedings, that trace the development of stereotomy and stereotomic design knowledge throughout history. The literature study aims to understand the evolution and diversification of stereotomy from a stonecutting technique into a versatile, "multifaceted" (Sakarovitch 2003), practical and theoretical, geometric discipline. In short, the literature study aims to direct the research approach to stereotomy beyond the established formal and aesthetic taxonomies and their visual, observation-based assessments.

Next, the research focuses on the analysis of the historic stereotomic masonry assemblies. Based on the literature study, stereotomic precedents are approached at their fundamental level, primarily as physical, spatial responses to multiple design constraints. The analysis focuses on their underlying geometric relationships and dependencies that formulate generative rules from which the form emerges.

Finally, the research pursues a comparative study between stereotomy and digital architecture. The research approaches digital architecture beyond its ties to digital technology. Instead, it focuses on digital design processes where the architectural form is based on generate rules and derived through computational processes. In short, the comparative study is possible since the research recognises digital architecture as an architectural practice grounded in the bottom-up approach to materiality, akin to stereotomy.

2. Stereotomy

2.1. Στερεός (Stereós) "Solid" + τομή (Tomē) "Cut"

"The meaning of the word stereotomy, the etymology of which broadly designates the art of cutting three-dimensional solids into shapes to be assembled, is restricted in architecture to designate more specifically the art of stone carving for the purpose of constructing vaults, squinches, cupolas or flights of stairs […]"
(Sakarovitch 2003, page 69)

2.2. Acrobatic Architecture [13]

"[Stereotomy uses] the weight of the stone against itself by making it hover in space through the very weight that should make it fall down."
(Perrault 1964, cited Etlin 2012, page 2)

Stereotomy emerged in the Gothic period as a reversal in architectural thinking. Throughout Antiquity and the Middle Ages, buildings were thought of in the same way as they were made, from the ground up. For the Gothic builders, on the other hand, supported parts, like arches, vaults, and domes gave shape to the supporting parts and imposed design thinking from the top down (Sakarovitch 2003).

The dominant stereotomic design attitudes regarded 'difficult' as a superlative and difficulties were as much sought after as found (Evans 2000): ever-greater formal complexity, elaborate ornamentation, and daring statics that appeared as effortless as their visual comprehensions (Figure 4). In short, stereotomy enabled versatile topological transformations in architecture. Their actualisations, on the other hand, necessitated proficient geometric, instrumental, and material knowledge and intensive fabrication and construction processes due to multiple varied ashlar configurations and elaborate falseworks.

At the end of the nineteenth century, major contextual shifts instigated polarly different design attitudes to the stereotomic ones. As a result, stereotomy was abandoned and stereotomic design knowledge relegated into the realm of "forgotten geometries lost to us [architects] because of the difficulties of their representation" (Moneo 2001, cited Kolarevic 2004).

[13] A term used by Richard Etlin to describe stereotomy (Etlin 2012).

Figure 4: Examples of Traditonal Stereotomy
a) Staircase at the Monastery of Notre-Dame de la Couture, Le Mans, France, 1720-39
Source: Etlin, R. 2012, from (Etlin, 2012), page 23
b) The City Hall Vestibule, Arles, France, by Jules Hardouin-Mansart, 1637
Source: Etlin, R. 2012, from (Etlin, 2012), page 12
c) Henry VII Chapel, Westminster Abbey, London, UK, by William & Robert Vertue, 1519
Source: Jenner, M., Henry VII chapel, Westminster Abbey, Westminster, London, England, digital image, Great Big Canvas, viewed on 11 March 2019, https://www.greatbigcanvas.com/view/henry-vii-chapel-westminster-abbey-westminster-london-england-uk,2089492/

2.3. Geometric Nature

"The key to understanding of [stone] masonry is to be found in a correct understanding of geometry."
(Heyman 1995, page 154)

Since stereotomy was intrinsically geometric, it established a knowledge exchange network with several geometry-based disciplines: mathematical [theoretical] geometry, technical drawing, structural theory, practical masonry, and military [civil] engineering (Evans 2000). The resultant, positive feedback loop continuously expanded stereotomic design knowledge. It increased stereotomy's proficiency in the design, representation, and execution of complex architectural geometries (Witt 2010), "freed from Euclidian metric" (Sakarovitch 2003, page 25).

Stereotomy became an epitome of geometrical complexity in architecture though its ability to derive geometric procedures that instrumentalised design knowledge on negotiating multiple contextual constraints [14] and design intents [15] (Witt 2010). Geometric procedures discretised contextual constraints and design intents through their underlying procedural rationality and externalised them as a system of geometries and geometric

[14] The reference is made to contextual constraints of available resources and materials, their properties (primarily stone’s lack of tensile strength), variations in the force flow during construction, the complexity of the force flow upon execution, and limitations of fabrication.
[15] The reference is made to design intents like symbolism, aesthetics, and phenomenology.

interdependencies. The system itself was subject to evolutionary change yet once in a fixed instance, it could be fleshed out in a wide variety of forms (Heyman 1995).

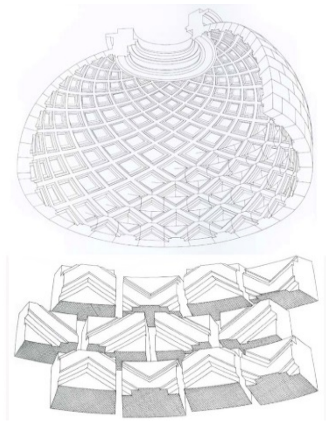


Figure 5: Anet Castle Chapel, Philibert de l'Orme, 1549-1552.
Source: Potié, P., 1996, from (Potié, 1996), page 54.

2.4. System of Geometries and Geometric Interdependencies

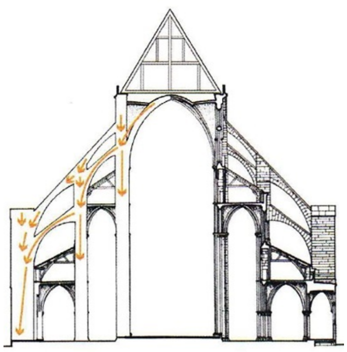
"Stereotomicly determined masonry, despite the immanent presence of geometry throughout, shows less obvious trace of geometric regulation … This effect is largely dependent on a normative idea about what geometry looks like."
(Evans 2000, page 195)

The stereotomic system of geometries encompassed the assembly geometry, the ashlar geometry, the structure geometry, the falsework geometry, and geometries defined by available tools and technology. The geometries were neither hierarchical nor discrete, and their interdependencies were almost non-exhaustive.

The most evident, mutually-defining interdependency was between the assembly geometry and the geometry of its constituent ashlars: any assembly was a whole tessellated into parts and propagation of parts generating a whole (Fallacara 2007) (Figure 5).

The structure geometry reflected a system of structural actions that resolved the force flow (Figure 6). The structural geometry also reflected the appropriateness and efficacy of these structural actions (Sekler 1965). Jointly, the assembly geometry and the ashlar geometry were in a formative dependency with the structure geometry: any assembly and its constituent ashlars were subservient to the structure geometry while, concurrently, their shape and proportion ensured the stability (Heyman 1995). In short, the assembly and ashlar geometry ensured the validity of the structure geometry.

Figure 6: Load paths of thrusts from main vault and buttresses
Source: Addis, B., 2007, (Addis, 2007), page 98.



Further, the structure geometry had to respond to force flow variations at each stage of the construction process. Together with the assembly geometry and constraints of the construction process, the structure geometry determined the falsework geometry. At the same time, the falsework geometry had to allow for the falsework's fast and simple mounting and dismantling, its easy use, and its multiple reuses. Due to necessary falsework optimisations, thus, the falsework geometry influenced the formulation of both the assembly geometry and the structure geometry (Figure 7). The falsework geometry also determined the sequencing of the construction process (Fitchen 1967).

Similarly, there was a co-evolution between the construction process, representation tools, and the knowledge embedded in

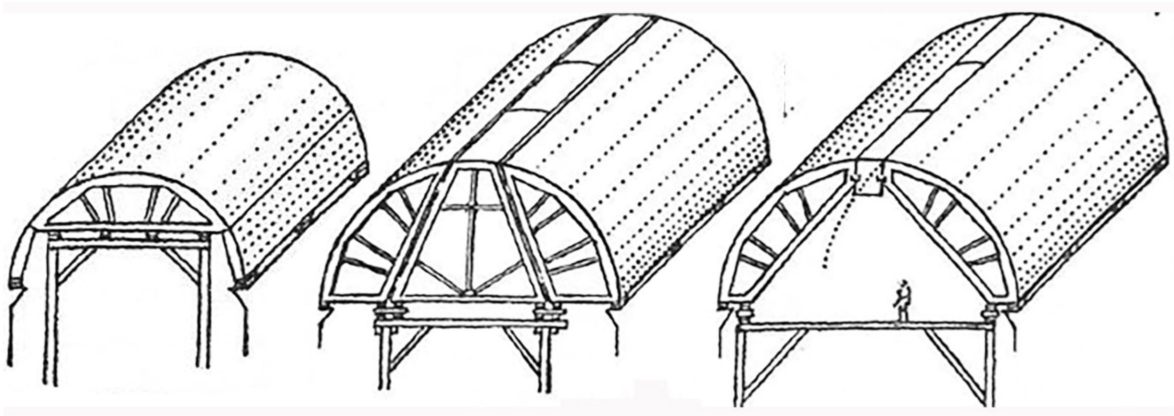


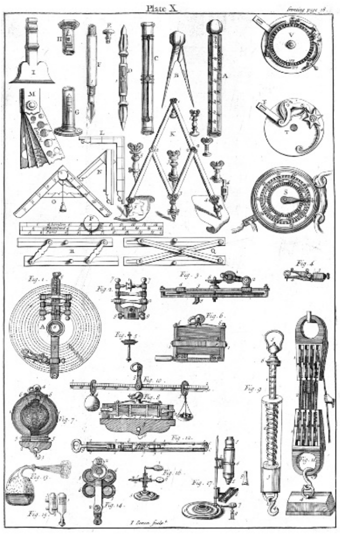
Figure 7: Possible Types of Barrel Vault Formwork and Centering
Source: Fitchen, J., 1967, adapted from (Fitchen, 1967), page 54.

these tools. More specifically, the advances in the geometric rigour, precision, and control improved the design of drafting, fabrication, and construction tools and procedures, and vice versa (Witt 2010) (Figure 8).

2.5. Trait

"… in the late Middle Ages, drawings, whether on parchment, a plaster of Paris floor, or wooden planks erected on scaffolding, were used to set out the curvature of the vault ribs and the profile of their stones. In the Sixteenth century with the rise of stereotomy, it appears that a new type of drawing was produced that enabled the masons to establish not only the shape of the vault but also the often complex three–dimensional shape of each stone."
(Etlin et al. 2008, page 19)

Figure 8: Drafting instruments that embedded geometric knowledge on complex geometries, from "Traité de la construction et des principaux usages des instruments de mathématiques", by Nicolas Bion, from 1709
Source: Bion, N., 1709, (Witt, 2010), page 46.



Stereotomy was a geometry-based discipline that discretised contextual constraints and design intents through their underlying procedural rationality and externalised their negotiations as a system of geometries and geometric interdependencies. Stereotomy's platform for formulating the system was the trait. The trait was both a preliminary drawing that regulated the ashlar and the assembly geometry to ensure their buildability (Figure 9 a) and a layout drawing that enabled precise ashlar fabrication, the formulation of the falsework geometry, and the sequencing of the construction process (Figure 9 b).

The onset of the printing press motivated the production of traits as a way to dissipate the oral secrets of the masons' lodges in a drawing format[16]. Numerous architectural treatises were published

[16] The first trait in a print format was published by the French architect Phillbert De l'Orme in his 1597 treatise "Le premier tome de l'architecture" (Etlin et al. 2008). In the treatise, De l'Orme also urged

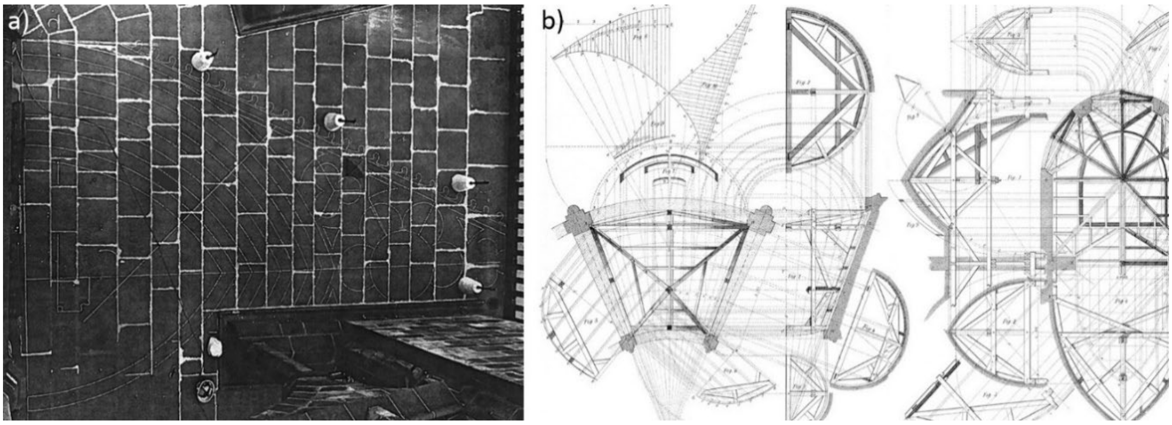


Figure 9: Trait Types
a) A proto-trait drawn on the ground, Clermont-Ferrand Cathedral, end of 13th century.
Source: Sakarovitch, J. 1998, from (Sakarovitch 1998), page 126.
b) An advanced, late 19th century trait describing a complex, vaulted falsework. Its comprehension required proficient geometric knowledge to handle the trait's "spatial development and measurement of compound curvature, including the calculation of complex unrolled shapes" (Witt 2010, page 52).
Source: Mazerolle, L., 1895, from (Witt 2010), pages 52 and 53

that catalogued the established stereotomic assemblies (Sakarovitch 2003, Evans 2000). Since within stereotomy there was no separation between the design and execution concerns, throughout history, the production of traits instigated the development of graphical representation techniques that merged master masons' applied and mathematicians' erudite geometric knowledge. In this way, the trait's representational role progressively transformed into a didactic one. The traits' focus becomes theorising and abstracting stonecutting problems into universal spatial studies. As a result, the production of traits embedded and instrumentalised practical and theoretical geometric processes that controlled two-dimensional into three-dimensional transformations, and vice versa (Sakarovitch 2003, Sakarovitch 1998).

"Traits were not illustrations and yield little to the casual observer. They were orthographic projections, but they were not like other architectural drawings" (Evans 2000, page 179). The 'other' architectural drawing was predicated on the notational sameness between its architect's intent and the maker's translation of that intent into a three-dimensional object (Carpo 2011). Here, the author codified the form. The trait author encoded form's formation process. More specifically, the trait author embedded design knowledge within the trait to parametrically formulate a stereotomic system of geometries and their dependencies. As a result, both the production and the understanding of the trait necessitated proficient geometric knowledge of complex

architects that "stereotomy [was] a technique too important to be left only in the hands of stonemasons and that knowing traits should be part of architect's education" (Sakarovitch 1998, page 136).

geometries and proficient instrumental knowledge of drafting tools (Witt 2010). On the other hand, the trait made the embedded design knowledge accessible and, thus, susceptible to appropriation and assimilation by others, both architects and makers, blurring the boundaries between the two.

2.6. Digital Nature of Stereotomy

"Open-endedness, variability, interactivity, and participation are the technological quintessence of the digital age [and digital architecture]."

(Carpo 2011, page 126)

2.6.1. Structuring

In the realm of contemporary architectural theory, the stereotomic process that discretises and externalises contextual constraints through procedural rationality as a system of geometries and their dependencies is referred to as structuring[17]. More specifically, the digital architectural theory defines the structuring as a set of bottom-up, computational processes[18] that analyse and recognise the underlying mathematical/geometric, syntactic, and formal logic of material properties, structural patterns, geometric attributes, and configurative transformations. The outcome of structuring is a system of generative rules, or more specifically, a material system (Oxman, Oxman 2010). The material system is, thus, an arrangement system of generative rules instigated by contextual constraints and activated by contextual feedback where a fairly simple behaviour by an individual element results in a complex and irreducible collective behaviour (Spuybroek 2011). Akin to the stereotomic system of geometries and geometric dependencies, the material system is derived from and for a specific context and is, thus, intrinsically susceptible to contextual changes.

2.6.2. Objectile

Similarly, from the theoretical perspective of digital architecture, the trait can be understood as an objectile. The objectile is an open-ended algorithm based on a parametrical function that determines infinite object variations. Each variation is different, defined by different parameter sets and yet all variations are similar, since they are derived from the same underlying function (Carpo 2011). In the

[17] Structuring is one of the processes proposed by New Structuralism theory that argues for a digital architectural practice based on spatial, structural, and material principles synthesis in lieu of the traditional linear [Modernist] form- structure-material sequence (Oxman, Oxman 2010).
[18] Reference is made to both digital software simulations and physical experiments.

same way, a specific stereotomic element belongs to a general category from which it is differentiated by the trait.

For example, the arch trait can actualise an arch through preset construction instructions. On the other hand, the arch trait as a fixed normative genus, an exactly transmissible but nonvisual notation (Carpo 2011), embodies infinite virtual variations. The comprehension of the arch's underlying generative rules enables its contextual activations as varied, different, yet similar forms. The trait embeds a parametric description of the geometric procedure that differentiates a specific arch for the specific context from an infinite number of arches. In short, a specific arch is derived as a negotiation of contextual constraints that define the geometric dependencies within the stereotomic system embedded in the arch trait (Figure 10).

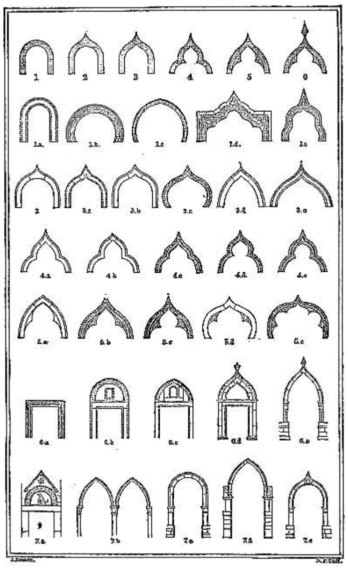


Figure 10: Ruskin's "The Orders of Venetian Arches" illustrates configurational variations defined by the arch trait.
Source: Ruskin, J., from (Ruskin 2009), plate XIV

The trait, like the objectile, has two types of authors: the author that designs the (or a series of) generative notation(s) that are general, generic, and parametric, and the author that specifies these notion(s) to design individual forms (Carpo 2011). Throughout history, the trait's author pairs changed and multiplied: master mason and stone carver, architect and master mason, scholars and geometers, etc. (Sakarovitch 2003). As a result, the trait's role became multifaceted yet, in Deleuzian terms, remained singular and clear: to differentiate multiple actual forms from a single virtual idea (Moussavi, López 2009).

2.6.3. Digital Architectural Practice

In conclusion, stereotomy is akin to digital architecture as an architectural practice grounded in the systemic approach to a context that derives solutions from bottom-up, computational processes. Similarly, digital architecture is akin to stereotomy as an architectural practice that pursues the assimilation of multiple contextual constraints within the design process [19]. The digital nature of stereotomy and the stereotomic nature of the digital architecture, thus, expose a persistent, uninterrupted development of an architectural practice that explores contextual affordances and engages them as architectural responses. In short, the fundamental similarities of the historical and contemporary architectural practices expose a historical continuity of the digital architecture.

[19] Reference is made to publications like AD Magazine issues "New Structuralism" (Oxman, Oxman 2010), "Material Computation" (Menges 2012a), and "Material Synthesis"(Menges 2015) and FABRICATE conferences proceedings from years 2011, 2014, and 2017 (R. Sheil, Menges et al. 2013, B. Sheil, Menges et al. 2014, B. Sheil, Menges et al. 2017). The dominant contextual constraints they considered are the structural, climatic, material, and fabrication ones.

Finally, stereotomy and digital architecture, as architectural practices grounded in the structuring, fold the context within the design process to establish a material system. The material system, in turn, unfolds the context within its outcomes, the architectural response. In this way, the visual, formal complexity of the derived architectural responses is not necessarily a pursued design intent but an intrinsic by-product of the contextual engagement of their material system.

2.7. From Contemporary Stonecutting …

"The tool and the knowledge that it encapsulates [or their lack of] enable or disable the designer in the act of design."
(Witt 2010, page 69)

The current leading research into stereotomy is located in, and thus folds into its design process, the context dominated by an abundance of resources, high-end technology, and instrumental knowledge[20]. The contemporary stereotomic investigations engage digital tools to parametrise multiple design constraints within rule-based processes and associative geometry models that directly inform the design, fabrication, and construction of complex masonry assemblies. The research gives precedence to the latter, geometrically complex masonry construction, rather than the former, the structuring. As a result, the traditional stereotomic system of geometries is amplified but remains fundamentally unchanged. The contemporary stereotomic research achieves and resolves an increased complexity of the ashlar and the assembly geometries, while it retains, even increases, the intricacy, labour intensity, and cost of the falsework geometry. In this way, the contemporary stereotomy retains the stumbling block that initially denied its viability (Figure 11).

In conclusion, contemporary stereotomic research delivers unprecedented advancements for the stone masonry construction within the context of abundant resources, technology, and instrumental knowledge. These advancements have little relevance for a context with different contextual realities, a context like Malta.

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[20] Instrumental knowledge refers to the understanding of procedures, like software, program, and script to successfully operate tools to an intended effect that facilitates the design aims. The notion also includes the ability to abstract the inverse constraints of tools to pre-rationalise the design. The power of proficient instrumental knowledge lies in the ability to access, hack, and transform the procedures encapsulated in the tools (Witt 2010).

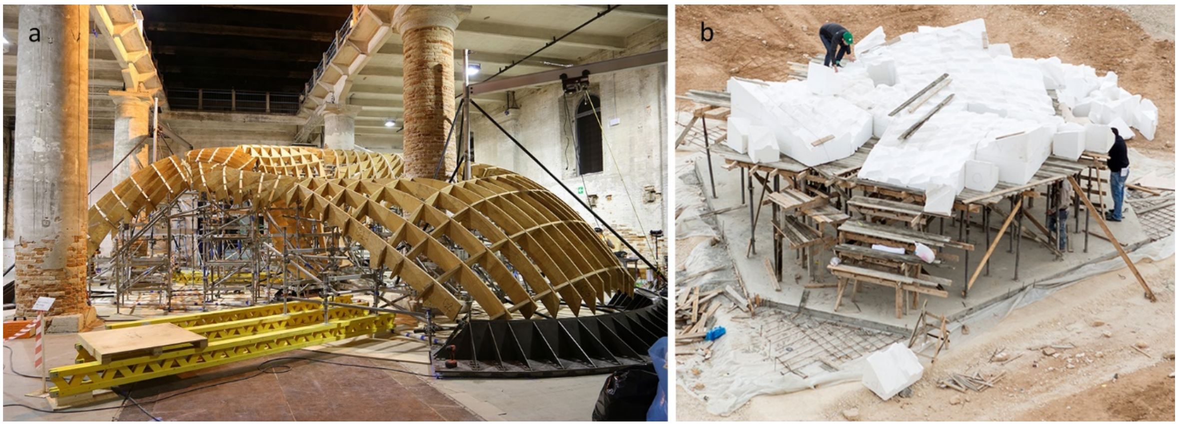

Figure 11: Elaborate Falsework
a) The assembly of the Armadillo Vault at the 2016 Venice Biennale, by The Block Research Group (BRG) used a geometrically complex and laborious falsework consisting of a waffle plywood structure propped on scaffolding.
Source: Escobedo, D., 2016, Installation - Corderie Dell'Arsenale, Venice Italy, digital image, The Escobedo Group http://www.armadillovault.com/armadillo-installation/
b) The assembly of the 2017 Stone Matters project by AAU ANASTAS used a falsework consisting of large, CNC milled, expanded polystyrene blocks propped on scaffolding.
Source: Burtstow, M. 2017, Stone Matters, digital image, ArchDaily, viewed on 14 March 2019, https://www.archdaily.com/870512/stone-matters-aau-anastas/590a1927e58ece2d8a000042-stone-matters-aau-anastas-photo

2.8. … Towards Digital Rethink of Stereotomy

The research sets up a premise if stereotomy is investigated at its fundamental level its full potential for contemporary architecture in general, and digital architecture, in particular, is exposed. Firstly, it approaches stereotomy beyond its immediate definition as a stonecutting technique for executing the geometrically complex masonry construction. Further, it approaches stereotomy beyond its ties to pre-set, specific material and construction choices.

Similarly, the research sets up a premise that if digital architecture is approached beyond its perceived ties to digital tools, it fosters a conceptual design thinking to include contextual heterogeneity, interconnectivity, and relatedness in architecture. In this way, digital architecture gains a wider relevance in an expanded context that also includes Malta, a context marginal to the digital (and contemporary stereotomic) research 'hot spots'.

In short, the research premise is that stereotomy is an intrinsically digital architectural practice grounded in establishing material systems through contextual structuring. Approached at this fundamental level, stereotomy, thus, lends itself as a theoretical framework to guide an architectural analysis that differentiates the underlying design logic, methods of working, and contextual constraints that instigate a built environment. Further, stereotomy also lends itself as a theoretical framework to guide architectural thinking that establishes a contextually engaged, and thus contextually responsive, contemporary architectural practice.

3. Digital Architecture

3.1. Systemic Thinking and Computation

"Computational thinking is influencing research in nearly all disciplines, both in the sciences and the humanities … It is changing the way we think."
(Bundy 2007, cited in Kotnik 2016, page 43)

Digital architecture opposes the Modernist, top-down design process that imposes universal solutions to any context. Instead, the digital design process approaches design problems through systemic thinking about context and derives solutions through computational, bottom-up design processes that instigate context-driven solutions.

Systemic thinking is a holistic examination of broadly applicable interaction patterns that underlay, drive and govern a system. Contrary to reductionist thinking, where a whole is divided into parts, systemic bottom-up thinking recognises the overall global arrangement of parts as a cohesive synergetic distribution of their dependences.

The system's behaviour is expressed through emergent generative processes. These are the regulatory feedback mechanisms that process and react to information to influence and to be influenced by context. The notion of context is, thus, understood as a network of processes, not a collection of forms. Within it, the tangible, static boundaries, obvious to our senses of vision and touch, become indistinct and "fuzzy" when understood as processes of intense activity and information exchange (Turner 2000).

Computation focuses primarily on the problem formulation and process expression, from which a solution, or a range of solutions, is derived. Computation can both describe a process through inner principles of its activity and plug-in into process's activity, its unfolding (Picon 2017).

3.2. Digital Tools

Digital tools have made systemic thinking the dominant contemporary scientific exploration method. More specifically, they enabled computational means which could handle large sets of interactions between various quantifiable entities and in depth exploration of the self-regulating effects of feedback (Kotnik 2016).

Digital tools also allowed for systemic concepts to be embedded as software, and cross over and diffuse within the architectural discourse (Kotnik 2016). As a result, they have instigated architectural explorations that are referred to as digital architecture. Since digital tools facilitate and amplify explorations' computational processes, they are often perceived as indispensable to the digital architecture. This notion "veils the mind-changing potential of the digital and limits the conscious recognition of computation as a paradigmatic shift within the [architectural] discipline" (Kotnik 2016, page 43).

3.3. Systemic Notions in Architecture

The assimilation of systemic concepts within architecture has altered some of its fundamental notions.

Firstly, nature ceases to be understood as a dialectical opposition to the manmade as the two intertwine. The tangible static boundaries between dichotomies, like animate and inanimate, subject and object, sensation and technology, physical and abstract, concept and percept, and virtual and actual become indistinct when understood as regulatory processes (Turner 2000, Moussavi, López 2009, De Landa 1995, Blumer, Danuser 2009).

Similarly, the notion of context is understood as a comprehensive, complex system of interdependent, continuously changing realities[21]. Within it, architecture operates as an all-encompassing web of relationships that are expressed in its dynamic forms and constantly negotiated meanings (Hosagrahar 2012). In short, context is a scale-less, topologically continuous landscape of affordances, i.e. contextual capacities and constraints.

Further, “[t]he Aristotelian view on matter as an inert receptacle of [arbitrary] form superimposed from the outside" (Menges 2015, page 10) with “unbound violence” (Picon 2017) is abandoned. Instead, the matter is recognised as a notion that is inherently animate. It embeds generative processes that enable it to affect and be affected by its context.

In the same way, the Newtonian idea of an obedient material, governed by general laws, shifts towards recognising material's spontaneous activities (Menges 2015). The material is recognised through its multiple, immanent, virtual patterns of being that become discrete and actual at specific environmental thresholds

[21] The term contextual reality refers to any, tangible or intangible, aspect of the context, like climate, materials, skills, knowledge, tools, technology, cultural traditions, social idioms, political and economic trends, etc.

(De Landa 1995). In short, the material is understood through its affordances, specific capacities and constrains that are activated within a certain circumstantial set of contextual realities.

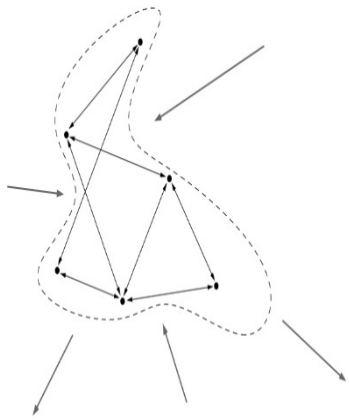

Figure 12: Form, a relative actualisation of a material system's relationships.
Source: Kotnik, T 2012, from (Kotnik 2012)

3.4. From Material to Materiality, From Form to Formation

"[…] a change in our approach towards materiality [is required], away from an understanding of material as exclusively physical and tangible […] This expanded notion of materiality […] allows built forms to address multiple causes and hybrid concerns […]"
(Moussavi, López 2009, page 8)

Akin to stereotomy, digital architecture encompasses the design process that seeks to understand materials' affordances and develop construction processes that activate them. It shifts away from design processes that engage synthesised, pre-empted material properties to meet specific phenomenological or utilitarian requirements of the design intent. Instead, the digital design process pursues materials' spontaneous activities and embedded affiliations.

As a result, the digital design process is not subservient to the final form as a fixed design imposition that dictates its structural solutions and material choice. Instead, the digital design process derives the form from a material system. The material system is an arrangement system formulated by an internal logic and external adaptation. The internal logic is based on the relationships between material system's constituent elements. The external adaptation is based on the material system's contextual feedback. The derived form is, thus, a relative actualisation of material system's relationships (Kotnik 2012) (Figure 12). In this way, the form is defined by the formation, the underlying, active, generative rules that establish the material system's relationships.

In conclusion, the digital architecture recognises the notion of the architectural form as an emergent outcome of a contextually engaged material system.

3.5. Material System's Behaviour

"The material system morphology is an expression of external and internal forces in equilibrium in subsequence of variable material properties [i.e. affordances] and [contextual] force distribution."
(Menges 2012, page 20)

3.5.1. Structure and Construction

The behaviour of the material system, its contextual engagement, establishes and is formulated through continuous a negotiation between the structure and construction.

The structure is a virtual arrangement system destined to cope with forces [of the contextual realities] at work (Sekler 1965). It is derived through the process of structuring. The structuring encompasses a set of computational processes that discretise contextual realities and their dependencies through their underlying logic and externalise them as a system of generative rules (Oxman, Oxman 2010).

Construction encompasses any process by which the structure actualises as a communicable[22] form (Sekler 1965).

3.5.2. Design Knowledge and Tectonics

The negotiations between the structure and construction are enabled and disabled by design knowledge and expressed through the architectural tectonics.

Design knowledge refers to knowledge of material system's affordances. It combines the understanding of the structure's organisation principles (parts to whole relationships, dependencies of program constraints, requirements of spatial organisations), with material, geometric, and instrumental knowledge (Witt 2010). Design knowledge expands with each iteration of the material system's actualisation. More specifically, with each actualisation, newly gained design knowledge refines and redefines either the material system's structure, construction, negotiations, or all of its three aspects.

The architectural tectonics is an expressive result of the structure realised through construction (Sekler 1965). As both deliberate and derived, the architectural tectonics concurrently drives the material system, its structure and construction negotiations, and emerges from it as the particular manifestation of empathy in the field of architecture (Sekler 1965) (Figure 13).

The notion of the material system's behaviour is further explained with two examples. The first example engages digital tools, while the other predates them.

[22] The notion of the communicable form refers to any means by which the form is described. This includes the form described through either its physical and spatial resolve, graphical representation, digital simulation, algorithmic encoding, or programming.

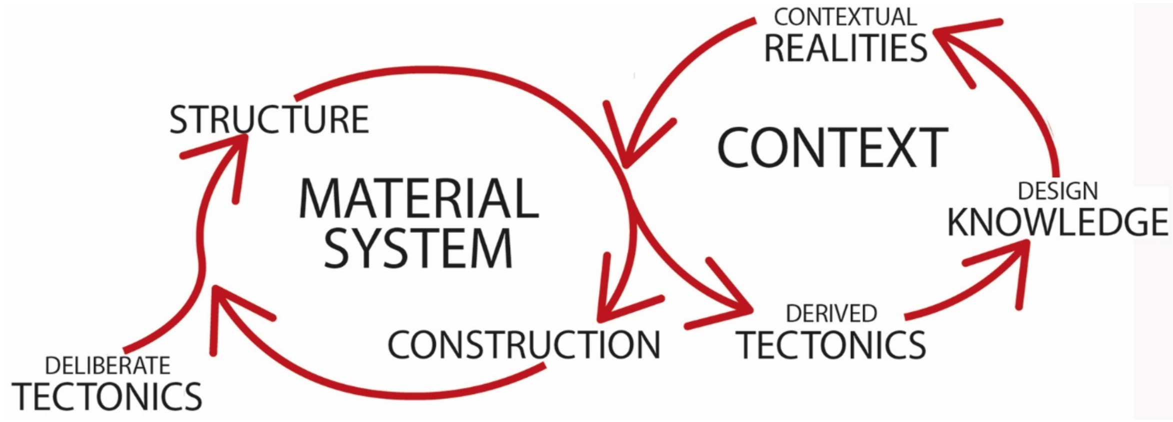

Figure 14: Behaviour of contextually engaged material system.
Source: Author

3.5.3. 2010 ICD/ITKE Research Pavilion

In 2010, the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE), together developed a pavilion (Figure 14) that was the first in a series of collaborative research pavilions that investigated the notion of augmented analogue material computation. The augmented analogue material computation engages the process of structuring to establish material-driven, bottom-up, generative design processes. Both the structuring process and the digital design process are expanded and amplified through the use of digital tools. The specific focus of the 2010 ICD/ITKE research pavilion was on exploring the affordances of extremely thin plywood strips.

Firstly, the physical experiments were conducted that elastically bent the plywood strips. They discretised the deflection range of the bending-active structural action (Figure 15 a) and externalised it as geometric information (Figure 15 b).

Next, encoded as a digital parametric computation model, the geometric information allowed for performative explorations that structured the bending-active structural principle as a topological arrangement. The topological arrangement was based on the pleating of the adjacent plywood strips into a segmental arch. For each pair of adjacent plywood strips, the pleating configuration allowed for the energy stored in a bent region of one strip to be maintained by the tensioned region of the other (Figure 15 c).

Finally, the negotiation of the topological arrangement with contextual constraints of the site, fabrication, and manual assembly was structured as a set of generative rules that formulated a material system (Fleischmann, Knippers, et al. 2012).

Figure 13: ICD/ITKE Research Pavilion,
University of Stuttgart, 2010
Source: Lienhard, J 2012, from (Fleischmann et al., 2012), page 48.

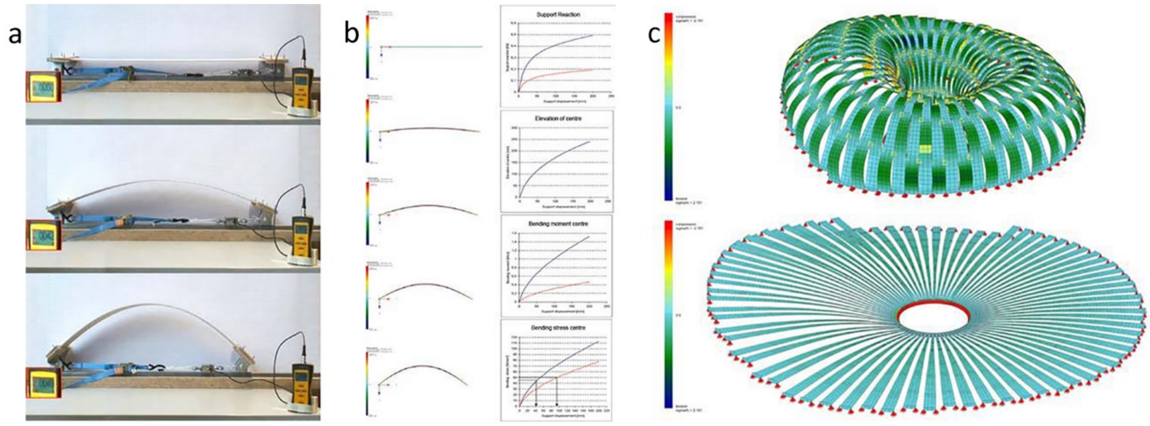

Figure 15: ICD/ITKE Research Pavilion
a) Material computation based on physical experiments elastically bent thin plywood strips to discretise the deflection range of the material's bending-active structural action
Source: Eisenhardt, A; Vollrath, M; Wächter, K 2012, from, (Fleischmann et al., 2012), page 47.
b) The deflection range of the bending-active structural action externalised as geometric information.
Source: Eisenhardt, A; Vollrath, M; Wächter, K 2012, from, (Fleischmann et al., 2012), page 47.
c) Geometric information encoded as a digital parametric computation established pavilion's topological arrangement.
Source: Lienhard, J 2012, from (Fleischmann et al., 2012), page 48.

3.5.4. Gothic Architecture

Several architectural theoretical discourses recognise Gothic architecture as a historical instance of digital architecture[23]. They approach Gothic forms as different emergent topological outcomes of the same material system. The material system was instigated by an active space of interactions and converged tangible and intangible contextual forces of gravity, perception, and social organisations (Lynn, Kelly 1999, Moussavi, López 2009).

For Moussavi (2009), the Gothic material system consisted of bays acting as dynamic, versatile base units that varied when repeated and mutated when hybridised with other base units. The material system responded to its context to derive novel, unpredictable forms that were temporarily and spatially specific (Moussavi, López 2009).

Likewise, for Spuybroek (2011), the Gothic architecture was an organisational amalgam of form variations derived from a dynamic material system. The material system emerged from operational

[23] Apart from the Gothic architecture, the digital architectural theory traces a number of other historical instances of 'proto-digital' architecture. The 'proto-digital' architecture is an architectural practice that derived the form from a contextually engaged material systems. These include, among others, vernacular architectures (Moussavi, López 2009, Hensel 2008), traditional craftsmanship (De Landa 1995), and the work and theory of Antonio Gaudi, Josef Albers, Hans Isler, and Frei Otto (Moussavi, López 2009, Menges 2015). From a wider theoretical perspective, thus, digital architecture predates digital tools.

and procedural rules. Its relationships were fixed, but not its derived forms. They emerged from the material system as ever-shifting combinations of variable, flexible sub-elements: the ribs (Spuybroek 2011).

3.6. Beyond Visual Assessments …

"For one thing, premechanical classicism was as much parametric and generative as medieval [Gothic] stereotomy."
(Carpo 2011, page 128)

Although relevant, the interpretation of the Gothic material system is limited by an analysis grounded in visual observations of architectural forms' structural plausibility and legibility. The analysis solely seeks the expressive potential of their construction techniques through their parts-to-whole relationship logic (Frampton, Cava 1995). As a result, the visual-based analysis differentiates between stereotomy's early, Gothic period and its late, 'acrobatic' variations. While it praises the former for an apparent structural clarity, it dismisses the latter as frivolous.

As discussed throughout this chapter, stereotomy, including the Gothic architecture, cannot be divorced from its geometric nature and its underlying procedural rationality. A valid analysis of stereotomy, thus, needs to encompass the process of structuring. More specifically, a relevant stereotomic analysis is procedural and recognises its ability to discretise and externalise multiple contextual constraints as generative material systems.

3.7. … Towards Procedural Analysis

"Paradoxically, quest for depth led to an infatuation with the façade or skin, in other words with superficial, the two-dimensional."
(Picon 2010, page 23)

Stereotomic design knowledge expanded through contextual explorations and geometric knowledge exchanges with multiple disciplines. Through appropriating and assimilating the external knowledge, stereotomy increased its proficiency in resolving multiple design constraints as architectural, spatial responses.

When with the twentieth-century paradigm shift stereotomy was abandoned, architecture left the multidisciplinary geometric knowledge exchange. Instead, its design process focused on the rationalisation and standardisation of the structure and construction and streamlining their negotiations. More specifically,

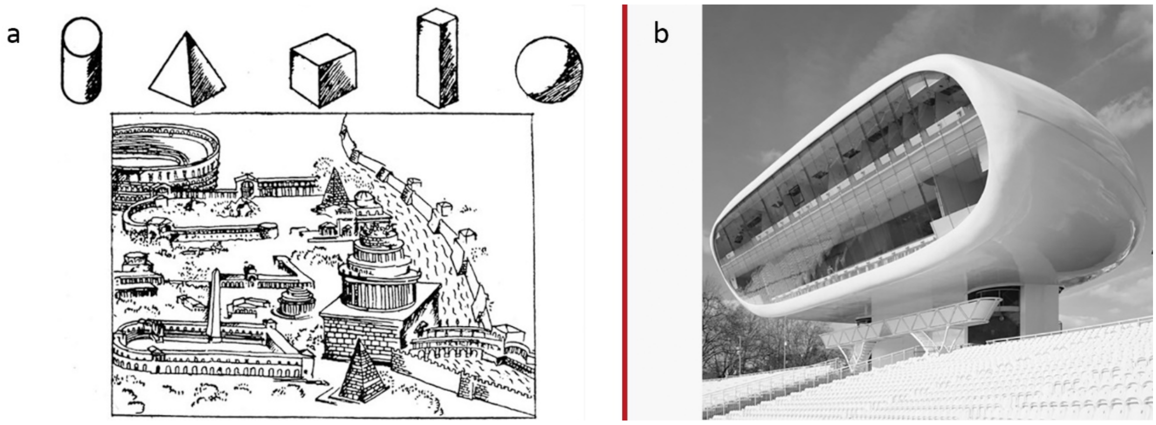

Figure 16: Platonic and Geometrically Complex Architectural Forms
a) Le Corbusier's "The lesson of Rome"
Source: Le Corbusier 1923, from "Towards a New Architecture" (Vers une architecture, 1923), Dover Publications, New York 1986.
b) The NatWest Media Centre, Lord's Cricket Ground, London, UK, 1999, by Future Systems is an aluminium, semi-monocoque building designed and manufactured in shipyard then brought in segments and assembled on site.
Source: Future Systems, from (Kolarevic 2004), page 9.

to achieve repeatability, speed, and mass production, the design process became subservient to machines' pre-set constraints (Witt 2010) and synthesised pre-emptied materiality. The scarce, Platonic-based geometries of the resultant architectural forms become the norm[24] (Kotnik 2012) (Figure 16 a).

On the other hand, the geometric knowledge exchange continued between the sciences and other industries. Since a great number of the industries (aviation, automobile, shipbuilding) were based on sheet materials, the geometric research focused primarily on surfaces. The geometric research into volumetric complexities dealt with either small scale, like within product design, or was not concerned with materiality, like within digital modelling and film animation.

By the end of the century, the accumulated geometric knowledge was embedded in different CAD and CAM digital tools that were appropriated by architects. Easily employed, digital tools did not require users' understanding of embedded geometric knowledge. Instead, the design, representation, fabrication, and construction of geometrically complex architectural forms were attained through instrumental knowledge (Witt 2010). In short, solutions were directly borrowed from other disciplines (Figure 16 b). As a result, architectural practice only partially appropriated knowledge on complex geometries. Unlike stereotomy, contemporary digital architecture remains surface-based and technology-driven. It has yet to develop large-scale volumetric actualisations (Picon 2010).

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[24] Configurations assumed too complex to be machine produced were marginalised (Witt 2010).

In conclusion, stereotomy is a digital architectural practice that encompasses design thinking grounded in the systemic approach to context, methods of working grounded in procedural rationality, and design knowledge developed through contextual explorations and knowledge assimilations. The research premise is, thus, that approached at its fundamental level, stereotomy is an architectural practice that is more relatable and relevant to the Maltese context than any contemporary architectural practice of the hinterland regions. As a result, the research focuses on the procedure-based analysis of stereotomy, i.e. the structuring of stereotomy.

4. Structuring Stereotomy

4.1. Research-by-Design Structuring

The process of structuring stereotomy is based on a research-by-design analysis approach. More specifically, the structuring of stereotomy encompasses personal investigations based on digital and material computational processes. The derived outcomes of the investigation are tested through tutoring of the Design Workshop projects and several research collaborations.

Firstly, the process of structuring stereotomy analyses several case studies. They are historical precedents, the established stereotomic typologies, as case studies to structure a material system. The stereotomic material system's structure is discretised as an arrangement system of geometric parameters and their dependencies that are externalised as a system of geometric, generative algorithms. More specifically, the structure of the historic stereotomic material system is encoded through visual programming and actualised within digital parametric models of associative geometry [25]. The digital parametric models provide fabrication information that allows for further physical evaluations and explorations of the process of structuring of the stereotomic material system through prototyping.

Next, the research explores the limits of the stereotomic material system. It investigates the intrinsic potentials for adaptation and transformation that go beyond the stereotomic material system's original (historic) design intents and construction choices. More specifically, the research investigations use the diverse topological outputs of the digital parametric models and physical prototypes that range from small-scale working models to full-scale mock-ups. The latter ones are demonstrations tests of the material system's actualisations within a specific set of contextual circumstances.

4.2. Case Study 1: Topologically Interlocked Stereotomic Assembly

The main case study of the stereotomic structuring is an established typology that is referred to in the traditional stereotomy as the Abeille Flat Vault (Figure 17 a) and in the contemporary material

[25] Grasshopper, the associative modelling plug-in for Rhinoceros 3D-modelling software, is used for visual programing and investigations into interdependencies and variations of the digital parametric models.

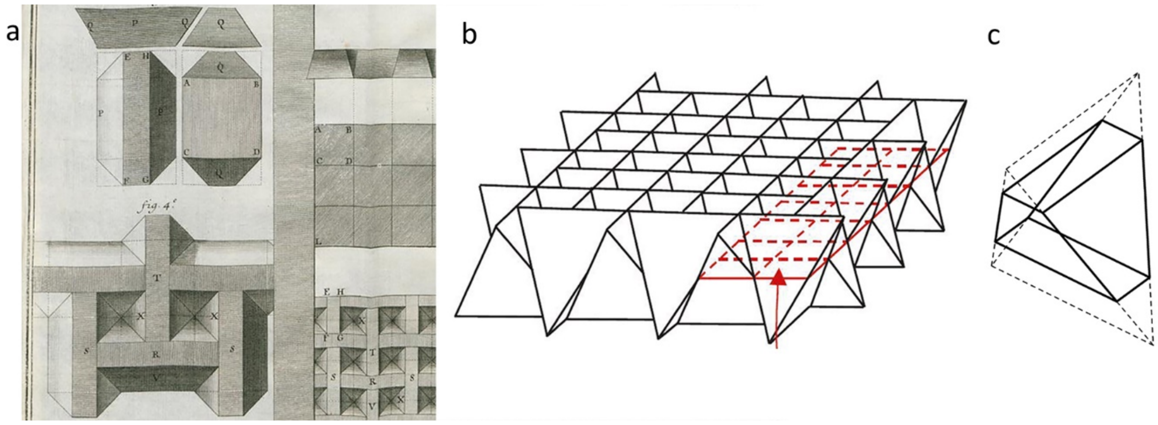


Figure 17: The Main Case Study of the Stereotomic Structuring
a) The Abeille Flat Vault by Joseph Abeille pattented in 1699.
Source: Gallon, J 1777, from (Gallon 1777).
b) Topological interlocking assembly of regualr tetrahedra.
Source: (Dyskin, Estrin et al. 2003), page 198
c) The Abeille ashlar's configuration based on a planarly truncated regular tetrahedron.
Source: Tessmann, O. 2013, from (Tessmann 2013).

science as the topological interlocking assembly (TIA) of regular tetrahedra (Figure 17 b).

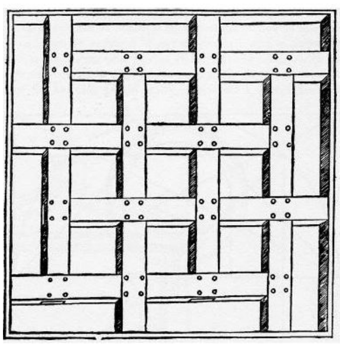
4.2.1. Abeille Flat Vault

"The stereotomic system known under the name voûte plate [or the flat vault] represents one of the most interesting technical and stylistic investigations into the art of stonecutting applied to building construction."
(D'Amato Guerrieri, Fallacara 2006, page 327)

The flat vault is a stereotomic typology that was invented by Joseph Abeille in 1699 to concurrently provide a ceiling for the lower storey and pavement for the upper storey (Fleury 2009).

Each Abeille ashlar has an identical configuration. It is a regular tetrahedron planarly truncated at its centre and some distance below it (Figure 17 c). The unique ashlar configuration allows for a simple method of the mutual arrangement where each ashlar is placed perpendicularly to its adjacent ashlars. In this way, each ashlar "is carried on two others through its protruding cuts, and at the same time carries two others on its sloped cuts […], this being reciprocal in all the vault’s area, it supports itself at level” (Gallon 1777, cited in Fleury 2009).

Figure 18: Drawing of a Reciprocal Frame Structure by Sebastiano Serlio.
Source: (Hart and Hicks 1996)



Visually, the woven-like organisational pattern of the Abeille stereotomic assembly resembles the organizational pattern of reciprocal timber frame structures of Leonardo da Vinci (Larsen, 2008), Villard de Honnecout (Lassus 1858), or Sebastiano Serlio (Hart and Hicks 1996) that provide a constructive solution of covering a space with a flat floor using small, discrete, identical elements (Figure 18). Structurally, however, the Abeille Vault behaves as neither a vault nor a reciprocal frame structure but generates an interlocking mechanism as a network system of interacting elements. For each 'inwardly' rotated contact face there is a corresponding 'outwardly' rotated one on the other side of the same ashlar that directs the force flow within the overall system and results in ashlars' interlocking. Structurally, thus, the Abeille Vault behaves like a topological interlocking assembly.

4.2.2. Topological Interlocking Assembly (TIA)

The notion of TIA was introduced by Yuri Estrin and Arcady Dyskin in material science in 2001 (Glickman 1984, Dyskin, Estrin, et al. 2001). A TIA is defined by an identical configuration of its constituent elements, their mutual arrangement, and a boundary constraint that holds the whole assembly together (Dyskin, Estrin, et al. 2003).

Elements' arrangement imposes local kinematic constraints that keep each element locked in its position solely by geometrical constraints of its adjacent elements. In this way, except for the elements at the assembly's periphery, the removal of each element by either upward, downward, sideways, or rotational displacement is prevented by its neighbours (Dyskin, Estrin, et al. 2003).

4.2.3. Contemporary Stereotomy's Case Study

Throughout history, the Abeille Vault was rarely used due to the high amount of horizontal thrust that required a demanding construction of its boundary constraints, like buttresses or massive walls (Brocato 2012). In the last fifteen years, on the other hand, contemporary stereotomic research has extensively referred to the Abeille Vault as a case study[26]. The contemporary investigations primarily focus on applying the Abeille-based TIA principle on non-planar surfaces (Figure 19 a-c).

4.2.4. The Abeille-Based TIA Material System

The contemporary stereotomic research of the Abeille-based assembly exposes a direct dependency between the TIA principle and the surface curvature in U and V directions. More specifically, the contemporary investigations expose the interdependency between the rotation angle of the 'inward' and 'outward' ashlar contact faces from the underlying surface grid and the surface directions defined by the same grid (Figure 19 d).

In short, the contemporary stereotomic research exposes that different yet similar configurations of the historical and

[26] The reference is made to multiple built and published research projects (Tessmann 2013, Arch Daily 2017, Brocato, Mondardini 2012, Etlin et al. 2008, Fallacara 2006, Fleury 2009)

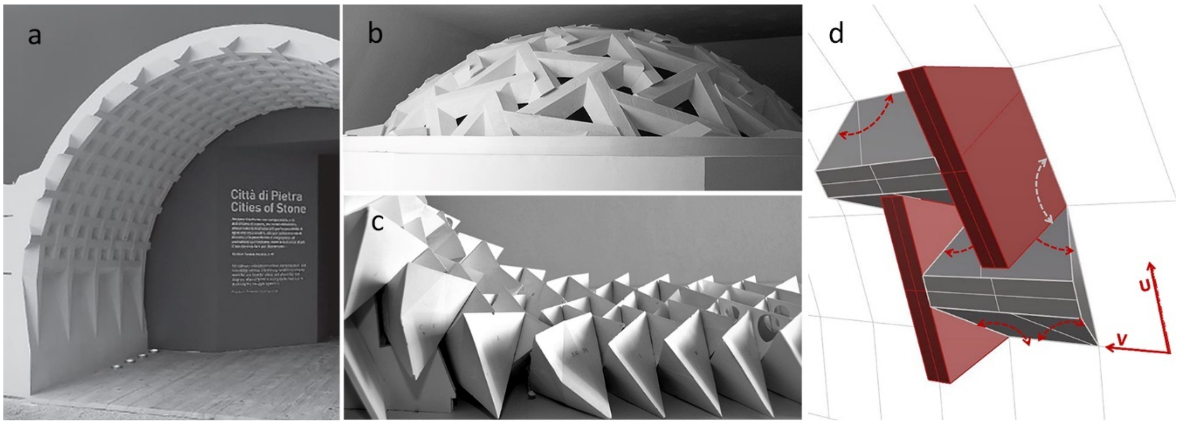


Figure 19: Contemporary Research Examples of the Abeille Vault
a) The Abeille-Based TIA Barrel Vault, Cities of Stone Exihbition, Venice Biennale 2006, by Giuseppe Fallacara.
Source: Fallacara, G 2006, Portale Abeille, Atelier Fallacara d'Architettura, digital image, viewed on 1 April 2019 http://www.atelierfallacara.it/_images/lavori/prototipi/3/zoom/5.html
b) The Abeille-Based TIA Dome, Voûte du Qatar, Doha, 2013, by Giuseppe Fallacara and Luc Tamborero.
Source: Ateliers Romeo, Voûte digital image, Ateliers Romeo, viewed on 1 April 2019 https://ecitydoc.com/download/presentation-ateliers_pdf#
c) Investigations of the Abeille-Based TIA on Free-Form Surfaces, Architecture and Performative Design Studio, 2013, Staedelschule (Frankfurt), tutor Oliver Tesmann.
d) The Abeille-based interlocking principle on non-planar surfaces depends on the surface curvature in the directions defined by the underlying surface grid.
Source: Tessmann, Oliver 2013 from (Tessmann 2013).

contemporary Abeille-based TIAs represent varied outcomes of the same interlocking principle. More specifically, they are understood as varied actualisations of the same Abeille-based TIA material system.

4.3. Case Study 1: Structuring

The structuring process of the Abeille-based TIA material system is expressed through a geometric construction method that discretises its structure and externalises it as a set of geometric parameters and their dependencies.

The starting point of the geometrical construction method is the formulation of a quad distribution grid on a given surface. For each quod defined by vertices ABCD, four points at vertices mid-span are derived as Pt0, Pt1, Pt2, and Pt3. Points Pt0 and Pt2, and Pt1 and Pt3 that lay at opposite sides of the quad define vectors in U and V direction respectively. Thus, each mid-point Pt that does not lie at the surface boundary defines a pair of vectors in opposite directions, Vu+ and Vu-, or Vv+ and Vv-. Further, at each mid-point Pt, a sum vector of the vector pairs is defined. For the vector pair Vu+ and Vu-, the sum vector is referred to as Vδu and for the vector pair Vv+ and Vv-, the sum vector is referred to as Vδv. The

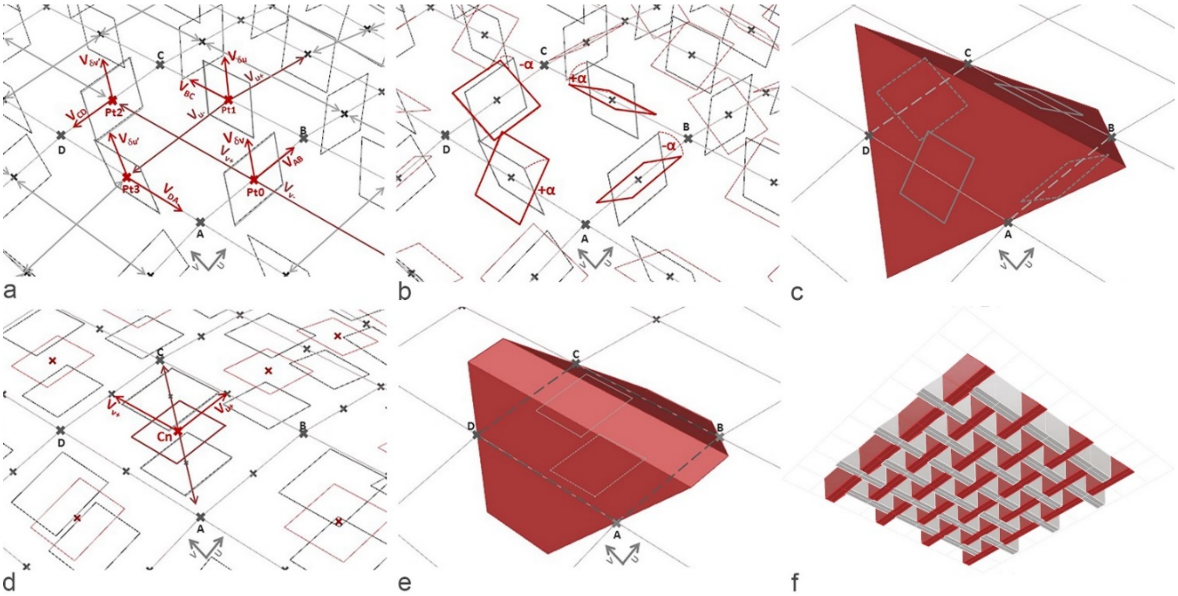


Figure 20: Geometric Construction Method of the Abeille-based TIA
a) A quad with vertices ABCD defines points Pt0, Pt1, Pt2, and Pt3 at vertices' mid-span. Pt0 and Pt2 define vectors Vu+, Vu-, and their sum vector Vδu. Pt1 and Pt3 define vectors Vv+, Vv-, and their sum vector Vδv. Each point Pt and its adjacent vertex define vectors V_{AB}, V_{BC}, V_{CD}, and V_{DA}. At each point Pt, a plane Pl is defined by V_{AB}, V_{BC}, V_{CD}, and V_{DA} and corresponding Vδu or Vδv.
b) Each Pl is rotated around corresponding V for an angle α in the direction opposite from the rotation direction of its adjacent Pl.
c) The intersection of the four rotated Pl of each quad defines a tetrahedron.
d) A pair of trimming plane Plt is defined. Each Plt is an offset of a plane defined by vectors Vu+ and Vv+ at the quad centroid Cn.
e) The Plt pairs define a truncated tetrahedron for each quad and,
f) An Abeille-based TIA for the surface distribution grid.
Source: Author

magnitude of vectors Vδu and Vδv reflects the surface curvature in U and V directions respectively at the given mid-point Pt. A plane Pl is defined at each mid-point Pt based on two vectors. The first vector referred to as VAB, VBC, VCD, and VDA is defined by the mid-point Pt itself and its adjacent vertex. The second vector is the sum vector, either Vδu or Vδv, at that mid-point Pt (Figure 20 a).

Each Pl plane is rotated around the first vector for an angle α. The rotation direction is opposite to the rotation direction of the adjacent planes (Figure 20 b). Four rotated planes intersect to define a regular tetrahedron for each grid (Figure 20 c), and their propagation on the surface distribution grid defines a TIA of tetrahedra.

Finally, a pair of trimming planes are defined. Each trimming plane is an offset of the surface tangent plane defined by vectors Vu+ and Vv+ at the centroid Cn of each field (Figure 20 d). The pair of trimming planes defines a truncated tetrahedron for each grid field (Figure 20 e) and the Abeille-based TIA for the surface distribution grid (Figure 20 f).

4.4. Case Study 1: Structure

Four geometric parameters define the structure of the Abeille-based TIA material system: the surface distribution grid, the surface curvature in U and V directions, the position of the trimming planes, and the angle of the alternating rotation of the ashlar's contact faces.

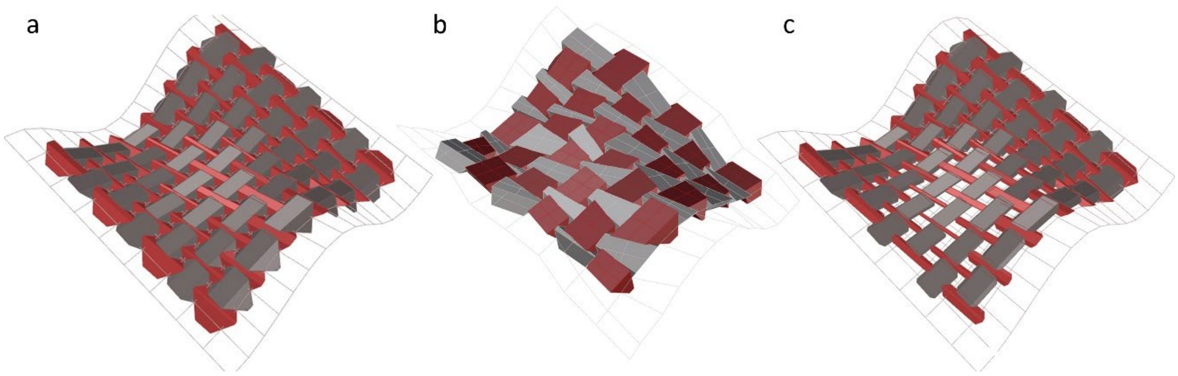
The Abeille Flat Vault is, thus, an outcome of the material system that is defined by the following parameter values: square distribution surface grid, planar surface (nil surface curvature in both U and V directions), and the angle of the contact faces' alternating rotation that is 54.7 degrees from the surface. One trimming plane coincides with the surface tangent plane, while the other is positioned at some distance below it.

4.4.1. Parametric Dependencies of the TIA Principle

Further, the research explores dependencies between the established parameters to ensure that the Abeille-based interlocking principle is established. More specifically, the research explores variations in the structure's parametric values that instigate the alternating rotation direction of the ashlar contact faces. The parameter values are assigned arbitrarily, often extremely, to amplify possible inconstancies of the structuring process and expose limits of the TIA principle (Figure 21).

The first dependency that the research investigations expose is the inverse proportion between the surface curvature in U and V directions and the angle of the contact faces' alternating rotation: the higher the curvature, the lower is the rotation angle, and vice versa. This dependency concurrently ensures that properly keyed ashlars within a planar assembly and avoids any awkward ashlar

Figure 21: Actualisation Variations of the of the Abeille-Based TIA Material System.
The structure is based on a sinusoidal double-curved surface, a 54.7° angle of the alternating contact faces rotation, and
a) a regular quadrilateral grid, trimming planes positioned equidistantly from the grid,
b) an irregular quadrilateral grid, trimming planes positioned equidistantly from the grid,
c) a regular quadrilateral grid, trimming planes' positions varies.
Source: Author



configurations in the areas with a high degree of surface curvature (Figure 22).

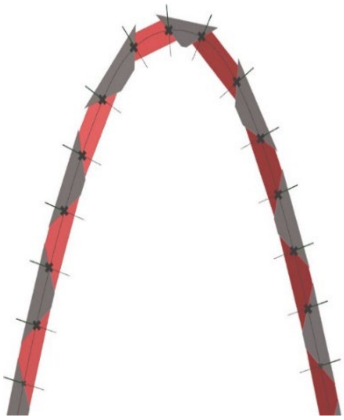


Figure 22: The parametric interdependencies of the Abeille-based TIA material system.
Source: Author

The second, directly proportional dependency established is between the surface curvature in the U and V directions and the density of surface distribution grid. In this way, the high degree of curvature instigates a high grid density that, in turn, defines smaller ashlar configurations that more precisely approximate the steep curvature (Figure 22).

The third dependency exposed is between the surface curvature in the U and V directions and the configuration of the surface distribution grid. The dependency defines the domain of the possible positions of the trimming planes. When the initial surface is non-planar or the surface grid distribution non-rectangular, the nonadjacent ashlars of the same orientation tend to intersect[27]. More specifically, only ashlar configurations derived from a planar surface and square grid, i.e. the Abeille Flat Vault ashlars, do not intersect. For any other parameter values, the positions of the trimming planes need to be defined in a way to enable the trimming planes to modify and rectify ashlar configurations by removing the intersections (Figure 22).

Finally, the fourth parametric interdependency is necessary for a specific set of parameter values that places both trimming planes on the same side of the surface distribution grid[28] (Figure 21 c). In this case, the dependency between the distance of two trimming planes and their offset distances from the surface grid ensures that the Abeille-based interlocking principle is maintained.

4.4.2. Evaluating the Structuring and the Structure

The structuring of the Abeille-based TIA material system is twofold. Firstly, the structuring is based on personal research investigations. Next, the conclusions and premises derived from these investigations are tested and further explored through tutoring of the Digital Design Workshop, a Year 2, BSc in Built Environment Studies, 3 ECTSs, elective design workshop[29].

The overall aim of the Digital Design Workshop is to introduce the students to computational thinking and digital design in architecture. The design workshop brief asks the students to firstly structure and then explore the limits of a given, historic,

[27] In the figures 21,22, and 23, the non-adjacent ashlars are shown as differently shaded. They are either red or grey.
[28] The specific set of parameter values that places both trimming planes on the same side of the surface distribution grid establishes a TIA configuration with perforations within the assembly.
[29] The author tutored the Digital Design Studio during the second semester of the academic years 2012/2013, 2013/2014, and 2014/2015.

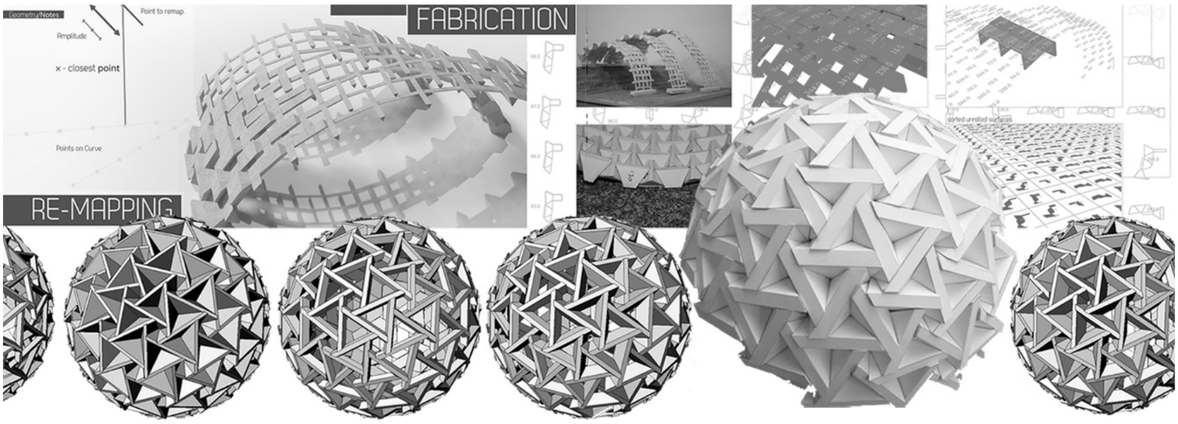


Figure 24: A Sample of students' projects of the 2012 / 2013 Digital Design Workshop that investigated the Abeille-based TIA material system.
Source: Azzopardi C, Bugeja N, Camilleri M, Cutajar S, Pace K, Pellicano L, Vella M, 2012.

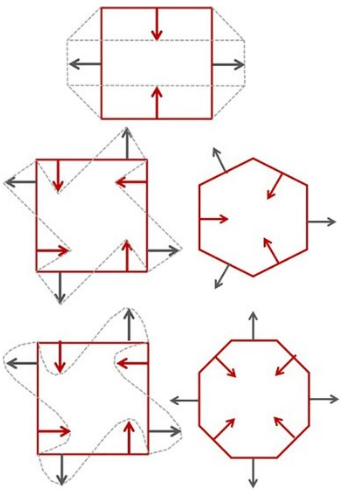
stereotomic material system based on the TIA principle[30]. Students start by structuring the underlying geometric rationality of the given stereotomic material system and the procedural rationality of its construction. The main exploration tools of the Design Workshop are physical scale models and digital parametric models that seek to encode the structure of the material system through associative geometry (Figure 24).

4.5. Case Study 1: Construction

4.5.1. Variations in the Geometric Actualisation

Variations in construction's procedural rationality complexify the materials system outcomes. The construction, a set of process that actualises the materials system's structure, encompasses varied geometric actualisations of the Abeille-based TIA principle. The research investigates the complexification of the Abeille-based TIA principle through its geometric actualisations on surface distribution grids that have an increased number of polygon sides and on an increased number of rotation alternations per a single ashlar contact face (Figure 23). The resultant material system outcomes represent configurations of several established stereotomic TIA-based typologies.

Figure 23: Complexification of the Abeille-Base TIA Material System Through Geometric Actualisations of the TIA Principle.
Source: Author



4.5.2. Truchet Flat Vault

The Truchet Flat Vault (Figure 25 a1) was developed in 1704 by Jean Truchet as an improvement to the Abeille Vault. The Truchet ashlar actualises the alternating contact faces rotation of the Abeille ashlar as morphed undulations of concave and convex surfaces (Figure 25 a2). Although the interlocking of the Truchet ashlars leaves no void

[30] The three historic stereotomic material systems investigated were the Abeille Flat Vault, the Truchet Flat Vault, and the TIA of octahedra.

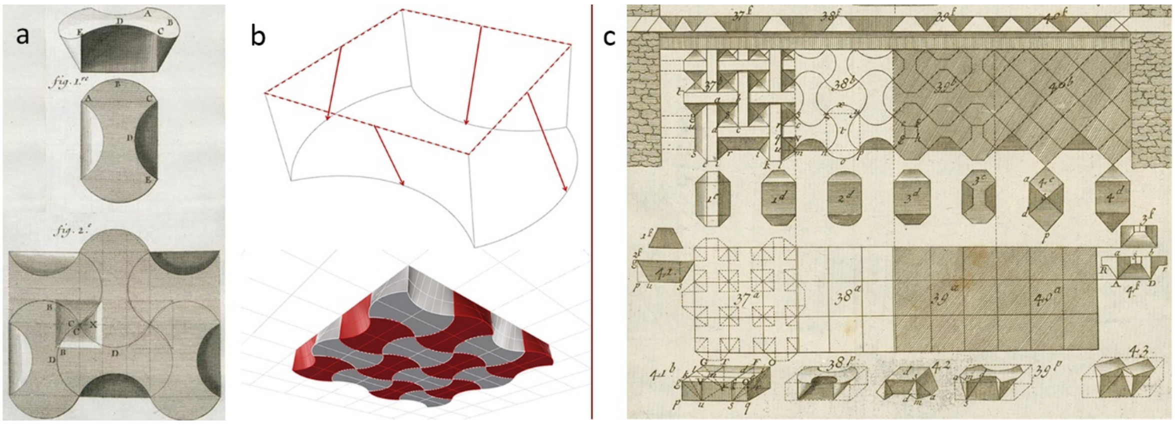


Figure 25: Truchet and Frézier Flat Vault Variations
a) Truchet Flat Vault patented by Jean Truchet in 1704.
Source: Gallon, J 1777, from (Gallon 1777)
b) An individual Truchet ashlar and its TIA.
Source: Author
c) Frézier's variations of the flat vault stereotomic typology.
Source: Frézier, A.F 1738 adapted from (Frézier, A.F. 1738), Planche 31

on either side of the flat vault's surfaces (Figure 25 a3), their configuration was too difficult to fabricate until the introduction of contemporary CAD/CAM tools (Etlin et al. 2008).

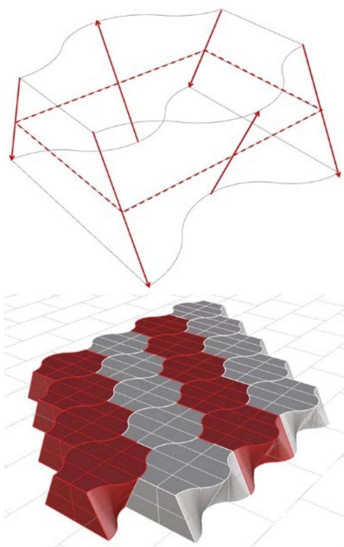
4.5.3. Frézier Flat Vaults

In 1737, Amédée-François Frézier published a treatise in which, along with the Abeille and the Truchet Vaults, he presented his own two variations of the flat vault typology (Figure 25 b) (Frézier 17 b). The configurations of the Frézier ashlars are simplified configurations of the Truchet ashlar. Instead of the double-curved, undulating surfaces of the Truchet ashlar's contact faces, the contact faces of the Frézier ashlars actualise the alternating contact faces rotation as multiple, segmented, planar surfaces.

4.5.4. TIA of Osteomorphic Blocks

The osteomorphic block is invented for a wall and column construction in high seismic zones (Dyskin et al. 2003c). It actualises the Abeille-based TIA principle as multiple alternations of concave and convex surfaces on horizontal ashlar's contact faces. Ashlars' vertical contact faces remain planar. The topological interlocking principle is achieved within the assembly when osteomorphic blocks follow the running bond surface distribution grid (Figure 26).

Figure 26: An individual osteomorphic block and its TIA
Source: Author



4.5.5. TIAs of Cuboids and Octahedra

The Abeille-based TIA principle actualised on a hexagonal surface distribution grid (Figure 27 a) formulates a TIA of cuboids (Figure 27 b). When a pair of trimming planes truncates the TIA of cuboids, it formulates a TIA of irregular octahedra (Figure 27 c).

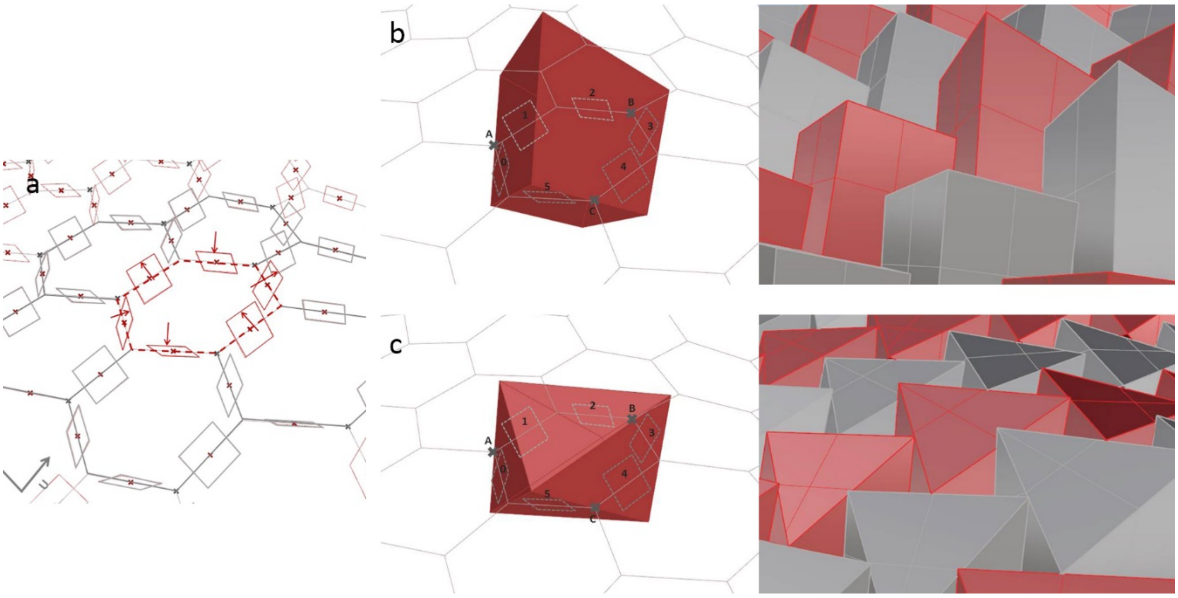


Figure 27: The TIA Principle Actualised on a Hexagonal Surface Distribution Grid
a) Six planes rotated in the alternating direction,
b) The intersection of six rotated planes formulates a cuboid,
c) The intersection of six rotated planes and two trimming planes defines an irregualr octahedron
Source: Author

4.6. Case Study 2: Vaulted Assemblies

Structurally, however, stereotomic assemblies are most often based on a vaulted system, not TIA. A vaulted structural system is ideally shaped as a catenary, as it was discovered by Robert Hooke in 1675. Hooke describes the relationship between a hanging chain and the inner force flow in an arch "[…] as hangs the flexible line, so but inverted will stand as the rigid arch" (Heyman 1998).

Similar to TIAs, vaulted stereotomic assemblies can be structured as a material system. The vaulted stereotomic material system's structure retains a definition based on the four geometric parameters, yet redefined certain parameters' values and interdependences. Within the vaulted stereotomic material system's structure, the surface geometry is based on a catenary, and the ashlar contact faces remain consistently perpendicular to the surface. In short, the structuring process allows for any vaulted stereotomic typology to be described as an outcome of the same material system, or more specifically, an actualisation of the same structure.

4.6.1. The Arch

The arch is an outcome of the vaulted stereotomic material system that actualises the structure as a curve of varying or constant degrees of curvature (Figure 10). Ashlar contact faces are perpendicular to the surfaces and actualised as either planar, joggled or undulating surfaces. The position of the trimming planes ensures that the catenary is within the middle third of the ashlars' thickness (Heyman 1995).

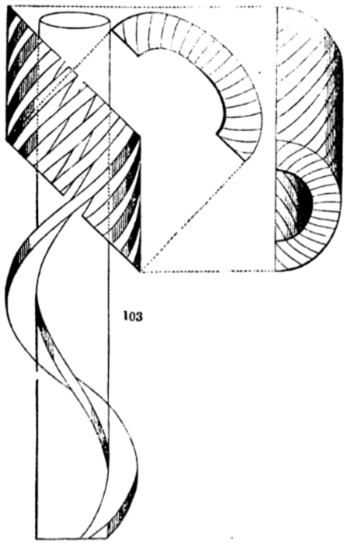


Figure 28: Helicoidal, "Corkscrew" Vault Trait
Source: Fox, C 1836, On the Construction of Skew Arches, digital image, Wikimedia Commons, viewed on 1 April 2019 https://en.wikipedia.org/wiki/Skew_arch#/media/File:Plate_from_Fox_Skew_Arch.png.

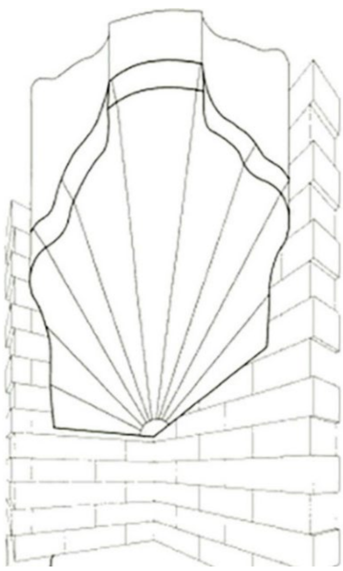
4.6.2. The Barrel Vault

Similarly, the barrel vault is a material system's outcome that actualises the structure based on a cylindrical surface. Since the cylindrical surface is a linear extrusion of the arch, it embeds the same parametric dependencies as the arch. The onsite execution, as a construction process that actualises the structure as physical, spatial forms, establishes the surface distribution grid. The surface distribution grid establishes two surface directions. Historically, the most present surface distribution grids were the running bond and the rectangular grid.

4.6.3. The Helicoidal Barrel Vault

The helicoidal, "corkscrew" vault is a formal complexification of the barrel vault. It is an outcome of the vaulted material system that establishes when the angle between the vault and the abutments is acute. More specifically, when the value of this angle is between fifteen and thirty degrees (Figure 28). Here, the structure actualises as a cylindrical surface patch. The surface distribution grid follows the U and V surface directions and establishes as a skewed rectangular grid. Within it, the ashlars are arranged in such a way that their long, 'horizontal', contact faces are perpendicular to the cylinder patch surface. Ashlars' shorter, 'vertical' contact faces are perpendicular to the two planar surfaces that form the bases of the skewed cylinder.

Figure 29: Trompe vault.
Source: Potié, P 1996, from (Potié, P. 1996), page 100.



4.6.4. The Dome

The dome is an outcome of the vaulted stereotomic material system that actualises the structure as a double-curved, concave surface of varying or constant degrees of curvature. The ashlar contact faces remain perpendicular to the surface and establish the shell structural action. The trimming planes positions ensure that the force flow is accommodated within the ashlar thickness. The onsite execution process establishes the surface distribution grid as the running bond.

4.6.5. The Trompe Vault

The trompe vault, or the trumpet vault, is the unique vault type that cantilevers out a shallow ledge into space to carry a heavy stone tower. It is referred to as “an absolute masterpiece of the stereotomy, both for the constructive boldness and the novelty of its forms” (Fallacara 2007, page 68) (Figure 29). It actualises the vaulted stereotomic material system as a conical surface patch. The surface distribution gird is based on a radial running bond. The derived ashlar configurations are wedge-shaped with the contact faces perpendicular to the surface.

4.6.6. One Material System

In conclusion, the Abeille-based TIA material system and the vaulted material system derive different yet similar stereotomic assemblies. More specifically, the TIA and the vaulted stereotomic assemblies actualise different parameter values of the same parameter set. They are the outcomes of a single, open-ended, stereotomic material system.

4.7. Stereotomic Material System

The underlying parameters that activate the stereotomic material system are surface geometry, surface distribution grid, single unit's contact faces rotation, and its unit thickness.

4.7.1. Base Surface Geometry

The surface geometry parameter is concurrently determined by the complexity of the force flow and the diversity of design intents. The latter may vary from the pursuits of structural optimisations to seeking specific formal aesthetics. The surface geometry parameter is interdependent with the single unit geometry parameters, primarily the angle and the rotation direction of the single unit's contact faces and its thickness.

4.7.2. Surface Distribution Grid

The surface distribution grid is a parameter determined by the force flow and construction choices. The typical distribution grids are the running bond, the rectangular grid, the hexagonal grid, the radial grid, and their regular and irregular variations.

4.7.3. Single Unit Contact Faces Rotation

The single unit contact faces are the faces that constitute neither the intrados nor the extrados surface of a masonry assembly. The angle and rotation direction of the single unit contact faces are the parameters that define the structural action of the whole, or parts of, an assembly. For example, contact faces perpendicular to the base surface determine the arch structural action for linear assemblies and shell structural action for volumetric assemblies. The alternating, inward-outward, contact faces rotation establishes either a TIA or a reciprocal frame structural action.

4.7.4. Single Unit Thickness

The thickness of a single unit is the distance between its intrados and extrados faces. For statically determinate assemblies, the single unit thickness depends on the force flow that is has to be accommodated within the material thickness. In statically indeterminate assemblies, the single unit thickness is dependent on construction choices.

4.7.5. Geometrically Driven, Stone Independent

The proposed parameters are neither final nor conclusive, but open to further contributions and revisions. Still, they allow for the structuring of any stereotomic assembly, historical or contemporary, as a material system. In this way, a link establishes between stereotomy's past and present, as well as its intrinsic potential and genuine relevance for the contemporary context.

Finally, the structuring of the stereotomic material system also exposes stereotomy as solely grounded in the geometric parameters, not a specific material or execution technique. More specifically, through the structuring process, specific construction choices are assimilated within the stereotomic material system as its structure's parameter values and their dependencies. In short, construction processes that actualise the structure only inform but do not directly activate the stereotomic material system.

4.8. Demonstration Test 1: Stereotomic Plate Pavilion

"Similar processes do not necessarily beget similar shapes. Understanding these processes, on contrary, will help us shape better things."
(Carpo 2011, page 128)

The aim of the demonstration test was to assess the research premise that stereotomy is a geometry-driven, not material-driven, architectural practice. The scope of the demonstration test was to actualise the stereotomic material system as a non-masonry assembly. More specifically, it tested the premise through the design, fabrication, and assembly of a prototype of the Abeille-based interlocking principle using the marine plywood. The prototype was developed as a pavilion for the Malta Design Week 2014, held at Fort St Elmo, Valletta (Figure 30). The pavilion was an outcome of a research collaboration between the PhD supervisor, Prof Dr Toni Kotnik (Aalto University, Helsinki), architect Steve DeMicoli (a principal at DFab Studio and a senior associate at DeMicoli & Associates), and the author.

Figure 30: Stereotomic Plate Pavilion, Malta Design Week 2014, Fort St. Elmo, Valletta
Source: Author

4.8.1. Limited Tangible Resources

The switch in the material choice from stone ashlars to marine plywood sheets was prompted by a limited budget, available digital technology, and the site sensitivity.

Firstly, the only digital fabrication tool available for this research was a desktop-sized CNC machine. Its limited power and travel distances along three axes only eliminated the possibility of using the stone, or any other volumetric material, and directed the research towards a sheet material. Further, the marine plywood allowed for the "in-house" testing of prototypes during the design process and the fabrication of the final pavilion design. Finally, working with a light-weight material like marine plywood allowed for pavilion's fast, manual onsite mounting and demounting and its total reversibility as requested by the organisers.

4.8.2. Structuring of Marine Plywood Sheets

The design process used the previously developed digital parametric model of associative geometry that encoded the Abeille-based TIA material system. The first step was to discretise affordances of marine plywood sheets to inform the stereotomic material system. The Abeille-based topological interlocking principle was retained by 'merging' contact faces of two adjacent ashlars. More specifically, rotated planes that were shared by ashlar contact faces defined a single, six-pointed, plywood plate (Figure 31 a). A single unit configuration emerged consisting of four rotated plates (Figure 31 b). The limited CNC bed size[31] determined the plate dimensions. In short, material properties of the marine plywood sheets folded within the Abeille-based TIA material system that actualised as a propagation of the single unit, in a checker

[31] The travel distances of the CNC drill bit were limited to 12"x 36"x 3" (305mm x 914mm x 76mm) along X, Y, and Z axes respectively.

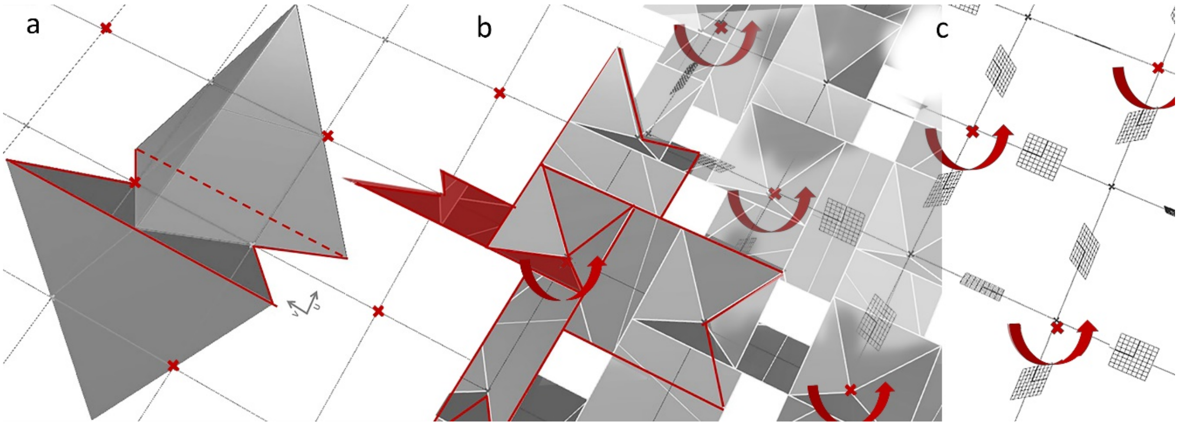


Figure 31: The Structuring of the Sheet Material
a) Contact faces of two adjacent ashlars 'merge' to establish a six-pointed plate.
b) A single unit emerges that consisits of four plates.
c) The single unit populates the quad surface distribution grid in a checker pattern.
Source: Author

pattern, over a non-uniformed, quad surface distribution grid (Figure 31 c).

4.8.3. Construction of the TIA of Plates

The next step in the design process was to establish a construction process that actualised the structure of the Abeille-based TIA material system. Following the research-by-design approach, the construction process was developed during a two-week workshop[32]. By the end of the workshop, several single units were designed and fabricated. Their configurations and assembly logic were assessed and evaluated through scale models and full-scale prototypes (Figure 32).

4.8.4. Parameter Values

The design process used the research-by-design approach to negotiate the force flow and material affordances. Physical tests based on scale models and full-scale prototypes discretised the negotiation and externalised it as parameter values of the material system's structure. More specifically, they derived the base surface geometry (Figure 34) and the angle of the plate rotation (Figure 33).

The base surface geometry was a parabolic vault, a linear extrusion of a catenary curve. The changing curvature of the catenary derived an irregular quad distribution grid and varied plate sizes. The linear extrusion reduced the fabrication time by generating repeated plate configurations. The tests determined that the angle of plate rotation

[32] The workshop was held at the DFab Studio during the Easter recess in the spring of 2014. It was an informal, voluntary workshop that, apart from the DFab Studio team, brought together a number of students and recent graduates from the Faculty for the Built Environment, University of Malta.

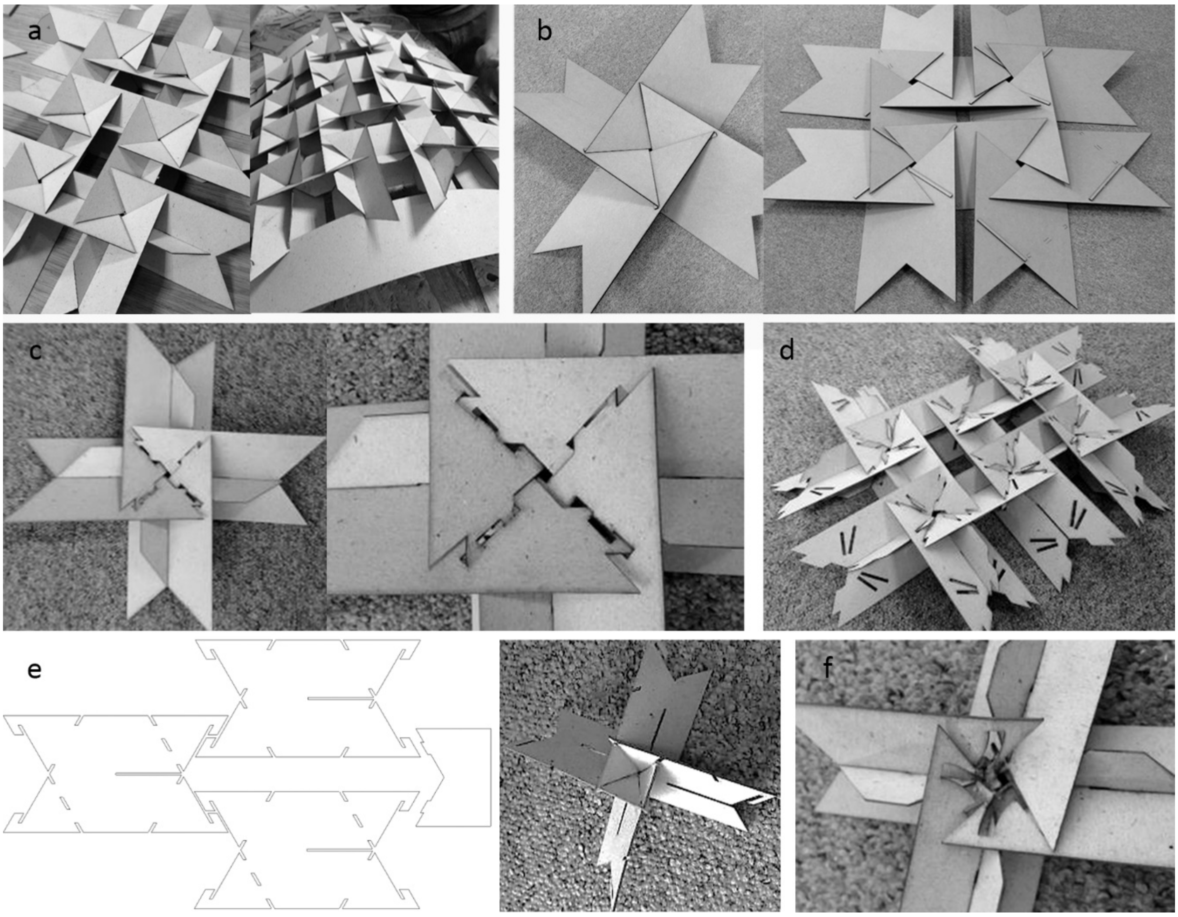


Figure 32: The TIA of Plates Principle Actualised as Different Single Unit Configurations
a) A plate its slid at the 'waist' of each rotated plate.
b) A strip at the contact between the two touching plates prevents slipping.
c) The nibs on the edge of one plate protruded through the slits on the other palate.
d)Configurations a) and c) merged and propagated on a planar surface.
e) The 'hook' on one plate slides into the slit of the other plate.
f) A design attempt of a single unit with the plates rotated into the interlocking position.
Source: Author

from the surface grid of sixty degrees eliminated deviations in the vertical plates that formed the parallel arches of the vault.

4.8.5. No Falsework Construction Constraint

The site, time, and budgetary constraints did not allow for an elaborate falsework. Structurally self-stabilising assembly configurations were established that dealt with the varying force flow during the onsite mounting. The onsite mounting sequence, thus, instigated further modifications of plate configurations and a specific logic of the single unit assembly.

The final configuration of each plate contained several protruding nibs on its slanting edges and slits on its surface (Figure 35 a). In this way, the two touching plates were connected by the nib of one plate sliding through the slit of another. In assembling of a single unit some plates were rotated and some slid into place (Figure 35 b). As

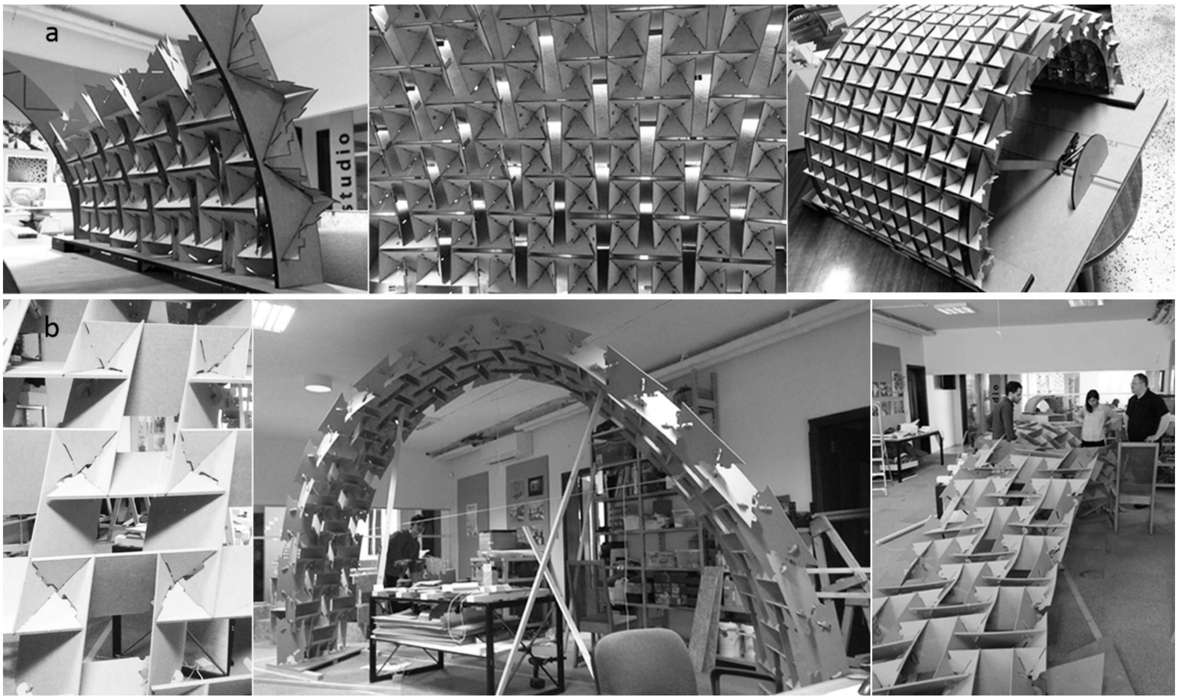
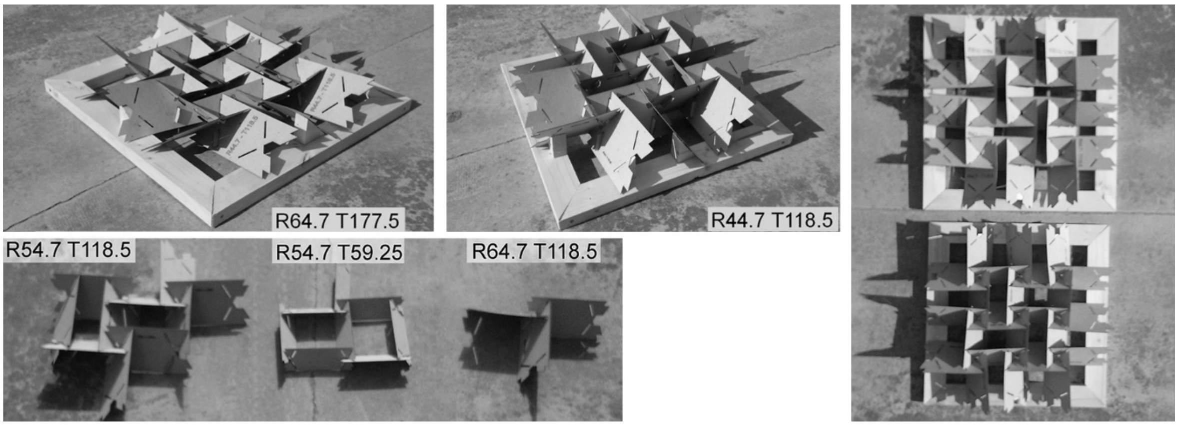


Figure 34: Test Models to Derived Based Surface Geometry
a) A cardboard scale model of a barrel vault pavilion. The construction is based on fixed boundary arches, trammel, and plate configuration with nibs and slits
b) Full scale prototype of three circular arches of the barrel vault pavilion in MDF.
Source: Author

a result, the number of nibs and slits varied for each plate within a single unit.

In the initial steps of the onsite mounting sequence, when the sides of the vault were not yet connected and the arch mechanism not in place, an additional stiffness was required. It was achieved by each nib having a hole to accommodate a temporary dowel (Figure 36 a). The nib and dowel system remained within the boundary arches to prevent slipping of the peripheral plates that were not interlocked (Figure 36 b). The self-stabilising assembly configurations were achieved through a diagonal, weave-like onsite mounting sequence

Figure 33: Scale Models Investigating Plates' Height (T) and Angle of the Rotation (R)
Source: Author



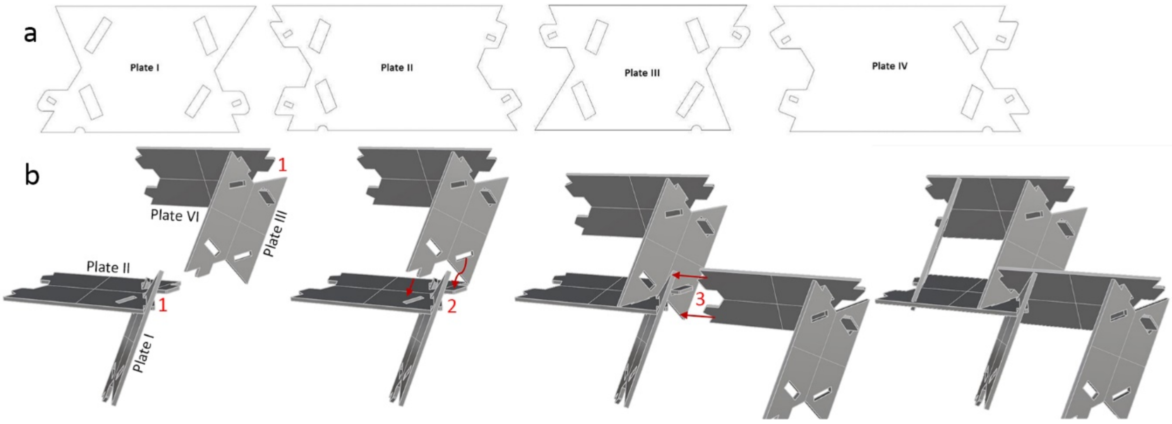


Figure 35: Plate Configurations and the Single Unit assembly
a) The configuration of each plate varies in the number of nibs and slits.
b) Plates' assembly sequence: (1) Plate I and Plate II, Plate III and Plate IV are rotated into place to form two L shape configurations (2) The two Ls are connected by rotating into place the vertical Plate III to interlock with Plate I and Plate II (3) Plate IV slides into place to complete the single unit.
Source: Author

of the single units that continuously increased vault's stiffness. As a result, the onsite mounting process sufficed only nominal propping (Figure 36).

4.8.6. A Contextually Specific Material System

In the outcome, the traditionally solid appearance of the masonry Abeille-based TIA was transformed into a lightweight lattice, Abeille-based TIA of plates (Figure 37). Still, the Plate Pavilion remained a physical, spatial expression of the generative, geometric rules of the stereotomic material system, a material system derived from and for its immediate context.

Figure 36: The onsite execution of the pavilion
a) The temorary used of dowels
b) Nominal propping during the early stages of the pavillion's mouting process.
c) The onsite mounting process of the pavilion near its compleation.
Source: Author

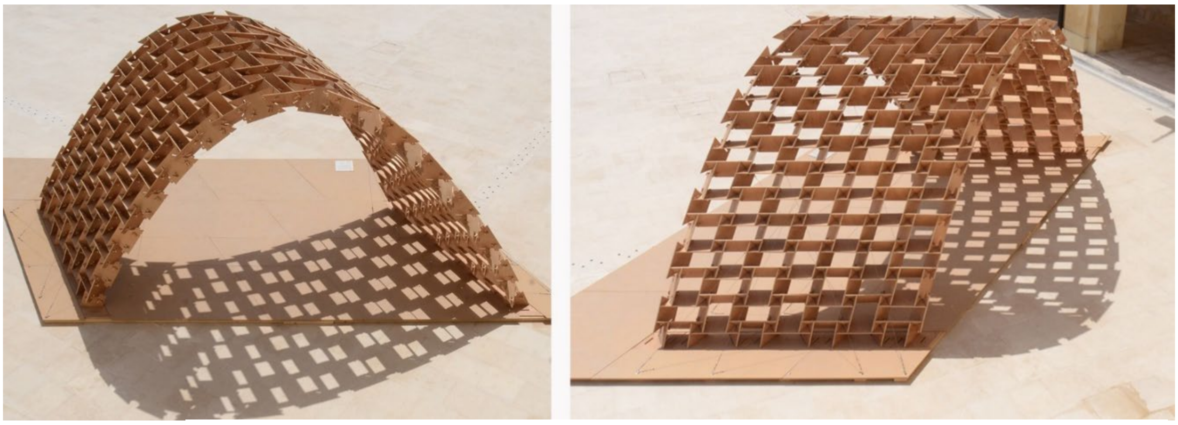


Figure 37: The Stereotomic Plate Pavilion, Malta Desing Week 2014, Fort St. Elmo, Valletta, by Irina Miodragovic Vella, Steve DeMicoli, and Professor Dr Toni Kotnik
Source: Author

4.9. Architectural Practice of Structuring Contextually Engaged Material Systems

Stereotomy, approached beyond its immediate definition as a stonecutting technique, is a digital architectural practice grounded in the systemic approach to its context. The systemic approach to context makes stereotomy susceptible to appropriations and assimilations of both of its tangible and intangible aspects. These include, among others, design knowledge, like geometric, material, and instrumental, and new materials, techniques, and technologies. In short, since stereotomy is grounded in contextual structuring, it is a fluid and contextually responsive digital architectural practice.

This notion focuses the research on exploring and theorising the process of contextual structuring. The contextual structuring is a twofold process. Firstly, it discretises negotiations between specific contextual realities and design intents and establishes their interdependencies. Next, it externalises the contextual realities, design intents, and their interdependencies as a material system.

The research, thus, seeks a more fluid understanding of the stereotomic material system, its structure, and construction. More specifically, the research recognises the material system's structure primarily as an underlying logic that defines contextual realities, design intents, and their mutual negotiations and relationships. Similarly, the research recognises construction, the actualisation of the material system's structure, as a set of generative processes based on procedural rationality, a system of algorithms.

In conclusion, the research premise is that if stereotomy is approached as a digital architectural practice grounded in contextual structuring, it becomes a relevant and valid architectural response to the contemporary contextual shifts within both the 'local', Maltese realities and the 'global' realities of the technology- and resources-driven architecture.

5. Regional Digital Architectural Practice

5.1. The Notion

"[Designing] is more creation of a curation of existing qualities found […] then the imposition of a formalist overlay from above."
(Sand Helsel, cited in Barac 2012)

The research approaches stereotomy as a theoretical model of the structuring process. The structuring is a set of computational, bottom-up processes that formulate material systems to derive architectural responses from and for their context. More specifically, stereotomy's intrinsic nature becomes a basis for theorising the notion of regional digital architectural practice.

The regional digital architectural practice is grounded in the systemic approach to context. From the digital theoretical perspective that negates boundaries and dichotomies, the notion of 'regional' surpasses physical confinements of a specific geographical location. Instead, it recognises that in the contemporary realm of globalisation, any context is at once globally connected and precisely situated in space and time (Hosagrahar 2012). In the same way, the digital notion of 'regional' supplants the postmodernist definition that refers to a dialectic opposition to 'global'. Instead, it refers to different levels of contextual connectivity.

In conclusion, the regional digital architectural practice encompasses architectural analysis, design, production, and teaching that approach context as a system of affordances and recognise it as topologically continuous capacities and constraints of the available and accessible knowledge, resources, materials, skills, tools, and technology.

5.1.1. Malta as a Case Study

The notion of regional digital architectural practice is theorised using Malta as a case study. Malta is an ideal exploration platform due to its small scale and a contained, geographically disconnected environment. Malta's particular nature allows for an understanding of the dominant realities and their changing constraints that throughout history, shaped its context. In this way, it is possible to expose influences that shaped successive changes in design thinking, instigated different approaches of the architectural practice, and reflected in the built environment established.

5.2. Regional Digital Architectural Analysis

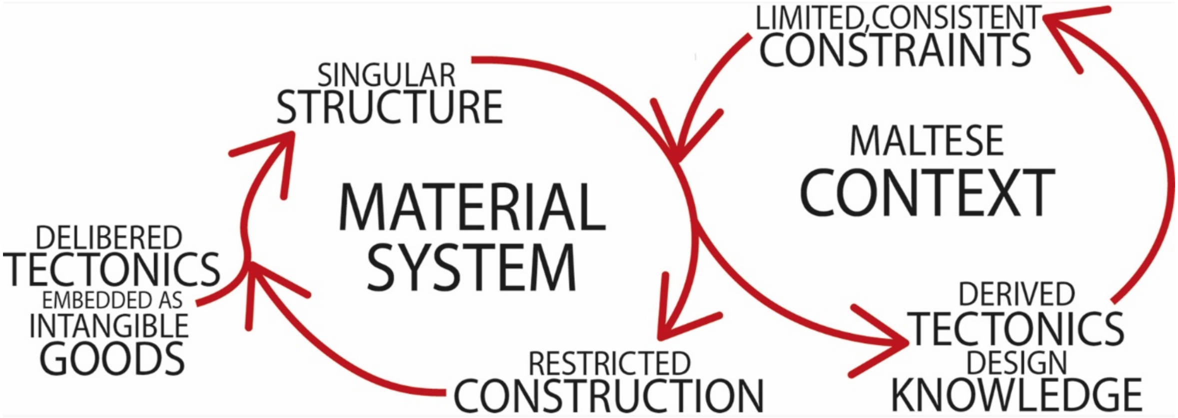
The research engages the notion of regional digital architectural practice as a theoretical framework that guides the analysis of the Maltese context. The analysis seeks to expose contextual shifts that instigated the divergent approach to materiality between the traditional and the contemporary architectural practice.

5.2.1. The Maltese Material System

The traditional Maltese architectural practice, grounded in a bottom-up approach to materiality, is a clear example of regional digital architectural practice. It established a cultural landscape as a system of performatively connected, topologically continuous, and tectonically coherent forms. The cultural landscape, thus, was an outcome of a contextually engaged material system that folded and unfolded its regional context. The regional context was defined by three dominant constraints: the limestone as the single available building material, limited resources, and geographic discontinuity.

For most of its history, Malta's geographic discontinuity retained the consistency of the dominant contextual constraints and hindered large-scale imports of tangible goods. Any contextual shifts were primarily instigated by the influx of intangible goods susceptible to contextual appropriations and assimilations. As a result, the material system established a singular structure that actualised through restricted construction yet was continuously inflected through assimilations of intangible goods. More specifically, the imported intangible goods did not fundamentally change the material system and the nature of its outcomes but expanded its underlying structure-construction negotiations. As a result, the material system unveiled novel contextual affordances that increased the structure's versatility and construction's proficiency in actualising the structure (Figure 38).

Figure 38: The Diagram of the Maltese Material System.
Source: Author



5.2.2. The Singular Structure

The structuring of consistent, contextual constraints established a singular structure. It was derived from a negotiation between limestone material properties, its various pursued performances, and restricted construction. The continuous, iterative actualisations of the singular structure established standard configurations at different architectural scales.

For example, an ashlar had to have, concurrently, low weight and high volume. Lower weight increased ashlars' workability with simple tools and manual labour, while with a higher volume ashlar achieved wider spans and retained its structural integrity. The negotiation between its contradicting requirements established standard ashlar configurations, like the block, the voussoir, and the slab.

On a larger scale, the negotiation assimilated the limited availability of materials suitable for falsework. In this way, standard building configurations embedded construction based on minimal use and extensive re-use of falsework. The notion is further explained with the example of the standard roofing systems developments.

The early negotiation actualised as a roofing configuration based on slabs spanning over corbeled rubble walls or identical diaphragm arches (Figure 39 a). As construction's proficiency increased, the negotiation developed along two directions that pursued different performances. One negotiation direction, found primarily in religious buildings, pursued an increase in the building's volume by concurrently increasing its span and its height. It established standard vaulted configurations based on diaphragm arches propagated in one, two directions, and around a polygonal base with slabs following the arch curvature (Figure 39 b). The other negotiation direction sought to increase the ceiling span while providing a flat, usable floor above. It established standard roof configurations that supplanted labour-intensive diaphragm arches to support slabs on either timber, steel, or concrete beams.

Utilitarian and climatic constraints [33] assimilated within the negotiation and actualised standard configurations of vernacular architecture. These included architectural forms, like the loggia, the courtyard, the flat roof, and their assemblages, the farmhouse, the narrow village street, and the winding street network of a village core. As the construction proficiency increased, the negotiation

[33] Utilitarian constraints were derived from the requirements of the rural lifestyle, like storing food, raising livestock, and providing shelter from the extreme weather and intruders (Jaccarini 2002). Climatic constraints, on the other hand, instigated requirements for shading, cooling, ventilation, and rainwater capture.

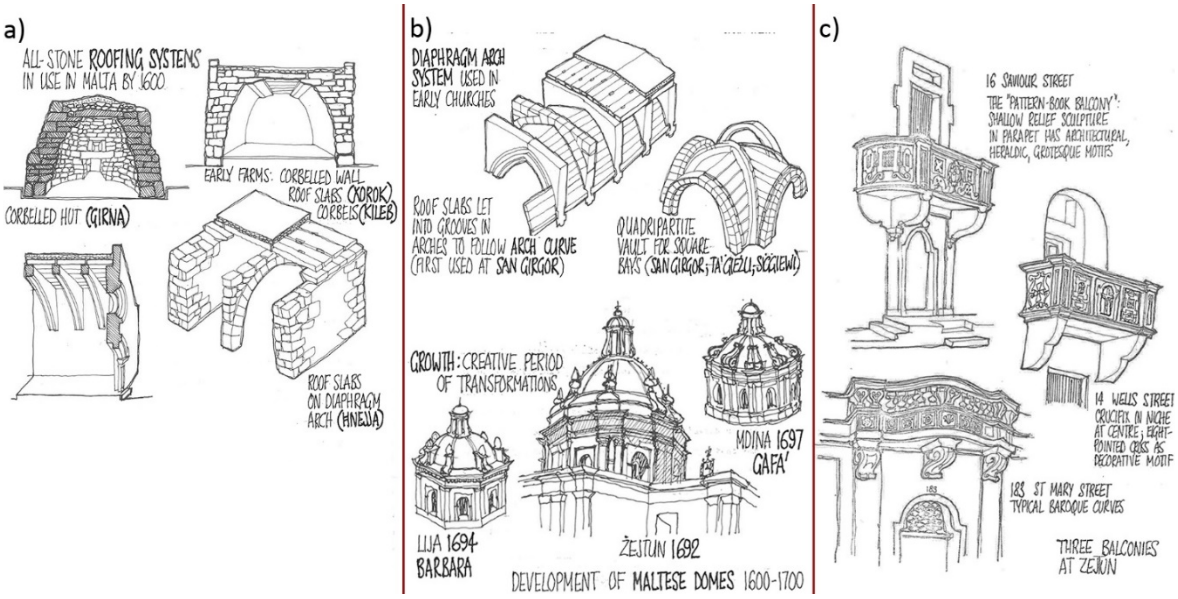


Figure 39: Standard Configurations
a) Early roofing configurations consisting of slabs resting on corbeled, rubble walls and diagraphram arches.
Source: Tonna, J 1971, adapted from (Tonna 1971) pages 27 and 77.
b) Later roofing configurations consisting of slabs resting on arches propagated in one, two directions, and around a polygonal base.
Source: Tonna, J 1971, adapted from (Tonna 1971) pages 27 and 77.
c) The deliberate tectonics, driven by socio-cultural contextual realities instigated variations of balcony configurations.
Source: Tonna, J 1971, adapted, from (Tonna 1971) pages 29 and 93.

became susceptible to assimilations of deliberate tectonics driven by socio-cultural contextual realities. In this way, standard configurations complexified. In the urban areas, the deliberate tectonics assimilated within the negotiation actualised as standard traditional architectural configurations. These included traditional forms like the townhouse and variations of its expressive components, like the balcony (Figure 39 c), the portico, and specific façade ornaments (Tonna 1971).

5.2.3. The Frugal Construction

Limited local resources and the limited access to tangible goods from hinterland regions grounded construction in frugality. The proficiency of construction processes increased as pursuits of workability within careful husbandry of resources (Tonna 1971).

For example, since the brittle limestone was difficult to quarry, cut, and transport without breaking, dressed stone was used only when structurally necessary. Instead, early construction processes relied affordances of the site, like on the onsite quarrying, assembling rubble walls from found, unhoned stones, and integrating the existing topography. Similarly, when construction's increased workability decreased the self-weight of voussoirs in vaults and arches, the gravel had to be compacted at their hunches to control the line of thrust. In this way, construction processes exposed novel affordance of the quarry waste by engaging it for within a structural performance (Tonna 1971).

5.2.4. Contextual Assimilations of Intangible Goods

Malta's strategic position in the Mediterranean region continuously increased its geopolitical connectivity, that decreased its geographical isolation. When the geopolitical connectivity gained military relevance, it instigated a dominant presence of outside political powers. Consequently, the influx of intangible goods amplified. Actualisations of the deliberate tectonics to assert authority (Hosagrahar 2012) and utilitarian, primarily military and infrastructural, design intents were tied to the established material system. On the other hand, the structuring of the pursued deliberate tectonics within the material system necessitated assimilations of outside design knowledge and technical skills. As a result, the assimilations expanded the established material system.

For example, during the rule of the Order of St. John[34], favourable economic conditions together with the influx of stereotomic design knowledge and technical skills enabled the pursuit of the Roman Baroque deliberate tectonics in monumental architecture (Tonna 1971).

In Rome, Baroque's complex curvilinear façades were achieved with materials foreign to Malta: small brick, thick cement mortar, and travertine cladding. Limestone Baroque façades, on the other hand, required expanded design knowledge to mediate between the geometric complexities and regional contextual constraints. In this way, an innovative design thinking emerged through an exchange of tacit knowledge between Order's architects, its military engineers, and local master masons. Also, local master masons expanded their design knowledge through education and training in hinterland regions and access to printed architectural treatises (Tonna 1971, Abela 2013).

Innovative design thinking was reflected in resultant architectural forms' increased scale, span, and geometric complexity. On the other hand, the full Baroque complexities of hinterland regions, like the volumetric undulations and spatial modulations, were rare[35]. In short, although the assimilated, imported, intangible goods expanded limestone's affordances and, in turn, material system's structure, its construction remained a challenge.

[34] The Order of St. John was in Malta from 1530 until 1798.

[35] For example, representations of the actualised Baroque volumetric complexities are found in the work of Francesco Sammut. His St Paul of Shipwreck Church in Valletta, from 1639, adopts an elliptical form both in plan and section, and the Carmelite Church in Mdina, from 1667 has an elliptical plan (Tonna 1971).

In this way, apart from monumental architecture that engaged amplified resources from the design to the execution stage, construction remained restricted. As construction remained an unchanged actualisation of the structure, it hindered the structure's modifications. Instead, restricted construction perpetuated the established singular structure. On the other hand, construction's proficiency increased in terms of technical proficiency, sophisticated detailing, geometric precision, and systematic execution (Tonna 1971, Sutera 2013). As a result, the assimilation of the outside intangible goods primarily expanded the complexity of surface designs and the structural performance of vaulted typologies. Through iterative actualisations, they folded within the context to derive the Maltese Baroque.

As the deliberate tectonics, both the monumental and the anonymous architecture appropriated the Maltese Baroque. It has remained the idiom of Maltese cultural identification in architecture until today. As the derived, hybrid tectonics, the Maltese Baroque is a physical expression of the Maltese material system's ability to appropriate, assimilate, and respond to shifts in contextual realities.

5.2.5. From Fluid Negotiations to Fix Procedures

"[…] even [today,] the way you design even without knowing […] it's never a light structure […] we always think [of the structure as] heavy, because the stone gives you something heavy, something load-bearing, something stuck to the ground."
(Sherly Cefai, cited in Mallia 2018, page 54)

Due to a prolong consistency of the dominant contextual constraints, construction became an iterative, repetitive actualisation of the singular, unchanged structure. As a result, construction processes progressively ceased their contextual negotiations that actualised the form. Instead, they became procedures, the codified, preset execution sequences that replicated the form. In Deleuzian terms, the machinic nature of construction that depended on connections with the structure and context to foster multiple interpretations and open-ended relationships became a mechanistic, isolated, repetitive function that actualised closed, autonomous forms with a fixed identity (Moussavi, López 2009, Carpo 2011).

The fluid negotiation between the structure and construction ceased and was replaced by a fixed, constant relationship. Construction procedures, as unaffected, simplified, actualisations of the singular structure, retained the structure within the design thinking and, thus, within the dominant architectural practice and the built environment it instigated (Figure 40).

Figure 40: The shift from fluid contextual negotiations to a fixed structure-construction relationship model.
Source: Author

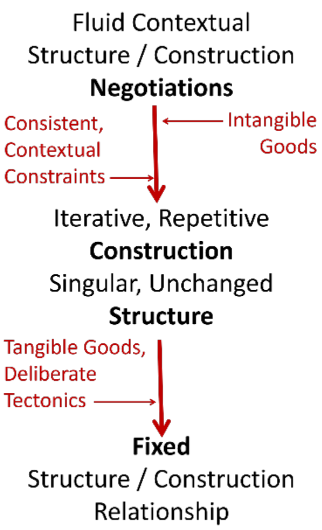


Figure 41: Diagram of Design Thinking Grounded in a Fix Realtionship between the structure and construction endowed in the deliberate tectonics.
Source: Author

5.2.6. Imposed Deliberate Tectonics

The increasing geopolitical connectivity has continuously amplified the influence of the globally dominant deliberate tectonics within the Maltese context. In the twentieth century, the unprecedented influx of tangible and intangible goods negated Malta's geographic isolation. Multiple deliberate tectonics became purposely pursued design impositions. They neither inflected nor assimilated within the established model of the fixed structure-construction relationship. Instead, deliberate tectonics were simply applied to it (Figure 41).

For example, four deliberate tectonics typically pursued by a newly independent nation to express its unique identity (Hosagrahar 2012) are found within the Maltese context. Firstly, in the post-World War II period, the newly accessible materials[36] within the regional context were engaged as the deliberate tectonics of the International Style to portray Malta as a modernised, sovereign nation (Hosagrahar 2012, Miodragovic 2002). Next, in the early post-independence period, the pursuits of the Late Modern deliberate tectonics engaged the limestone and standard configurations to instigate regionalism and familiarity. They were succeeded by the pursuits of multiple Post-Modernist deliberate tectonics that sought to interpret shifts in contextual realities that fragmented the twentieth century (Hosagrahar 2012, Vella 1992). Finally, the contemporary Maltese architectural practice has appropriated globally recognised deliberate tectonics to express built forms' modernity and Mediterranean authenticity. When programmatic requirements or the pursued deliberate tectonics surpass the abilities of the established structure-construction model, the contemporary Maltese architectural practice engages imported structure-construction models.

[36] The newly accessible materials primarily included the cast concrete, pre-cast concrete elements, standard steel and aluminium sections, and sheet glass.

For example, several pursuits of the deliberate tectonics to portray Malta as a significant player in the globalised world engage internationally recognised, high-profile designers and brands [37] . More specifically, the pursued deliberate tectonics is achieved through the actualisation of designers' and brands' recognisable models of structure-construction. Their models do not allow contextual negotiations as they embed closed, fixed structure-construction relationships derived from and for a separate context. As a result, the models are imposed onto the context, and their actualisations necessitate imported construction procedures.

In short, there is an unprecedented influx of tangible and intangible resources that are not appropriated and assimilated within the Maltese contemporary architectural practice and its regional context. Instead, they are imposed on both.

5.2.7. Contemporary Fragmentations

"[A contemporary context is] characterized by difference and multiplicity, and this unprecedented level of complexity has increased the demand for built forms that provide higher levels of performance [variations]."
(Moussavi, López 2009, page 7)

Although Malta's regional context continuously complexifies, its contemporary architectural practice ceases to structure its multiple constraints. Instead, it engages various models of fixed structure-construction relationships that it endows in arbitrary deliberate tectonics. On the other hand, the established models offer valid responses to the economic requirements of the current speculative building boom. In this way, they discourage architectural investigations and research incentives that would appropriate and assimilate the newly available tangible and intangible resources within the Maltese architectural practice and expand its design knowledge.

A boundary emerges between architectural design and architectural production. This "epistemic, formal, and technical rupture" (Witt 2010) erodes the material system established by the traditional architectural practice and inflicts the topological continuity, connected performance, and coherent tectonics of its cultural landscape. Instead, contemporary architectural practice produces a visually and performatively fragmented contemporary built environment.

[37] The reference is made to projects like the City Gate Project, Valletta, by Renzo Piano Building Workshop (RPBW), completed in 2015 (Refer to Figure 2b and its caption), currently built Mercury Towers, by Zaha Hadid Architects and the proposed Hard Rock Hotel, both in St. Julians.

5.3. The 'Maltese-ness' of the Maltese Architectural Practice

Figure 42: A Typical Sign Found at the Entrance of a Quarry indicating, in Maltese, "Limesotne Gravel for Free".
Source: Author

The regional digital theoretical perspective exposes that the notion of 'Maltese-ness' in Maltese architectural practice is not tied to specific material, form, or aesthetics but emerges from design thinking grounded in the systemic approach to context. More specifically, the contextual authenticity of the Maltese architectural practice emerges from its regional digital approach. The regional digital approach exposes novel contextual affordances through innovative structuring and enables the architectural practice to respond to shifts in contextual realities.

In this way, the regional digital theoretical perspective exposes its two contemporary examples in Malta. They are research endeavours that explore regional shifts in contextual realities to derive valid architectural responses. They develop, intentionally or unintentionally, contextually engaged material systems by structuring available and accessible resources, technology, and knowledge.

5.3.1. The Regional Digital Material Engineering

The first example is a material engineering research on reconstituted limestone led by Professor Dr Dion Buhagiar from the University of Malta. The research was instigated by the unavoidable depletion of limestone reserves by the year 2036[38] (Cromie, Cole 2002), the lack of access to sand for aggregates by the year 2020 (Thorns 2018), and the exhaustion of landfill space for the disposal of construction and demolition waste by the year 2020 (Debono 2010).

The research engages proficient regional material knowledge to explore methods of recycling and re-engaging the abundant and inexpensive crushed limestone waste[39] (Figure 42). The research structures interdependencies between material properties and different binder types to expose novel affordances of the limestone gravel. Its explorations seek to achieve multiple, optimised performances, like strength, durability, aesthetics, and recyclability (Buhagiar, Montesin 2017, Cutajar 2016). As a result, the inert waste becomes a versatile, semi-finished material, susceptible to fluid,

[38] The access to the unquarried limestone has been recently further reduced. The Maltese Globigerina limestone was granted an international recognition as a Global Heritage Stone Resource (GHSR) for its significance as a cultural, historic, and economic resource. The aim of the recognition is to ensure the availability of the limestone for future restoration projects of the built heritage (Cassar, Torpiano et al. 2017, Times of Malta 2019).

[39] As quarries are progressively becoming landfill sites for construction and demolition waste, quarry operators give out the limestone gravel for free, transport included.

open-ended contextual negotiations that derive material systems. Its structure is prone to variability and innovations and actualises through frugal construction processes. In short, the reconstituted stone is a material susceptible to deriving contextually engaged material systems.

5.3.2. The Regional Digital Fabrication Approach

The second example of regional digital architecture is research instigated by affordable digital tools and attainable instrumental knowledge. The research, led by architect Steve DeMicoli at DFab.Studio Malta pursues the rekindling of architectural design through making. It engages commons-based, peer-produced instrumental knowledge to hack CAM tools and expand their fixed affordances preset by the manufacturer. More specifically, by using open-source hardware and software, the research developed a CAD/CAM workflow that attained three objectives. Firstly, it placed the CAM tool controls within the CAD environment. Secondly, it established feedback between the fabricated material and the CAM tool. Finally, it allowed for design decisions to be taken as informed responses to and during the fabrication process. The result is an intuitive design environment that enables the structuring of materials' spontaneous activities and their negotiations with top-down design impositions (DeMicoli, Rinderspacher, et al. 2018).

The validity of the developed CAD/CAM workflow was tested and assessed within a research based on material computation that explored a link between the water erosion process and properties of limestone[40] (DeMicoli et al. 2018). The established CAD/CAM workflow engaged a locally sourced, disused CNC plasma cutter that was reconditioned with a water-jet lance end-effector and a micro-controller. The micro-controller ran a g-code parser that bypassed the main machine-controller by parsing the stepper-motion signals directly to the motor drivers (Figure 43 a). The CAD/CAM workflow enabled the material computation to structure dependencies between fabrication parameters, limestone's heterogeneous lithology, limestone's self-computed surface formations, and ashlar's integrity. In short, the appropriation of the available digital technology through exposing its novel affordances enabled structuring of dependencies that formulated of a material system. The material system's actualisations expanded material knowledge and derived novel tectonics (Figure 43 b) (DeMicoli et al. 2018, Cutajar 2016).

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[40] The practical part of the research included two student workshops conducted in Malta in 2015 that were attended by the the MArch (Architectural Design) students, from the Faculty for the Built Environment, University of Malta. The workshop description, aims, and outcomes are described in detail in Sacha Cutajar's 2016 MArch Dissertation entitled "Material Dialogues: Exploring Design Methodologies in Material Tectonics through Stone Morphologies".

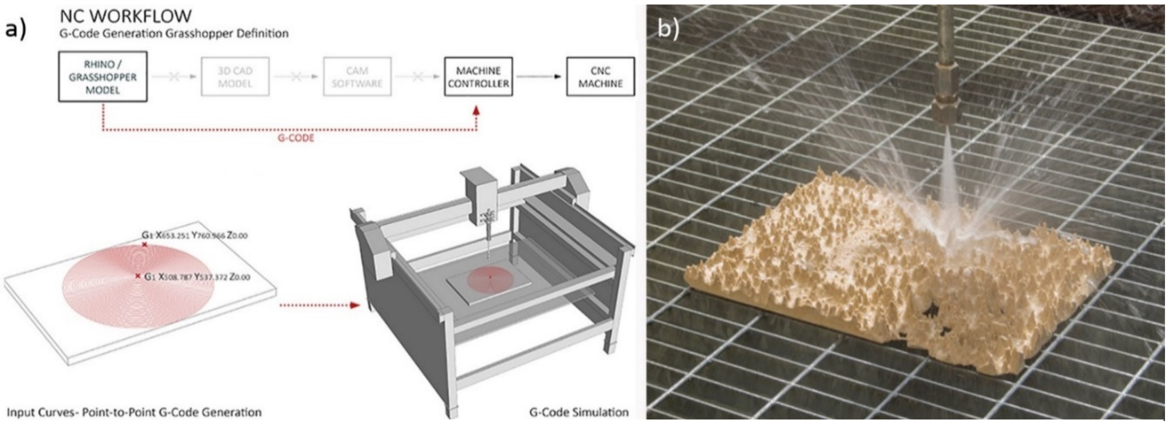


Figure 43: The Regional Digital Fabrication Approach
a) The CAD/CAM workflow diagram for the disused CNC plasma cutter reconditioned with a water-jet lance end-effector and a micro-controller. The micro-controller bypassed the main machine-controller by raning the stepper-motion signals directly to motor drivers
Source: DeMicoli, Steve 2015, NC Workflow, digital image, ICD Institute, viewed on 1 April 2019, https://icd.uni-stuttgart.de/?p=13156
b) Material computation established a dependency between machine settings and limestone's spontaneus activity.
Source: Rinderspacher, K. 2018, form (De Micoli, Rinderspacher et al. 2018), page 115.

5.4. Demonstration Test 2: Contemporary Regional Masonry Construction

"In exploring these new [geometrically complex, digital] forms, are we doing it just because we can or, because it is a good idea?" (Whitehead, cited, Kolarevic 2004)

5.4.1. Reduced Falsework Stereotomy

The contemporary stereotomic advancements in hinterland regions motivated the research that pursued stereotomic construction with reduced falsework. More specifically, the research aimed to make the advancements applicable to the Maltese regional context.

Locally, the cost of the elaborate, labour intensive falsework is typically at least four times higher than the cost of limestone ashlars[41] for the same assembly. The falsework was, thus, perceived as the main obstacle that hindered stereotomy in responding to contemporary architectural concerns. Akin to the Stereotomic Plate Pavilion prototype, the research scope was to develop a geometrically complex, non-traditional, stereotomic, limestone prototype that was designed, fabricated, and executed from and for its regional context. In short, the research set out to expose and

[41] Based on the quote submitted by Vaults Co. Ltd. Malta, the stone restoration and conservation company that the author co-applied with for the 2015 University of Malta Research Grant.

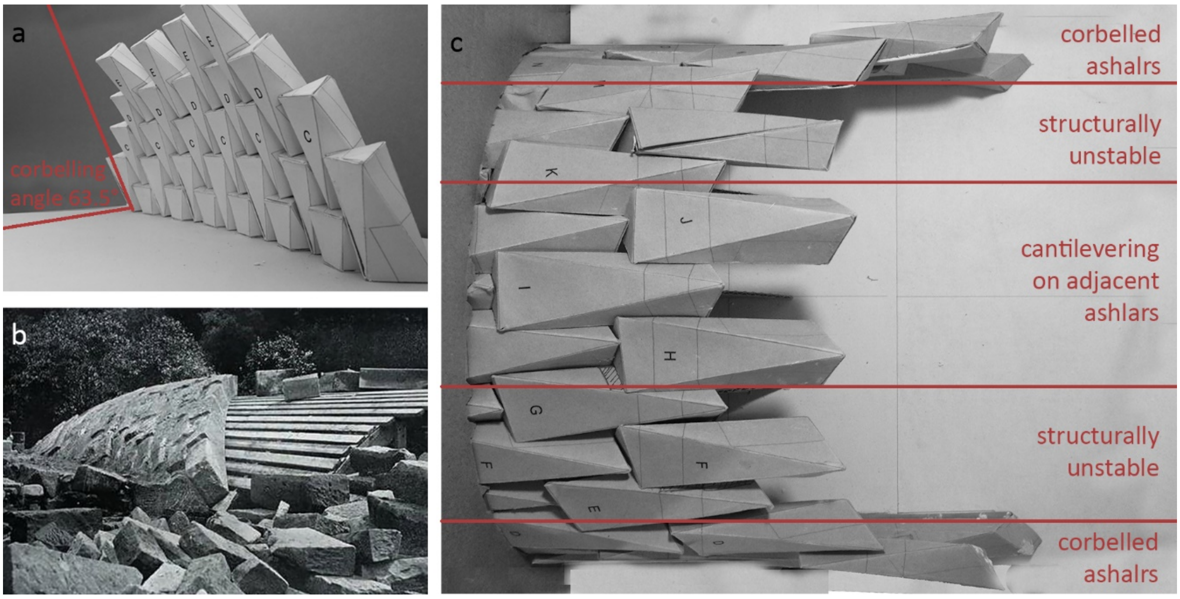


Figure 44: The Structural Concept of the Stereotomic Assembly Based on Nominal Falsework combined structural actions of corbeling (a), cantilevering (c), and topological interlocking (a, c) within the onsite execution sequence of an helicoidal arch (b).
Sources: a) & c) Author. b) Bell, G J 1896, a plate from "A Practical Treatise on Segmental and Elliptical Oblique or Skew Arches", digital image, Public Domain, viewed on 1 April 2019 https://commons.wikimedia.org/w/index.php?curid=9389347

structure novel limestone affordances by engaging the stereotomic material system and regional digital approach.

5.4.2. Structuring

The proposed prototype was an outcome of the stereotomic material system's structure defined by a vaulted surface [42] and hexagonal surface distribution grid. The onsite execution with nominal falsework meant that the falsework geometry was assimilated within other stereotomic geometries, primarily the structure, the assembly, and the ashlar geometry. More specifically, the aim was to establish a system of structurally stable sub-assemblies during onsite execution by combining several structural actions through varying the angle and direction of ashlars' contact faces rotations.

The initial step of the design process structured variations in the structure geometry during the onsite execution. More specifically, physical tests on scale models discretised the force flow variations and externalised them as a structural design concept. The structural concept combined structural actions of corbeling, cantilevering, and topological interlocking with the onsite execution sequence of a helicoidal arch (Figure 44).

[42] The base surface was a single curvature, concave surface based on an extruded catenary curve.

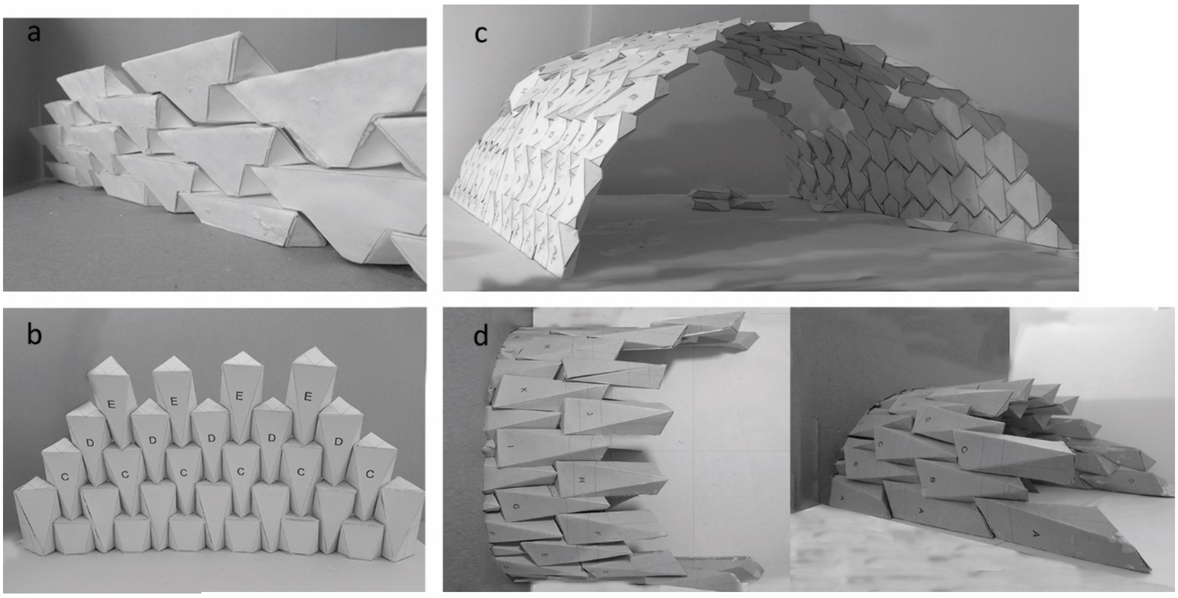
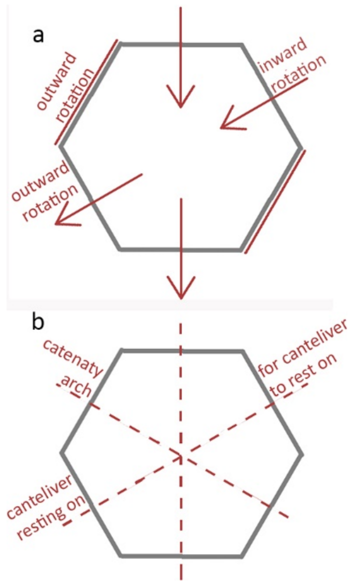


Figure 46: Scale Models Investigating the Execution Sequence of an Assembiy Based on Self-Stabliasing Sub-Assembiles
a) & b) Sub-assemblies based on crobeling and topological interlocking,
c) A number of symetrical, catenary arches abutting a central, circlaur arch,
d) Layering of inclined arches: each arch rested on catnaliered ashalrs of the previous arch
Source: Author

The hexagonal grid established three directions of the surface distribution grid. The structural concept actualised different structural actions for each surface direction. In this way, the rotation angles and directions of ashlar contact faces were established (Figure 45 a). The non-uniform rotations established multiple, locally specific structural actions between adjacent ashlars that mutually stabilised both the ashlars and the assembly during the onsite execution process. Each ashlar was concurrently a voussoir in a catenary arch, a voussoir in a flat arch, and supported adjacent, cantilevered ashlars (Figure 45 b). The structural concept, thus, directly determined the ashlar geometry that actualised as a set of standard configurations based on irregular octahedra (Figure 48 b).

Figure 45: Rotation Directions of Ashlar Contact Faces vary along each surface direction.
Source: Author



Similarly, the structural concept determined the assembly geometry as an amalgamation of self-stabilising sub-assemblies while upon the completed execution, the non-uniform rotations of ashlars' contact faces established a topological interlocking assembly that evened the load distribution.

5.4.3. Construction

The research used physical scale models to assess the premise that falsework could be reduced in the onsite execution of a stereotomic assembly if the assembly was as a system of self-stabilising sub-assemblies and to structure the execution sequence (Figure 46).

a b

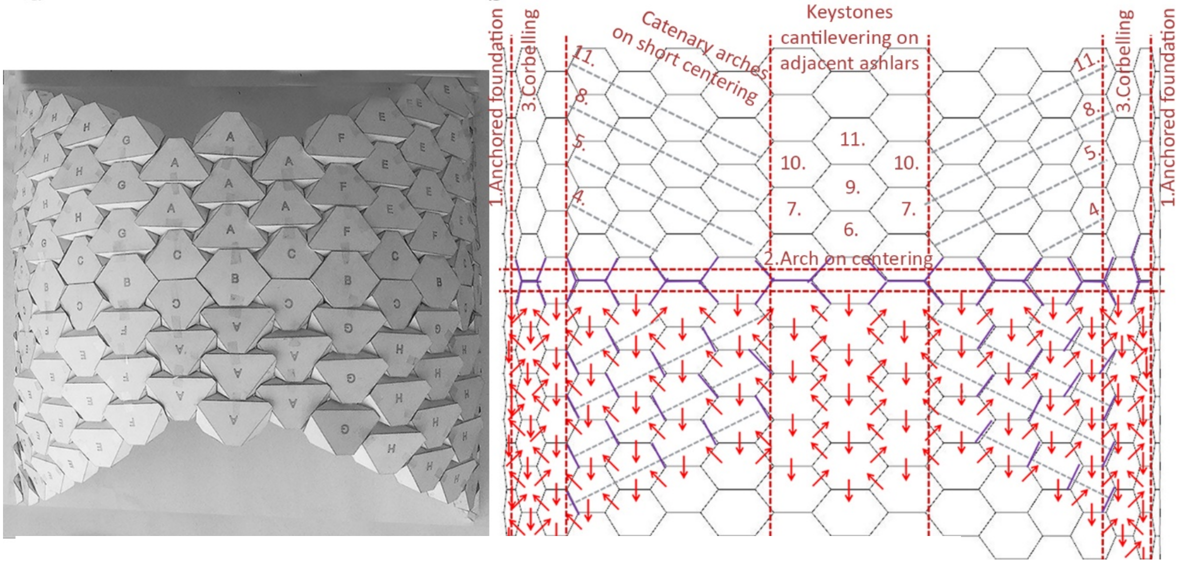
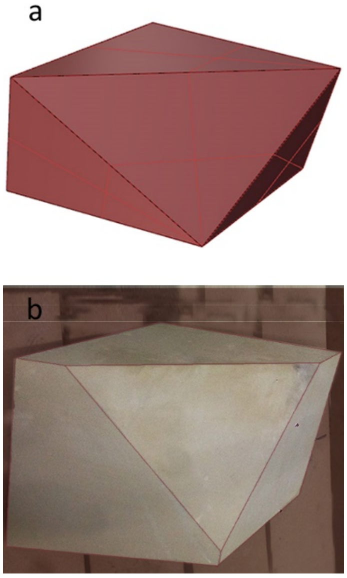


Figure 48: Prototype's Design Concept
a) Assembly consists of a set of standardised ashlars that are irregular octahedra.
b) Self-stabilising sub-assemblies are established at each step of onsite execution.
Source: Author

The initial step of the onsite execution was to establish a restrained boundary condition by anchoring foundation ashlars into the ground and erecting a central, spine arch using falsework. The sub-assemblies laid on the foundations were based on corbelling structural action. They were rows of ashlars placed at an inclination that was within 26.5 degrees from the vertical axis. Next, a succession of short catenary or flat arches was erected spanning between the corbelling ashlars and the voussoirs of the central arch. The catenary and flat arches consisted of ashlars that cantilevered of previously completed sub-assemblies and thus required simple, reusable falsework (Figure 48 b).

Figure 47: Ashlar Fabrication
a) Digital model of the ashlar submitted for the CNC cutting.
b) Fabricated ashlar.
Source: Author

a



5.4.4. Limited Regional Intangible Resources

The collaboration with a local stonecutting company allowed access to a six-axis CNC with a circular saw, a versatile digital fabrication tool. On the other hand, the available instrumental knowledge of the digital tool was limited to machines' preset applications. As a result, discrepancies persisted between the stonecutting fabrication and its CAM simulation and, in turn, between configurations of fabricated ashlars and their digital models (Figure 46).

Further, when applying for the necessary funds to advance the research, the validity of the limestone stereotomy for the contemporary architectural practice and building industry became an issue. It was difficult to justify the feasibility of the lengthy fabrication process [43], the practicality of vaulted forms for

[43] The length of CNC stonecutting fabrication tests was approximately one hour per limestone block.

contemporary design briefs, and the sustainability of the limestone extraction.

Finally, the lack of access to appropriate prototyping digital tools, like a 3D printer, affected the precision of the scale models and reflected on the viability of the physical tests undertaken. As a result, although the conducted investigations indicated the falsework could be significantly reduced in the stereotomic limestone construction, no conclusive proof of concept was reached.

On the other hand, the lack of research progress enabled a better understanding of the contemporary regional contextual realities. It became apparent that the Maltese building industry used digital tools extensively, albeit solely to automate the established construction procedures. More specifically, only machine's pre-set 2.5D cutting applications, like water-jet cutting, laser cutting, and milling were engaged that sufficed limited instrumental knowledge. As a result, affordances of the available digital tools were not accessed, and their full activation hindered.

5.5. The Regional Digital Approach to Teaching Architecture

5.5.1. Regional Digital Materiality

The research exposes that the regional digital architectural practice is inevitably grounded in materiality. Here, the notion of materiality encompasses both the immediately available and accessible materials and their material knowledge. Material knowledge encompasses an understanding of material affordances and instrumental knowledge of construction processes that activate these affordances.

The current and anticipated contextual shifts in resource availability inflect and will inflect Malta's regional materiality. Regional materiality is, thus, intrinsically indeterminate and necessitates continuous contextual explorations. It is an approach fundamentally opposite to the dominant design thinking that guides the contemporary Maltese architectural practice.

The research premise is that to instigate the change of direction of the dominant design thinking towards contextual structuring, it is necessary to start at the grassroots level, architectural education. The research tested the premise by engaging the regional digital approach as a methodology for teaching architecture.

5.5.2. Instigating Computational Thinking

"If you want to understand the 21st Century then you must first understand computation."
(Bundy 2007, cited in Kotnik 2016, page 43)

When engaging the regional digital approach as a methodology for teaching architecture, students' understanding of computation becomes pivotal. The computation focuses primarily on the problem formulation and the expression of the process from which a solution, or a range of solutions, is derived. It is, thus, fundamentally opposed to the established approach of the current educational system that architecture students were previously, and possibly still are, part of characterised by the prompting of a single, final solution.

The Computational Design Theory study unit was a 4 ECTS study-unit of the BSc in Built Environment Studies course, thought by the author. The study-unit aim was to instigate computational thinking within the students and to recognise and appropriate underlying rules that generated form.

The study unit started by introducing students to existing formation processes found in nature, mathematics, and architecture. More specifically, it observed examples of material systems within biomimicry, design of structures, facade design geometry, digital fabrication, material computation, art, music, and parametric architectural design.

Next, the students had to pursue research on the topic of their choice, guided by the following steps:

1. Formulate a set of generative rules, by either recognising existing or creating your own.
2. Develop the rules into an algorithm.
3. Run the algorithm through analogue or digital means to generate a form.
4. Discuss the resultant generated form.

The teaching methodology of the study unit is further explained with an example of a students' research project. The research topic was procedural and generative art with the focus on the notions of process, randomness, and predictability. Students developed a generative art project based on the story about the city of Zobeide, from Italo Calvino's book "Invisible Cities".

"*Zobeide, the white city, well exposed to the moon, with streets wound about themselves as in skein […where] men of various nations had an identical dream. They saw a woman running […and] dreamed of pursuing her. As they twisted and turned, each of them lost her […] they decided to build a city like the one in the dream*

[…They] changed the positions of arcades and stairways to resemble more closely the path of the pursued woman and so, at the spot where she had vanished, there would remain no avenue of escape.”
(Calvino 1978, page 45)

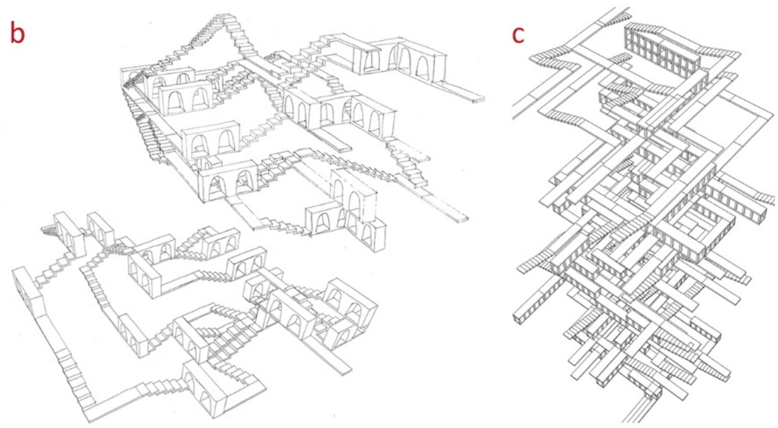
The recurring dream that prompted the never-ending rearrangement of three basic elements, the path, the arcade, and the stair, was structured as a recursive algorithm based on randomness (Figure 49 a). The encoding of the algorithm necessitated a for-loop control flow statement to specify iterations. The algorithm was actualised in two ways: through analogue computation and as programming. The former comprised of tossing a coin and 3D -modelling the sequence of the elements accordingly (Figure 49 b). The later included developing a generative script (Figure 49 c). Both sets of outputs truly represented the ephemeral, directionless, dream-like nature of the city of Zobeide. More importantly, in developing comparable analogue and digital methods of algorithm's actualisation, the students appropriated computational thinking.

On the other hand, a majority of students choose visual programming software, primarily Grasshopper, to develop their research projects before choosing the research topic. Compared to the example discussed, thus, they matched the problem to the digital tool rather than the other way around. In this case, most of the students' time was dedicated to acquiring instrumental knowledge of the software to encode an algorithm within it, rather than in exploring its generative potentials. Further, since the digital tool engaged was based on associative geometry, research topics focused on generative, geometric rules. The topics tackled included, among others, spider web geometry (Figure 50), the parametric design process for stadium seating bowls, Gothic architecture

Figure 49: The Zobeide Project
a) The Zobeide algorithm.
b) The analogue actualisations was done by coin toss and 3D modelling of the sequnece of the three basic elements.
c) Digital outcomes of the programmed script.
Source: Sammut, T.; Buttigieg, I.; Theuma, N., 2016

a

```
1 Start at Origin
2 //Choose Element // Flip a Coin:
if Heads = Path
    //Choose Path Type // Flip a Coin:
        if Heads = Normal Path
        if Tails = Arcade
    //Choose Path X Direction//Flip a Coin:
        if Heads = -x
        if Tails = +x
    //Choose Path Y Direction//Flip a Coin:
        if Heads = -y go to 3
        if Tails = +y go to 3
if Tails = Stairs
    //Choose Stair Direction // Flip a Coin:
        if Heads = //Up// +z go to 3
        if Tails = //Down// -z go to 3
3 Check if Limits have been reached
    if yes = stop
    if no = go to 2
```



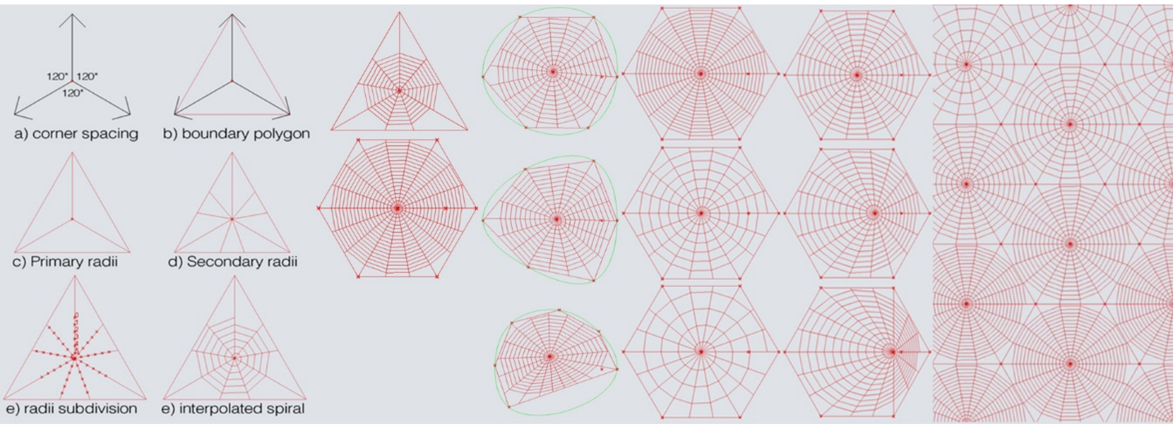


Figure 50: A study-unit research project on spider webs.
The research aim was to derive parameters of orb web geometry and analyse their variability using parametric digital models of associative geometry.
Source: Attard, D., Cutajar S., Pace, K., and Spiteri, A., 2013.

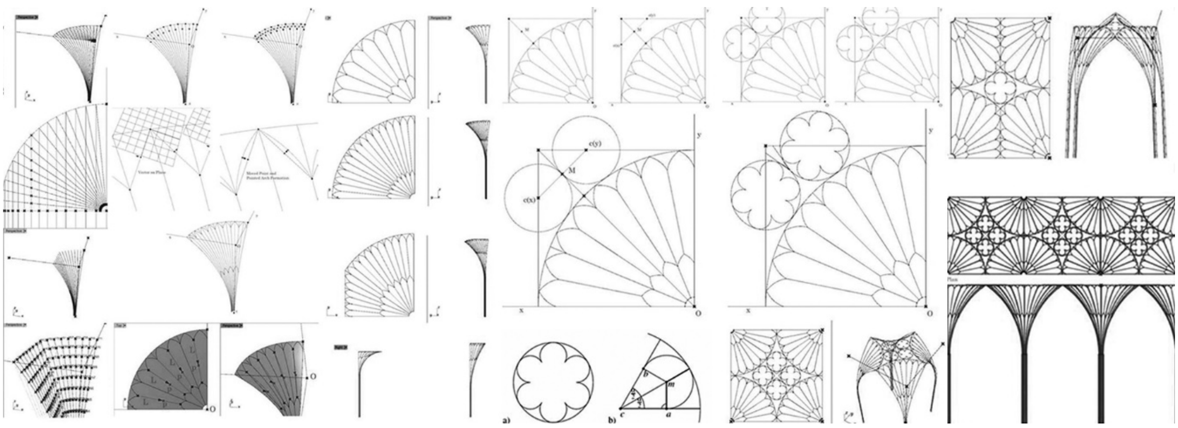
(Figure 51), tessellations, and shell structures. Still, the resultant projects reflected students' understanding of computational processes, variations of their outcomes for different contexts, and problem-solving capabilities for multiple scenarios.

In conclusion, the study-unit outcomes exposed that digital tools were a straight forward way to introduce computerisation into architectural design processes. On the other hand, they were sometimes detrimental in instigating computational thinking. More effective methods were research-based, like material computation and physical tests on scale working models that engaged digital tools to match problem's nature and student's affinities.

5.5.3. Regional Digital Architectural Design Processes

At the Masters Level, the regional digital approach became the basis for tutoring the Year 1 Design Workshop of the MArch (Architectural Design) Programme. More specifically, the tutoring methodology approached the context as topologically continuous capacities and

Figure 51: A Student Assignment for a History Study-Unit Used the Computational Approach to formulate geometric parameters that define the Gothic fan vault
Source: Azzopardi, C., 2013.



constraints of the available and accessible knowledge, resources, materials, skills, tools, and technology. In this way, architecture's traditional split into design processes of different pursuits was negated. Instead, the multiple design pursuits of sustainability, conservation, and performance of resources, heritage, and sociocultural aspects became inseparable architectural concerns.

The approach is explained with three examples of Final Project, Year 2, MArch (Architectural Design) for which students consciously developed design processes grounded in the structuring of the regional context. Each Final Project questioned the capacities and constraints of a different regional contextual reality. The site chosen as an investigation platform was the town of Marsalforn, Gozo, a traditionally built yet rapidly developing the urban area.

5.5.4. The Regional Digital Approach to Materiality

The first example of the Final Project tackled the notion of regional materiality. Its focus was the unavoidable depletion of limestone, sand, and freshwater[44] . Its scope was to investigate construction processes that actualised novel affordance of the abundant construction and demolition waste. The construction processes recognised and worked within constraints of limited regional instrumental knowledge and physically restrictive nature of the chosen site in terms. The construction processes had to be, at once, sensitive, feasible, reliant on manual execution, and address low volumes yet varied demands of architectural production.

The Final Project proposed construction based on small, cast blocks that could easily vary in configuration and material properties. The block, thus, provided workability, versatile performances, and minimal waste production [45] . The proposed material palette consisted of material mixtures made from the crushed construction waste, limestone gravel, resin, several aggregates, expanded polystyrene, and untreated seawater (Figure 52).

The use of seawater went against one of the guiding rules of the established construction procedures to avoid salts. Salts caused damage to the materials used by the contemporary Maltese architectural practice, like limestone, concrete, metals, and metal alloys. On the other hand, seawater was the most abundant and accessible resource in the Maltese regional context. The consideration of seawater in regional construction illustrated the design thinking that guided the Final Project. It was a bold rethink of architectural responses to contemporary regional contextual realities.

[44] The depletion of aquifers is predicted by the year 2100 (McGrath, 2007), while the current seawater desalination process, based on non-renewable energy, is perceived as too taxing to persist.
[45] Compared to subtractive fabrication methods.

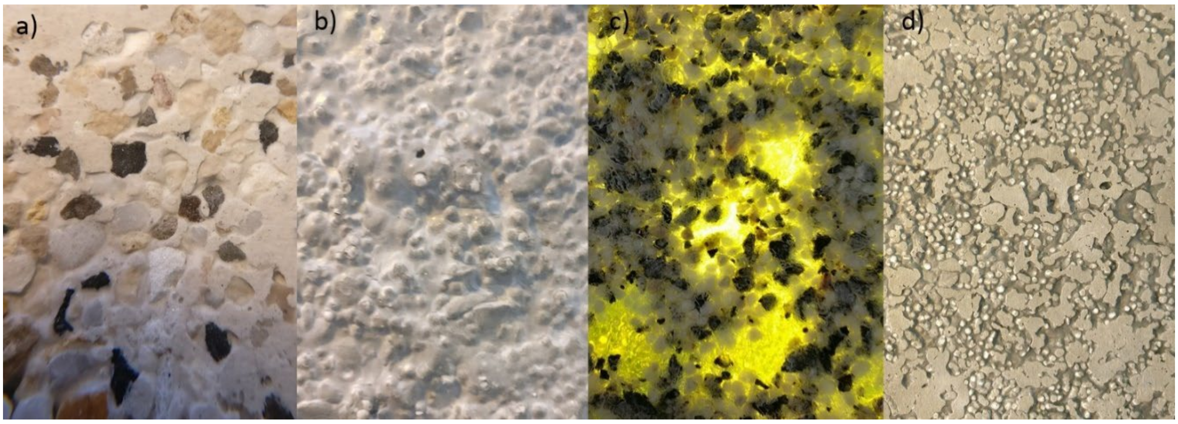
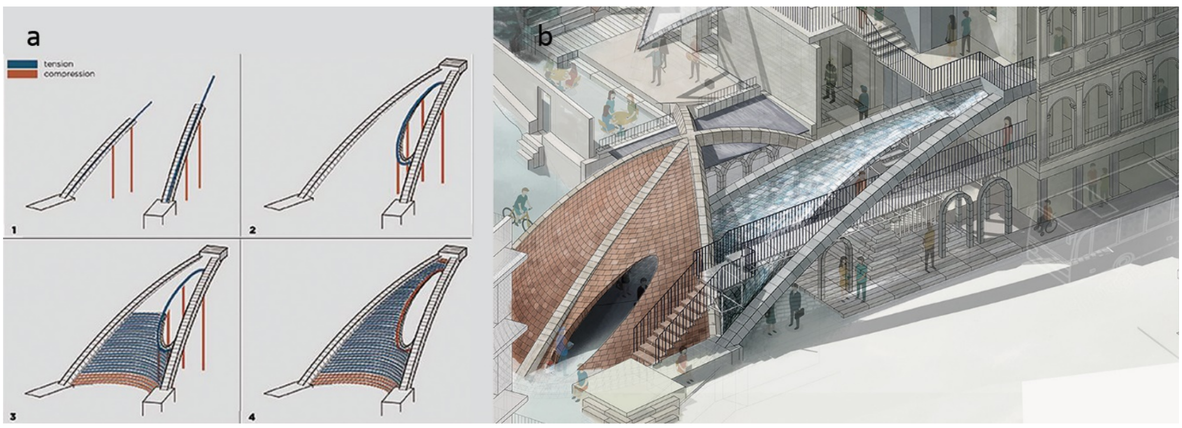


Figure 53: Samples of cast material mixtures:
a) crushed construction waste, b) concrete with expanded polystyrene,
c) crushed limestone, d) resin with aggregates.
Source: Theuma, N., 2018.

The developed material mixtures embedded mutually comparable properties of a constant mass, the lack of deflection under compression loading, and the preserved loading configuration when loaded. Further, the presence of seawater eliminated the use of metals that restricted possible structural actions to compression and shear. More specifically, the proposed material mixtures cast as small blocks allowed for the structuring of their spontaneous activities and engineered behaviours as systems of geometries and geometric interdependences. In short, the Final Project developed a stereotomic material system.

The stereotomic material system was a negotiation between material properties, limited instrumental knowledge, manual execution, simple falsework, and programmatic requirements of the project brief. The negotiation derived the structure of the material system an amalgamation of self-stabilising sub-assemblies that merged the arch and topological interlocking structural actions. The structure actualised as varied block configurations and a specific

Figure 52: The Final Project tackling regional materiality
a) The proposed onsite execution sequnece.
b)The visual illustrates sevral different acualsaitons of the steretomic material system
Source: Theuma, N., 2018..



onsite execution sequence. The joggled surfaces of the blocks' contact faces were either perpendicular to the line of thrust or rotated in the alternating directions. The onsite execution sequence started with the lighter blocks that acted as falsework for the heavy, loadbearing ones. A certain amount of temporary external post-tensioning, like clamps and ties, was anticipated, necessary until the structural actions were activated (Figure 53 a).

The visual appearance of the resultant architectural forms reflected the regional materiality and contextual heterogeneity. Their derived tectonics expressed familiarity, albeit their non-traditional configurations and materials (Figure 53 b).

5.5.5. The Regional Digital Approach to Programme

The second example of the Final Project based on the regional digital approach focused on the structuring of continuously shifting programmatic requirements within the built environment.

The initial point of the project research was universally bland, visually and performatively segmented built environment established by the contemporary architectural practice. The research explored an area of Marsalforn characterised by distinctly separated zones, primarily the open water, fishing boats' marina, a parking area, restaurant marquees, a 5-star hotel, its service road, several abandoned and poor-quality housing blocks, and inaccessible fields (Figure 54 a). Firstly, the research assessed the capacities and constraints of physical boundaries between building typologies and strong intangible boundaries between singular activities (and "inactivities"). The research assessment then focused on the 5-star hotel, its globally standardised typology, its assumed users, and the universality of their experience.

Next, a design process was developed as a curation of the existing contextual capacities and constraints. It pursued minimal

Figure 54: The Final Project tackling shifting programmatic requirements
a) Boundaries between different building typologies and activity zones on the site.
b) A plan drawing showing the prosposed gradient of activities and spatial variations.
Source: Buttigieg, I., 2018.

interventions that instigated maximum opportunities for negotiations between insular spaces and activities. In this way, the design process negated the static boundaries as they became indistinct and "fuzzy" areas of activities that varied in intensity and quality (Turner 2000). As boundaries dissolved, the site became a gradient of spatial variations responsive to contextual changes and programmatic requirements instigated by the changes (Figure 54 b).

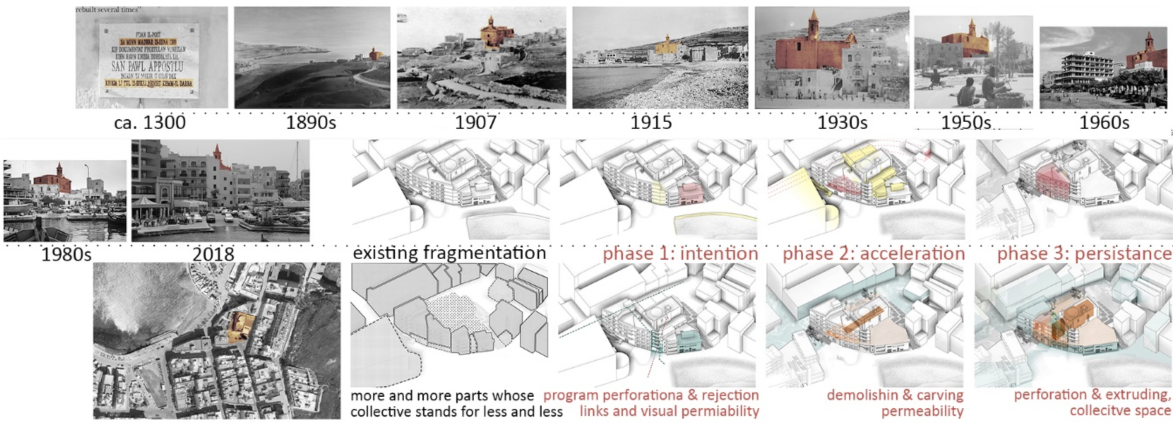
The Final Project exposed the current economic and political shifts in the regional context that collapsed the traditionally established classifications of users into travellers, tourists, seasonal workers, temporary residents, long-term residents, locals, and foreigners. By assimilating the heterogeneity of the immanent yet uncertain shifts within regional contextual realities, the Final Project developed a design process that derived architectural forms that could accommodate the multiplicity of users and varying lengths and types of their residency.

5.5.6. The Regional Digital Approach to Socio-Cultural Contextual Realities

The third example of a Final Project based on the regional digital approach looked at how shifts within the sociocultural context reflected in the built environment. More specifically, the Final Project aimed to understand the influence that the intangible shifts within the regional context had on the relationship between the Marsalforn church and its urban environs.

In the initial research, the Final Project mapped historical changes of the sociocultural context and its current dominant trends (Figure 55). The research exposed that, over time, the church over lost its prominence as both a physical and religious landmark. The former was instigated by the overwhelming density of surrounding

Figure 55: Diagram mapping reflections of contextual shifts on the urban environment as the changing relationship between the Marsalforn church (orange) and its environs (black & white). The last eight slides show the assimilation strategy of the proposed design intents within the context.
Source: Ebejer, J., 2018



buildings much taller than the church. The latter was due to the changing urban nature of Marsalforn from a local summer destination to a permanent residence of a growing, non-local workforce.

The Final Project premise was twofold. Firstly, a design process grounded in the continuity of the contextual changes could negotiate proposed design intents with and within the context. Secondly, if the notion of the church was recognised not solely as a place of religious worship but as a hub of activities that instigated the sense of community and belonging, the church could reinstate its physical and sociocultural landmark status.

The design process, as an urban curation, proposed a slow yet continuous expansion of the church's activities that increased its spatial legibility. In the first phase, recent accretions were removed to create public, open, non-consumption spaces susceptible to organised and informal encounters, gatherings, and lingering. In the later phases, the anticipated growth of the church's novel, open-ended activities progressively encroached and appropriated space within the surrounding buildings. In this way, the church reinstated its socio-cultural role by not imposing onto but assimilating as the context.

5.6. What Is the Question?

"Technology is the answer … but what was the question?"
(Price 1979)

The regional digital architecture is grounded in contextual structuring akin to stereotomy. The regional digital design process engages computational thinking to formulate material systems that derive architectural responses from and for their immediately accessible contextual realities. Due to globalisation, contemporary contextual realities do not exist in isolation and are mutually connected. Changes within one set of realities instigate ripple effects that are felt within multiple other contexts, albeit at varying scales and with different intensities.

Contemporary architectural practices engage digital technology, in some capacity or other, to address and respond to contextual realities and contextual changes. The contemporary Maltese architectural practice omits to address the full complexity of its contextual changes and engages digital technology to automate the production of established, fixed structure-construction models. In this way, digital technology fortifies the imposition of contemporary built forms on the context and perpetuates their lack of concern for sustainability, relatedness, and authenticity.

Engaging digital technology as a tool that fosters contextual negotiations necessitates proficient instrumental knowledge and, more importantly, a proficient understanding of the regional context. In short, although the regional digital architectural practice relies on digital tools to derive answers, its crux remains the formulation of continuously shifting questions that it has to address.

6. A Stereotomic Approach to Regional Digital Architecture

"... it is good to ask oneself: What are we exactly doing?"
(Picon 2017).

6.1. Research Summary

The motivation of the undertaken research was to establish personal design thinking to guide architectural teaching and practice within Malta's built environment, a context that embedded multiple contradictions. The contradictions emerged from the divergent approach to the materiality between the traditional and the contemporary architectural practice. The research scope was, thus, to understand shifts in contextual realities that caused the divergence. The research focus was neither the appearance nor performance of Malta's built forms but their underlying design logic, and the contextual constraints that instigated it.

Stereotomy, an architectural practice grounded in materiality, became a theoretical framework that guided the research development. Historically, stereotomy emerged from the bottom-up approach to materiality akin to the Maltese traditional architectural practice. The availability of digital tools caused a renewed interest in stereotomy and enabled its contemporary advancements. The research focused on stereotomic design thinking grounded in the systemic approach to the context and recognised on the stereotomic design process as structuring. Structuring was a term put forward by digital architectural theory. It encompassed a set of computational processes that discretised and externalised multiple contextual constraints, and their negotiations, as a generative system of geometries and geometric interdependencies. More specifically, the research approached stereotomy was an architectural practice that folded context to derive material systems that, activated by contextual feedback, unfolded architectural responses. The research, thus, exposed stereotomy as an early example of digital architecture.

The research formulated the structure of the stereotomic material system as an arrangement of four geometric parameters and their multiple interdependencies.

Next, the research focused on the actualisation of the material system's structure. It followed two lines of investigations. One engaged a specific material and construction method: limestone ashlars and masonry construction with reduced falsework. The other line of investigations focused on a specific structural action, the topological interlocking. The progress of the former was hindered by the limited instrumental knowledge within the Maltese context. The outcome of the latter was the stereotomic material system actualised as a full-scale, non-masonry prototype, the Stereotomic Plate Pavilion. Both lines of investigations confirmed the research premise that stereotomy was a generative geometric material system structured from and for its context, not specific materials or construction techniques.

The wider understanding of stereotomic design thinking and structuring became a theoretical perspective from which the research theorised the notion of regional digital architectural practice. The notion encompassed architectural analysis, design, production, and teaching methods and processes that approached context as a system of affordances, of topologically continuous capacities and constraints.

Following the regional digital architectural analysis of the Maltese context, the research draws four conclusions.

Firstly, the traditional Maltese architectural practice was an example of regional digital architecture. It could structure multiple contextual realities as a material system that actualised as the topologically continuous, performatively connected, and tectonically coherent cultural landscape. Its derived forms and their familiar tectonics were inseparable from their formation process that was established from and for the context. More specifically, constraints of Malta's limited tangible resources and geographical discontinuity established the material system as a frugal, self-sufficient, and self-referential yet robust and susceptible to assimilations of intangible resources.

Secondly, the contemporary Maltese architectural practice was based on the established singular structure and fixed construction procedures. The singular structure emerged from the consistency of the dominant contextual constraints. The structure's repetitive, iterative actualisations, in turn, established fixed construction procedures and standard configurational outcomes. In this way, the design process progressively ceased contextual negotiations, and the singular structure remained unaffected by contextual changes.

Next, the analysis recognised Malta's contemporary built environment as a result of a gradual contextual shift from the isolative geographical discontinuity to geopolitical connectedness. The shift instigated an unprecedented influx of tangible and intangible resources that complexified Malta's context. On the other hand, its contemporary architectural practice responded only to a limited set of constraints imposed by the persistent, speculative building boom. It retained the fixed construction procedures and the established singular structure as they successfully met the economic and utilitarian requirements of the building boom. The result was an architectural practice that operated within a restricted design space of universal solutions, a limited material palette, and fixed procedures.

Finally, the analysis exposed that the notion of the "Maltese-ness" of the Maltese architecture was tied the contextual structuring. Since the contextual engagement of the contemporary architectural practice was limited, it expressed contextuality by engaging phenomenological, surface-based tools, like standard configurations and limestone cladding. Further, the lack of contextual engagement also limited the ability of the contemporary Maltese architectural practice to respond to the current contextual shifts in resources, knowledge, materials, skills, tools, and technology. On the other hand, its successful responses to the speculative building boom allowed the contemporary Maltese architectural practice its denial of the contextual shifts and hindered any change within its design thinking. The analysis, thus, concluded that engaging the regional digital architectural practice grounded in the contextual structuring was only possible at its grassroots level, architectural education.

As a result, the research engaged the regional digital approach as a teaching methodology for several Desing Workshops and study-units that dealt with both theoretical and practical student projects. The teaching methodology pursued design thinking that was grounded in the notion of regional context. It aimed to encourage students to question both their understanding of context, its tangible boundaries and its dichotomies. Students were also encouraged to question the formally established differentiation between architectural disciplines that each discipline focused on a different, specific, limited set of contextual constraint. Instead, aspects like sustainability, conservation, and performance of resources, heritage, and sociocultural were approached as inseparable architectural concerns. In this way, the undertaken research established an open-ended theoretical framework for a teaching methodology. It approached architecture as an indivisible discipline that actualised a complex, all-encompassing web of multiple contextual realities as dynamic responses whose forms and meanings were constantly negotiated (Hosagrahar 2012).

6.2. Further Research

"The most widely acknowledged external forces impinging upon architecture and cities today are digital technology, globalization, environmentalism, and local politics [that shape local architectural practices ...] Certainly, the speed with which change occurs in architecture […] *has accelerated."*
(Cuff 2012, page 391)

Within the realm of contemporary globalisation, contextual realities do not exist in isolation and are mutually connected. Changes within one set of realities instigate ripple effects felt within multiple other contexts, albeit at varying scales and with different intensities.

In the same way, Maltese contextual realities are concurrently regional and global. Due to Malta's small scale and geographically discontinued yet globally connected environment, with its context, changes are amplified, and their ramifications more apparent. These include, primarily, the increasing urbanisation, diminishing natural resources, the unwavering dependence on universal solutions, the abundance of waste, the lack of assimilation of the available digital technology, and sustainability. In short, Malta's regional context is a microcosm of global contextual realities.

The main contribution of the research undertaken is a better understanding of the context within which the Maltese architectural practice operates. The research offers itself as a knowledge platform for further explorations. Although their focus is on regional contextual realities, their research concerns are concurrently global.

6.3. Research Direction 1: Regional Materiality

Contemporary contextual shifts that have instigated the increasing urbanisation reflect within the Maltese built environment as a continuously changing, diverse yet specific, programmatic requirements. The Maltese building industry addresses the heterogeneity, multiplicity, and temporality of the programmatic requirements through imported, universal solutions embedded in the established architectural typologies. Their construction engages a limited set of materials whose properties are specifically synthesised to achieve homogeneity and permeance. In this way, the energy used in the construction and untimely demolition of the resultant architectural forms is disproportional to the lifespan of their programmes and their materials.

The regional digital theoretical perspective exposes a necessary rethink of the current notions of materiality. A research direction that purses the question:

- What is a valid Maltese regional materiality?

More specifically: What regional resources are appropriate as building materials within the Maltese regional context? How to develop material knowledge of their affordances? How to develop construction processes that activate these material affordances?

6.3.1. Demonstration Test 3: Volumetric Digital Architecture

The notion of regional materiality has motivated the current research into the development of a stereotomic assembly of discrete volumes. The research is grounded in the regional digital approach and builds on the outcomes of the Demonstration Test 2 that focused on developing the regional stone masonry construction. The research aim remains to establish a contextually engaged material system that responds to the changing resource availability while it also addresses commercial viability and sensitive onsite construction. The research scope is to understand the economic cost of architectural production based on the energy invested in its procedures, the sourcing of materials, and materials' lifespan, lifecycle, recyclability, and waste generation. The research methodology follows six premises.

Firstly, the research seeks to expose the embedded opportunities for use and reuse of the available resources. Materials considered are mixtures of resin and crushed construction and demolition waste. The research assumption is that in this way, material properties can be derived to address different yet specific performance requirements of each element within the assembly. In this way, stereotomic assembly is resilient and sustainable.

Secondly, the fabrication process for the research is casting. It generates less waste than subtractive fabrication and allows for precise fabrication of geometrically complex configurations. It can be combined with subtractive manufacturing to post-process elements' configurational details. It also allows onsite fabrication of the elements that address misalignments during execution.

Thirdly, elements' material properties encompass a constant mass (density), lack of deflections under a compression loading, and retained loading configuration when loaded. In short, the stereotomic assembly is masonry construction, and its dominant structural actions are compression and friction.

Next, the stereotomic assembly is based on a hexagonal surface distribution grid that generates three surface directions. In this way, elements can perform differently along each surface direction. Their contact faces are either convex or concave surfaces akin to the configuration of an osteomorphic block. The undulating contact faces achieve alignments and address shear stress between adjacent elements.

Further, the onsite execution of the stereotomic assembly follows a weave-like sequence to achieve stable sub-assemblies that deal with the changing force flow (Figure 57). It combines light, workable elements and heavy, loadbearing ones. The former ones are either installed first and act as falsework for the latter ones or are installed

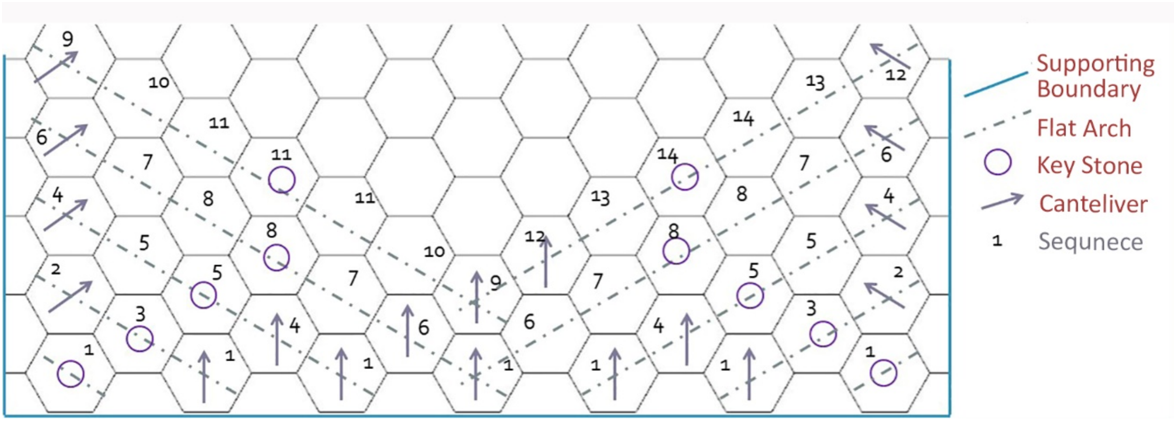


Figure 56: Diagram of the weave-like sequence of prototype's onsite execution.
Source: Author

last and act as infill. In this way, the onsite execution suffices light machinery and nominal, reusable falsework.

Finally, the onsite execution of the stereotomic assembly relies both on builders' participation (Ruskin's “savageness”) and digital tools to achieve exact tolerances and address accumulative mistakes. For example, a keystone, the last element placed in a sub-assembly, is designed as the least geometrically complex configuration that is defined[46] onsite (Clifford et al., 2015).

The research into the development of a stereotomic assembly of discrete volumes is akin to several current research pursuits[47] within the digital architecture of hinterland contexts. The research pursuits engage digital tools to assimilate multiple contextual constraints[48] within the digital design process and fabricate geometrically complex architectural forms. Through proficient instrumental knowledge, they expose the ability of digital tools to negotiate multiple design constraints and derive architectural responses. The responses are primarily surface-based, and the challenge remains to actualise volumetric digital architecture (Picon 2010).

In short, the main research challenges when pursuing the development of a stereotomic assembly of discrete volumes are the limited regional instrumental knowledge and the lack of case studies of volumetric digital architecture in the hinterland context. Concurrently, the challenges make the research more valid.

[46] The exact configuration of a keystone is determined through 3D-scanning or simple measuring.
[47] They include, among others, the digital design approaches like the New Structuralism (Oxman, et al. 2010) and Material Computation (Menges, 2012; Menges, 2015), and conferences like FABRICATE (Sheil, et al. 2017).
[48] Contextual constraints tackled include, amongst others, force flows, climatic performances, material properties, and fabrication limitations.

6.4. Research Direction 2: Expanding Regional Design Knowledge

Due to its persistently low volumes yet varied and unique demands, Malta's architectural production never reached the economies of scale that in hinterland contexts instigated the industrial mass production synonymous with the Modernism. More specifically, Malta's architectural practice never switched to rationalised, modular, highly efficient, specialised components. Instead, it retained strong ties with craftsmanship that engaged manual labour, high technical skills, and proficient tacit material knowledge to negotiate between design intents and material affordances.

In the past decade, architectural production has progressively shifted towards digital tools yet remained reliant on manual labour. Due to its ties to fixed procedures, it engages digital tools solely for their automation that suffices limited instrumental knowledge. As a result, boundaries emerge between the accumulated regional technical skills and material knowledge, CAM tools, and material affordances. Similarly, design intents are directly affected by the designer's limited ability to encode and represent them in a CAD environment. As a result, their formal outcomes often express recognisable aesthetics as an imprint of the CAD tools used (Kolarevic 2016). Boundaries emerged between design intents, their representations, CAD tools, and their formal outcomes. In short, digital tools provide contemporary Maltese architectural practice with vast opportunities that they instead hinder.

The regional digital theoretical perspective exposes a necessity for a research direction that explores ways in which the contemporary Maltese architectural practice engages with digital tools. More specifically, although digital tools are instrumental in deriving architectural answers to continuously shifting contextual realities, the crux remains the formulation of valid design questions and design processes. The main research questions, thus, include:

- How can digital tools encode, encapsulate, and instrumentalise the wealth of regional design knowledge?

- How can digital tools explore the affordances of immediately accessible resources and materials?

- How can digital tools enable the assimilation of novel and imported design knowledge with regional design knowledge?

- How can digital tools enable the appropriation and assimilation of accessible instrumental knowledge from hinterland contexts within regional design knowledge?

6.5. Research Direction 3: Instrumental Knowledge in Architectural Education

From the regional digital theoretical perspective, the contemporary architectural practice has to rekindle its, intrinsically Maltese, systemic approach to t context. More specifically, the contemporary architectural practice has to return to its vernacular design thinking rather than to vernacular forms.

The main aim of architectural education is to instigate within students' design thinking grounded in explorations and innovations that access and engage affordances of the continuously changing regional context. Research initiatives within the contemporary Maltese architectural practice are hindered by the building industry driven by the speculative building boom. Instead, the pivotal responsibility lies with architectural educators and students to expand their instrumental knowledge to become "expert amateurs" (Paulos 2013) who curate regional contextual realities. In this way, architectural education can align Maltese architectural practice with complexities of its context.

The main challenge of the research direction that pursues ways to expand the limited instrumental knowledge is to establish it at intrinsically regional. More specifically, instrumental knowledge from hinterland context and models of instruction and exchanges cannot be imposed but appropriated and assimilated as regional design knowledge.

6.6. Research Direction 4: Understanding the "Maltese-ness" of Maltese Architecture

Finally, the research conducted argues for an assessment of the established expressions of the Maltese authenticity in architecture and its prevailing notions of contextuality. More specifically, it establishes a research direction that pursues the open-ended question:

What is the "Maltese-ness" of the Maltese architecture?

The research scope is to explore how the structuring process engages the regional context within the design process. The research premise is that the derived tectonics of the design process grounded in contextual structuring as affects. Affects are pre-personal, unmediated intensities that generate multiple meanings, thoughts, and emotions yet express relatedness (Moussavi, López 2009). In this way, architectural forms that embed affects are unavoidably, intrinsically contextual.

In theorising the notion of affect, the research instigates more questions than it accepts answers. The research, thus, necessitates multidisciplinary discussions and projects, and the inclusion of a wide number of participants.

6.7. Final Thoughts

"Disaster scenarios hold the potential for innovation: the old ways have not worked, so new solutions are necessary. It can start with a challenge to the [established] model [of design thinking […] but it will inherently lead to changing our [architectural practice and] production […]"
(Cuff 2012, page 390)

The shifts within contextual realities, current and imminent, instigate an intrinsically indeterminate regional materiality. The current architectural practice can still ignore it or embrace it. Both options are, in some way or another, an opportunity for a change. The difference lies if the change within the current architectural practice is pre-empted or becomes imperative.

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8. Appendix

8.1. Geometric Versatility of Abeille Vault, A Stereotomic Topological Interlocking Assembly

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Conference Proceedings of the 34th eCAADe[49] Conference, 391-397
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Eds. Aulikki Herneoja, Toni Österlund, and Piia Markkanen

[49] Education and Research in Computer Aided Architectural Design in Europe

Geometric Versatility of Abeille Vault

A Stereotomic Topological Interlocking Assembly

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The Abeille flat vault, patented at the end of 17th century, consists of identical ashlars arranged in a woven-like pattern that generates their interlocking mutual support. In recent years, the availability of digital design and fabrication tools has caused new interest in the Abeille vault. Several studies investigate the interlocking principles through their application onto non-planar assemblies. This paper is a is a more systematic exploration into the underlying geometric interdependencies behind interlocking principles. It approaches the Abeille vault as a topological interlocking assembly (TIA), an assembly where basic identical elements of a special shape are arranged in such a way that the whole structure can be held together by boundary constraint, while locally the elements are kept in place by kinematic constrains imposed through the shape and mutual arrangement of the elements. The paper looks at the full potential of the Abeille vault application and studies the relation between the surface geometry and TIA

Keywords: *stereotomy, Abeille vault, topological interlocking*

Introduction

Stereotomy is a discipline that accumulates theoretical and practical knowledge of stone cutting and stone construction. Since, as Jacques Heyman explains: "the key to understanding of masonry is to be found in a correct understanding of geometry" (1995, 154), stereotomy is based on essential geometric relationships embedded within masonry. It started in the Gothic period, had its peak during the Enlightenment in the examples such as the undulating vaulted space of the Arles City Hall vestibule by Jules Hardouin-Mansart, completed in 1637. The main reasons for the later decline of stereotomic techniques were the introduction of steel and concrete that were less labour intensive and did not require knowledge of complex geometries, as well as change in cultural mind set where the rationalist tectonics did not approve of "deformed, showy tricks" (Evans 2000).

Stereotomic architecture is primarily based on vaulted systems to cover large spans. Such material systems ideally are shaped as an arch, as it was discovered by Robert Hooke in 1675. Hooke described the relationship between a hanging chain and the inner force flow in an arch, as "ut pendet continuum flexile sic stabit contiguum rigidum inversum" (Heyman 1998). The flat vault or voûte plate (Figure 1) invented by Josph Abeille in 1699, thus, has to be seen as an exceptional stereotomic solution that provides "all in one a ceiling for the lower storey, and a pavement for the upper storey" (Fleury 2009). In an Abeille vault the shape of each ashlar or voussoir is identical: a polyhedron with axial sections in the shape of an isosceles trapezium. The unique ashlar geometry and the rotation of neighbouring ashlars by ninety degrees allows for a simple method of their mutual arrangement: each ashlar is carried by two neighboring ones, and at the same provides support for two other ashlars. "With this arrangement, each voussoir is carried on two others through its protruding cuts, and at the same time carries two others on its sloped cuts [...], this being reciprocal in all the vault's area, it supports itself at level" (Fleury 2009).

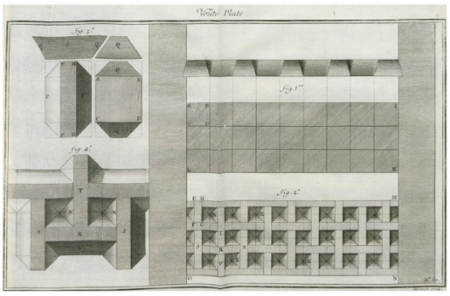


Figure 1
Abeille Vault.
(Gallon 1735).

The woven-like organizational pattern of the Abeille vault resembles the organizational pattern of reciprocal timber frame structures of Villard de Honnecout (Lassus 1858) or Sebastiano Serlio (Hart and Hicks 1996). Both structures overcome the problem of finding a constructive solution to cover a space with a flat floor consisting of small discrete elements.

Structurally, however, the Abeille vault behaves differently than a reciprocal frame structure, namely as topological interlocking assembly (TIA), a notion introduced by Yuri Estrin and Arcady Dyskin in material science in 2001 (Glinckman 1984 and Estrin et al. 2011). TIA are defined by basic identical elements of a special shape which are arranged in such a way that the whole structure can be held together by boundary constraint, while locally the elements are kept in place by kinematic constrains imposed through the shape and mutual arrangement of the elements. TIA are scale and material independent, they are a configurational condition based on geometry. Research into TIA is currently focused on planar configuration comparable to the Abeille vault, looking primarily into configurational properties and aspects like the bearing capacity, stiffness, deformation, indentation or sound absorption (Carlesso et al. 2012, Dyskin et al. 2003a, Dyskin et al. 2012, and Dyskin et al. 2003b). The Abeille vault, thus, can be seen as a historic example for TIA, and understood not so much as a vault, but rather as network of interacting elements.

Historically, the high amount of horizontal thrust within the Abeille vault was resolved by boundary constraints like buttresses or massive walls (Brocato 2012). Due to the effort needed to support Abeille vaults it is no surprise that they were rarely used throughout history despite being "one of the most interesting technical and stylistic investigations into art of stonecutting applied to building construction" (Cities of Stone 2006).

In recent years, the availability of digital design and fabrication tools has caused new interest in stereotomy, its geometric rules, and the Abeille vault as specific case study (Etlin et al. 2008). The topological nature of the interlocking principles of the Abeille vault has been used by Giuseppe Fallacara to apply the construction principle onto non-planar vaulted structures and domes with focus on the woven aesthetics expressed in the construction principle. Oliver Tessmann (2013) has started to investigate the potential of variation within the ashlar itself and its generative effect on the shape of the assembly, as well as the potential for architectural differentiation of surface qualities. From both investigations it is apparent that the non-planar assemblies can be achieved through rotation of 'protruding' and 'sloped' ashlar faces. The ashlar configuration is directly dependant on the surface curvature, specifically the surface curvature in an underlying grid system directions.

This paper is a more systematic exploration of the full potential of the application of the Abeille vault to non-planar assemblies and studies the relation between the surface geometry and TIA. A geometric construction method is defined based on underlying point density and smaller ashlars that in turn approximate closer the steep curvature (Figure 3).

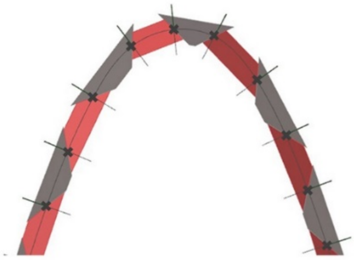


Figure 3
Curvature, point grid distribution and plane rotation interdependancy.

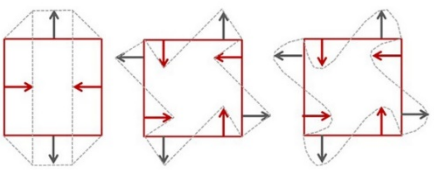


Figure 4
Diagram of Abeille-based TIA complexification .

When the initial surface is non-planar and/or point grid distribution non-rectangular, the non-adjacent elements with the same orientation intersect i.e. only in the case of the TIA of regular tetrahedra that is based on a planar surface with rectangular point grid, like the original Abeille vault, no tetrahedra intersect. The trimming planes modify and rectify elements' configuration by removing elements intersection for every other situation. The domain of possible trimming plane positions is, thus, determined by both the curvature of the initial surface and its point grid distribution.

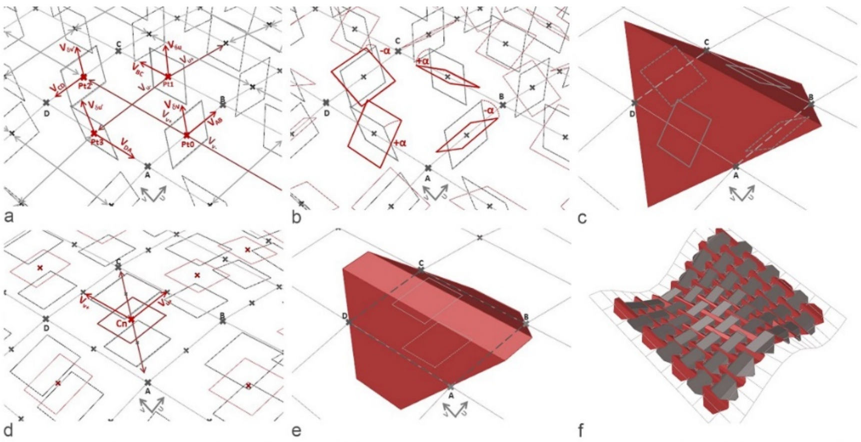
The Abeille-based TIA geometric construction method can generate a vast number of different assembly configurations. Due to the geometric definition of the individual ashlars an Abeille-based TIA is not limited to vaulted shapes but can be defined along more general formed surfaces. From the construction sequence shown above, it is clear that the interlocking mechanism is a system based not so much on precise geometry of the intersection surface of two adjacent ashlars but rather on the orientation alternation of the intersection surface along the ashlar. It is this alternation that directs the force flow within the overall system and results in the reciprocal behaviour and the interlocking of the ashlars. Abeille vault, thus, represents a basic example of this system that conceptually lends itself for further complexification. The complexification of the system can be done by either increasing the number of polygon sides that make up the point grid, or increasing the number of alternations per ashlar face. In this way the Abeille-based TIA defines assemblies starting from TIA of tetrahedra, towards TIA of more complex Platonic solids, and ultimately free form geometries (Figure 4).

Hexagonal Grid, Truchet Vaults and Osteomorphic Blocks

Abeille-type configurations, are easily applied to other gridded systems, like hexagonal grids, and transformed into more fluid interlocking systems, like Truchet vaults or osteomorphic blocks. The Abeille vault's concept of alternating plane rotations applied on a hexagonal grid generates TIA of cuboids (Figures 5a & 5b). Further, when the pairs of trimming planes are introduced the ashlar configuration becomes that of irregular octahedron (Figure 5c).

Truchet flat vault is based on the same underlying logic like the Abeille vault, with the difference that the alternating plane rotation is morphed into alternating undulation of the ashlar intersecting surface (Figure 6). The grid coincides with the vault extrados, and defines the ashlar extrados as squares, while the intrados are made up of alternating semicircular protrusion and indentations. The Truchet was developed soon after the Abeille vault as its improvement, since its interlocking ashlars leave no void on either side of the surface (Fallacara 2007). Although the solution was considered "truly ingenious" at the time it was developed the alternation of concave and convex surfaces was found to difficult to actually execute (Etlin et al. 2008) until the introduction

Figure 2
Abeille-based TIA geometric construction method.



stereotomic rules and interdependencies of the original Abeille vault.

Abeille-based TIA

The starting point of the geometrical construction method is formulation of a point grid on a given surface. For each grid field defined by vertices ABCD four points at vertices mid-span are derived: Pt0, Pt1, Pt2 and Pt2. Points Pt0 and Pt2, and Pt1 and Pt3 laying at opposite sides of the field define vectors in U and V direction respectively. Thus, each mid-point Pt that does not lie at the surface boundary defines a pair of vectors in opposite directions, Vu+ and Vu-, or Vv+ and Vv-.

A plane Pl is defined at each mid-point Pt based on the vector between the mid-point and adjacent vertex, and the sum of the vector pairs at that mid-point, referred to as Vδu or Vδv (Figure 2a). The magnitude of vectors Vδu and Vδv reflects the surface curvature in U and V directions respectively at the given mid-point. Each Pl plane is rotated around the first axes for an angle α. The rotation direction is opposite to the rotation direction of the adjacent plane (Figure 2b). The intersection of the four rotated planes defines a tetrahedron (Figure 2c).

Finally, pairs of trimming planes are defined. Each trimming plane is an offset of the plane defined by vectors Vu+ and Vv+ at the centroid Cn of each field (Figure 2d).

The Abeille-based TIA geometric construction method is, thus, based on the four main variables: the point grid distribution of the initial surface, curvature of the initial surface in U and V directions, angle of plane rotation, and the position of the trimming planes. Through establishing the interdependences between the variables the construction method is further parametrized, and the interlocking properties assessed.

First geometrical interdependency established is between the curvature of the initial surface in U and V directions , and the plane rotation angles. The values of these variables are inversely proportional: the higher the curvature, the lower is the planes rotation angle, and vice versa. In this way the elements within a planar assembly are keyed in, while elements within an area with a high curvature degree do not have awkward configurations (Figure 3).

Second geometrical interdependency established is between the curvature of the initial surface in the U and Vi directions, and the point grid density, and is directly proportional. Through this parametrization high curvature defines high grid

Figure 5
The Abeille-type configuration applied on a hexagonal grid.

Figure 6
Truchet Vault.

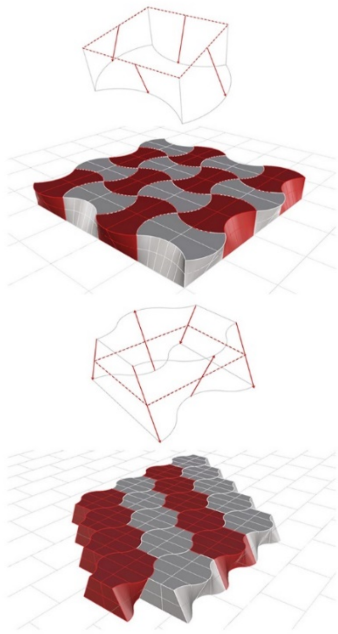
Figure 7
TIA of ostemorphic blocks.

of CAD/CAM processes.

The osteomorphic block is based on the same concept of Truchet's alternating concave and convex surfaces, with the difference that the alternation is developed along the same ashlar face (Figure 7). The interlocking is achieved only along one axes and since the system was invented for a wall and column construction, ostemorphic block is not based on a grid, but a running bond (Dyskin et al. 2003c).

Further complexifications investigated in the introduction of perforations within the Abeille-type system. Perforations can be achieved by manipulating the tetrahedral ashlar configuration. Tessman subtracts volumes form the tetrahedral ashlar to investigate the variations of the intersecting surface contact zones. The resulting cropped ashlars define perforations while maintaining the interlocking principle (Tessman 2013). Perforations can be achieved also through variation of the trimming plane positions, specifically when both trimming planes are placed either below or above the initial grid (Figure 8). To ensure the interlocking within the system, further parametrization is established between the ashlar thickness and distance from the grid between neighbouring pairs trimming planes.

Looking at the examples shown, it can be concluded that for defining the interlocking ashlar geometry, it is enough to consider the alternation only along the parameter of the grid field i.e. an 'inward' rotation has its identical, corresponding 'outward' rotation on the other side of the same ashlar. This is the same principle used in two dimensions by Escher in a mastery way in his planar tessellations (Figure 9) (Haak 1976).



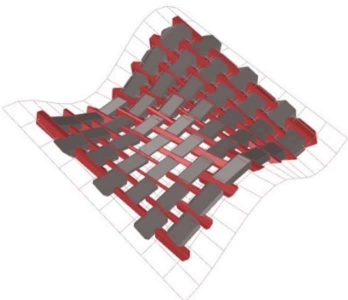


Figure 8
Variation in trimming planes position in a Abeille-based TIA.

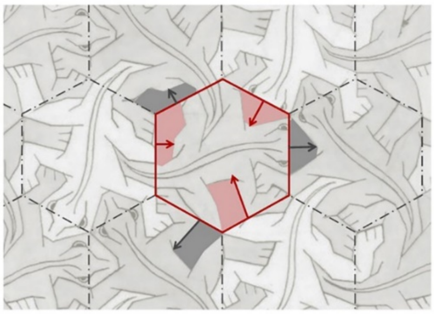


Figure 9
Escher's tessellation based on hexagonal grid .

Conclusion

The discussion shows that the Abeille-like configuration can be seen as generic example of TIA. Other examples like the Truchet vault or osteomorphic blocks and their parametric variation can be understood as simple variation of the principles that define the Abeille-vault. Such a unifying approach allows a more systematic study of the structural behaviour of TIA and the limitation of the material system with respect to the geometry of the underlying surface. TIA are characterized by a systemic transfer of loads based on the interaction of neighbouring ashlars. This way a cyclic distribution of loads appears within the material system that resembles the non-hierarchical load pattern in reciprocal frame structures (Kohlhammer et al. 2011). A more detailed analysis is required, however, to understand in more detail the influence of curvature on the structural behaviour of TIA.

The local interaction of the ashlars is not only providing a more even distribution of loads within the structure itself but at the same time providing a local stabilization of the configuration that has positive effects for the assembly. First test that have been conducted with an Abeille-like pavilion structure show that the interlocking of the ashlars enables a significant reduction of falsework that is typically needed for the construction of masonry vaults. This means that TIA have the potential to increase again the interest in vaulting structures that is in a building typology that had not been used very much in developed countries since the late 1970s due to the high amount of labour that is needed for the preparation of falsework.

This study on Abeille-like configurations therefore demonstrates clearly how the combination of digital design tools and digital fabrication enables the reanimation of historic construction techniques for the benefit of contemporary architecture. In addition, the geometric nature of the Abeille-like construction allows for a more holistic understanding of the interplay of geometric relationship within the assembly, specifically surface curvature and the configuration of individual elements, and enables the transfer of structural principles between different construction typologies which in turn helps to delimit system boundaries and opens up the possibility of a more fluid understanding of structures in architecture.

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8.2. Stereotomy, an Early Example of a Material System

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[50] Education and Research in Computer Aided Architectural Design in Europe

Stereotomy, an Early Example of a Material System

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Stereotomy originated as a technique that accumulated theoretical and practical knowledge on stone material properties and construction. At its peak in the nineteenth century, by pushing the structure and construction limits, it gained the ability of using ``the weight of the stone against itself by making it hover in space through the very weight that should make it fall down'' (Perrault 1964, cited Etelin, 2012). The modern architectural tectonics, based on structural comprehension in architecture, found no value in stereotomy beyond its early, Gothic period. Similarly, digital architectural theory recognized in Gothic the early examples of a material systems. This paper reassesses stereotomy at its fundamental levels, as a material system based on generative processes that assimilate structure and construction through parameterization. In this way, a theoretical framework is established that exposes stereotomy's intrinsic potentials: the continuity of historic and contemporary examples, overlaps between current research endeavours, and its genuine relevance for contemporary digital architecture.

Keywords: *stereotomy, material system, Abeille vault, parametric design*

Introduction

Stereotomy is a technique that accumulated theoretical and practical knowledge on stone material properties and construction. It was primarily based on essential, complex geometric relationships embedded within stone masonry. In recent years, the advancement of digital design and fabrication tools that easily handled complex geometries had caused a renew interest in stereotomy (Fallacara, 2012; Fallacara, 2016; Rippmann, et al. 2011; Rippmann, et al. 2017; Burry, 2016; Varela, et al. 2016; Fernando, et al. 2015; Weir, et al. 2016; Clifford, et al. 2015). Historically, stereotomy was connected to certain structure and construction choices. Contemporary research initiatives, driven by various motivations and objectives, explored and questioned these choices at different levels.

Paper proposes a theoretical framework where the continuity of historic and contemporary stereotomy and overlaps between current research endeavours are exposed. Stereotomy is observed beyond its formal resolves and approached at its fundamental levels. More specifically, paper moves away from analysing stereotomy using traditional tectonic notions and approaches it as a generative material system.

Historic Overview

Stereotomy (Greek: στερεός (stereós) "solid" and τομή (tomē) "cut") originated in the Gothic period as a result of a reversal in construction thinking. Throughout Antiquity and the Middle Ages, buildings were thought of in the same way as they were made, from the ground up. For the Gothic builders, supported parts gave shape to the supporting parts, and imposed construction thinking from the top down (Sakarovich, 1998). Stereotomic form was seemingly based on a paradox: it used "the weight of the stone against itself by making it hover in space through the very weight that should make it fall down" (Perrault 1964, cited Etelin, 2012). It was actually derived from the underlying interdependencies that varied its constituent ashlars towards coping with the contextual forces.

Figure 1
Monastery of Notre-Dame de la Couture, Le Mans, 1720-39. (Photo: R. A. Etlin, from Etlin, 2012 page 23.)

As a technique, stereotomy explored the limits of spatial, structural and material principles through the application of current fabrication technologies and geometric knowledge. It offered immense novel possibilities that brought about an enthusiasm for amplifying the force flow complexity while providing solutions that purposely obscured structural comprehensions. By the nineteenth century, stereotomy became known as a 'bizarrely daring acrobatic architecture' (Etlin, 2012) (Figure 1). Concurrently, from the seventeenth century onward attitudes had developed that sought architectural "visual qualities capable of convincing a viewer about its solidity, and in this sense vraisemblance (plausibility) became important" (Sekler, 2009). "A structure should always look stable as well as be stable" (Evans, 2000). Stereotomy, an audacity bordering on foolhardiness (Evans, 2000) was shunned and abandoned.

Structural plausibility and legibility continued into twentieth century tectonics, and greatly remained a yardstick for architecture until today. In this context, any reassessment of stereotomy praised the early period, the Gothic, for its tectonic clarity, while the late 'acrobatic' (Etlin, 2012) variations were continuously found offensive and frivolous.

Stereotomy in Contemporary Architectural Theory

Similarly, the Gothic found relevance within digital architectural theory. It was recognized as an organizational system that defined the form from the convergence of forces (gravity, perception, and social organization) resolved through the elements' mutual relationships. Form was an amalgam of variations driven by operational and procedural rules (Spuybroek, 2011). In short, the Gothic provided digital design processes with historic case studies on topological form conceptions instigated by active space of interactions.

Moussavi interpreted Gothic as a system of bays acting as base units. Each base unit was versatile, not fixed and could vary as it repeated, or even mutate, when hybridized with other base units. The novel and unpredictable forms were temporarily and spatially specific, yet capable of responding to external concerns (Moussavi, 2009). Likewise, Spuybroek interpreted the Gothic as a system that changed through ever-shifting combinations of variable and flexible subelements: the ribs. The system's relationships were fixed, but not the resulting forms (Spuybroek, 2011). In conclusion, the Gothic was understood as an early example of a material system, where fairly simple behaviour by individual elements resulted in complex and irreducible collective behaviour (Spuybroek, 2011).

Although relevant, the interpretation remained limited. Its analytical processes, derived from traditional tectonics, observed solely the expressive potential of construction techniques (Frampton, 1995) through the parts-to-whole relationship logic. Stereotomy, on the other hand, required analysis beyond the visual legibility offered by Semper and Frampton, that recognised "classicism was as much parametric and generative" as the Gothic (Carpo, 2011). The understanding of stereotomy could not be divorced from a procedural analysis of its formation processes.

Material System Based on Generative Rules

Sekler recognized architectural formation processes in his definition of tectonics, the expressive result of a structure realized through construction. Structure, an abstract concept, was an arrangement system or principle destined to cope with the contextual force flow, and construction was its concrete realization (Sekler, 2009). Construction encompassed material properties, tools, technology and procedures, fabrication constraints, and design, geometric, and instrumental knowledge (Witt, 2010). Tectonic was not a result of mechanistic notions as form reproduction tools, but machinic notions that determined elements' variations, interrelation, multiplication, and complex organizations (Moussavi, 2009). It was inseparable from the architectural form in general, stereotomic in particular, albeit varied visual comprehensions that were unintentionally clear in the Gothic period, and intentionally ambiguous during the stereotomic peak.

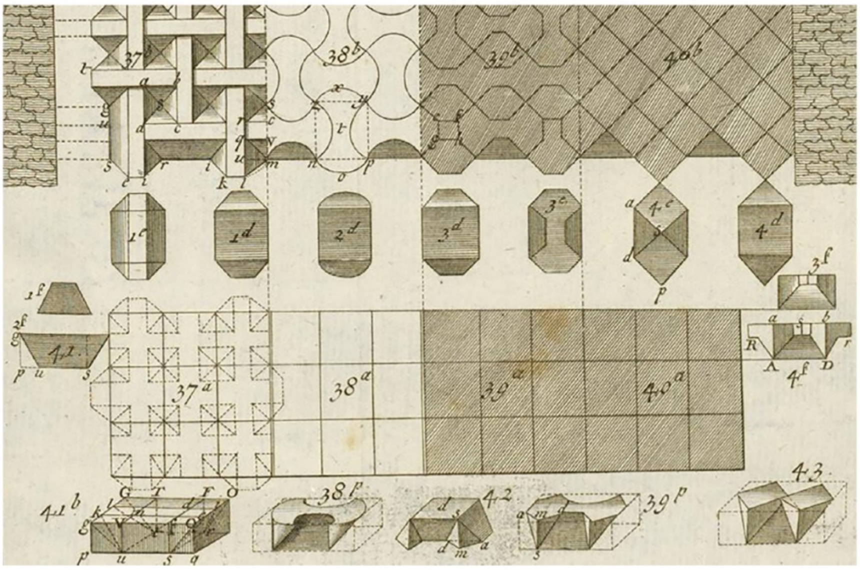

Figure 2
Flat Vaults 37&41 - Abeille Vault 38 - Truchet Vault 39, 40, 42 & 43 - Frézier (Adapted from La théorie de la pratique de la coupe des pierres et des bois, by Amédée François Frézier, Planche 31, http://www.e-rara.ch/zut/content/pageview/8691852)

Defined in this realm, stereotomy was a material system that assimilated structure and construction negotiations as a set of generative rules that were themselves subject to evolutionary change, and once fixed could be fleshed out in a wide variety of [tectonic] forms (Heyman, 1998).

Stereotomic Analysis Methodology

New Structuralism theory argued for digital architecture based on spatial, structural, and material principles synthesis in lieu of the traditional form-structure-material sequence. (Oxman, et al. 2010). Due to their intrinsic overlaps, New Structuralism offered relevant analysis procedures for assessing stereotomy as a material system. A set of historic stereotomic assemblies was analyzed (corbel, circular and flat arches, corbel and circular domes, barrel, groin, helicoidal, trompe and shallow vaults, and Abeille, Truchet and Frézier flat vaults (Figure 2)) through New Structuralism's processes (structuring, digital tectonics, and digital morphogenesis).

In the first step, the structuring process, the mathematical/geometric, syntactic and formal stereotomic logic was analysed and recognized. Specifically, structural patterns, geometric attributes, and configurative transformations were discretised into generative rules. In the next step, the digital tectonics, generative rules were formulated into parameters and their interdependencies to establish the digital parametric model design substance. In the last step, the digital morphogenesis was enabled within the parametric models and provided diverse topological outputs, design explorations and prototype fabrication information. The analysis actualized novel forms that explored adaptive, configurational, and transformability potentials beyond their original design intents (Oxman, et al. 2010). Finally, the analysis exposed common underlying stereotomic parameters.

Stereotomic Parametrization

The four common underlying parameters that activate a stereotomic material system were: base surface geometry, distribution grid, and two relating to the single unit configuration: perimeter faces rotation and thickness.

The base surface geometry was determined by the force flow, the line of thrust, and directly reflected

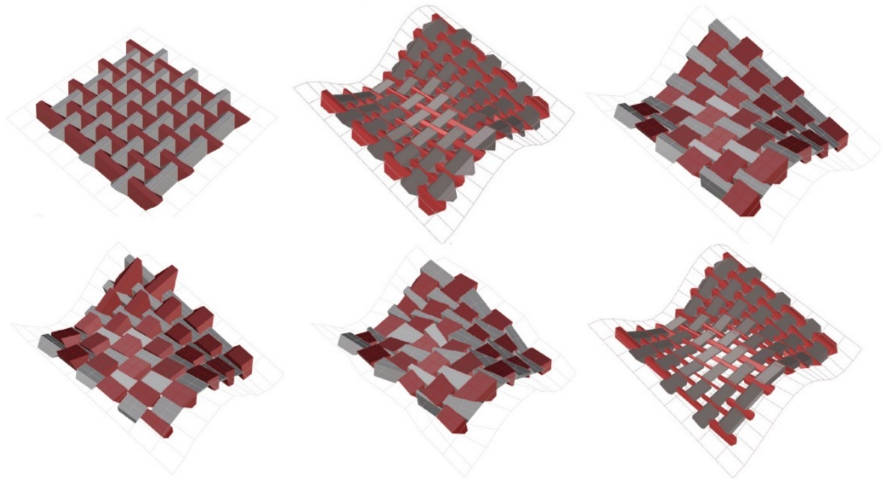

Figure 3
Configurational variations of the Abeille stereotomic material system

structure. Structure varied during the construction process due to varied force flow. It also had varied final intents, from pursuits in the force flow optimization to specific aesthetics. The base surface geometry was interdependent with the single unit geometry, since an assembly was concurrently a whole subdivided into single units and a propagation of single units creating a whole.

Distribution grid was determined by structure and construction choices. Historically, typical distribution grids used were: running bond, rectangular grid, hexagonal grid, radial grid, and irregular grid.

The rotation of the single unit faces that were neither intrados nor extrados, the perimeter faces, defined the structural action of the whole, or parts of, the assembly. Faces perpendicular to the force flow determined arches for linear assemblies and shells structures for surface-based assemblies. Alternating inward outward perimeter faces rotation established either a topological interlocking or reciprocal frames type structure.

The single unit thickness was the distance between intrados and extrados faces. For statically determinate assemblies it was dependent on structure, as the force flow had to be accommodated within the material thickness. In statically indeterminate assemblies it was dependent on construction.

The four formulated parameters and their interdependencies defined the stereotomic material system. Specific structure and construction choices were assimilated within the material system by providing specific parameter values. In conclusion, structure and construction choices were not necessarily predetermined, as they informed the stereotomic material system, but did not activate it.

Abeille Flat Vault Material System

The stereotomic parametrization process was illustrated through the Abeille flat vault example. Firstly, the Abeille vault was defined as a material system, followed by formal explorations through parametric variations. Further, nontraditional, non-masonry structure and construction assimilations within the material system were explored through the design and construction of a stereotomic plate pavilion, technically an oxymoron.

Visually, the Abeille vault was based on identical ashlar truncated tetrahedral configurations: a poly-

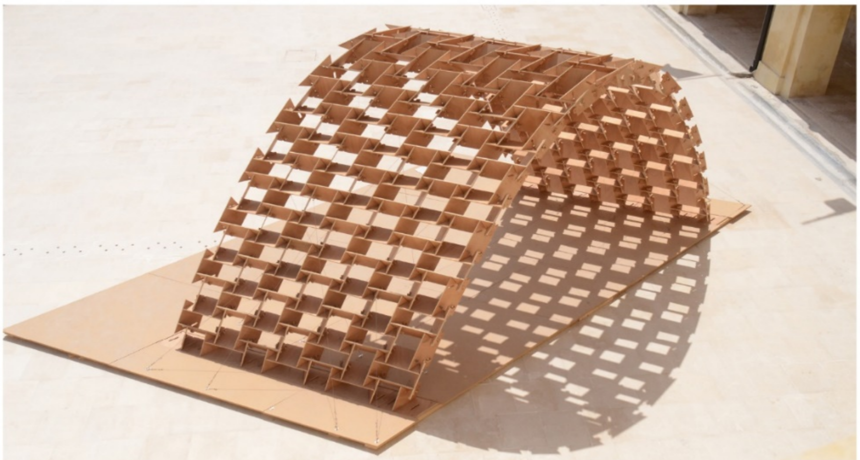

Figure 4
Stereotomic Plate Pavilion, Malta 2014, Irina Miodraogic Vella (University of Malta), Steve DeMicoli (DeMicoli & Associates, dfab.studio) Dr Professor Toni Kotnik (Aalto University)

hedron with axial sections in the shape of an isosceles trapezium. The ashlar geometry and the rotation of neighbouring ashlars by ninety degrees established their mutual arrangement: each ashlar was carried on two neighbouring ones through its protruding cuts, and at the same time provided support for two others on its sloped cuts resembling reciprocal frames structures (Miodragovic Vella, et al. 2016).

Defined parametrically, as a stereotomic material system, the Abeille vault was based on a planar, horizontal base surface and a square distribution grid. Each parameter face was rotated 54.7 degrees from the base surface, in the direction opposite to the rotation direction of the adjacent faces, instigating topological interlocking structure. Thickness was determined by two trimming planes, differently positioned base surface tangent planes, one at the surface level, and the other at some distance below. Finally, the parameters interdependencies were established (Miodragovic Vella, et al. 2016).

The Abeille stereotomic material system's configurational variations were explored. Initially, the focus was on parameter values, assigned arbitrarily, often extremly to amplify possible inconstancies and limits in the validity of the digital tectonics formulation and corresponding digital morphogenesis. The resulting outputs remained virtual, without any pursuits for their physical resolve (Figure 3). Next, the Abeille stereotomic material system was further complexified by increasing the number of polygon sides that made the distribution grid and/or increasing the number of rotation alternations per ashlar face. In this way, other established stereotomic elements were derived confirming the parameters' validity (Miodragovic Vella, et al. 2016).

Finally, the Abeille stereotomic material system structure and construction assimilation was tested through a full scale prototype, a pavilion built for Malta Design Week 2014, held at Fort St Elmo, Valletta (Figure 4). It was a collaboration between the authors and Steve DeMicoli (DeMicoli & Associates, dfab.studio). Due to site sensitivity and budgetary concerns the material used was not stone masonry, but a sheet material, marine plywood. This allowed for "in-house" prototyping and fabrication, fast, manual on-site mounting/demounting and total reversibility requested by the organizers.

The design process started with the translation of the structure and construction choices into values to inform the stereotomic parametric model. The solid blocks assembly logic was discretized into an assembly of plates. The plate configuration was derived by 'merging' the touching single unit perimeter rotated faces of adjacent elements: the two faces that shared the same rotated plane became a six-pointed plate (Figure 5). The resulting structure remained topological interlocking, of single unit perimeter faces, rather than the volumes they enveloped.

The base surface geometry was a linear extrusion of a catenary curve defined by the force flow and fabrication optimizations. The result was a five meter span, four meters long, parabolic vault. Although the plate configurations varied along the changing cur-

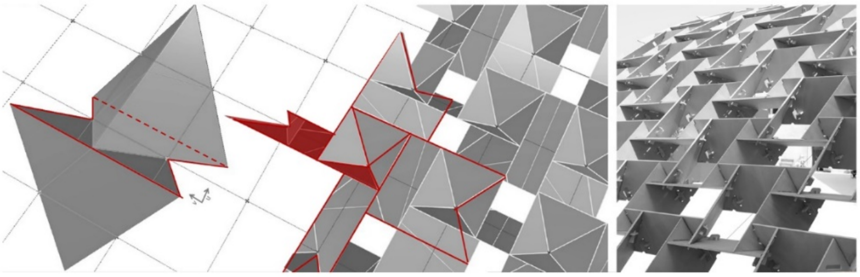

Figure 5
Discretization of the solid blocks assembly logic into an assembly of plates

vature of the catenary profile, the linear extrusion allowed for repetitive plate types, and thus, faster fabrication.

The structure also determined the plate rotation angle. Through full scale prototype testing, a sixty degree rotation angle from the base surface was determined as the optimum to avoid deviation in the vertical plates that formed the arches. The limited CNC bed size defined the irregular rectangular grid field sizes, maximum plate lengths and widths.

Due to site, budget and mounting constraints, elaborate falsework had to be avoided. To deal with the varying force flow during construction a self-stabilizing structure was achieved thorough plate rotation and plate configurations. Through topological interlocking, corbelling and nominal propping various stable configurations were achieved prior to the vault sides being connected and the arch mechanism activated. By following a diagonal, weave-like mounting sequence the assembly stiffness was continuously increased (Figure 6).

In the final outcome, the traditionally solid stereotomic appearance was transformed into a lightweight lattice assembly (Figure 7). Still the generative rules that activated the material system remained apparent showcasing that it was driven by underlying parameters informed by the structure and construction choices.

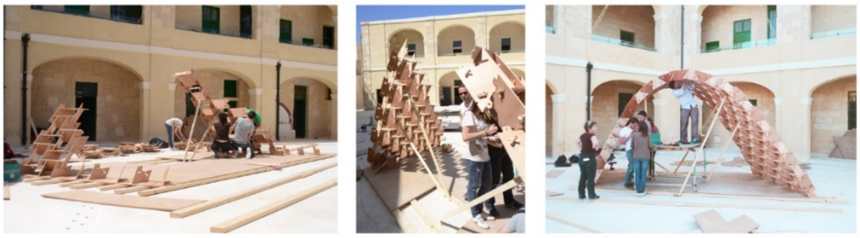

Figure 6
Various
self-stabilizing
configurations
during construction

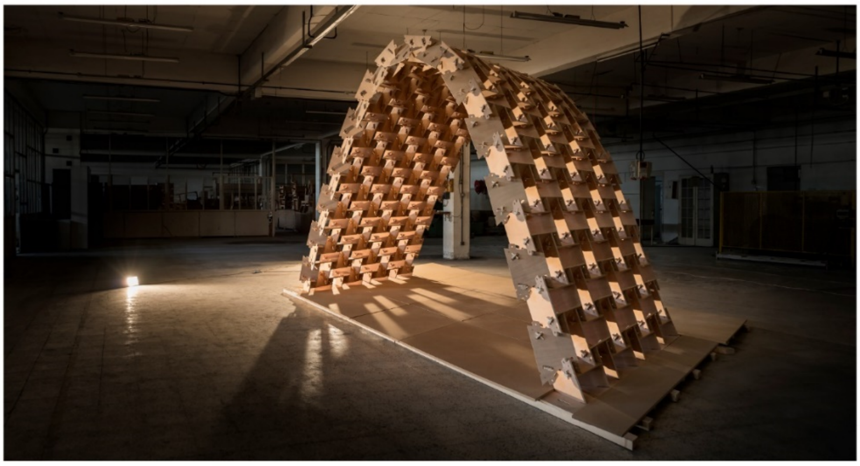

Figure 7
Stereotomic plate
pavilion (Photo by
Alex Attard)

Conclusion

"Similar processes do not necessarily beget similar shapes. Understanding these processes, on contrary, will help us shape better things" (Carpo, 2011).

The main objective of the presented assessment, and resulting theoretical framework was to view stereotomy beyond its formal visual comprehension of traditional tectonics to include generative processes that assimilate structure and construction through parameterization. Any stereotomic assembly, historic or contemporary, could be referenced, defined, and described to establish a productive relationship between stereotomy's past and future. In this way, stereotomy's intrinsic potentials were exposed and its genuine relevance for contemporary digital architecture could be traced and recognized.

Finally, the proposed theoretical framework is neither final nor conclusive, but open to further contributions and revisions.

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8.3. Contemporary Stereotomic Trait, an Opportunity for the Development of the Volumetric Digital Architecture

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Contemporary Stereotomic Trait, an Opportunity for the Development of the Volumetric Digital Architecture

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Stereotomy is generally known in architecture as a stone carving technique for the purpose of constructing masonry assemblies. A deeper analysis reveals stereotomic design processes' ability to resolve multiple structure and construction constrains, derived as underlying geometries and their relationships, into architectural volumetric complexities. The paper argues that the trait, stereotomic geometric negotiations platform, re-examined in a contemporary context, lends itself as a theoretical model for the current digital architecture's pursuits of multiple constraints assimilations within design processes and their physical reflection in formal complexities.

Keywords: *stereotomy, trait, digital architecture, digital design*

INTRODUCTION

The contemporary notion of stereotomy in architecture is restricted to designate the stone carving technique for the purpose of constructing masonry assemblies.

The word's etymology defines a broader meaning of three-dimensional solid cutting into shapes to be assembled. Historic studies that encompass form taxonomies, their practical and theoretical evolutions, and cultural assimilations illustrate a wider polymorphic diversity (Sakarovitch, 2003).

Stereotomy, re-examined in a contemporary context due to its intrinsic qualities offers an opportunity to respond a volumetric lacuna within digital architecture.

More specifically, as this paper argues, the stereotomic trait understood as the Deleuzeian objectile lands itself as the crux for resolving multiple structure and construction constraints into volumetric complexities.

VOLUMETRIC LACUNA IN DIGITAL ARCHITECTURE

Stereotomy originated at the overlap of several disciplines: architecture, mathematical geometry, technical drawing, structural theory, practical masonry, and military engineering. Shared by all, it flourished where definitions blurred, where one thing began to glide off into others, as an unrecognized border joining many diverse regions (Evans, 2000). A mutual knowledge exchange was generated between all disciplines involved due to the common reliance on geometry. As stereotomy was increasingly approached as correct understanding of geometry (Heyman, 1995) the knowledge exchange became more fluent. By the end of the nineteenth century this generated progress in all the disciplines in the areas of design, representation and fabrication of complex geometries, "freed from Euclidian metric" (Sakarovitch, 2003).

Figure 1
L: Arles City Hall Vestibule, Jules Hardouin-Mansart, 1637 (http://farm4.static.flickr.com/3765/19564585458_-3c1da000d7.jpg) R: Henry VII Chapel, William Vertue & Robert Vertue, 1519 (http://www.alamy.com/stock-photo/henry-vii-chapel.html)

Complex stereotomic geometries developed due to the design attitudes that regarded 'difficult' as a superlative. Difficulties were as much sought after as found (Evans, 2000): ever greater formal complexity, elaborate ornamentation, and daring statics that appeared as effortless as their visual comprehension (Figure 1). Their design processes necessitated concurrent handling of multiple structure and construction constraints and their interdependences. Structure, an abstract concept, was geometry-based statics (Sakarovitch, 2003) principle destined to cope with the contextual force flow. Construction, its concrete realization, was carried out in a number of materials (Sekler, 2009), tools, technologies and procedures, fabrication constraints, and design, geometric, and instrumental knowledge (Witt, 2010). Design processes derived structure and construction constraints as geometric constraints and formulated form as their continuous negotiations. Design knowledge on multiple constraints handling was deduced, embedded, and instrumentalized in geometrical tools and procedures (Witt, 2010) that enabled volumetric complexities, topological transformations, variations, and differentiations. In short, stereotomy became the epitome of architectural complexity by acknowledging the centrality of geometry, tools, and procedures in the design process.

In the twentieth century, there was a paradigm shift in architecture that prioritized economy of design, fabrication and construction. Efficacy-driven design processes abstracted machine constraints to achieve repeatability, speed, and mass production (Witt, 2010) towards structure and construction rationalization. As a result, design processes favoured steel and concrete as materials, standardization as modus operandi, and scarce geometries as aesthetic expression (forms that were assumed too complex to be machine produced were marginalized (Witt, 2010)). Stereotomy could not compete in this milieu. It required extensive geometric and tacit knowledge, intensive fabrication due to varied ashlar configurations, and lengthy, costly construction processes due to elaborate falsework. Stereotomy was shunned and abandoned into the realm of "forgotten geometries lost to us [architects] because of the difficulties of their representation" (Moneo 2001, cited Kolarveic 2004).

The advancements in resolving multiple design constrains as geometric complexities continued through the knowledge exchange between sciences and other industries. Since a great number of the industries (aviation, automobile, and shipbuilding) were based on sheet materials, the geometric research focused primarily on surfaces. The geometric research into volumetric complexities dealt with either the small scale (product design), or was not concerned with material resolutions (digital modeling and animation).

By the end of the century, the accumulated geometric knowledge was embedded in different CAD and CAM digital tools making it easily employable. Appropriated by architects, digital tools expanded the architectural formal repertoire by enabling the complexity of conceived forms and their transfor-

Figure 2
Possible Types of Barrel Vault Formwork and Centering (Fitchen, J. 1967, p.54)

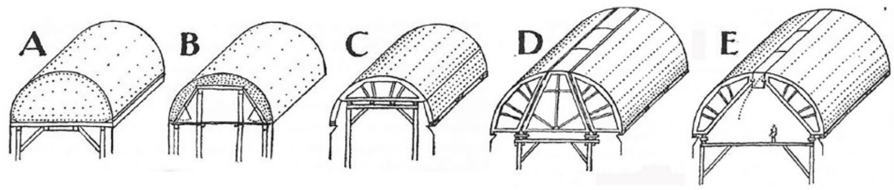


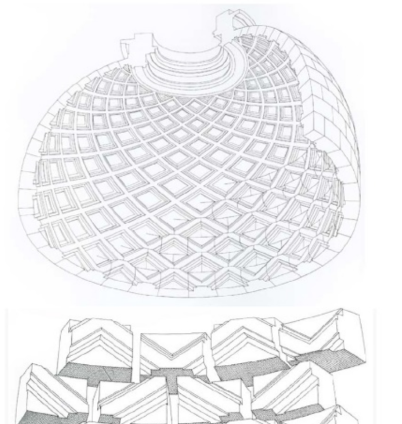
Figure 3
Anet Castle Chapel, Philibert de l'Orme, 1549-52 (Potié, P. 1996, p.54)

mations into viable construction assemblages (Picon, 2010). They provided physical resolves for the theory driven by the Deleuzeian Fold and the form defined by the rules of its variations (and variations of variations), an objectile (Carpo, 2011). Digital tools did not require users' understanding of the embedded complexities to handle their design, representation, fabrication, and construction. They were attained through instrumental knowledge that directly enabled or disabled the act of design (Witt, 2010). In this way, knowledge on resolving multiple constraints, directly borrowed from the other industries, was only partially assimilated into architectural design knowledge. Digital architecture did not establish large scale volumetric form actualization processes based on intrinsic, multiple constrains and remined surface-based. "Paradoxically, quest for depth led to an infatuation with the façade or skin, in other words with superficial, the two-dimensional" (Picon, 2010).

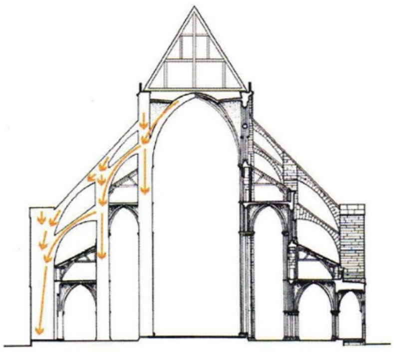
STEREOTOMY, COMPLEX VOLUMETRIC ARCHITECTURE

Stereotomic design processes, as comprehensive resolutions of multiple structure and construction constrains, offer a valid framework for establishing digital architectural form formation processes. The central aspect of stereotomic design processes was deriving structure and construction constrains as geometric constraints and their relationships. Stereotomic form emerged from multiple, neither hierarchical nor discrete, underlying geometries: assembly geometry, ashlar geometry, structure geometry, falsework geometry, and geometry defined by tools and procedures. Their sub-stereotomic interdependencies were almost non-exhaustive.

The most evident, traditional, mutually-defining interdependency was between the assembly geometry and its constituent ashlar geometries: any assembly was concurrently a whole subdivided into parts, and a propagation of parts generating a whole (Figure 2). It is determined by material and fabrication constraints.



The structure geometry formulated structure and assessed its appropriateness and efficacy (Sekler, 2009). Jointly, the assembly and ashlar geometries were in a formative interdependency with the structure geometry: any assembly and its ashlars were subservient to structure, and concurrently, through their shape and proportions, ensured stability (Heyman, 1995), the validity of the structure geometry (Figure 3).



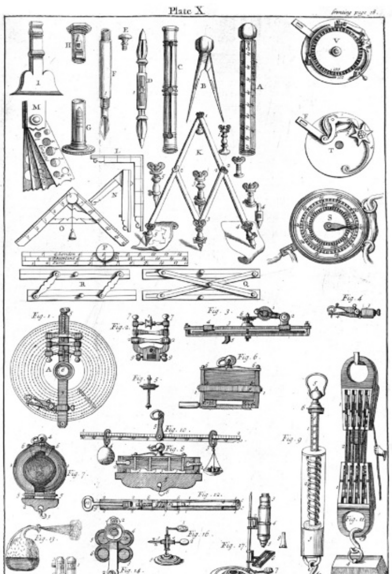
Further, structure geometry responded to the varied force flow at each construction process stage. Together with the assembly geometry and construction assembly constraints, it determined the falsework geometry. At the same time, due to its necessary optimizations (towards fast, simple mounting and dismantling, the ease of use and reuse, etc. (Figure 4)), the falsework geometry influenced the assembly and structure geometries formulations, and determined construction assembly sequencing.

Similarly, a continuous coevolution developed between tools and procedures, and their embedded knowledge. As a result, the geometric rigor, precision, and control improved and, in turn, improved the design of the drafting, fabrication, and construction tools and procedures (Figure 5).

Despite the immanent geometric presence throughout, stereotomy showed less obvious trace of geometric regulation: by using more geometry, it appeared to be used less (Evans, 2000). As the negotiations proficiency within the system of sub-stereotomic geometries increased, so did the pursued stereotomic complexities, and stereotomy became more stereotomic.

STEREOTOMIC TRAIT

The platform for sub-stereotomic geometric negotiations was the trait. Traits were preliminary drawings that allowed design and definition of assembly and ashlar geometries, and regulated their configurations to ensure buildability. Simultaneously, they were layout drawings that enabled precise ashlar fabrication, falsework design, and construction sequencing (Figure 6). Traits enabled geometric generative rules formulations, form variations computations, and their executions.



The initial motivation for the trait establishment was to record and dissipate the oral secrets of the masons' lodges in a drawing format. Throughout history, their representational role transformed to a didactic one. The focus shifted from cataloguing the existing assemblies towards communicating the underlying ge-

Figure 4
Load paths of thrusts from main vault and buttresses, due to gravity (Addis, B. 2007, p.98)

Figure 5
Drawing Instruments, from "Traité de la construction et des principaux usages des instruments de mathématiques", Nicolas Bion,1709 (Witt, A. 2010, p.46)

Figure 6
Traits by Frézier, Planches 33, 34 & 70 (Frézier, A.F. 1738, Tome II p.116, Tome II p.123, Tome III p.24)

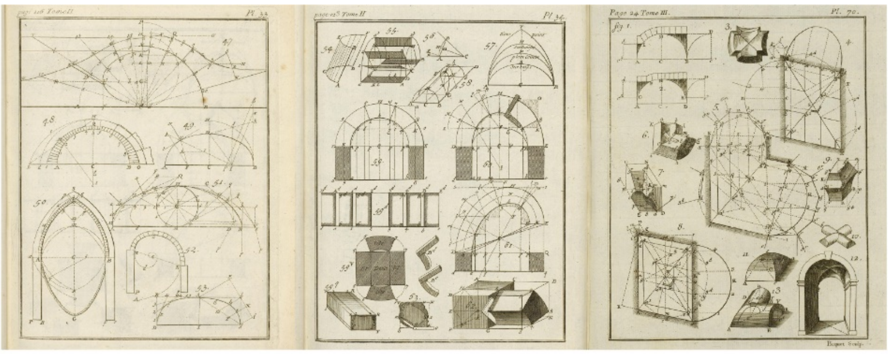
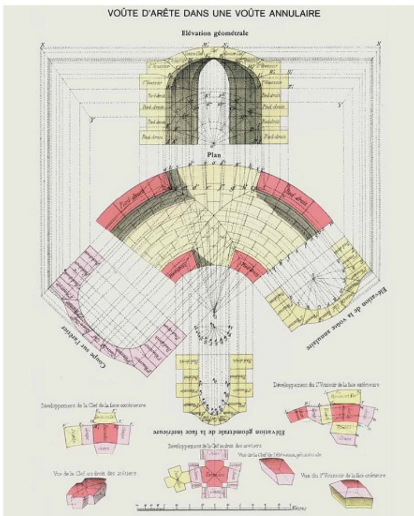


Figure 7
Trait from "Traité théorique et pratique de stéréotomie", Louis Monduit, 1889 (Witt, A. 2010, p. 60 & 61)

ometric processes to facilitate original designs and wider theoretical and practical explorations of two-dimensional into three-dimensional transformations (Sakarovitch, 1998).

Progressively, traits theorized and generalized stonecutting problems, abstracting them into spatial studies. Further, traits instrumentalized stereotomic design knowledge, derived from merging practical, traditional, local knowledge with universal, scientific knowledge, into geometric procedures. Traits embedded master masons' applied and mathematicians' erudite geometric knowledge (Sakarovitch, 2003) to become drawing 'machines' (Witt, 2010).

During the traits' evolution, graphical techniques based on geometric representation were initiated (Sakarovitch, 1998). Later a geometric language was established that enabled mutual interconnections, multiple interpretations and open-ended relationships. It made the embedded knowledge accessible and susceptible to development and assimilations. By the nineteenth century, traits facilitated knowledge exchange between stereotomic design, scientific geometry, conceptual geometric procedures, irregular stonecutting procedures, and drafting instrument developments.



The positive feedback loop outcomes were, among others, the Descriptive Geometry formulation, geometry of curves and curved surfaces advancements, drafting instruments with embedded complex geometric knowledge, and the stereotomic architectural peak (Witt, 2010) (Figure 7).

In the contemporary architectural theory realm, traits could be understood as objectiles. An objectile, an open-ended algorithm based on a parametrical function, determined infinite object variations, all different (from one parameter set) yet all similar (from the same underlying function) (Carpo, 2011). Similarly, specific stereotomic elements belonged to a general category and were differentiated by the trait. For example, the arch trait, a geometric procedure, differentiated a specific arch for the specific context from an infinite number of arches. The arch trait was the structure and construction negotiation expressed though underlying geometric interdependencies. As a fixed normative genus, the trait was exactly transmissible but nonvisual notation that embodied infinite variations, clearly different yet similar forms (Carpo, 2011).

Trait, like objectile, had two types of authors: the author that designed the (or a series of) generative notation(s) that are general, genetic, and parametric, and the author that specified the notion(s) in order to design individual forms (Carpo, 2011). Throughout history traits' author pairs changed and multiplied: master mason and stone carver, architect and master mason, scholars and geometers, etc.

The multiple authorships and geometric negotiations defined traits' multifaceted nature and varied legitimacy from practical validations through execution to theoretical rationale affirmations. Their role, in Deleuzeian terms, remained singular and clear: to differentiate multiple sensible forms from virtual, abstract ideas (Moussavi, 2009).

DIGITAL ARCHITECTURE TODAY

The dominant design attitudes (New Structuralism (Oxman, et al. 2010), Material Computation (Menges, 2012; Menges, 2015), FABRICATE conferences (Sheil, et al. 2017), etc.) in the current digital architecture argue for necessary multiple design constraints (structure, climate, material, fabrication, etc.) assimilation within design processes and their physical reflection in formal complexities. Akin to stereotomic, digital design processes are driven by intrinsic structure and construction constraints and strive to formulate genuinely architectural form formulation processes. The technology context, instigated by diversity of contemporary digital tools, provides architecture with vast opportunities that, when translated into multitude of constraints, can concurrently hinder them. This is reflected in the challenge to resolve multiple constraints as large scale, volumetric complexities.

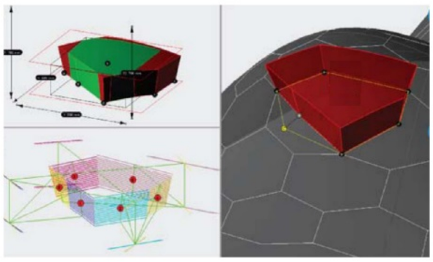


Figure 8
Rhino 5.0 custom-made plugin the design, fabrication, and material parameters manipulation and production process analysis, visualization, and simulation (Rippmann, M. et al. 2011, p. 186)

The renewed interests in stereotomy, facilitated by the digital tools availability, initially focused on previously difficult to achieve formal complexities designs and explorations, topological transformations, precise varied irregular ashlar configurations fabrications, and complex structural resolves. In the recent years, stereotomic rule-based design processes, parametrized into digital associative geometry models, enable a number of assimilations to directly informe form formations: contemporary geometric knowledge, material limitations, structural optimizations, CNC/robotic fabrication requirements, etc. (Fallacara, 2012; Fallacara, et al. 2015; Fallacara, 2016; Rippmann, et al. 2011; Rippmann, et al. 2017; Burry, 2016; Varela, et al. 2016; Fernando, et al. 2015; Weir, et al. 2016; Clifford, et al. 2015). The resulting forms illustrate the digital tools and procedures ability to proficiently control and handle underlying geometric negotiations, as an overlap of assimilated constrains (Figure 8) into volumetric complexities. Unfortunately, they preserve stereotomy's stumbling block that originally denied it viability: the costly, elaborate falsework (Figure 9).

Figure 9
Falsework for the Armadillo vault, Venice Biennale, 2016, (Source: <http://www.armadillovault.com/armadillo-installation/>)

CONTEMPORARY DIGITAL TRAIT

The aim of this paper is to understand trait's historic nature and theorize its contemporary relevance and drawbacks towards its adaption to the digital realm. Contemporary digital trait, developed as geometry-driven objectile, offers "open-endedness, variability, interactivity, and participation [that] are the technological quintessence of the digital age" (Carpo, 2011). More specifically, it offers the possibility of becoming the crux of resolving multiple architectural constrains as volumetric complexities.

The contemporary trait necessitates reinstating of its intrinsic nature and certain adjustments. The primary role remains: computation-based platform for multiple structure and construction negotiations abstracted as geometric constrains and their interdependencies. The knowledge embedded in a trait remains open source: easily accessible, communicable, repeatable, hackable, and transformable (Witt, 2010). On the other hand, the trait's authorship requires redefinition from the demarcation and polarization of the historic types, into a gradient that spans the two. The fluid authorship enables multiple trait authors and concurrent knowledge embedding and activating to instigate collaborations and innovations at multiple levels. In this way, the contemporary trait can narrow, if not fully challenge, the Albertian splits as "the synthesis of architect, engineer and fabricator again controls the historical responsibility for the processes of design, making and building" (Oxman, et al. 2010). Further, the authorship fluidity through participation and novel connections sustains knowledge exchange, development and assimilation between theory and practice, industry and academia, traditional and contemporary, and local and global.

Conclusion

Volumetric complexity is primarily the domain of architecture and its viable resolve is possible only through architectural design knowledge and innovations. Through comprehensive multiple structure and construction constraints negations, complex volumetric forms, differentiated through digital traits, articulate meaningful tectonics as a particular empathy manifestation in the field of architecture (Sekler, 2009). In a wider contemporary digital theory realm, the trait enables architectural tectonics that addresses a number of its pursuits: Moussavi's affects (Moussavi, 2009), Spuybroek's sympathy (Spuybroek, 2011), Picon's narrative and nostalgia (Fabricate 2017 conference lecture), etc.

The first step, though, remains to overcome the historic stumbling block: the assembly construction as feasible and timely process through all relevant constraints computation.

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8.4. Rethinking Digital Architecture in an Expanded Field, Using Malta as a Case Study

Irina Miodragovic Vella and Prof Dr Toni Kotnik, 2016

Unpublished article

Rethinking Digital Architecture in an Expanded Field, Using Malta as a Case Study

Abstract:

The paper examines the notion of digital architecture beyond its ties to digital technology, as a theoretical perspective grounded in systemic thinking and computation that instigates contextually engaged material systems. More specifically, the paper examines the relevance of digital architecture a contemporary context that is at once globally connected and precisely situated in space and time, yet not dominated by high-end technology and resource abundance.

As a result, the paper theorises the notion of 'regional digital' architecture, a digital architecture derived from and for the margins, driven by, not technological solutions, but fundamental architectural concerns. Regional digital architectural analysis, thinking, design, production, and teaching are grounded in exploring, exposing, and engaging affordances of immediately accessible contextual realities. In short, regional digital architecture is an architectural practice that folds and unfolds context to derive visually divergent yet intrinsically authentic forms and tectonics that generate multiple meanings, thoughts, and emotions yet express relatedness.

Keywords: regional, digital architecture, computation, systemic thinking, Malta

Introduction

During his keynote lecture at FABRICATE2017, Antoine Picon stated: "I do believe in digital fabrication … but it is good to ask oneself: What are we exactly doing?" (Picon 2017). The question is similar to Hugh Whitehead's introspection from 2004: "In exploring these new [complex, digital] forms, are we doing it just because we can or, because it is a good idea?" (Kolarevic 2004). Both questions seem to echo Cedric Price's 1966 question: "Technology is the answer … but what was the question?" (Price 1979).

Digital architecture opposes Modernist top-down design processes that impose universal solutions to any context by pursuing computational bottom-up design processes that instigate context-driven solutions. Digital architecture, thus, folds and unfolds the context.

The current leading digital architectural research and production is located in the context dominated by high-end technology and resource abundance. As a result, digital architecture steers towards specialised, technology-driven solutions that address niche problems of academia and high-tech industries, like robotic fabrication, material engineering, and formal and performative complexities.

The paper aims to examine the relevance of digital architecture in a context marginal to these digital 'hotspots'. The notion of digital is approached beyond its ties to digital tools from a theoretical perspective that fosters conceptual thinking to include contextual heterogeneity, interconnectivity, and relatedness in architecture.

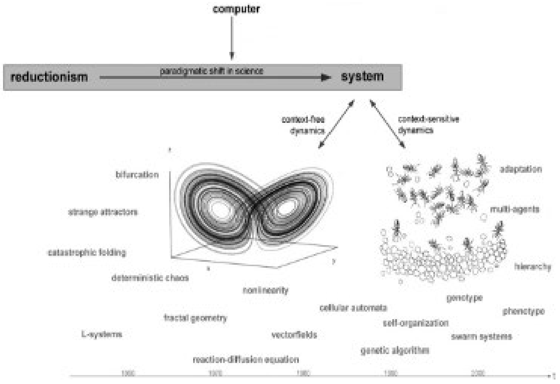
The approach is tested on Malta as a case study, a context whose particular nature (small scale, contained, and geographically disconnected environment) allows controlled analysis, observation, and mapping. As a result, a 'regional' digital architecture is theorised, from and for the margins, driven by, not technological solutions, but fundamental architectural concerns.

Digital Architecture

Digital architecture approaches design problems through systemic thinking about context and derives solutions through computation**.**

Systemic thinking is a holistic examination of broadly applicable interaction patterns that underlay, drive and govern a system. Contrary to top-down reductionist thinking, where a whole is divided into parts, systemic bottom-up thinking recognises the overall global arrangement of parts as a cohesive synergetic distribution of their interdependences. The system's behaviour is expressed through emergent generative processes, the regulatory feedback mechanisms that process and react to information to influence and to be influenced by the environment. The notion of the environment is, thus, understood as a network of processes, not a collection of forms. The tangible, static boundaries between contextual dichotomies, obvious to our senses of vision and touch, like natural and manmade, subject and object, global and local, concept and percept, and virtual and actual become indistinct and "fuzzy" when understood as processes of intense activity and information exchange (Turner 2000).

Digital tools made systemic thinking the dominant scientific exploration method by enabling computational means which could handle large sets of interactions between various quantifiable entities and in depth exploration of the self-regulating effects of feedback (Figure 01) (Kotnik 2016). Digital tools also allowed the systemic concepts, embedded as software, to cross over and diffuse into the architectural discourse altering the comprehension of its fundamental notions, like context, matter, materiality, and form (Kotnik 2016).



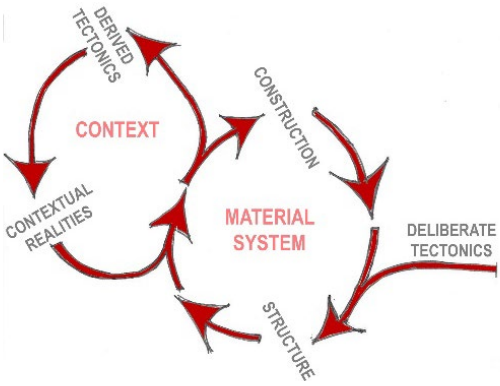


Figure 01 (Source: Authors) *Figure 02(Source: Authors)*

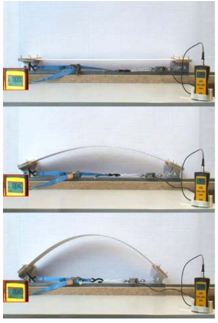
Context is approached as a comprehensive, complex system of multiple realities, like climate, materials, skills, knowledge, tools, technology, cultural traditions, social idioms, etc. "The Aristotelian view on matter as an inert receptacle of [arbitrary] form superimposed from the outside" (Menges 2015) with "unbound violence" (Picon 2017) shifts towards recognising matter as inherently animate, embedding generative processes that enable it to affect and be affected by context. Similarly, "the Newtonian idea of an obedient materiality governed by general laws" (Menges 2015) shifts towards recognising material's spontaneous activity: its multiple immanent virtual patterns of being that become discrete and actual at specific thresholds, i.e. within a certain set of contextual circumstances (De Landa 1995).

As a result, architectural concerns shift from the form, a top-down imposition, to the formation, bottom-up generative processes. Instigated by contextual realities and activated by contextual feedback, the generative processes formulate material systems. A material system's behaviour is formulated through structure and construction, enabled and disabled through design knowledge, and expressed through tectonics. The structure is a virtual arrangement of contextual interdependencies destined to cope with contextual forces at work and construction is any process by which structure actualises as a communicable form (Sekler 1965). Design knowledge, an amalgamation of material, geometric, instrumental knowledge, is an intrinsic understanding of the material system's affordances: structure's organisation principles (parts to whole relationships, program constraints dependencies, spatial organisations) and construction processes (material properties, tools, technology, procedures)(Witt 2010). Tectonics is the expressive result of a structure realised through construction (Sekler 1965). As both deliberate and derived, it concurrently drives the material system and emerges from it as "the particular manifestation of empathy in the field of architecture"(Sekler 1965). In conclusion, a material system develops from and for a specific context. The complexity of its emergent forms is not necessarily a pursued design intent but an intrinsic by-product of its contextual engagements (Figure 02).

Context, a continuous landscape of capacities and constraints, does not suffice single-dimensional analysis of its formal, cultural, or political aspects. Instead, digital architecture engages computation's ability to both describe generative processes and plug-in into their activity, unfolding (Picon 2017). Through bottom-up computational processes, material systems are derived to drive architectural form formations. More specifically, computation enables structuring, a process that discretises contextual realities through their underlying mathematic, geometric, syntactic, and formal logic (Oxman, Oxman 2010) and externalises their interdependencies as generative processes that formulate a material system. Since digital tools facilitate and amplify computational processes, they are often perceived as indispensable to the digital approach in architecture. This notion "veils the mind-changing potential of the digital and limits the conscious recognition of computation as a paradigmatic shift within the discipline" (Kotnik 2016).

On the other hand, several theoretical discourses trace historical instances of material systems that expanded architectural limits by unveiling novel contextual affordances. They expose, from a wider theoretical perspective, that the digital approach in architecture predates digital tools. The proto-digital material systems are found, among others, in the Gothic architecture (Moussavi, López 2009, Ball 2009, Spuybroek 2011), stereotomy (Witt 2010, Miadragovic Vella, Kotnik 2017b), vernacular architectures (Hensel 2008, Moussavi, López 2009), traditional craftsmanship (De Landa 1995), postcolonialism (Hosagrahar 2012), tectonics (Sekler 1965), and the work and theory of Antonio Gaudi, Josef Albers, Hans Isler, and Frei Otto (Menges 2015, Moussavi, López 2009). The premise is explained with two material system examples: one is aided by digital tools, while the other predates them.

The ICD/ITKE 2010 pavilion (Figure 03) was the first in a series of research pavilions that investigated the augmented analogue material computation, the material-driven, bottom-up generative design processes amplified through the use of digital tools. It explored affordances of extremely thin plywood strips. The physical experiments that elastically bent the material discretised and externalised the deflection range of the bending-active structure as geometric information (Figure 04). Encoded as a digital parametric computational model, the geometric information allowed performative explorations (Figure 05) that discretised and externalised the main structural principle as a topological arrangement: by pleating the adjacent strips into segmental arches the energy stored in a bent region of one strip was maintained by the tensioned region of the other. Negotiations of the structural principle with the capacities and constraints of fabrication, manual assembly, and site were encoded as generative processes that established a material system (Menges 2010).



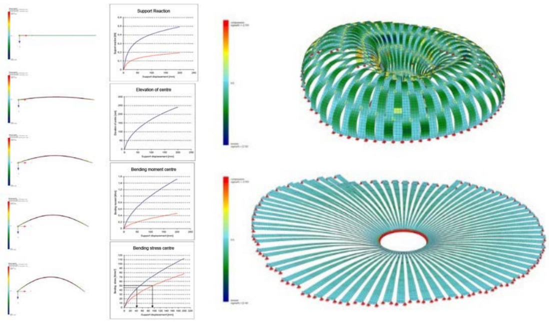


Figure 03 *Figure 04* *Figure 05*

Image sources: (Fleischmann et al., 2012) Figure 03: page 50, ICD/ITKE University of Stuttgart, Andrea Lautenschlager; Figure 04: page 47, ICD/ITKE University of Stuttgart, Andreas Eisenhardt, Manuel Vollrath, Kristine Wächter; Figure 05: page 48 © ICD/ITKE University of Stuttgart, Julian Lienhard;

Stereotomy, the art of cutting three-dimensional solids into shapes to be assembled, in architecture, designates the art of stone carving to execute geometrically complex stone masonry assemblies (Sakarovitch 2003) (Figure 06; Figure 07). It emerged from the economic, cultural, and intellectual contextual impetus of the Gothic period as an accumulation of the expanded geometric knowledge (formulation of projective geometry), rediscovered classical knowledge (Neoplatonism), and imported technical skills (by the Crusaders) (Ball 2009). Stereotomy discretises and externalises stone's inherent spontaneous activity as a correct understanding of its underlying geometric logic (Heyman 1995). More specifically, it derives generative processes from interdependencies of stone's lack of tensile strength, a complex web of structural forces (during and upon execution), rigorous ashlar configurations of tightly fitted joints, and design intents (symbolism, style, phenomenology). Validated through success and failure of their actualisations, generative processes are codified as rules (traditions, secrets of the lodges, masons' manuals, stereotomic treatises) that are either execution sequences for a specific stereotomic form or externalised knowledge on stereotomic generative processes. For example, the arch, as an architectural typology, can be actualised through preset construction instructions. On the other hand, the arch as a fixed normative genus, an exactly transmissible but nonvisual notation (Carpo 2011), embodies infinite virtual variations. The comprehension of the arch's underlying generative processes enables its contextual activations that are fleshed out in a wide variety of different, yet similar forms (Heyman 1995) (Figure 08). Stereotomy, thus, can be understood as an early example of a material system (Miadragovic Vella, Kotnik 2017b).

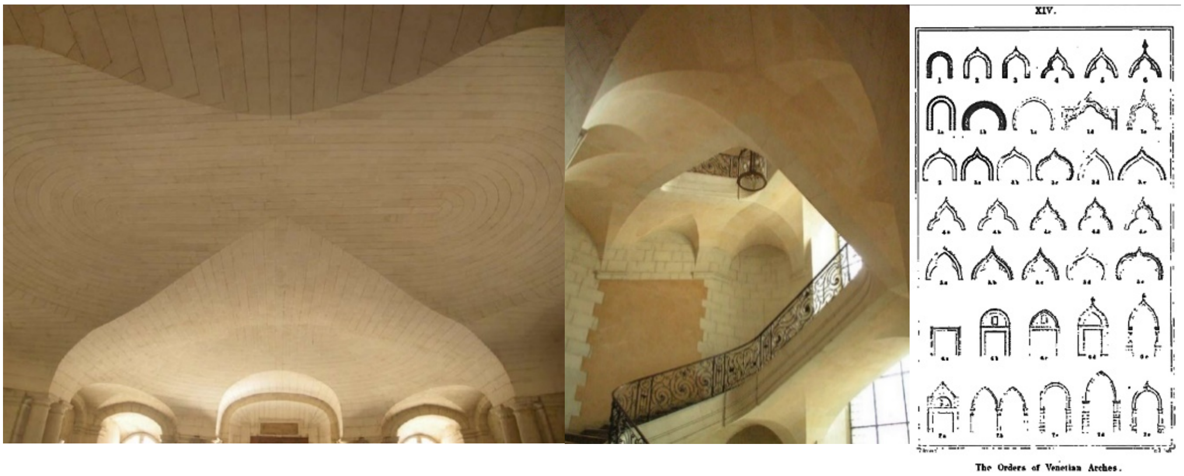


Figure 06: Arles City Hall Vestibule, Jules Hardouin-Mansart, 1637; Figure 07: Monastery of Notre-Dame de la Couture, Le Mans, 1720-39. Figure 08: The Orders of Venetian Arches.
Image Sources: Figures 06 and 07 (Etlin 2012), page 12, page 23. Figure 08: (Ruskin, 2009), plate XIV

Since a continuity persists in the development of the design processes that expose and engage contextual affordances as architectural responses, the digital approach in architecture is grounded history. Further, since it explores affordances of immediately accessible, tangible and intangible (knowledge, influences, ideas, solutions, skills, funds) contextual realities, the digital approach in architecture is regional. Within the digital theoretical perspective, that negates dichotomies, the notion of 'regional' supplants the postmodernist dialectic opposition to 'global' to refer to levels of connectivity. In conclusion, the initial question becomes: How to rekindle a regional digital architecture?

To provide an answer, the discussion uses Malta as a case study.

Maltese Reginal Digital Architecture

"Malta is a small [316 km2], densely populated [1,265 inhabitants / km2] island country that is located in the central Mediterranean Sea, 100 kilometers (km) south of Italy and 290 km north of Libya. The three inhabited islands of Malta, Gozo, and Comino host few mineral resources except for clay, limestone, and salt, and no indigenous mineral fuel resources" (Hastorun 2014).

Like any contemporary regional context, Malta is at once globally connected and precisely situated in space and time (Hosagrahar 2012). Due to its high population and urban density, it can be equated with a small European city, yet its operations have neither environs nor a surrounding region to rely on. The small scale and geographical isolation amplify its contextual realities and make it an appropriate investigation platform.

The investigation starts with a premise that any context embeds certain context-driven, digital in approach, architecture(s)

(Stevens, Nelson 2015). They enable formulation of an origins model as a basis for theorising a contemporary digital approach that pursues neither technology imports, nor returns to precedents, but innovative variants of contextual curations to expose novel contextual affordances. In short, regional digital architecture seeks to simultaneously embed and inflect its origins models (Cuff 2012).

The Maltese contextual architecture emerged from four dominant contextual realities: the Mediterranean climate, limited resources, a single building material, and a continuously increasing connectivity.

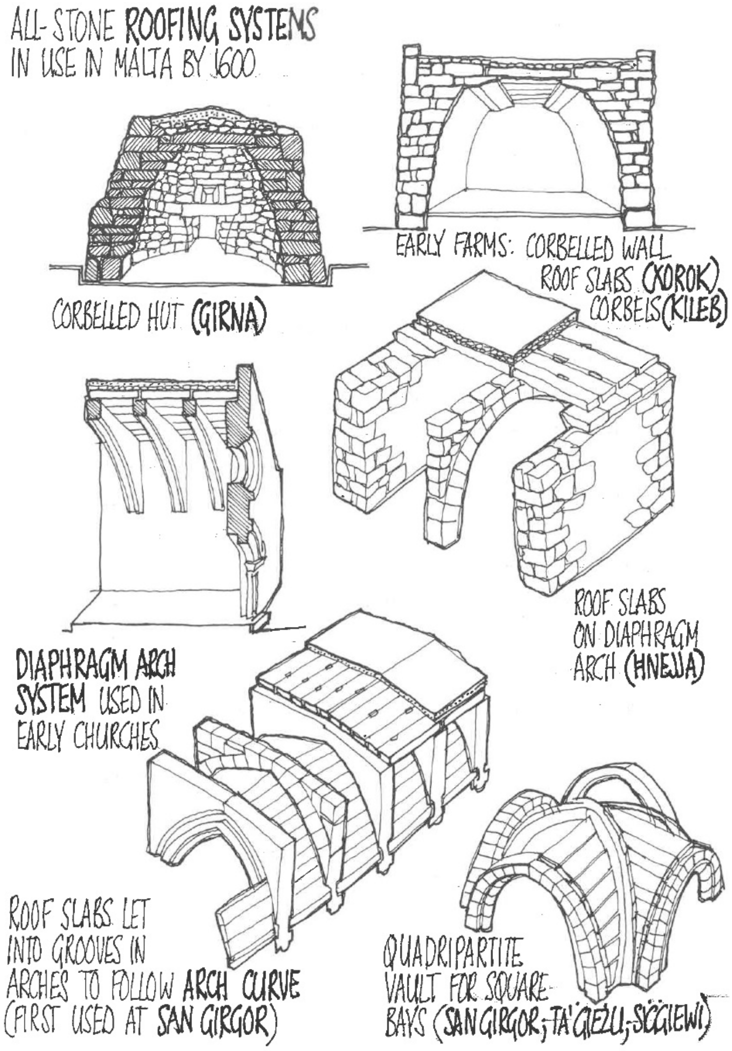
Limited resources made the globigerina limestone the only available building material. The limestone is brittle, heavy, and "remarkable for its softness; it is sawed more easily than wood […] Hence, it is worked easily, but it is not strong enough against moistures and the sea-breezes; and […] it is not strong enough for mortar and cements [either]" (Quintin d'Autin, cited in (Cassar 2010). Its heterogeneous lithology generates a highly inconsistent performance that requires proficient craftsmanship (technical skill and tacit material knowledge). The lack of material variation also resulted in minimal use and extensive reuse of alternative materials that tied construction to simple tools, techniques, and details that were transferred from one generation to another. The resultant architectural formation, subservient to strict limestone constraints and limited construction, was derived from a continuous negotiation between the performance optimisation and workability.

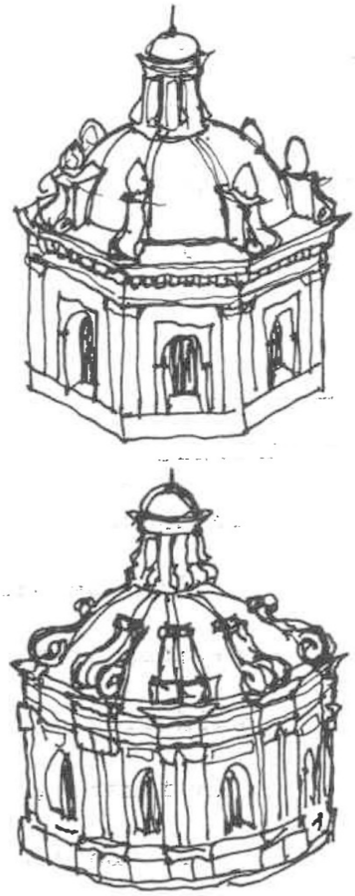
For example, since the brittle limestone was difficult to quarry, cut, and transport without breaking, the developed frugal construction processes maximized its site availability, like integrating found, unhoned stones (rubble walls), topography (caves and rock outcrops that also provided high thermal mass), and onsite quarries (subsequently used as cellars and rainwater reservoirs).

Similarly, negotiations between limestone's lack of tensile strength, structural optimisations, limited falsework, and manual execution established an underlying virtual arrangement that lacked variation, i.e. a singular structure. Its iterative actualisations though context-driven construction processes established standardised dressed stone configurations, the three ashlar types: the block, the slab, and the voussoir.

For example, the roofing system that pursued either a wide span and height or a wider span with a flat surface above develop as form variations based on standard ashlars: slabs spanning over corbeled rubble walls and diaphragm arches propagated in one, two directions, and around a polygonal base (Figure 09; Figure 10). The structure remained unchanged even when timber beams and rolled steel joists replaced arches and when concrete supplanted the stone-dominated construction.

Figure 09: (Tonna 1971), page 29; Figure 10: (Tonna 1971) page 77.





In the same way, climatic requirements (shading, thermal mass, ventilation, passive cooling, rainwater capture) instigated form variations yet retained structure and construction. Continuous actualisations assimilated these forms as the context, the vernacular configurations like the south loggia, the central courtyard, the flat roof, and their assemblages the farmhouse, the narrow village street, the winding street network, etc. In the urban areas, the deliberate tectonics overly, driven by socio-cultural forces, instigated form variations that assimilated as recognisable traditional configurations, like the townhouse and its expressive components: the balcony, the portico, and specific façade ornaments (Tonna 1971).

Although Malta's geographical isolation rendered tangible goods imports unfeasible, its increasing connectivity allowed intangible goods flows. When Malta's connectivity reached a geopolitical position of strategic military relevance, it started an almost continuous presence of outside political powers. Their deliberate tectonics pursuits were enabled by the amplified availability of intangible goods. The imported utilitarian, performative, and expressive (anagogical meaning, political authority, social status) design intents assimilated as the context. They unveiled novel contextual affordances that expanded structure's versatility, construction's proficiency, formal repertoire, and design knowledge.

For example, during the Order of St. John rule, the favourable economic conditions and the influx of stereotomic geometric knowledge and technical skills enabled the pursuit of the Roman Baroque deliberate tectonics in monumental architecture. The resultant forms' scale, span, and geometric complexity increased, yet the full Baroque complexities, like the volumetric undulations and spatial modulations, were rare. Although the increased intangible resources expanded limestone's affordances and derived novel structures, their execution remained a challenge. The amplified intangible resources primarily expanded four aspects: the surface design complexity, vaulted forms' structural performances (dome, barrel vault, cross vault), construction's technical proficiency (sophisticated detailing, geometric precision, systematic execution), and design knowledge. They derived the Maltese Baroque idiom, the preferred deliberate tectonics of both monumental and anonymous architecture, and the idiom of cultural identification until today (Figure 11). The Maltese Baroque idiom's derived tectonics is a physical expression of a dominant narrative's subservience to and assimilation as the regional context.

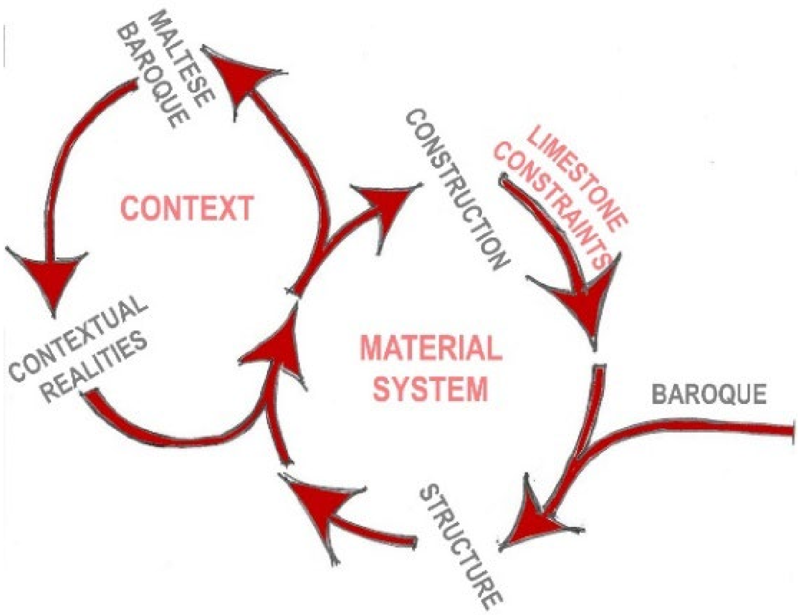


Figure 11

Malta's geographical isolation made advancements self-referential, retained innovations within an established ideas' framework, and developed an architecture that was at once rigid and robust. Its structure was fixed yet capable of assimilating diverse deliberate tectonics and design knowledge. Its actualisation was based on limited construction yet assimilated a plethora of regional crafts within a proficient heritage of making (Mahoney 1996). Finally, it could actualise a web of multiple, dynamic contextual realities as topologically continuous, performatively connected, and tectonically coherent forms. The Maltese context-driven architecture is, thus, a clear example of the digital approach in architecture. It establishes a material system, an arrangement of interdependent generative processes, that actualise different, ever-changing, yet similar forms (Figure 12). Malta's geographical isolation made the material system frugal, self-sufficient, contingent, and situated.

The initial question, thus, becomes more specific: How to rekindle the Maltese material system?

Figure 12: Left: Citadel, Gozo; Centre: Valletta; Right: Mdina. Sources: Left (Trade and Tourism Malta DeLuxe Ltd. unknown), Centre (Schager 2012), Right (pensivelaw1 2008)

<u>Reconstituted Limestone</u>

The research into reconstituted limestone is a response to the predicted shift in regional contextual realities, the unavoidable depletion of limestone reserves by the year 2036 (Cromie, Cole 2002), sand for aggregates by the year 2020 (Thorns 2018), and space for construction waste disposal by the year 2020 (Debono 2010). As material engineering, the research explores methods of recycling, reconstituting, and re-engaging the limestone waste (Buhagiar, Montesin 2017). It establishes interdependencies between the properties of the crushed limestone and different binder types to derive optimised performances, like strength, durability, aesthetics, and recyclability. The research is driven by the abundant regional material knowledge that enables the hacking of material properties to expose their novel affordances. As a result, the previously inert, cast-off material becomes a versatile, semi-finished material susceptible to dynamic contextual negotiations. More specifically, it becomes susceptible to formulating contextually engaged material systems that embed structure prone to variability and innovations, and construction rooted in frugality and self-reliance.

Regional Manufacturing Thinking

The shift in contextual realities that made digital tools affordable and instrumental knowledge attainable enabled the research that pursues rekindling of architectural design through making. Instrumental knowledge is an understanding of procedures (software, program, script) to successfully operate digital tools that also enables the user to access and transform these procedures to intended design aims and to assimilate tools' constraints within the design process (Witt 2010). The research engages the commons-based, peer-produced instrumental knowledge to hack CAM tools and expand their fixed affordances preset by the manufacturer. More specifically, by using open-source hardware and software, the research developed a CAD/CAM workflow that placed the CAM tool's control within the CAD environment, developed feedback between the fabricated material and the CAM tool, and enabled design decisions as responses to and during the fabrication process. The result is an intuitive design environment that allows negotiations between the material's bottom-up spontaneous activity and top-down design impositions, like the formal intent and optimised performance.

The workflow validity was tested and assessed within a material computation based research that explored a link between the water erosion process and limestone's properties (De Micoli, Rinderspacher et al. 2018). The established CAD/CAM workflow engaged a locally sourced, disused CNC plasma cutter that was reconditioned with a water-jet lance end-effector and a micro-controller. The micro-controller ran a g-code parser that bypassed the main machine-controller by parsing the stepper-motion signals directly to the motor drivers. The developed workflow enabled the material computation research to establish interdependencies between fabrication parameters, limestone's heterogeneous lithology, limestone's self-computed surface formations, and the ashlar's integrity (Figure 13). In short, the expanded digital tools' affordances enabled contextual independencies to formulate a material system that exposed both novel material knowledge and tectonics.

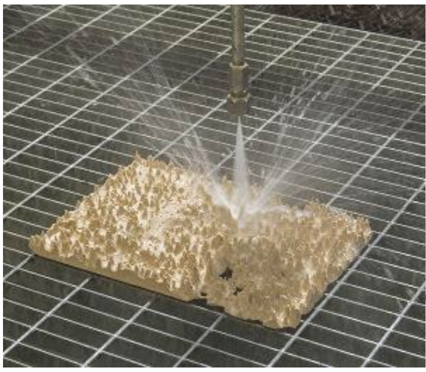
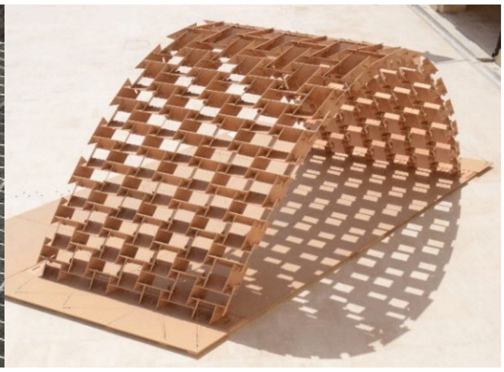



Figure 13 *Figure 14*

Stereotomic Parametrisation

Digital tools availability expanded stereotomic knowledge, enabled design and fabrication of previously unattainable complex stone masonry assemblies, yet retained actualisations that necessitate abundance of tangible and intangible resources (Fallacara 2016, Rippmann, Van Mele et al. 2017). It instigated research into stereotomy's intrinsic governing patterns to assess its validity for regional contexts with different resource realities. The research approached stereotomy as a material system and discretised and externalised its structure and construction through geometric procedural rationality. The structure was formulated as an arrangement system of four geometric parameters: base surface geometry, surface distribution grid, contact faces rotation, and the distance between intrados and extrados (Miadragovic Vella, Kotnik 2016, Miadragovic Vella, Kotnik 2017b). Construction discretised and externalised multiple contextual realities of materials, formal intents, technology, design knowledge, etc., as a negotiation between geometries of assemblies, ashlars, force flow, and techniques used (Miadragovic Vella, Kotnik 2017a). Finally, negotiations between structure and construction specified parametric interdependencies and specific parameter values. In conclusion, stereotomy, a contextually engaged material system based on geometric interdependencies, it is not dependent on specific material or fabrication techniques.

The premise was tested through the design and fabrication of a stereotomic plate pavilion (Figure 14). Its form was an output of a material system that embedded multiple design impositions and contextual forces: topological interlocking structural action based on the Abeille vault, small prototyping CNC router, limited budget, quick manual assembly, reversible demounting, and structural design noncompliant to FEA simulations. The resultant lightweight lattice assembly visually differed from the solid Abeille Vault yet retained its underlying generative processes.

Regional Digital Approach in Architectural Education

The regional digital approach guided the design process of one of the Final Projects for the Masters of Architecture (Architectural Design) at the University of Malta. The project questions materiality within Maltese contextual realities of the abundant construction waste and diminishing resources of limestone, sand, and fresh water. (The depletion of aquifers is predicted by the year 2100 (McGrath 2007), while the current seawater desalination process, based on non-renewable energy, are perceived as too taxing to persist.) It formulates a material palette that consists of crushed construction waste, limestone gravel, resin, several available aggregates, expanded polystyrene, and untreated seawater (Figure 15). Their resultant material mixtures share the following properties: constant mass, lack of deflection under compression loading, and unchanged loading configurations when loaded. Since the presence of seawater eliminates the use of metals, structural actions are restricted to compression and shear structural actions, and structural behaviour is expressed as geometric interdependences.

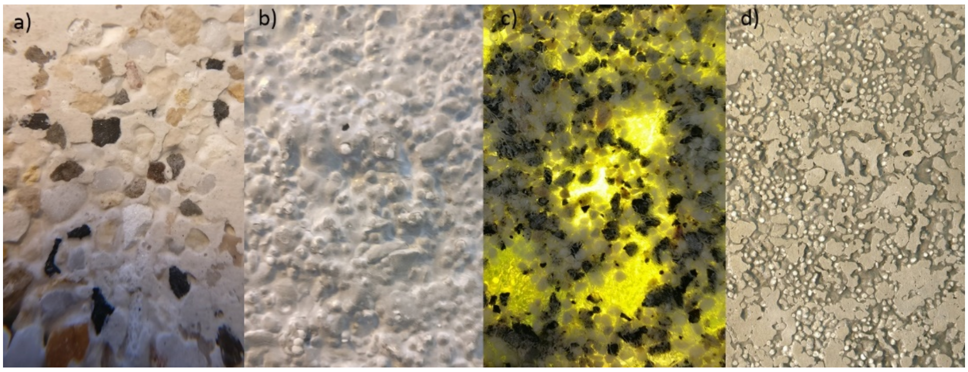


Figure 15

Fabrication constraints are based on the current dominant construction procedures that achieve feasibility for low volumes and varied demands through manual labour, simple techniques, and semi-finished materials. Further constraints are derived from the project established materiality and specific site and its environs restrictions (limited machinery access due to narrow streets, working within confined spaces of existing buildings, sensitive execution due to heritage values). Together, they direct fabrication towards the production of discrete elements that provide workability and versatile performances. A suitable fabrication method, thus, becomes the casting of small size, low weight ashlars

In short, regional contextual realities derive masonry as the material and stereotomy as the design approach. They are not a romantic return to the past, but materiality and a material system capable of contextual engagements.

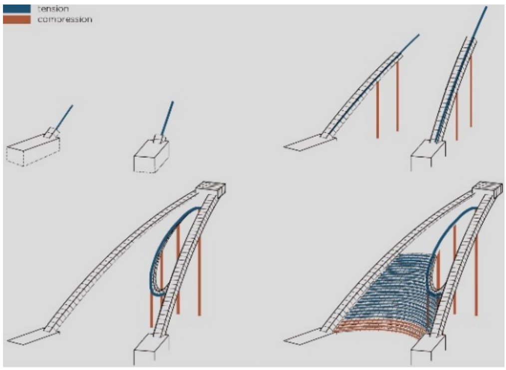


Figure 16 *Figure 17*

The stereotomic material system is customised through feedback between capacities and constraints of materiality, fabrication (limited instrumental knowledge), execution (manual assembly, simple falsework), force flow, site, and programme. The feedback specifies the four stereotomic parameters and externalises the main structural principle: a system that combines arch and topological interlocking actions to achieve self-stabilising sub-structures. It actualises as ashlar configurations and the assembly sequence. Ashlar joggled contact faces are either perpendicular to the line of thrust or rotated in the direction opposite to the rotation direction of the adjacent contact faces. The weave-like assembly sequence begins with the lighter ashlars that become a sacrificial falsework for the heavy, loadbearing ones (Figure 16). A certain amount of temporary external post-tensioning (clamps, ties) is anticipated, necessary until the structural actions activate. The resultant architectural forms express the regional contextual heterogeneity (Figure 17).

Conclusion

The research examples expose the digital approach in architecture as inevitably grounded in materiality. Within the digital theoretical perspective, materiality refers to the immediately accessible materials and material knowledge, the understanding of material affordances and construction processes that activate them. Continuously shifting realities make regional materiality indeterminate, versatile, and necessitate continuous contextual explorations. In short, technology is the answer to the digital approach in architecture, if it facilities contextual explorations to address contextual realities through contextual curations. The current dominant architectural approach, on the other hand, addresses contextual realities through the economy of design and production by engaging preset affordances of materiality and technology. More specifically, it engages automation, repeatability, speed, and mass production to drive homogenous material properties, anticipated material behaviours, and actualisations through established construction procedures.

For example, Malta's limited available footprint, lack of structured urban planning scheme and architectural quality standards, and the recent amplified influx of materials, resources, technology, investments, clients, and users guarantee profitable returns of the building industry. The dominant architectural approach, subservient to the continuous, speculative building boom, streamlines materiality and technology towards efficient, utilitarian, top-down procedures that suffice limited material and instrumental knowledge. The resultant restricted design space reduces architectural concerns to the deliberate tectonics, endowing the form with unique sensorial qualities, and documents production that accurately describes it (Moussavi, López 2009, Carpo 2011). Boundaries emerge between design and materiality and propagate within the design process between intents, their representations, CAD tools, and outcomes, and within materiality between skills, CAM tools, materials, and material knowledge. The resultant "epistemic, formal, and technical rupture" (Witt 2010) is reflected in contextual fragmentations that erode the material system's continuity, connected performance, and coherent tectonics.

In conclusion, technology is the answer if it facilitates the switch from the production of forms to the production of formations, generative processes that formulate contextually engaged material systems. More specifically, technology is the answer if it enables the production of design knowledge susceptible to assimilations and appropriations within regional contexts towards explorations and innovations.

The pivotal responsibility, thus, lies with designers and educators to rekindle their computational thinking, expand their instrumental knowledge to become "expert amateurs" (Paulos 2013) who tinker and hack materiality. In this way, the regional digital architecture truly becomes an approach that explores, exposes, encapsulates, and engages contextual affordances as architectural responses. Their visually divergent forms become unavoidably, intrinsically authentic and the derived tectonics become an affect, a pre-personal, unmediated intensity that generates multiple meanings, thoughts, and emotions (Moussavi, López 2009), yet expresses relatedness.

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