Craft-inclusive Construction
Design Strategies for Thin-tile Vaulting

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Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted or is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit of 80,000 words. All figures are by the author unless otherwise is mentioned. All translations are by the author unless otherwise is mentioned.
Craft-inclusive Construction: Design Strategies for Thin-tile Vaulting

Mohammad Wesam Al Asali

Abstract
Design and digital analysis tools can be a fertile space in which situated building knowledge, represented in crafts, act in dialogue with methods of construction. This research examines this possibility in thin-tile vaulting - a Mediterranean ceiling-craft technique that employs less material, but more skill, than the conventional construction with reinforced concrete. Through historical analysis of buildings, ethnographic, and purpose-designed case studies, the research intersects three areas in the built environment: material limitations, vernacular construction, and building technology.

The study focuses on three approaches to craft-inclusive construction: policy, training, and design. The policy approach is extracted from two historical studies on the industrialisation of thin-tile vaults in Cuba during 1960s and Syria during 1980s. The training approach is an ethnographic study that examines training programmes of vaulting during the construction of three thin-tile vault projects in Rwanda, Jordan and Spain. Learning from the two previous aspects, the approach to design uses design-build methodologies to explore how digital analysis tools can mediate between technology, policy, and labour for a craft-inclusive construction of vaults. This design-focused approach explores material alternatives, off-site manufacturing, and recyclable formwork for thin-tile vaulting.

My PhD finds that construction for environmental resilience operates within the same limitations as vernacular construction. While local building crafts are useful for sustainable construction, they are usually excluded from policies and 'formal building regulations' as they are inherently difficult to be abstracted into codes. The thesis concludes that architectural design can play a decisive role in bridging this gap. At a policy level, architects can play an essential role in demystifying building crafts by using digital modelling and analysis to understand how they work. At a design level, they can develop construction tools in conversation with craftspersons to help the latter to find new possibilities of their craft, build faster, or build more efficiently.
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Content

Abstract ..................................................................................................................................................... I

Declaration ................................................................................................................................................... I

Acknowledgement ....................................................................................................................................... IV

Content ....................................................................................................................................................... VI

List of Figures ............................................................................................................................................... IX

List of Tables .................................................................................................................................................. XV

Chapter 1 Introduction .................................................................................................................................. 1

1 Thin-tile Vaulting: Limitations and Opportunities .................................................................................. 1
   1.1 Background: from Objects to Processes ........................................................................................... 2
   1.2 Setting the scene: On vernacular construction and scarcity .............................................................. 6
      1.2.1 Vernacular Construction ........................................................................................................ 6
      1.2.2 Scarcity ................................................................................................................................... 7
      1.2.3 Craft: Scarcity through Vernacular Practices ...................................................................... 9
   1.3 Thin thin-tile vaulting ....................................................................................................................... 9
      1.3.1 Definition ................................................................................................................................ 9
      1.3.2 History .................................................................................................................................. 10
   1.4 Literature Review ............................................................................................................................ 17
      1.4.1 References and Key Publications .......................................................................................... 17
      1.4.2 Urban Development and Tile Vaulting .................................................................................. 19
      1.4.3 Studies of Tile Vaulting in Modern Construction .................................................................. 20
   1.5 Framework: Rises and falls of Thin-tile vaulting ............................................................................ 22
   1.6 Methodologies .................................................................................................................................. 29
      1.6.1 Summary of Research Methodologies .................................................................................. 30
   1.7 Discussion ....................................................................................................................................... 31

Chapter 2 Policy Approaches to Thin-tile Vaulting .................................................................................. 35

2 Historical Case Studies from Cuba 1960s and Syria 1980s. ................................................................. 35
   2.1 Background: Building Codes and Vernacular Practices ................................................................... 36
   2.2 Vaults in Cuba after the Revolution, Beyond the Art Schools ........................................................ 38
      2.2.1 Introduction: Context ........................................................................................................... 38
      2.2.2 Vaulting in Cuba .................................................................................................................. 39
      2.2.3 Early Experiments ................................................................................................................. 42
5 Towards a Craft-Inclusive Construction 207

5.1 Approaches in Thin-tile Vaulting 208
5.1.1 Policy Approach to thin-tile vaulting 210
5.1.2 Training Approach to thin-tile vaulting 210
5.1.3 Design Approach to thin-tile vaulting 211

5.2 Contributions 212
5.2.1 Towards a Craft-inclusive Architectural Practice 212
5.2.2 Building Craft Training Models 215
5.2.3 Digital Analysis for Vernacular Construction 215
5.2.4 Making as a Methodology 216
5.2.5 Future research 216

Bibliography 219
List of Figures

Figure 1. Le Corbusier: Résidence Peyrissac, 1941, sketch. (Boesiger 2015, 117). .......................................................... 3
Figure 2. Marcel Lathuilliere: Cité el Djenan Arch, 1941. (Lathuilliere 1945, 32) ................................................................. 3
Figure 3. Roland Simounet, Djenan-al-Hassan, Algiers, 1956-1958. (Architectes d’Algérie Pendant La Période Française 2017) ................................................................. 3
Figure 4. P. A. Emery and L. Miquel: Maison a Algiers, 1940s. (Architectes d’Algérie Pendant La Période Française 2017). ........................................................................................................ 3
Figure 5. Luis Moya: thin-tile vaulting definition sketch. (Moya Blanco 1947, 12,19). .......................................................... 12
Figure 6. Syassa mud stairs. (Almagro 2001, 168). .................................................................................................................... 12
Figure 7. Roman concrete vaults, according to Choisy. (Choisy 1873, 61). ................................................................. 12
Figure 8 Cesar Martinell 1921: Winery in Sant Cugat, an example of modernist architecture. .................................................. 12
Figure 9 Luis Moya: Museum of America, Madrid, Vaults in post-civil-war construction .................................................. 12
Figure 10. Guastavino System Patent. (Rafael Guastavino 1891). ......................................................................................... 14
Figure 11. Two projects of Guastavino Company with two different formwork treatment. Left: Cathedral St John’s the Divine: Minimum formwork. Right: Minnesota State Capitol: Intensive formwork, possibly for fast construction. (Avery Library). ............................................................... 14
Figure 12. National Art Schools, Cuba. Left: Plastic Art. Right: Modern Dance. (Paradiso 2016b, 50). ....................................... 14
Figure 13. System patented by Charles Daussin. (Fuentes and Ine 2019) .................................................................................. 15
Figure 14. Left: details of vaulted ceiling from Sattler 1984. Right: Tile vaults in Landeszentralbank, design by Sattler and built by the Ranks. (Huerta 2017) .................................................................................. 15
Figure 15. Pines Calyx Centre. (Ligth Earth Designs) ............................................................................................................. 18
Figure 16. Mapungubwe Centre. (Ligth Earth Designs) ............................................................................................................. 18
Figure 17. Drone Port Prototype in Venice Biennale, 2016. (Norman Forster Foundation) ....................................................... 18
Figure 18. Tile vault house in Ethiopia. (Davis and Block 2012a). ............................................................................................. 18
Figure 19. Free vaulting in ETH, 2012. (Block Research Group). ............................................................................................ 18
Figure 20. Mileto and Vegas, 2016: Panteón Soriano Manzanet. ............................................................................................. 18
Figure 21. Stair-making with tiles, Valencia. Source: Salvador Gomis ..................................................................................... 18
Figure 22. Ramon Guarda Parera, a master vault maker and trainer ....................................................................................... 18
Figure 23. Summary: Timeline of Tile Vaulting Transfer Until June 2020. The tree shows how the technique spread to different regions with different construction cultures and materials. Sometimes thin-tile vaulting did 'return trips' to its origins. The dynamic of this timeline tree suggests a study of thin-tile vaulting in different contexts and cultures. .................................................................................................................................................................................................................................................................................................................. 24
Figure 24 Theoretical framework: approaches of policy, labour and design in thin-tile vaulting ............................................. 28
Figure 25 Mythological framework in relation to policy, labour, and design approaches ........................................................... 32
Figure 26 Ricardo Porro, Vittorio Garatti, and Roberto Gottadri, Art Schools in Havana, 1961-64 .............................................. 41
Figure 27 A. Left: Juan Campos (Architect) and Alfredo Perez (Engineer), first brick vaults experiments after the revolution, Azorín Ceramic Factory, Camagüey, 1960 (Juan de las Cuevas Toraya, Restaura). B. Right: another experiment in Santiago de Cuba, 1960. (Juan de las Cuevas Toraya, Restaura) .................................................................................................................................................................................................................................................................................................................................................................................. 43
Figure 28 Juan Campos, Cabañas in Santa Lucía, Camagüey, 1960 (Juan de las Cuevas Toraya, Restaura). ................................................................. 43
Figure 29 Office building in the back of the Ministry of Construction, 1960 (Juan de las Cuevas Toraya, Restaura). ......................................................... 46
Figure 30 MICONS, Publications of the Department for Technical Investigation, 1960-1965 (Authors photo). .......................................................... 46
Figure 31 Tile-vault different training styles, top: training in the school of arts (Photo courtesy: Roberto Gottardi), and bottom: training in the courtyard of MICON, 1961 (Juan de las Cuevas Toraya, Restaura). ................................................................. 48
Figure 32 Tile-vault: symmetrical and asymmetrical load tests, 1961 (Juan de las Cuevas Toraya, Restaura). ................................................................. 48
Figure 33 From single to double curvature by adding a formwork on the sides, interpreted from the guide of building vaults in Ceramica Convencional. ......................................................................................................................................... 50
Figure 34: MICONS, drawings of some of the vaults realised in the Courtyard (Ceramica Convencional 1965). ................................................................. 50
Figure 35: MICONS, photos of vaults realized in the Courtyard (Ceramica Convencional 1965 and Restaura). ................................................................. 52
Figure 36: MICONS, all unreinforced tile- and brick vaults that were built in the courtyard. .................................................................................................. 53
Figure 37: Table for Parabolic vaults, note the table of spans, thickness, and the details of layers and stiffening arches (Ceramica Convencional, 1965). ............................................................................................................................................... 54
Figure 38: Table for Tile-vault formwork, bracing, and details based on span (Ceramica Convencional, 1965). ................................................................. 55
Figure 39 Verifying the implementation of formwork standardization. (Authors’ drawing over an image from Restaura). ................................................................. 57
Figure 40 Left: Ricardo Porro, School of Modern Dance, Havana 1961-1964 (Paolo Gasparini. Courtesy of John A. Loomis). Right: Jardinera test model in the courtyard of MICON (Author’s drawing) ........................................................................................................ 57
Figure 41 Juan Campos, housing experiments in Altahabana, Havana, 1961 (Photos from Viviendas Urbanans 1964). .......................................................................................................................................................... 60
Figure 42: Various architects, vaulted housing, Havana, 1961-1965 (Juan de las Cuevas Toraya, Restaura) ................................................................. 61
Figure 43: Various architects, vaulted Schools in Cuba 1961-1965 (Drawing from Arquitectura Cuba (334) 1965, pictures from Juan de las Cuevas Toraya, Restaura) .......................................................................................................................................................... 63
Figure 44 Josefina Rebellón, pre-University Centre, Ciudad Libertad, Havana.1961-1962 (Drawings from Restaura, images from Arquitectura Cuba (334) 1965). .............................................................................................................................................. 64
Figure 45 Unknown architects, vaulted recreational buildings in Cuba, 1961-1965 (Restaura) ........................................................................................................ 66
Figure 46 Map of Havana with Vaulted Projects. .......................................................................................................................................................... 70
Figure 47 Genealogy of vaults in Cuba after the Revolution 1960-1965 (Author’s drawing). ......................................................................................... 71
Figure 48 Late 80s experiments with vaults in Syria. Source: (Mousally 1988) ............................................................................................................. 75
Figure 49 Mouhanna Brothers vaulted system. (Archive of Ziad Mouhanna). .......................................................................................................................... 76
Figure 50 Qura Al Asad urban development ........................................................................................................................................................... 79
Figure 51 Damascus Expo 1981 (Archive of Maen Abaza). ............................................................................................................................................ 80
Figure 52 Milihouse Experimental Stone Building in Adra. The size of stone units is 400,200,200 mm for walls and 400,100,100 mm for vaults. (Al Hasan and Al Salti 1983) .......................................................................................................................... 81
Figure 53 The first vaulted houses in Al Sharqyat (Mousally 1988). ............................................................................................................................................ 81
Figure 54 Vaulted houses prototypes in Al Sharqyat. ................................................................................................................................................... 83
Figure 55 Prototype 1990: Simplifications and residents’ interventions. ............................................................................................................................. 84
Figure 56 Houses in Al Sharqyat today ........................................................................................................................................................................... 85
Figure 57 Genealogy of Milihouse Vaults timeline in Milihouse projects ......................................................................................................................... 86
Figure 58 Phases in state-led construction policies from material supply to building performance ........................................................................ 90
Context of training in terms of domain, practice, and community. ................................................................. 100
Figure 64 Context and modes of training. Left: top-down training for tasks. Right: Bottom-up training for values. 100
Figure 65 Making and Drawing with Builders, Rwanda. .................................................................................. 103
Figure 66 Mapping Training Space, Rwanda. .................................................................................................. 103
Figure 67 Development of Materials and structures in Rwanda by trainees. ................................................. 103
Figure 68 Rwanda Cricket Stadium, Kigali, Rwanda. (Light Earth Designs 2019). ........................................... 105
Figure 69 RCS Training 01 Joining Two Tiles. ............................................................................................... 108
Figure 70 RCS Training 02 Building Small Vaults. ........................................................................................ 108
Figure 71 RCS Building the Edge Arches. ...................................................................................................... 109
Figure 72 RCS Construction of Vaults. ......................................................................................................... 109
Figure 73 Spaces and organisation of training and construction of RCS. Both in the training and the construction, the trainer is at the centre of the space with training working around him or looking at him while demonstrating the work. ......................................................................................................................... 110
Figure 74 Positive development of training in RCS from tasks with strong classifications and framing (left) to values with weak framing (right). The development was noted by self-organisation and a better understanding of vault’s design among builders .............................................................................................................................. 112
Figure 75 Azraq School for Refugees. (EAHR 2018) .................................................................................... 116
Figure 76 Training 01 Building Small Barrel Vaults. ..................................................................................... 118
Figure 77 Training 2 Building Mock-ups for Project’s Vaults. ..................................................................... 118
Figure 78 Building Small Barrel Vault. ......................................................................................................... 119
Figure 79 Construction of the Dome. (2018 EARH). ..................................................................................... 119
Figure 80 Spaces and organisation of training and construction of the Azraq school for refugees in Jordan. No boundaries of clear structure can be noted (especially in phase 2). No trainers were in the space during full-scale construction. ......................................................................................................................... 121
Figure 81 Negative development of training in the Azraq school from (value) of a craft training with weak framing to (task) training in full-scale construction with strong framing ................................................................. 123
Figure 82 Santa Pola Pavilion Cultural Centre, 2019. .................................................................................. 126
Figure 83 Training making the Foundation and Formwork of the Pavilion. .................................................. 128
Figure 84 Construction of the Pavilion ......................................................................................................... 128
Figure 85 Classes of Vaulting Geometries .................................................................................................. 129
Figure 86 Building the small vaults ............................................................................................................... 129
Figure 87 Spaces and Organisation of Training and Construction of the Pavilion in Santa Pola. .................. 131
Figure 88 The positive development of training in Santa Pola from “task” training to “value” training be developing a weak framing into a stronger one. The training starts with reflections and explorations and ends with applications of skills. ......................................................................................................................................................................................... 133
Figure 89 Drawing vaults with participants in thin-tile vaulting workshops ..................................................................................................................................................................................................................................... 136
Figure 90 Designbuild pedagogy with practised and expanded training .................................................................................................................................................................................................................................. 138
Figure 91 Training Model within Existing Business Models .......................................................................................................................................................................................................................................... 138
Figure 92 Training model in Construction Craft ......................................................................................................................................................................................................................................................... 138
Figure 93 Construction of thin-tile vault floor for Montessori School in Valencia. (Salvador Gomis 2019) ................................................................................................................................................................................................................................... 143
Figure 94 Tools and Machines for Cement Block production in Syria ........................................................................................................................................................................................................................ 147
Figure 95 Existing formal and informal flooring systems in Syria. Top: Solid and hollow blocks slab that are common in formal and informal construction. Down: Steel frames with corrugated metal or CMU systems found in informal construction for fast construction of ceilings ............................................................................................................................................................................................................................................................................. 148
Figure 96 Proposed Vault geometry ......................................................................................................................................................................................................................................................................................................... 149
Figure 97 Graphic Statics, calculations of the vault’s web and edge arches. The values shown are forces in kN. ....................................................................................................................................................................... 152
Figure 98 Final vault’s design. All dimensions are given in metres. ........................................................................................................................................................................................................................................................................................ 153
Figure 99 Tile’s testing and fabrication ............................................................................................................................................................................................................................................................................................................. 154
Figure 100 Vault’s construction ................................................................................................................................................................................................................................................................................................................. 154
Figure 101 Physical test set-up and equipment ............................................................................................................................................................................................................................................................................................. 155
Figure 102 Test prediction calculations with graphic statics. The load cd is found from the angle between a, transferred from the thrust line diagram to the force diagram. Loads units are in kN ................................................................................................................................................................................................................................. 155
Figure 103 Diagrammatical displacement study using Kangaroo 2. A hanging surface model with line load applied to the mesh in addition to its self-weight. The diagram helps in estimating possible hinges along the short span (perpendicular on the line load). ................................................................................................................................................................................................................................................................................................. 157
Figure 104 As-built top-surface geometry comparisons from three-dimensional scans .................................................................................................................................................................................................................................... 157
Figure 105 Cracks patterns and the corresponding line load .................................................................................................................................................................................................................................................................................. 158
Figure 106 plot of displacement against load showing the loading curve pre and post cracking ............................................................................................................................................................................................................................................. 158
Figure 107 Displacement LED sensors in the vaults after the formation of mechanism and the appearance of cracks. Left: vault 1. Right: vault 2. Bottom: a comparison of the displacement of the two vaults. Note vault 1 displacements incorporates the y-direction in comparison with vault 2 whose displacement is almost only two dimensional. ......................................................................................................................................................................................................................................................................................................... 159
Figure 108 Thin-tile vaulting in comparison with other floor-systems. CMS: Corrugated metal sheets, SBS: Steel beam slab, HS: Hollow slab, SS: Solid slab ......................................................................................................................................................................................................................................................................................... 161
Figure 109. FR2 Interior. ...................................................................................................................................................................................................................................................................................................................................................... 165
Figure 110. Left: digital model, centre: positive computer numerical control (CNC) mould, right: silicon mould and built vault ................................................................................................................................................................................................................................................................................................................................................. 165
Figure 111 FR2 Process of construction ............................................................................................................................................................................................................................................................................................................. 165
Figure 112 Fabricarte Design and Construction Concept (inverted) ............................................................................................................................................................................................................................................................................................. 166
Figure 113 Steel frame system ...................................................................................................................................................................................................................................................................................................................................................... 168
Figure 114 Construction and manufacturing strategy .............................................................................................................................................................................................................................................................................................................. 168
Figure 115 Structural design and analysis ............................................................................................................................................................................................................................................................................................................. 169
Figure 116 Mould design and assembly .............................................................................................................................................................................................................................................................................................................. 169
Figure 121 Design impact on cutting tiles: A) original horizontal coursing design with many tiles to be cut. B) Vertical coursing minimises the number of tiles and the number of cuts, C) Cutting edge with a radial saw after building full tiles also minimises the number of individual cuts

Figure 122 Left: E. Ramm et al. Typology optimisation by nonlinear finite element methods. Right: Block and Ochsendorf thrust network analysis for lower-bound analysis of masonry

Figure 123 Subdividing a vault. A1 to C1: Minimum cut maximum weight large few moulds. A2 to C2: Minimum cut medium weight small many moulds. A3 to C3: Minimum cut medium weight, small fewer moulds. A4 and B4: Minimum cuts, minimum weight, few small moulds. C4 Minimum cuts, minimum weight, few many moulds

Figure 124 Approximation of isosceles triangulation in relation to the rise to span ratio. Left: groin vault, Right: Sail vault

Figure 125 Three approaches to shallow thin-tile vaulting panelling. A. production approach: with the use of cranes and lifting systems. B. structural approach using digital fabrication methods. C. Constructional approach using panelling analysis to approximate identical and small panels assembled without cranes

Figure 126 Construction and manufacturing methods that mix precision and imprecision techniques

Figure 127 Prototype vault model and mould

Figure 128 Prototype of Fabricarte II. Top: Mould arrangement, tiles and produced elements. Bottom: the assembled system

Figure 129 Up: Elastica and Parabola behaviours, the divergence starts after the rise to span of the curve is more than 0.5. Down: Results from approximation by changing stiffness in relation to the height of the parabolic arch

Figure 130 Physical modelling of the bending parabola. Top left: Using the cutting along the strip. Down left: Adding laminas to a rectangular strip. Right: the cut strip tested to different heights

Figure 131 In-situ, vaults prototype by bamboo strips as guidework. 2016. Up: Building the vault by using engineered bamboo with changing thicknesses by adding laminas of bamboo. Down: The built structure

Figure 132 Two ways for a sail vault guidework. Left: individual elements, right: boundary

Figure 133 Exploring the resulted unrolled curve for a changing rise to span arches

Figure 134 The relationship between the arch and the unrolled curve of the arch. Above: heights variation for a vault’s arch with 10-meter span. Below: the relationship between the two heights in the same vault

Figure 135 Physical verification of the unrolling method. For the tested thickness, the correlation between the arch and the unrolled curve starts to be affected after a rise to span ratio of 0.5 as the strips starts to become an elastica

Figure 136 Relationship between the thickness variation and the rise to span ratio of a parabolic curve

Figure 137 Thicknesses variation and for targeted curve. A: rise to span 0.1-0.3. B: rise to span 0.2-0.4. C: rise to span 0.3-0.5. D rise to span 0.4-0.5. E: rise to span 0.5-0.7

Figure 138 Thickness variation controlling parameter

Figure 139 Guidewok options for the web of the vault

Figure 140 Diagonal section and unrolled arch variations
Figure 141 The relationship between the arch and the diagonal curve height. Above: heights variation for a vault’s arch with 10-meter span. Below: the relationship between the two ratios.................................................................193
Figure 142 curved connection guidework..............................................................................................................................................................................................194
Figure 143 Curved connection physical modelling and testing.................................................................................................................................194
Figure 144 Modular vaults guidework..............................................................................................................................................................................................194
Figure 145 Exploration of bending-active plates for shell structures.............................................................................................................................................198
Figure 146 Bending active grid shell with variations of sections through adding laminas along the individual members..............................................................................................................................................................................................199
Figure 147 Flexible formwork over bending active plate for concrete casting. Making the mould .................................................................200
Figure 148 Floor system from flatpack sheets from drawing to casting.................................................................................................................................201
Figure 149 Floor-system from flatpack sheet, a possible application in self-built areas in Damascus..............................................................................................................................................................................................201
Figure 150 Three vaulting aspects. Top: Rubble-stabilised tiles. Middle: Concrete ribs vault. Bottom: Bending active-flexible formwork ..............................................................................................................................................................................................203
Figure 151 Diagram of approaches to thin-tile vaulting: Policy, Labour, and Design. The Nonagon shows the range of aspects related to each approach. The internal space of the diagram shows the methods associated with each zone of exploration..............................................................................................................................................................................................214
Figure 152 Approaches of thin-tile vaults across all case studies in the research.................................................................................................................................214
List of Tables

Table 1 Summery of Thin-tile transfer and revivals with conditions of rising and reasons for disappearing.................. 27
Table 2 Summary Vaults in Cuba and Syria.................................................................................................................................. 89
Table 3 Vaults in Cuba and Syria in Comparison with traditional vaults in Spain................................................................. 89
Table 4 Theoretical Framework: Content and Context List for Analysis.................................................................................. 99
Table 5 Methodological framework: Observations and techniques..........................................................................................102
Table 6 Minimum and Maximum loads for the vaulted floor system........................................................................................150
Table 7 Floor system Comparison..............................................................................................................................................160
Table 8 Construction methods of thin-tile vault panels..............................................................................................................181
Table 9 Overall comparison of the design approach in the three projects in this chapter.......................................................204
Table 10 Summary of Examined vaulted projects ....................................................................................................................209
Chapter 1
Introduction

Thin-tile Vaulting: Limitations and Opportunities
Approaching thin-tile vaulting as a craft integrated into construction poses several questions on the relationship between the two. Historically associated with discourses on identity and authenticity, vernacular building practices have been treated as objects for historical preservation and, sometimes, as a nostalgic image of a pre-industrial building. This leads to the question of how to elucidate the role of these situated building practices within the dynamicity of today’s construction advances. While the following research will embark on answering this question, this chapter will set the theoretical and methodological framework of the research.

The chapter will first shift the discourse on vernacular building from considering them as objects of identity to processes dealing with the site and material limitations. This shift to overcoming scarcity suggests an inevitable engagement with the knowledge associated with these practices; the dialogue between designers and master-builders can be fertile soil for technology to help sustain and develop vernacular building. Therefore, the chapter provides definitions for both ‘scarcity and ‘vernacular’ and shows how the building craft sits at the intersection between the two.

Finally, the chapter gives a review of the history and scholarship on thin-tile vaulting. Based on the review, the chapter outlines a theoretical framework of the research based on three approaches to thin-tile construction. The first is ingrained in state policies, the second is visible in maintaining the knowledge of building within programmes of training, and the third is the use of design and analysis tools to develop vaulting in construction. To study these three approaches, the chapter outlines a methodological framework that intersects archival and ethnographic research with design projects.
1.1 Background: from Objects to Processes

As with many of my peers studying architecture in the Middle East, I have always been confronted with the duality of ‘modernity’ and ‘tradition’. During my undergraduate studies, and by the time we were taught how to draw and calculate a concrete slab, we were also instructed to research Hassan Fathy, the renowned Egyptian architect of mud villages and Nubian vaults, and to learn from him how to preserve the identity of architecture in our region. When we raised the question about why one would both build with concrete and look into Fathy’s work, the typical answer would be: ‘for us to remember our past but still work for our modern times.’ Materials in construction are automatically classified into one of the two extremes in this binary, earth is understood as the material of identity and cement as the material of modernity. Societal and geographic properties of materials are also embedded in this duality: earth is useful for isolated countryside and cement for the crowded cities.

This discourse of conserving identity and designing modernity collapsed when I read the first chapter of Fathy’s book “Architecture for the Poor” titled “Paradise Lost: The Countryside”. In addition to using an explicit utopian term “paradise”, Fathy mentioned two pictures from his childhood that were “…combined in my imagination to produce a picture of the countryside as a paradise” (Fathy 2010, 1). For Fathy, the countryside, and the materials associated with it, are more of a field of ‘imagination’ than a practice of preservation. Fathy designed an identity.

Therefore, to understand the practice of using old and new materials, a shift beyond the binary of identity and modernity must occur. Only then can the classification of centres versus margins reveals more than the precipitous distinction between identity and modernity. Another rooted distinction became apparent, the one between ‘abundance’ and ‘scarcity’. When resources around the world appear infinitely available to serve urban centres, the margins will have to rely on the human and material resources in each locale. The notion of limitation is ingrained in local practices, lying dormant in site-specific and vernacular knowledge until a crisis hits and makes it visible and transferable. Later in his book, Fathy found his opportunity to construct the countryside he imagined when cement and steel were scarce in Egypt. During World War II, earth bricks and Nubian domes, both Egyptian vernacular techniques, were his answer to this scarcity (Fathy 2010, 5). But Fathy’s work was impossible without a partnership with builders’ know how to build with earth. In fact, Fathy’s first vaults collapsed, and he had to travel to Nuba to see how they build their vaults there (Fathy 2010, 5–6). The return to the material was also a return to the inseparable knowledge associated with this material.

In a broader geographic approach, the separation between materials and builders becomes a much broader problem embedded in the relationship between ‘developed’ or ‘developing’ contexts. Design in the developing context capitalises on the laborious, artisanal, and locally resourced building skills that are upraised, assumed, and sometimes even imagined by designers. The same circumstances of Fathy during World War II made Le Corbusier suggest the use of local materials and resources for the construction of the vaulted Peyrissac House in Cherchel in Algeria in 1941 (Figure 1). He was not alone in picturing Algerian houses as vaulted ones. In 1940, Marcel Lathuilliére built a five-unit housing project, Cite El-Djenan, with five identical parabolic vaults, and Jean-Pierre Emery and Louis Miquel also built a few vaulted houses in Algiers (Figure 1, Figure 2, Figure 4). Ten years later, Roland Simounet designed Dejnan-el-Hassan, a large complex of 210 units of vaulted apartments that sat on a large hill in Hussein Dey (Celik 1997, 165) (Figure 3). In a study about his project, Cite El-Djenan, Lathuilliére suggested that vaulted houses could answer the increasing demand for houses in Algeria (Lathuilliére 1945).
Figure 1. Le Corbusier: Résidence Peyrissac, 1941, sketch. (Boesiger 2015, 117).

Figure 2. Marcel Lathuilliere: Cite el Djenan Arch, 1941. (Lathuilliere 1945, 32).

Figure 3. Roland Simounet, Djenan-al-Hassan, Algiers, 1956-1958. (Architectes d’Algérie Pendant La Période Française 2017).

Figure 4. P. A. Emery and L. Miquel: Maison a Algiers, 1940s. (Architectes d’Algérie Pendant La Période Française 2017).
Like Fathy, Le Corbusier uses barrel vaults, which he considered a “discovery of ... harmony between the countryside, the climate and tradition” (Figure 1). He asserted, with enthusiasm, that vaults should be built with ‘native labour’ (Naranjo 2015; Boesiger 2015, 117). The Peyrissac house was never built (Naranjo 2015; E. L. García 2015). While the reasons are not clear, it can be inferred that Le Corbusier assumption of the existence of local builders to make the vaults and stone wall in Cherchel were rushed. In the 1950s, Le Corbusier would have to face a similar dilemma, this time in Sarahbi house in India. The house is assumed to have been built with thin-tile vaulting technique. However, a recent study by Aftab Jalia reveals that the lack of vaulting knowledge among the team of builders and the selection of heavier tiles than the traditional ones hindered the construction of the vault (Jalia 2017, 80–90). After failing preliminary attempts, the builders cast a concrete shell and clad it with tiles. While presented as a solution for material limitation in these examples, vaults as native or imported vernacular practices encountered another type of limitation: skill.

The cases of Fathy and Le Corbusier are not isolated anecdotes. History of construction abounds with examples of economic recessions or wars triggering adaptability and local knowledge transfer in the architectural discourse. If economic difficulties—whether temporal such as post-war recessions or locational such as inaccessibility and extreme climate conditions—have a clear association with local construction practices, designing with these practices is not as straightforward. On the one hand, local practices entail responsive and accumulated knowledge tied to a specific region. On the other hand, contemporary design practices are inherently disruptive and abstracted in building codes for the precise production of a preconceived object. How can a local practice of construction craft be included in a design process?

While embarking on answering this question, this research focuses on thin-tile vaulting as a medium to understand the relationship between craft and design. Thin-tile vaulting is a Mediterranean technique that requires minimal formwork in its construction—a more elaborate definition will be made in the next section. There are four main reasons to select this exact technique in depicting the relationship between design and craft. First, thin-tile vaulting makes structural components in buildings, ceilings, and thus entails many design aspects being structural, constructional, and aesthetic (Collins 1968, 1). Second, thin-tile vaulting has historically been a subject of exchange between different geographies and cultures; it offers a unique opportunity to examine how it is manifested in various contexts (Huerta 2017). Third, thin-tile vaulting relies on the knowledge of building to minimise the use of the materials, offering yet another opportunity to see how it is intertwined with solutions in contexts of limitations. Finally, thin-tile vaulting is emerging in contemporary architecture as a viable solution for sustainable and socially aware construction, recent projects have had a great impact on the recognition of its versatility as an efficient solution in different economic and cultural contexts (López, Mele, and Block 2016).

The studies of thin-tile vaulting today are still growing. In historical studies, new cases are now being found of its use outside its Mediterranean origin. In structural studies, thin-tile vaults, and load-bearing shells in general, are supplemented with new intuitive and interactive methods of form-finding and structural analysis. The ubiquity of design tools for structural shells is increasingly encouraging revisiting the crafts associated with shell’s construction. New thin-tile projects are now being built worldwide, but mostly in areas with limited financial resources. The association of thin-tile vaulting with local tradition and craft is challenged by its omnipresence in different geographies and across different design approaches.
Thin-tile vaulting bears multiple facets as a building material and a cultural artefact, as a manual skill and an industry, and as an expressive structure and a utilitarian building component. Addressing these facets requires widening the understanding of design and craft to engage with both critically. Moving towards a holistic understanding of designing and building thin-tile vaulting, this research explores: 1) the relationship between thin-tile vaulting as a building craft and today's construction, 2) the challenges and limitations of using thin-tile vault in design, 3) solutions on how the design of thin-tile shells itself can be craft-inclusive.

With current escalating climate challenges, addressing material limitations in construction has never been more urgent. The current methods of shaping the built environment around us are extractive and need to be rethought. Construction is one of the leading industries to consume materials such as sand and stones and energy to process them into building materials such as concrete. As a result, the industry produces 40% of the CO2 emissions around the world and enough waste to make it to the top of the list, and architects in the UK, and many other countries, are declaring climate emergency status reaching out for changing how the industry works via a new partnership between the technology and clientele of building industry (“UK Architects Declare Climate and Biodiversity Emergency” n.d.).

Acknowledgement of the fact that construction is one of the most environmentally destructive activities in society has fuelled increasing questioning of the way we build. Two strands of critique have emerged. The first seeks to introduce digital tools, intelligent applications and data-driven planning to optimise, recycle, reuse, or redistribute materials and resources. The second emphasises the role of situated knowledge, sometimes called ‘indigenous’, ‘vernacular’, or ‘traditional’, in the protection and development of ecology and the built environment. However, little has been said about the relationship between the two, how to use situated knowledge in contemporary construction. The research goal is to expand the ‘we’ in the impetus ‘changing the way we build’ to be more inclusive to hierarchies, actors, and modes than those illustrated and indeed assumed by more formal, conventional design processes. While anchored around thin-tile vaulting, the research expands on how the dialogue between local construction techniques and design can contribute to the urgent and pressing environmental challenges of our day.

Therefore, this project hypothesises the use of ‘analysis’ technology to optimise ‘fabrication’ technology. While tools of simulations and computational modelling can be used for panelling, standardisation, and approximation of material behaviour, on-site making will remain driven by artisans and builders’ usual tools. As a result, it is usually the geometrical properties of vaults that will be examined. The research will focus on how thin-tile shells’ geometrical properties or their formwork and guidework can facilitate their construction under the limitation of material, time, or skill. This proposition aligns with the increasing interests towards non-centralised construction with enough autonomy to be carried out without the conventional process of designing, detailing, and building. But instead of addressing autonomous building through the total use of robotics, the research shifts the focus to use computational methods to augment traditional craftsmanship capacity. Finally, this research’s original defining question was: how to use thin-tile vaulting in the post-war reconstruction in Syria? This question remains a primary driver of the research. Nevertheless, while the work progressed in literature and construction, the question about building limitations and the use of thin-tile vaulting repeatedly appeared in almost every historical cases and descriptions of ongoing project alike. This demanded a widening of the research to find design approaches for Syria and elsewhere. While keeping example associated with Syria within the research, it expands beyond one case to include learnings from Cuba, Spain, and Rwanda.
1.2 Setting the scene: On vernacular construction and scarcity

1.2.1 Vernacular Construction

With industrial advances, a regionalist approach to geography, art, and literature on the built environment surfaced in Spain, Germany, and France after 1890 and until the second world war (Storm 2003, 254). Paralleling nationalism, regionalism looked for the ‘soul’ of the region, its identity, costumes, and traditions. In architecture, it was manifested within movements such as Noucentisme in Catalonia and the Regional Movement in France, reproducing or interpreting local construction and materials in an industrialised world (Falgàs 2009, 280).

After the second world war, Modernism set the scene for an architecture of the global and supranational world. It was until the 1960s that theories about centres and peripheries triggered thoughts not only about regionalism but also about architecture outside the sphere of modernism with pioneering writings about possible architecture outside modernism from architects such as Sigfried Giedion (1954) and Pietro Belluschi (1955).

When post-modernism was looking for a historical or innate meaning in architecture and forms of building, another movement of acknowledging “authorless” buildings as valid architecture started to take place in discussions about the built environment, resembled in the influential exhibition of Bernard Rudofsky (1964) titled provocatively “Architecture without Architects”. Rudofsky coined the term vernacular architecture, but the work of Paul Oliver and Amos Rapoport on building practices and their relation to culture and society led to establishing the field. Vernacular in its basic forms reflects on the Latin work *vernaculus*, native, which incorporates’ buildings [that] tell what is indigenous, common and shared in a community or region” (Simon J. 2006, 23). This definition implies several complex elements in relation to meanings and fates of traditions, modernity, and authenticity, requiring a dynamic and critical understanding of what is vernacular and the way it relates to tradition. Hence, in the 1980s, Critical Regionalism emerged to stand against the “single world civilisation”, that is, in Kenneth Frampton’s words “; wearing away at the expenses of the cultural resources” (K. Frampton 1983, 16). Critical regionalism was more interested in the interpretation of the vernacular than the mere copying of its structural and architectural language.

Studies such as those of Rudofsky (Rudofsky 1964), Amos Rapoport (Rapoport 1969), and Paul Oliver (Oliver 1997) encompass documenting typologies of the vernacular building. Rudofsky places the vernacular building in the “without architect” discourse it is an architecture before “… architecture became an expert’s art”. He notes that many new technologies in today’s architecture are “old hat” in the vernacular. While the former gives people commodity, the second provides peace and harmony. Rapoport contrasts vernacular building to monumental buildings, where designers want to compose an image of impression. Unlike monumental construction, what Rapoport calls the folk tradition of building is a translation of the culture and need of people (Rapoport 1969, 2).

Oliver, in his encyclopaedia of vernacular architecture, makes a more extended definition. He specifies it as dwellings and other buildings “Related to their environmental contexts and available resources, they are customarily owner- or community-built, utilising traditional technologies “ (Oliver 1997, II). Oliver looked at the vernacular, which constitutes ninety per cent of the world’s housing stock, not as an obstacle in the way of progress but neither as the solution for modern urbanisation problems. Instead, he proposed learning from vernacular solutions and support vernacular builders (Oliver 2003, 15).

In the mentioned definitions, the vernacular is defined not by what it is but by what it is not— it is not monumental, designed by an author, or build uses modern technologies. The growing body of research on the vernacular building has expanded these definitions towards a more dynamic understanding of the vernacular
as evolving practices (Asquith and Vellinga 2006, 3). Propositions are made for a critical examination of the current methods of self-built and traditional architecture. Marcel Vellinga challenges the conventional “narrative of loss and decline” that only offers calls for preservations and embraces the dynamic, emerging, and changing pattern of the vernacular (Asquith and Vellinga 2006, 91). In general, studies on vernacular architecture have been developing to accommodate more purposes of its use for today's environmental and cultural goals.

The vernacular building has also been present in studies on design. Abstracting vernacular building for learning has been a subject of study since Christopher Alexander wrote his books “A Pattern Language” and “the Timeless Way of Building” in 1977 (Alexander et al. 1977). Alexander extracted urban and architecture solutions from a ‘timeless’ method that is ‘precise but cannot be used mechanically’. Such an approach parallels what the term tectonic offers in architectural criticism. Karl Bötticher’s defines the tectonic as unifying the structural and the representational in an artistic object (Hartoonian 1997, 2). In Kenneth Frampton’s words, the tectonic is “the focus on architecture as a constructional craft” (Frampton 2001, 3). The resemblance of this craft exists where materials join. For Frampton, the joint is crucial for it tells the logic of a construction (Andersson and Kirkegaard 2006, 30).

But if meanings and uses of vernacular ‘forms’ are thoroughly studied in Alexander’s patterns and Frampton’s analysis of modernist architects, meanings and uses of ‘techniques’ are still yet to be explored. In most recent studies about the vernacular, be it historical or theoretical, the object’s presence as a medium is overwhelmingly dominant. Whether it is the joint’s detail in a project of Carlos Scarpa or the spatial articulation of a shopfront in Alexander’s book, it is always the object that encapsulates and visualises the process. Similarly, the learnings from vernacular construction transmitted not from builders but from buildings, which are usually described as being self- or community-built. A shift must be made from studying the constructed building to studying the construction site to understand the process and the object.

Therefore, the proposed research focuses on tools, material, and construction techniques and not only on products. It defines the vernacular as:

the evolving body of situated knowledge, tools, and values that operates within a specific, mostly local, set of resources in the production of the built environment.

1.2.2 Scarcity

In economy, scarcity is understood through three elements and the relationships between them: supply, demand, and system of allocation (Goodbun, Till, and lossifova 2012, 9). In its basic form of definition, scarcity is the gap between demand and supply due to shortages in resources or poorly managed resources (Pettinger n.d.). Political economics and social sciences suggest that scarcity also entails a constructed principle of a socio-economic system that results in social and material inequality (Goodbun, Till, and lossifova 2012, 9).

Environmental studies push scarcity beyond the Malthusian linear relationship between resources and consumption (Goodbun, Till, and lossifova 2012, 10, Goodbun et al. 2014, 38). Instead, and while it relies heavily on the notion of materials, scarcity in environmental studies unfolds as social practices that dwell in culture and nature (Goldern and Proksh 2013). For example, the first colonisers in Australia saw few resources, while it was a place of abundance for its aborigines (Sahlins 2017, 5). Therefore, most environmental studies consider the escalating dilemmas of resources versus demand an inherent property in capitalism’s nature as an economic mechanism that is forever growing (Goodbun, Till, and lossifova 2012; Goodbun et al. 2014; Soper 2012). Two approaches are made within this claim: the first is reformist and relies on shifting scarcities by finding new margins, using creativity and innovation to decentralise the market from the giant capitalist players. The other
approach is more suspicious about the system altogether and calls for uprooting it through new formations of societies (Goodbun and Jaschke 2012). A similar pattern can be noted in approaching technological advances in construction. One perspective sees possible new solutions in the advancing technologies. Another approach looks for solutions by looking at societies before industrialisation (Goodbun and Jaschke 2012; Goodbun 2012).

Design studies addressing scarcity echo these two approaches. The reformist approach suggests that designers can either modify current systems or find new production systems with fewer, durable, or easily recycled materials. A clear example of these studies is the cradle to cradle approach by Michael Braungart and William McDonough (McDonough and Braungart 2010). In contrast, the abolitionist approach suggests that designers should engage with the immaterial dimensions of design beyond mere controlling parameters and to understand scarcity socially and culturally to resist design practices within capitalism (Goodbun et al. 2014).

In a continuum between these two approaches, we can note three tasks for architects and designers to embark on towards a scarcity-aware practice:

1- It is crucial to reconsider the clientele of architecture and expand it beyond the architect’s centralised figure— to relinquish the remnant of the idea that architecture is only a form of art. Similarly, the profession should raise questions in the circles of political and economic studies (Goodbun, Till, and Iossifova 2012, 10).

2- The practice of architecture should look for a new ‘aesthetic’ ingrained in ecology. This new ecological aesthetic aims to visualise the complex relationships between nature and culture (Goodbun 2012). Architects and inhabitants should understand the material dimensions of their design and its impact on resources (Goodbun and Jaschke 2012). Therefore, there is an urgent need for enhancing the visibility of the construction, which is currently obscured by its inherent complexities engendered in the nature of engineering (Goodbun, Till, and Iossifova 2012; Hartman 2012). To achieve this goal, designers and builders can enhance the accessibility to building knowledge by demystifying the complexity of construction and planning and extracting new learnings for future applications.

3- Design should adopt decentralised and error-friendly systems that can tolerate one of its components’ failure without compromising the overall system. Error-friendliness modality overcomes the necessity to foresee every possible error by proposing micro solutions’ decentralisation and diversifications. The error in this sense not only allows relying on local alternative functions but also pushes the failed function threshold to evolve (Manzini 2012, 60).

From the three previous schemes designing with scarcity in the field of the environmental design can be defined as:

The empathetic and explanatory movement between products and producers within a system of opportunities and limitations in the material and immaterial resources.


1.2.3 Craft: Scarcity through Vernacular Practices

The relationship between resources managements and vernacular practices in construction and architecture is always brought as an example of balance and harmony. But while this feature in the vernacular building is acknowledged, it has not been through much analysis yet. Studying the building’s craft offers a critical examination of how vernacular methods save materials and deal with scarcity within variable and nonlinear processes.

In specific, if scarcity drives us to design for error-friendly and visually accessible systems, the vernacular building can be helpful as those are its preconditions. Craft is a zone where the two become alive. Knowledge and practice in craft are not separable, and both rely heavily on the site conditions and limitations and sometimes on the improvisation of the builder to solve emerging problems on the move. This exhibit similarity to the needed flexibilities in systems to convert significant catastrophic failures into minor tolerated errors. Also, in contrast to conventional construction today, an artisan in action is almost a performance. The accessibility to see how a building is happening encourages its transparency.

Today’s construction operations are always hidden. Although for safety and pollution, the hoarding around under-construction sites is a metaphor for the opaque relationship between the city and the resources that shape the city. It resembles a separation between building as a verb and building as a noun; while the latter is a public concern, the former seems obscured and uninterestingly necessary. Building craft in vernacular construction offers a designer-maker-user unification where environmental values can be quickly adopted. Construction craft methods might be associated with secrets and tricks. But this is not always the case; the materials in use and the making of the building are usually more visible, comprehensible and enjoyable than in conventional construction process.

1.3 Thin thin-tile vaulting

1.3.1 Definition

Tile vaulting has various definitions based on origin, techniques, tools, and materials. In contrast to brick vaulting, the distinctive features of thin-tile vaulting are the use of fast-setting mortar and the planar positioning of the tiles in the soffit layer (Figure 5) (M. H. Ramage 2007, 49). Many definitions claim that thin-tile vaulting is a formwork-free construction that needs only geometric control (Mochi 2001, 113; Gulli 2001a, 59). Other explanations elaborate on the use of falsework as “various gridwork or cintreles... used to control the shape of the vault, in particular when it acquires certain dimensions or a careful execution is desired” (Huerta 2001a, 87).

Defining thin-tile vaulting solely as vaulting without formwork is not precise since there are other formwork-free vaults, such as the pitched brick barrel vault, also known as the Nubian vault, and the squinch vault from Mesopotamia (Huerta 2017). Although built without formwork, pitched brick vaults are different from thin-tile vaulting, as they use no fast-setting mortar and rely instead on the catenary section of the vault and the inclination of the mud-brick in the coursing to sustain the brick in place with minimum friction resistance of the mortar (Wendland 2007). Usually named as a precedent to thin-tile vaulting, the technique has spread along the Middle East and North Africa to Spain and Central Europe. In Iran, the vaults are still used in several regions where mud-brick are the primary construction material (Wendland 2007; Besenval 1984). In Egypt, where the technique is associated with Hasan Fathy’s work, vaults are also still vernacularly practised in the Nuba region, where Fathy brought his master builders, and recently in many other areas in Egypt for villas and touristic residencies. When
the technique has passed to Spain with the Arab occupation of the Iberian Peninsula, it pertained as a Spanish vaulting technique of vaults known as bóvedas por hojas and, possibly, extended from there to the construction of vaults of Central Europe (Wendland 2007, Lassaux 1831). Today, variations of these vaults are abundant in Latin and South American vernacular construction, known as ‘Ladrillo Recargado’ (Ramírez Ponce and Ramírez Melendez 2004). Another formwork-free vault construction is the one that uses terracotta tubes, which flourished for their use as formwork for Roman concrete vault and explored in detail by Stroz (Storz 1994, Huerta 2017), and Lancaster (Lancaster 2015). The technique uses cylindrical tubes as units that are joined with plaster. In his referral to this technique, Santiago Huerta suggests that it forms a necessary step to the appearance of thin-tile vaulting for its use of plaster as a fast setting mortar (Huerta 2017, 761). A recent study about these Ceramic fuses by Aftab Jalia explores this system’s use in the 20th century as a patent industry that was transferred to India (Jalia 2017, 97–145).

Tile vaulting relies heavily on the mortar’s property to bond the lightweight elements of tiles, sometimes hollowed to reduce the weight. To build a thin tile vault, one needs tiles, fast-setting mortar, plaster of Paris, or limestone mortar, known as rapid cement. After laying the tiles and bonding them with the fast-setting mortar to make the soffit, more layers, ribs, or concrete fill need to be added with ordinary mortar. One also needs skill, which is relatively easy to teach and learn, though it is refined over a lifetime of work. The skill to work with mortar and position the tile in the right place and at the correct angle is a precondition of a well-executed vault with minimum formwork. Therefore, the skill in constructing the thin-tile vaulting is more related to the knowledge of the various typologies and geometries of shells than the technique of placing the tiles itself.

Therefore, the common definition of thin tile construction has a hidden conditional clause: thin thin-tile vaulting, if built with skill, requires little or no formwork. There is a reciprocal relationship between formwork and skill and between labour and tools. These variables suggest many scenarios of building the same vault based on priorities of speed, scale, materials, and aesthetics. A thin tile vault could be built with relatively moderate skill if the formwork is extensive, the scale is small, or the visual quality is not a priority. This is a standard case in many workshops that teach the technique to novice builders. However, large-scale vaults, with precise coursing or speed construction, need good builders to eliminate formwork. Tile vaulting is a context-related construction; it is not a mere product but also a craft and skill. It can be both modest or expressive, low-cost or high-cost, built by skilled or unskilled labour.

1.3.2 History

Tracing the origins and history of thin-tile vaulting is not the aim of this study. But reviewing the history of thin-tile vaulting reveals two important aspects: its capacity for including different construction styles and its history of knowledge exchange and transfer. This review examines the application of the thin-tile vaulting technique in modern construction through the lens of scarcity and learning from its history.

Mediterranean Exchange: Different Cultural References

There is no firm evidence of where and how this technique was born. Some suggestions link it to a long development of Mesopotamian vaults with mud tiles and plaster, relying on some archaeological remnants in Spain, and comparison to vaults in Iraq, Iran, and Syria (Fortea Luna 2009, 496). A specific example is a vaulted stair with mud tile in the once Moorish city’s ruins in Syassa, Spain (Figure 6) (Almagro 2001). Other suggestions link the technique to the Roman concrete vault that uses stone as the permanent formwork (Massó 1965, Bassegoda Musté and Bassegoda Nonell 1947, Truño i Rusiñol et al. 2004). This interpretation juxtaposes Roman
Thin-tile Vaulting: Limitations and Opportunities

vaults from buildings, or drawings of buildings (such as those of Choisy and Le Duc), with drawings of tile vaults, suggesting the two techniques share a common element: the flat stones or bricks that make the soffit (Figure 7). There are no records yet about the dynamics that drove Roman and Mesopotamian vaulting to develop into today’s terracotta tile shells. The oldest official document about thin-tile vaulting is a letter from the King of Aragon in 1382, describing Valencian builders with fast and thin vaults (Ochsendorf 2010). This uncertainty has resulted in thin-tile vaulting described as a ‘Mediterranean technique’ (Huerta 2001a; Ochsendorf 2010). Allocating it to such a large area suggests different building cultures. Building with tiles is historically seen in Spain, France, Italy, and North African countries (Collins 1968). The variety of regional versions demonstrates a vibrant circle of knowledge exchange. For example, the influence of thin-tile vaulting from Catalonia, known as Bóveda Catalana, is evident in France’s adjoining area, where the vault à la Roussillon flourished in the 18th century and was studied by Comte d’Expie in 1754 (Bassegoda Musté and Bassegoda Nonell 1947). When the vault was brought back to Catalonia in the 19th century, it was revived in industrial buildings, such as the Batlo Factory by Rafael Guastavino. It developed into the exceptional period of the Modernisme (Catalan Art Deco) that celebrated tile vaults in the architecture and writings of Guastavino, Gaudí, Martellin, Puig i Cadafalch, and Domènech i Montaner. Modernisme took thin-tile vaulting to new levels, constructively and structurally, and more expressive forms of vaulting emerged during this period (Figure 8) (Neumann 1999). Schools of architecture and construction also taught the craft with rigorous training (Bassegoda Musté and Bassegoda Nonell 1947).

After Modernisme, thin-tile vaulting again declined in Catalonia but prospered in Madrid and central Spain, thanks to Juan Bautista Lázaro (1849-1919), who brought Catalan builders to Madrid in the last decades of the 19th century (Mosteiro 2001). Those builders had an essential role throughout the Spanish post-war reconstruction (Figure 9) (Mosteiro 1996, 233).

In Italy, thin-tile vaulting is noted in the old treaty, Architettura Civile (1737), of Guarino Guarini (Bassegoda Musté and Bassegoda Nonell 1947, 13). La Volta en Foglia is a vernacular tradition in the central region and Sicily (Verga 2014; Collins 1968). Another association of the vault is made to Toscana region known as light vaults volte leggere (Huerta 2017, 768). In 1941, Carl Salter studied these planar Italian vaults and built some in Germany (Thunniseen 2012, 240).

In North Africa, thin-tile vaulting is referred to by the term Rhorfa, which is a French transliteration of the word ‘Ghorfa’ that means ‘room of any form’ in Arabic, and ‘vaulted room’ in Berber (Camps and Longerstay 2000, 3361, Larousse n.d.). During the French Mandate in Algeria, thin-tile vaulting was used in residential projects by architects such as Pierre-André Emery, Louis Miquel, and Ronald Simounet and Marcel Lathiuliere (Lathuiuliere 1945).

An Atlantic Exchange: Transfer and Innovation

During the European colonisation of the Americas, thin-tile vaulting spread from Spain to other territories, in some of which it perpetuated and became widespread (Figure 23). The earliest example that we know about is the Spanish missionary and master builder’s work Fray Domingo de Petre, who built vaults in Colombia between 1759 and 1811 (Ochsendorf 2010, 22). However, scholarship highlights two stories in the history of thin-tile vaulting in America: the first is the Guastavino Company, between 1889 and 1961 in the US, and the second is the National Art Schools in Cuba, in 1961.
Figure 5. Luis Moya: thin-tile vaulting definition sketch. (Moya Blanco 1947, 1219).

Figure 6. Syassa mud stairs. (Almagro 2001, 168).

Figure 7. Roman concrete vaults, according to Choisy. (Choisy 1873, 61).

Figure 8. Cesar Martinell 1921: Winery in Sant Cugat, an example of modernist architecture.

Figure 9. Luis Moya: Museum of America, Madrid, Vaults in post-civil-war construction.
Guastavino Company, 1889-1961

Rafael Guastavino Moreno was a Valencian master builder who immigrated to New York and founded a tile vault construction company. Having made some tile structures in his homelands, such as the Batlo Factory and Vilassar Theatre, Guastavino arrived in the US in 1881 (Tarragó, Collins, and Rosselló i Mir 2002; Collins 1968, 178). There, he continued his profession as a vault maker by proposing, through patenting and physical testing, his system as a reliable and fire-resistant solution (Figure 10). Guastavino became successful, and his company worked with leading American architects, such as McKim, Mead, and White and Cass Gilbert, building vaults for more than 1,000 projects across North America. Guastavino wrote about thin-tile vaulting, too, though wrongly considered it a monolithic structure (Rafael Guastavino 1893, Huerta 2001a, 92). Guastavino patented his vaults, making it harder for thin-tile vaulting to spread outside his company (Figure 10, Figure 11). After the surge of reinforced concrete and changes in formal taste, the work of the Guastavino Company declined, until its ultimate closure in 1961 (Collins 1968; Ochsendorf 2010, 186).

National Art Schools in Havana

In 1961, Fidel Castro envisioned Cuban schools of art that would revolutionise culture and education to represent the ‘real identity’ of the Cuban revolution as a national and universal message (Loomis 1999). Five schools of art were designed, by three architects: Ricardo Porro, Roberto Gottardi, and Vittorio Garatti. Materials were scarce, but the architects fortuitously encountered a tile vault builder from Spain called Gumersindo; they decided to build with tiles in what became an exceptional example of vaulted construction (Figure 12). According to current research on the Art Schools, training took place in the garden in front of the Ministry of Construction (Micons) and Cuban builders were taught by Gumersindo (Juanas, José, and Rueda Jiménez 2013, 75). Students of architecture worked with the leading architects; the schools’ design and construction had a collective and enthusiastic start. But the political and cultural acceptance of those craft-produced structures started to be challenged by a wave of prefabrication and the concept of building for the masses. The schools eroded as an idea but remained as abandoned and unfinished buildings. Heretofore thin-tile vaulting has not been known to have existed elsewhere in Cuba; this research uncovers a large number of those buildings explained in the following chapter.

A European Exchange: Patents and Systems

The expanding research of thin-tile vaults is uncovering new cases of the technique being used in different regions. In central Europe, specifically in Belgium and Germany, thin-tile vaults were used extensively for public and religious building between the 1880s and 1950s. Recent research by Paula Fuentes and Ine Wouters reveals the path of thin-tile vaulting to Belgium through France by studying the work of Charles-Armand Demanet in Paris (Demanet 1847; Fuentes and Ine 2019).

However, it was not until the end of the 19th century that thin-tile vaults were introduced to Belgium’s building industry by the French construction company A. Fabre. The company patented a ceiling system in which thin-tile vaults are used as an interior ceiling and a formwork of concrete arches (Figure 13) (Fuentes and Ine 2019). The patent was brought from France to Belgium by Charles Daussin, who later made a patent himself similar to Fabre’s but with introducing hollow customised bricks as ribs. Daussin’s office itself was built with thin-tile vaults in Rue de l’Étendard 11, Brussels, and his work was mentioned in texts about construction such as Compaz and Araund (Fuentes and Ine 2019, 445). Historical records show that Daussin was later named Daussin and Tignol and then J. Tignol y A. Joly. The company built many vaults during the interwar period, encouraged for using no formwork, being light and efficient in the building, fast to build, and resistant.
Figure 10. Guastavino System Patent (Rafael Guastavino 1891).

Figure 11. Two projects of Guastavino Company with two different formwork treatment. Left: Cathedral St John’s the Divine: Minimum formwork. Right: Minnesota State Capitol: Intensive formwork, possibly for fast construction. (Avery Library).

Figure 13. System patented by Charles Daussin. (Fuentes and Ine 2019)

Figure 14. Left: details of vaulted ceiling from Sattler 1984. Right: Tile vaults in Landeszentralbank, design by Sattler and built by the Ranks. (Huerta 2017).
In Germany, and although records of d’Espie’s book were found in the 18th and 19th century in the country, no thin-tile vaulted projects were found. It was when vaults started to disappear in Belgium after WWII that they flourished in Germany. Thin-tile vaults were transferred from Italy and Spain thanks to the architect Carl Sattler and contractor Max Rank. A brief mention to the Rank brothers construction company using thin-tile vaulting was made by Bassegoda Musté in 1947 until a study by Santiago Huerta shows in detail the process of bringing the technique to Munich, Germany by the architect Carl Sattler and the construction company of the Ranks (Bassegoda Musté and Bassegoda Nonell 1947; Huerta 2017).

Carl Sattler worked in Florence and knew the Toscana light vaults between 1898-1906. His interests in the technique led to several visits to Italy to study the technique, and he wrote in 1935 an essay about the advantages of thin-tile vaulting as a solution to the increasing price of steel (Figure 14). He also appreciated the rapid construction of the vault, the saving in formwork material, and the versatility of the typologies it could generate. Sattler was aware of the needed steps to transfer the technique from Italy and Spain, encouraging training builders and considering the vaults in building regulations (Huerta 2017). Max Rank belonged to a family of builders with close ties to Spain, his father, Joseph Rank, founded a construction company in Spain called “Hermanos Rank” and was fascinated by the skill of thin-tile vaulting builders. Max inherited this interest and visited thin-tile vaulted building in the post-civil war period of Spain. The Rank company contributed to the building of vaults in Germany’s post-war reconstruction until it stopped in the 1960s where shells of reinforced concrete become a trendier alternative (Figure 14) (Huerta 2017).

The transfer to central Europe is characterised by approaching thin-tile vaulting as a system that holds the same values found in industrial construction at the beginning of the 20th century. The fascination with the construction versatility made architects translate it into patents and systems that can respond to challenges of costs and availability of materials. Like Guastavino, the patents of thin-tile vaults by architects and builders were tools of monopoly and a way to reconstruct a contemporary and non-traditional image of vaults outside their historical contexts; they are invented for and by the needs and aspirations of their time.

**A Global Exchange: Recent Re-emergence(s) of Thin-tile Vaulting**

Technological advances and industrialised construction contributed to the decline of thin-tile vaulting (Rodríguez García and Hernando de la Cuerda 2007). Although this did not happen abruptly, developing intensive and craft-based thin-tile vaulting in modern industrial construction is as old as Guastavino’s vault patent with steel reinforcement (Guastavino 1910). Similar patents were mentioned in Central Europe during the interwar period. The work of Eladio Dieste, on reinforcing brickwork or masonry, *cerâmica armada*, was one way to ‘upgrade’ and compete in the new world of steel and concrete, with large-span low-cost masonry construction. His earliest work began with a tile vaulted house, designed by Antoni Bonet i Castellana (Anderson 2004, 15). Eduardo Torroja, another master of reinforced brickwork, used thin-tile vaulting construction in projects like the Church of Pont du Suert, where a shell *a la tabicada* is covered with mortar and a metal mesh. He used the same system as permanent formwork for Sancti Petri Bridge’s foundation (Ochsendorf and Bernardo 2003). During post-war reconstruction in Spain, Moya reinterpreted the groined vault with vaulting over structural brick, or concrete, beams that beautifully segmented the church’s domes and vaults. Moya pioneered formwork made of metal and revolving cintrels, and built with reinforced brick in one of his final projects, Santa María del Pilar (Mosteiro 1996, 2001, 2006, 132). Amid those efforts to adapt tile vaults to mechanised construction, many architects explicitly dismissed it. In 1954, Miguel Fisac asserted that, after the effectiveness of thin-tile vaulting in the post-war reconstruction, “it is now absurd to use it due to its bad acoustic qualities and thick structure” (Fisac 1954). Indeed, Fisac is better known for experimenting with concrete.
Formal construction pronounced thin-tile vaulting nearly dead (Truño i Rusiñol et al. 2004, 4), but vernacular construction of maestros y oficios of vaulting kept the tradition alive; the vernacular architecture becomes the refuge and source of this knowledge. The restoration, vaulted stair-making, and self-building of rural houses maintained the technique within a circle of specialists and building artists (Moreno-Navarro 2005; Al Asali 2016). After this period of stagnancy, new projects started to revive the tradition. Research centres, such as MIT (Massachusetts Institute of Technology), ETH (Swiss Federal Institute of Technology), ETSAM (Escuela Técnica Superior de Arquitectura de Madrid), and the University of Cambridge, showed an interest in thin-tile vaulting as an innovative and expressive technique. They brought thin-tile vaulting to the construction scene and succeeded in building vaults in ‘real buildings’. These vaults are now examples that thin-tile vaulting can exist in today’s construction industry.

The Convention Centre in Pines Calyx, by John Ochsendorf, Wanda Lau, and Michael Ramage, marks the first contemporaneous example of the revival of the thin-tile vaulting technique. From observing Guastavino and Moya’s work, they built two 12-metre-span domes, with tiles made of waste clay from a nearby quarry (Figure 15) (M. H. Ramage 2007). Because it is labour intensive, thin-tile vaulting was taken to southern and sub-Saharan Africa. Mapungubwe Interpretation Centre in South Africa endeavoured to propose thin-tile vaulting as an ‘alternative’ building method for developing countries (Figure 16) (Ramage et al. 2010). A recent similar project is Rwanda Cricket Stadium by Light Earth Design. Davis and Block (2012) worked on thin-tile vaulting for housing in Ethiopia (Figure 18). The Foster Foundation proposed tile shells as drone hangars, and a prototype was built in the Venice Biennale in 2016 (Figure 17).

Modern technology and computation offer advanced tools for analysis, integrating thin-tile vaulting with structural design solutions. Also, the use of technology made some projects possible in countries with high wage rates. Light Earth Design built a pavilion in London, UK, from compressed earth tiles and interior vaults in the FR2 office in Chicago (M. H. Ramage, Hall, and Rich 2014). The BLOCK research group at ETH Zurich worked on the ability to design and build vaults with new digital tools (“Block Research Group” n.d.). Expressive and non-conventional forms of vaulting, known as ‘free form shell’ were built on the ETH campus (Figure 19) (Van Mele and Block 2011; Davis et al. 2011), and later in Barcelona (López López, Domènech Rodríguez, and Palumbo Fernández 2014). Another recent project is the Panteón Soriano Manzanet, by Mileto and Vegas, built by vaulted stair-maker Salvador Gomis (Figure 20, Figure 21). Recently, summer school workshops are also taking place in Spain and led by masters such as Ramon Guarda Parera and Jordi Domenech (Figure 22).

1.4 Literature Review

Tile vaulting is discussed in a range of contexts, from writings about specific architects who worked with structural tiles such as Antoni Gaudí or Cèsar Martinell, periods such as post-war reconstruction in Spain, regions such as Catalonia or Valencia, and architectural currents and styles such as Modernisme or neo-medieval architecture in Spain. However, despite the recent increasing interest in thin-tile vaulting, few writings are about its contemporary applications, construction, and materials.

1.4.1 References and Key Publications

There are two primary references for thin-tile vaulting. The first is published in 1997 by Bassegoda Nonell as part of the republished texts of his father Bonaventura Bassegoda i Musté: La Bóveda Catalana. The bibliographical list is written in a review essay style and chronologically orders treatises with summaries about thin-tile vaulting.
Figure 15. Pines Calyx Centre. (Light Earth Designs)

Figure 16. Mapungubwe Centre. (Light Earth Designs)

Figure 17. Drone Port Prototype in Venice Biennale, 2016. (Norman Forster Foundation)

Figure 18. Tile vault house in Ethiopia. (Davis and Block 2012a).

Figure 19. Free vaulting in ETH, 2012. (Block Research Group)

Figure 20. Mileto and Vegas, 2016: Panteón Soriano Manzanet.

Figure 21. Stair-making with tiles, Valencia. Source: Salvador Gomis.

Figure 22. Ramon Guarda Parera, a master vault maker and trainer.
The second text was prepared in 1999 and updated in 2010 by Santiago Huerta and then by John Ochsendorf (Huerta, López Manzanares, and Redondo Martínez 2001; Ochsendorf 2010). It focuses on Guastavino’s work in the US but expands to writings about thin-tile vaulting in general. It must be noted that after 2010 some publications about today’s vaulting have come to light, and they offer invaluable information about modern construction, analysis, and form-finding.

The books of Angel Truño (Truño i Rusiñol et al. 2004), Luis Moya (Moya Blanco 1947), and Bassegoda Musté (BassegodaMusté and Bassegoda Nonell 1947) are explicitly about thin-tile vaulting and are essential for any similar study. They were all written between the 1940s and 1950s, but some were published or republished after 2000. To document a dying technique, all three strive to provide comprehensive directions on tile vaults history, construction and structural principles, and cultural background. While Basegoda covers the main principles and calculations of thin-tile vaulting in Catalonia, Truño addresses the finest details a builder has to know such as coursing (the joints between tiles), guidework positioning, even where and how to scaffold.

Moya adds his own experience of pushing the techniques to new hybrid construction such as vaults over concrete ribs, steel expansion joints between the vaults, and concrete beams. Another key publication is George R Collins’s essay “The Transfer of Thin Masonry Vaulting from Spain to America” (Collins 1968), which explains the Guastavino Company’s work in the United States and history cultural background, main structural principles, and construction know-how in thin-tile vaulting. Collins’s pioneering work about Guastavino laid the foundation for later scholars. Neumann (1999) includes references and precedents of thin-tile vaulting in Spain. Ochsendorf (2010) expands the work on Guastavino’s archive to many other aspects of Guastavino’s work. The archive of Guastavino at Columbia University was studied to the level of analysing specific topics, like seismic assessment, or specific projects, or individual projects (Robertson 1999; Atamturktur S. and Sevim B. 2012, Hays 2017). In Spain, Santiago Huerta (2001b) edited a collection of essays that examine different thin-tile vaulting topics such as the mechanics, modern history, and relationship to reinforced masonry (Gulli 2001a; 2001b; Tomlow 2001). A recent review study by (López, Mele, and Block 2016) looks at thin-tile vaulting projects in the 21st century.

1.4.2 Urban Development and Tile Vaulting

In 1920, Cesar Martinell planned an agricultural village in Artesa de Lleida (Spain), where almost all the facilities would be built with tile vaults (Lacuesta and Antoni 1976, 70; Lacuesta et al. 1998). The village was not realised, but tiles for vaults in villages appeared again in the post-war reconstruction after the Spanish Civil War (1934-1939). Villages, such as Villanueva de la Cañada, were built almost entirely with tile vaults which were considered a low-cost construction method (Fungairiño and Castañon 1942). Another example of a thin-tile vaulted neighbourhood is Sant Narcis in Girona by Igansi Bosch Reitg where he used sial vaults for ceiling and floor systems. In France, Collins mentioned that French architect Poll Abraham presented a paper on the potential of thin-tile vaulting in response to reconstruction challenges after World War II (Collins 1968, 183).

In South America, vaulting is intertwined with the understanding of appropriate construction that replaces the expensive steel and concrete slabs with innovative alternative roofing systems. Eladio Dieste’s work is monumental, his reinforced brick system is an excellent example for proposing masonry and brick for industrial facilities with large spans (Anderson 2004). In addition to structural innovation, the key concept in Eladio’s proposal in construction is transforming vault-making into an industrialised construction, significantly reducing the need for skilled builders (Nordenson and Riley 2008, 46). Eduardo Sacriste is also known for his book, Houses with Vaults (Casas con Bóvedas), and for his prefabricated vaults in Casa Carrieri (Muñoz and Fernández 2014; Sacriste, Kechichian, and Mackintosh 1977). In Mexico, Carlos González Lobo had several vaulting systems for
housing and had a vision of ‘Prefabricación Cooperativa Popular’ to make reinforced mud blocks for popular housing (Ortiz 2004, 120).

The examples mentioned above of scalable construction in the Americas were not about tile vaults. The method of scalability in two well-known thin-tile vaulting examples in the Americas, the work of Guastavino and the construction of the National Art Schools in Havana, remains unexplored. Guastavino built many vaults. However, there are limited studies about how he recruited, trained, and supervised new vault maker to sustaining skilled labour during the company’s 70-year lifetime. Tools and formwork drawings are also unstudied but can be speculated about from construction images and verified in testing.

The five Art Schools in Cuba were studied by John A. Loomis (1999), who gave a comprehensive narrative about the background, process, and repercussions. The book has one chapter about thin-tile vaulting being introduced to Cubans. The architecture of the schools has also been touched upon in several exhibitions, dissertations, and publications (Scarano and Zamora 2007; Juanas, José, and Rueda Jiménez 2013; Juanas 2013; “Instituto Superior de Arte En La Habana, Cuba. Estructuras de Cerámica” 2015), but whether thin-tile vaulting was used beyond that remains unexplored.

1.4.3 Studies of Tile Vaulting in Modern Construction

The new wave of studying thin-tile vaulting has resulted in more specific research, which can be grouped into three categories: a) the experience of building a tile vault, b) technological advances in designing vaults, and c) construction and environmental applications of thin-tile vaulting in today’s architecture.

Building a tile vault (Labour)

Reports of materials, construction time, failure and successes, and learned lessons have reintroduced thin-tile vaulting in academia and practice and proved it possible and promising. They usually rely on following instructions directly from the texts and buildings (M. H. Ramage 2006), being trained by a master builder (P. Becker and Anderson 2004), or experimentation (Davis 2010). Learning thin-tile vaulting is considered a straightforward process for trainees with knowledge in construction (Davis and Block 2012a). For example, in Mapungubwe in South Africa, local labourers underwent a short training to start the twenty-one vault project as they also learned during the construction process (Figure 16) (Ramage M.H, Ochsendorf J.A, and Rich P 2010). Likewise, some construction schools offer thin-tile vaulting courses for less than a week (Al Asali 2016). Using the acquired skill ends when the vault, or project, is complete (Splaingard 2016, 175).

Learning how to vault can be quick. But training to be a builder with the ability to reproduce vaults entails more skills than laying tiles. It needs experience in decision-making, estimating and responding to on-site problems (Al Asali 2016, 65). During Catalan Modernisme, learning thin-tile vaulting took three years of training, becoming a vault master builder was an even longer process (Bassegoda Musté and Bassegoda Nonell 1947, 3). In the 1950s, Truño (Truño i Rusiñol et al. 2004, 7) lamented the poorly executed vaults accusing those who build them of degrading the legacy of vaulting. Even today, vault master builders have their apprentices for years until they feel confident for them to be independent (Al Asali 2016). The comparison between one project training model and the extended time master builder model is essential. Hence, training and knowledge transfer, specifically beyond individual projects, is one of this research’s leading focuses.
Application and Accessibility (Design)

Tile vaulting modern practice is intertwined with the use of ‘appropriate materials’. Before and during the construction of Pines Calyx, Ramage worked on testing Aircrete blocks instead of the terracotta tiles and methods of reinforcement with Geogrid, a geosynthetic material used to reinforce soils and retaining walls, between the vault layers (M. H. Ramage 2006; 2007; M. H. Ramage and Dejong 2011). Those approaches were developed in the Bowls project in San Francisco (Wray, Sinclair, and Ramage 2011). Mapungubwe Centre highlights three breakthroughs: the use of compressed tiles of stabilised soil instead of fired clay; tile making as a work relief model; and showing the versatility of thin-tile vaulting in Africa (Ramage M.H, Ochsendorf J.A, and Rich P 2010).

Light Earth Design (LED) projects show vaulting in different geographic and economic contexts, which necessitate altering thin-tile vaulting to respond to different economic and environmental conditions. LED defines sustainability beyond economic and energy calculations, it is also social and about “...the people around the building, and the people who make it and use it.” (M. H. Ramage, Hall, and Rich 2014, 305). This definition shows that adaptability and accessibility to build are part of sustainability. In thin-tile vaulting, both themes need to be explored and verified by further research of experiments and comparisons.

Vaults have long been considered for housing. Le Corbusier proposed vaulted houses in Europe like Villa Paul Poiret en Sans Lieu (1916), Monol (1919), Weekend-house Henfel (1934), and Jaoul (1951). Outside Europe, vaults had a clear advantage for Le Corbusier: rapid and low-cost construction. In India, he designed Maison des Péons (1950) and Villa Sarabhai (1955) but built only the latter. Today, vault building for low-cost housing has been revived, but an acknowledgement of its labour intensity is proposed primarily for contexts with low labour wages (Davis and Block 2012a). This seems a valid argument, although no studies of comparison between different contexts verify such assumption. In their project of applying tile and leaning brick vaulting to housing in Ethiopia, Davis and Block conclude that “we must better qualify the descriptive “appropriate building technology” for developing countries, and carefully interrogate the criteria for “sustainable” construction technologies while such terminology radically oversimplifies the complex dynamics of human and material resource constraints as they apply to new technologies” (Davis and Block 2012a, 230).

Technology and Analysis Tools (Technology)

Although we know little about it, the body of building knowledge known as scientia among the mediaeval masters was developed by testing and observing buildings to extract rules of thumb (Huerta 2002). Modern structural principles were laid in the 17th Century by Galileo, who worked on forces, Hooke, who worked on elasticity and materials, and Newton, who worked on gravity and motion. It was not until the 18th century that those principles were developed (Heyman 1999). Analytical work on structures, including vaults, was possible to do graphically, thanks to James Maxwell’s paper ‘On Reciprocal Figures, Frames, and Diagrams of Forces’ (Baker et al. 2013). Jacque Heyman projected concepts from the plastic theorem onto masonry structures, which led to the understanding of the structural behaviour of compression-based structures and the collapse mechanisms (Heyman 1997).

Digital form-finding is becoming one of the dominant tools for understanding and designing shell structures, defined as “Finding a shape of equilibrium of forces in a given boundary concerning a certain stress state” (Veenendaal and Block 2012, 3742). But the understanding is form-finding has been an old tradition since Hooke’s sentence that a vault shape is “as hang a flexible line”. Such a concept was used by structural designers, such as Antoni Gaudí, Frei Otto, and Heinz Isler, where hanging chains and fabrics generated lines and surfaces that
described the ‘right’ vault geometry. Today, the use of technology has moved form-finding to the computer. Block research on interactive form-finding, using Thrust Network Analysis (TNA), has developed a Rhinoceros Plug-in, RhinoVAULT – an interactive design and analysis for funicular structures (Matthias Rippmann, Lachauer, and Block 2012; Matthias Rippmann and Block 2013; McNeel and Others 2010). The tool uses projective geometry, duality theory, and linear optimisation to produce reciprocal diagrams of forces and forms as three-dimensional graphic statics (P. (Philippe C. V. Block 2009). Another tool for understanding and designing, through graphic statics, is GeoGebra, a mathematics software in which “Geometry, Algebra and Spreadsheet are connected and fully dynamic” (Hohenwarter 2013). Finally, methods such as Particle-Spring Systems (PSS) is used in computer science for physical simulation, but also has proven promising in form-finding as it “make[s] the designer aware of structural responses” (Kilian and Ochsendorf 2005, 83). PSS can be accessed by Rhinoceros® plug-in Kangaroo-Grasshopper, which provides a parametric user platform to form-find shell structures (“Kangaroo Physics” 2010).

These tools help the visualisation and calculation of complex structures. But they also raise questions about the nature of “design” and the emergence of design abstraction that neglects other factors of buildings such as material and labour. After acknowledging the importance of form-finding for shell structures, Wanda Lewis (Lewis 2005, 185) concludes that “Neither physical nor computational modelling alone is sufficient to complete the design of a novel structure. However, when used interactively with each other, they can produce aesthetically pleasing, durable and safe solutions”. Indeed, Frei Otto is considered a pioneer in noticing forms in nature that are usable in buildings, but his work is inspired not only by nature, but also by the basic human needs that generate minimal solutions which “…even in poverty… can be very beautiful and good in ethical sense” (Schanz 1995, 13).

Few but promising technological applications in vault construction focus on making guidework. The free form vaults in ETH, Zurich and Barcelona had sets of CNC cardboard and wire systems as guidework (Davis et al. 2011; López López, Domènech Rodríguez, and Palumbo Fernández 2014). Light Earth Design’s office interior project in Chicago had an entrance vault that a skilled mason built. However, there were also 200 identical vaults built by workers with no vaulting experience. A virtual model was designed and prototyped in Cambridge, UK, from which a detailed template was made in Chicago to help the workers (M. H. Ramage, Hall, and Rich 2014). Finally, interactive cable-net and fabric formwork could improve the making of shells beyond the use of straight lines in ruled surfaces (Van Mele and Block 2011). Although very helpful, most of those applications can only be used in specific lab conditions with access to advanced tools.

But what is a hanging chain for a Nubian builder and a bent cane of reed for a Catalan vault maker? They are a ‘form finder’ and a ‘guidework’ integrated with rules of thumb. Strings are minimal but potent tools in thin-tile vaulting with multiple uses: they form-find, make guidework, and help in the coursing for an eye-pleasing un-rendered vault (Truño i Rusiñol et al. 2004, 137). Bringing the interactive virtual form-finding of complex structures back to the physical world will improve the accessibility of design and construction. This study looks at materials and methods with which in-situ form-finding can be a tool for teaching and guiding labour on how to vault.

1.5 Framework: Rises and falls of Thin-tile vaulting

The historical and literature review on thin-tile vaults showed several cases of vaulting moments in construction history. It seems that the technique was adopted for a specific demand or limitation, such as post-war economic hardship, and then stopped due to other specific conditions, such as the prevalent use of reinforced concrete.
These two whys (why it was adopted, and why it was abandoned) are essential to understanding the relations of thin-tile vaulting to the notion of scarcity. The following table shows all prominent cases from the historical and literature review are places and categorised in terms of the limitations and opportunities that helped thin-tile vaulting be used at a large scale and the limitations and opportunity that made the technique disappear. The chronologically arranged case are these whose reasons and methods were studied by scholars. The table is not a summary of the history of thin-tile vaults. Cases of isolated projects or uncovered cases of thin-tile vaulting in history might exist outside the content of this table. However, it is a summary of the relationship between vaults and scarcity.

Although the table presents cases within regions, the exchange of thin-tile vaulting among these regions is also essential (Figure 23). Borrowing, developing and adapting to local materials and regional influences on thin-tile vaulting that kept the practice vibrant and alive support the proposed definition of thin-tile vaulting that tolerates two extremes of construction styles: predetermined design versus in-situ building. There is a considerable difference between the Roman model of perfectly cut stones placed on wooden formwork and the Middle Eastern model of roughly moulded mud tiles, built with no falsework whatsoever. These two scenarios are seen in the variation of thin-tile vaulting in different contexts and cultures; the vaults with fine exposed tiles in the winery of Puig i Cadafalch are different from the Algerian Rhorfas, and both are distinct from the prefabricated vaults for houses in the proposal of Eduardo Sacriste in Argentina. However, clustering all cases in one table shows a pattern in which elements are repeated. For example, the case of materials is a double-edged sword. On the first hand, the lack of materials in post-war reconstruction periods gives thin-tile vaulting visibility as a viable option. On the other hand, the surge of new material use, such as concrete shells, creates a competition in which vault starts to disappear. In both cases, structural design's rhetoric is essential, one that fluctuates between investing in traditional craft or industrialised construction. This fluctuation has helped the vaults be introduced to new building methods such as reinforced ceramic and fused concrete and tiles shells.

Furthermore, it is only recently that the thin-tile vaulting association with the notion of sustainability starts to appear. The new wave of thin-tile vaulting revival is happening in tandem with the awareness of the environmental challenges and the role traditional building and natural material can play in reducing buildings' carbon footprint. Investing in the sustainable aspect of thin-tile vaulting has become essential in the discourse justifying their use. However, it seems that the same discourse rightly limits thin-tile vaulting use to areas where labour wages are cheap as it is a labour-intensive practice. Investigation labour training and construction speed can be one of the priorities of the current research on thin-tile vaulting. From Table 1, I could find three main approaches to thin-tile vaulting through limitations. The first is introducing the vaults as a top-down strategy, a policy, or a will within the state to use vaults in construction. The second is a bottom-up approach that concerns small initiatives of building capacity within local workers and builders or bringing builders from regions with rich thin-tile vaulting traditions to teach or work on restoration or building new structures. Finally, a third approach is usually led by specific key figures, it is a design approach that combines the top-down and bottom-up to develop thin-tile vaultings as patents or careers. The word design here includes both architects and master builders, as the latter had an essential role in building vaults by collaborating with architects— the cases of Guastavino and Max Rank are clear examples.
Figure 23. Summary: Timeline of Tile Vaulting Transfer Until June 2020. The tree shows how the technique spread to different regions with different construction cultures and materials. Sometimes thin-tile vaulting did 'return trips' to its origins. The dynamic of this timeline tree suggests a study of thin-tile vaulting in different contexts and cultures.
North Africa / Eastern Spain 1100 -1600

Key figures

Rising Conditions
- Existence of plaster
- Fast construction of crossed vault's web

Falling Conditions
- Not applicable
- Thin-tile vaulting is still practised in the region

Method
- Introduction of new materials (plaster)
- Mixing thin-tile vaulting with other techniques

Legacy
- Establishing thin-tile vault as a construction craft
- Versatile use in vernacular and expressive structures

France (voie roussillon) 1750-1800

Key figures

Rising Conditions
- Fire Resistance System
- Lightness in building
- Neoclassic architecture in France

Falling Conditions
- Not known

Method
- Experiments with vaults and systems
- Diffusions of the techniques in writings

Legacy
- Popularity in Central Europe
- Translation of d’Espie’s writing

Catalan Modernisme / Noucentisme 1880-1925

Key figures

Rising Conditions
- Identity and Heritage.
- Experimentation of new shell geometries.
- The rise of industrial architecture

Falling Conditions
- Transforming to international design (GATEPAC)
- Emergence of Reinforced concrete

Method
- Empowerment of construction craft
- Education in design and construction
- Industrialisation of vaults

Legacy
- Efficiency in structural design
- Extensive use of parabolic sections

Madrid 1880-1910

Key figures

Rising Conditions
- Economic restoration and religious buildings.
- Appreciation to craft

Falling Conditions
- Not applicable
- Thin-tile vaulting is still practised in the region

Method
- Labour transfer from Catalonia to Madrid.

Legacy
- Reactivation of thin-tile vaulting in Central Spain
## France and Belgium 1850-1930

### Key figures
- A. Fabre Daussin

### Rising Conditions
- Expensive steel construction
- Fast economic and robust building

### Falling Conditions
- Interruption of WWII
- The emergency of concrete shells

### Method
- Patenting and systemising vaults
- Development of industry by contractors

### Legacy
- Inventions and industrialised systems

## Guastavino 1885-1962

### Key figures
- Guastavino
- Guastavino Jr.

### Rising Conditions
- Fire resistance systems
- Decorative and structural shells
- American renaissance

### Falling Conditions
- The emergency of engineering and building codes
- The increasing prices in labour
- The shift to the international style

### Method
- Patenting
- Development of industry as a contractor
- Establishment of material supply

### Legacy
- Patents
- New technical aspects in thin-tile vaulting

## Post Spanish Civil war 1940-1970

### Key figures
- Moya, Torroja Bosch I Reitg

### Rising Conditions
- Appreciation of heritage
- Economy and limitation to resources
- Rural construction

### Falling Conditions
- Changes in architectural ideology
- The emergency of restoration as a discipline
- The emergence of reinforced concrete shells

### Method
- Expressive design with thin-tile vault
- Planning projects of vaulted neighbourhoods
- Fusing thin-tile vaulting with other systems

### Legacy
- Vaulted houses typologies
- A hybrid language or steel and vaulting

## Germany Post WWII 1945-1970

### Key figures
- Max Rank Carl Sattler

### Rising Conditions
- Port-war economic crises
- The need for restoration of old and religious building

### Falling Conditions
- The emergence of building codes
- Using reinforced concrete shells

### Method
- Labour training between Spain and Germany
- Development of industry by contractors
- Study of the craft in its origin

### Legacy
- Not known
South America 1940-

**Key figures**
- Dieste
- Sacriste

**Rising Conditions**
- Solutions for low-cost housing
- Solutions for large span low-cost buildings
- Search for local solutions in construction

**Falling Conditions**
- unknown
- Some practices of vaulting are still undergoing

**Method**
- Prefabrication of vaults
- Reinforcing vaults with steel

**Legacy**
- Reinforced ceramic
- Departure from vault to reinforced ceramic

Cuba 1960-1964

**Key figures**
- Porro
- Gottardi
- Garatti

**Rising Conditions**
- Lack of steel for construction and wood for formwork
- Availability of training
- Cubanidad: search for new architectural language

**Falling Conditions**
- Change in state policy
- Emergence of prefabricated concrete

**Method**
- Training (school of builders)
- Expressive shells

**Legacy**
- New shell geometries
- Sculptural use of vaults
- Controversy of craft vs mechanisation in construction

Earth Shells 2010-

**Key figures**
- Light Earth Design

**Rising Conditions**
- Sustainability
- Low cost large span vaults
- Labour intensity for low-cost labour

**Falling Conditions**
- The practice is still ongoing

**Method**
- Design and construction of two projects in South Africa and Rwanda

**Legacy**
- The use of stabilised earth tiles
- Development of seismic reinforcement

‘Freeform’ Vaults 2011-

**Key figures**
- Block Research Group

**Rising Conditions**
- Low cost building
- Versatility in geometry

**Falling Conditions**
- The research is still ongoing

**Method**
- Research
- Pavilions

**Legacy**
- Form-finding digital tools and applications

Table 1 Summery of Thin-tile transfer and revivals with conditions of rising and reasons for disappearing.
The framework of the three approaches is summarised in Figure 24. By examining and comparing policy-led, labour-led, and design-led approaches to thin-tile vaulting, this research hopes to examine how thin thin-tile vaulting responded, logistically and culturally, to various contexts of building culture.

1- **Policy-led Approach** by addressing construction from the availability of natural and human resources, opening the possibility for research and adoption of thin-tile vaulting construction either from own heritage or transferred from a region with thin-tile vaulting tradition. Usually, thin-tile vaults are used as a part of a larger body of techniques and can be adapted to different uses than in their original habitat.

2- **Labour-Led Approach** by training people to build their vaults and transforming knowledge into popular construction. This approach focuses on how knowledge is transferred, with training models for one or many projects. Also, it studies how local and traditional construction cultures influence thin-tile vaulting when introduced to new places.

3- **Design-Led Approach** by designing for optimised labour intensity, time of construction, and materials. This theme focuses on materials, the process of construction (whether traditional or partially manufactured), and tools that facilitate access to building vaults. This approach usually includes consideration of transportation and on-site building procedures. The contribution to knowledge in this part will be finding new ways to make tile vaults by rethinking what craft production is, in contrast to mass or flow production.
1.6 Methodologies

In defining the relationship between scarcity and vernacular practices, I concluded with the importance of addressing flexibility, or error-tolerance, and visualisation within systems and practices of inquiry and production. Methodology in this research is not excluded. On the contrary, to show how thin-tile vaulting operates in contexts of limitation, the research show uses flexibility and visualisation as two main critical concepts in its methodology, both already hint at the involvement of design as a tool of research.

Proposing a strategy comprises a set of different challenges that cannot be met by linear analysis and have no one solution (Van Ouwerkerk and Rosemann 2001). A strategy is “a plan of action designed to achieve a long-term or overall aim” (OED 2017). Such plans “cannot be approached by regular thinking. They require counterintuitive thinking and the development of new knowledge... Design is a very suitable approach for these types of problems because it makes creative jumps in thinking and solving possible” (Roggema 2016, 1). Design and research could be contrasted in architectural practice: design is a profession, research is an inquiry (Groat and Wang 2013). However, an in-depth analysis of the two suggests that the proposition between them is essential (Roggema 2016). Research for design seeks the best design solution, the product represents the knowledge outcome. Research in design defines how design works and how it was expressed in the past and is expressed in the present; this research is the most common in the literature about art and design history. Research by design makes and observes cycles of design for a specific inquiry, the outcome knowledge is both the research and the artefact. The latter is what design research usually uses as a central method (De Jonge and Van der Voordt 2002, 24; Zimmerman, Stolterman, and Forlizzi 2010, 318; Roggema 2016, 3). Although the three propositions show three approached to design research, it is rather unlikely that design research relies entirely on one of the three. Iterations between the artefact (or the product) and the research will be needed. This will require two central techniques that are observed in craft and explained in section 1.2.3:

**Flexibility:** Shifts between for, in and by will integrate design as a tool that can flexibly adapt to the research requirement. This is where the methodology’s flexibility is introduced in the inquiry about an object that can be a vault built in the past, a project in ongoing construction, a pavilion design, or a prefabricated vault system. Understanding these shifts can be only achieved by acknowledging the role of design and working systematically with it.

**Visualisation:** The tools of design such as drawing, modelling, and diagramming are an integral part of the inquiry. There are already many methodological techniques that include these tools. In engineering studies, reversed engineering relies entirely on modelling and simulation (Eigenraam and Borgart 2016). In ethnographic studies, drawings and visual elements are recently acknowledged as powerful tools to show aspects that are otherwise unseen through textual analysis only (Pink 2007). Visual and volumetric representation in the methodology is also a tool for communication that, in addition to the text, will give a comprehensive overview of the design processes and products. Therefore, making in methodology is a tool for both research and communication. While design will be used within this paper’s method, its role is to supplement and not replace other essential methodologies such as archive research, content analysis, and ethnographic studies. Therefore, the overlap between the design tools and the research tools starts with drawing and modelling previous and current projects and proposing a design for future projects; the two cycles are explained in Figure 25.
1.6.1 Summary of Research Methodologies

Because the research is segmented into three approaches (policy, labour, and design), each section holds a specific approach to methodology inherent in the study: historical, ethnographic, or experimental. Therefore, the research will elaborate on these specifications within each section. The overall methodological approach is illustrated in Figure 25. Which is structured into data collection (first row), processing (central rows), and outputs (results).

Data collection

Site visits
Most of the site visits were made during the historical research to observe and note the studied building’s status and cross-reference the observation with images or texts from the archives.

Archival work
Uncovering or studies already examined archives was the central data in the historical studies. Most of the archival work took place in libraries and schools of architecture. However, informal and personal collections were also essential. Therefore, part of the archival work was made by reaching out to scholars working on similar topics or regions.

Interviews
Open and semi-structured interviews were done with architects and engineers during the historical study. In the same manner, group discussions and interview were also conducted with trainees and trainers in construction sites after and before training.

Questionnaires
The questionnaires were only used in this research with thin-tile vaulting trainees in Jordan, Rwanda, and Spain. Questionnaires were used to understand the background of the participants, aspirations, and reflection on learning and working with the technique.

Observations
Observations were central in the ethnographic study about thin-tile vaulting training; it was structured in the form of notes taken during the training and reflections made as a summary of each day’s training. The logbook composed in training was treated as a primary resource in the analysis.

Artisan input
In the experimental and design section, the phase of ideation was thoroughly discussed with the master-builder of thin-tile vaulting. Because the research is inclusive to artisans in on-site construction, their input was essential and, in some cases, contributed to changing or consolidating the direction of the design.

Case studies
Case studies refer to the context in which the experiment’s design is developed and the limitation that is tackled in such a context. In some instances, the case study is a commissioned project (a pavilion), while in others, it is an overall need that is observed, such as the need for cheap roofs in post-war construction in Syria. The input from each case study is treated as a design limitation and as data to analyse.
Data analysis

Thematic Content Analysis (Historical studies)

In the historical case study, thematic and content analysis was central to understanding buildings, interviews, journals, reports of projects, and other primary resources. The thematic and content analysis looks into the gathered data for patterns and concepts related to the specific research question (Vaismoradi, Turunen, and Bondas 2013). Thematic analysis is about qualifying data with a non-linear process, while content analysis is about quantifying data and relies on the frequency of the theme occurrence to validate its relevance; both techniques have similar procedures known as Braun and Clarke’s six steps (Braun and Clarke 2006): familiarising, initial codes, find themes, review themes, define and name themes, and reporting. Coding, in particular, is a synthesis process of the gathered data and can be carried out with help from digital tools such as Altas.ti (*ATLAS Ti: The Qualitative Data Analysis & Research Software* 2017).

Content Analysis (Ethnography)

Like historical studies, content analysis is central in ethnographic studies to process and analyse interviews, notes and observations. However, in contrast to Qualitative Content Analysis QCA, Ethnographic Content Analysis EQA is more reflexive and highly interactive with the investigator, participants, and data. Reflexive in this context means that the researcher’s description of objects and events is also considered part of the analysed data provided that it is done systematically and within the limits of the researcher’s position in the investigation (Altheide 1987).

Prototyping (Design)

In simple terms, a prototype is an early model of a product made for testing and evaluation whose outputs aims to develop the final product. Prototyping stands on the intersection between design and research, and it is used in companies for software and hardware alike and in research on products and systems. Prototyping incorporates sets of iterations of one solution to enhance its performance. Parallel prototyping explores the performance of many solutions to derive one. In this research, prototyping is integrated into the design-led approach of thin-tile vaulting wherein each project or system there are sets of iterations of scaled models. The prototypes’ evaluation is dependant on each case, such as load testing, constructionability, cost, and efficiency (Camburn et al. 2017).

1.7 Discussion

Thin-tile vaulting as a technique offers an opportunity to study building crafts’ multifaceted connections to design and construction. Instead of approaching these connections through discussions about architectural styles or preservation strategies, the research shifts the focus to examining the resourcefulness in vernacular building practices and its relevance to today’s construction, especially under the pressing climate challenges.

To understand how to work and engage with thin-tile vaulting as a building craft, the research conditions a dialogue with builders to visualise their craft and see how it can be flexible and adoptable to limitations by being small, error-tolerant and non-centralised. In the specific case of thin-tile vaulting, this chapter has reviewed the literature and examined the history of thin-tile vaulting through the lens of abundance and scarcity. The review shows three main areas of thin-tile vaulting in construction. The first is construction policies within states during periods of recessions. The second is the knowledge transfer and training through periods and locations. The third is the advancement of design and computational tools as an opportunity to integrate building craft and craftsperson in construction.
Figure 25 Mythological framework in relation to policy, labour, and design approaches.
The research in the following chapters will be built on these three approaches. Each chapter can be read as independent research on policy, knowledge, and design of thin-tile vaulting with case studies for history and contemporary instances. Then the three approaches will be compared in the conclusive chapter for a revised framework on craft and construction based on Figure 24. In summary, the research will examine this notion on three levels:

Policy-led approach: by examining cases from Cuba and Syria of vaulted construction during economic hardship and embargo.


Design-led approach: by studying and designing thin-tile vaulting strategies of three scenarios. Each scenario focuses on one limitation of material, time, and skill of labour.

The combination of these approaches does allow to navigate within different fields, methods, and topics. This has been a challenging but productive practice. For example, it linked findings from historical cases to developing prefabricated vaulted systems. History and ethnography become a provider of design tools.

Although placed as such, the process of composing the theoretical and methodological framework of this research was never straightforward. Thin-tile vaulting is a new field of research; although it has been fifty years since Collins published his article about Guastavino and brought the interests of English written scholarship to thin-tile vaulting, it is only since the 2000s that the domain sprung out research in history to the application in current architecture. Even in historical studies, the last ten years have shed light on new cases of thin-tile vaults. Therefore, in this field of growing interests, a balance between seizing all research opportunities and focusing on one specific and narrowed case is very challenging.

Finally, this research starts with the intentions of finding strategies to incorporate thin-tile vaulting in the reconstruction of Syrian destroyed areas. But while these intentions are present, one step backwards was taken to look at a comprehensive image of how thin-tile vaulting responds and responded to post-war reconstruction cases. Instead of dedicating specific chapters to case studies in Syria, there will be cases from the Syrian contexts extending all chapters. In the historical study, a case of vaulted houses projects during the eighties will be examined. In the research about labour, there will be a case about Syrian refugees in Jordan. In the design study, a case of recycling buildings into vaults will focus on Syria.
Chapter 2
Policy Approaches to Thin-tile Vaulting.

Historical Case Studies from Cuba 1960s and Syria 1980s.

This study on policies of construction and thin-tile valuing focuses on two historical cases. The first is in Cuba right after the revolution, the second is in Syria during the 1980s’ sanctions. In both instances, the state facilitated the use of vaults for housing and other projects as steel was not available. Also, in the two cases, the use of vault was momentary and did not prolong in the long-term; it was abandoned as soon as resources were available again. This and other instances of resorting to what is at hand at an institutionalised level triggers a two-folded question: How can scarcity provoke jumping over standardised construction for the sake of using local methods of building? How could this return be rooted in practice when limitations are elevated?

In Cuba’s case, the story of the rise and fall of thin-tile vaults in Cuba has always focused on Havana’s National Schools of Art. Current scholarship presents the school as an anomaly in modern Cuban construction. They are not; this study examines many more thin-tile vaulted buildings and experiments that unveil a systematising vaulted construction model at a national scale. In 1960, the Ministry of Construction (MICONS) founded the Department of Technical Investigations, one of its urgent tasks was conducting an in-depth study of ceramic shells in a context of strict limitations of resources. In the case of Syria, the chapter elucidates construction directions during the sanctions of the 1980s, an understudied but important period in the history of architecture in Syria. The sanction pushes many architects to look for an alternative to steel. One project stood out in this context for its large scale. Al-Sharqyat, which means the Orientals, was part of a state-led housing project directed by the Military Housing Association (Milihouse) to provide middle-class vaulted housing in the suburb of Damascus. Drawing on original resources and archives, the research investigates how vaults were used and then abandoned in the project. The two historical studies’ learnings will form a guideline to how policy approaches to thin-tile vaulting can be introduced in contemporary construction.
2.1 Background: Building Codes and Vernacular Practices

Policies in construction are guidelines for building, they are sets of measurements imposed by the state as “quality-control” systems. These systems are usually translated into codes and conditions that need to be fulfilled. Historically, building codes are also a product of post-disaster construction. Rebuilding large and damaged areas were also seen as an opportunity to mitigate further similar catastrophes. The Great Fire of London is a clear example. Following the devastating impact of the fire, rebuilding London was regulated through the London Building Act 1667, which was later reinforced by another Act in 1772 and 1774 (Ley 2000, xvii).

Building codes are associated with engineering and the transformation of construction into an industry (Harries and Sharma 2019). There are two main types of regulations. The first is about the materials used in building and its properties, such as bricks, woods, and steel. The second is about the building components and their structural and functional specifications (Hall, Lindsay, and Krayenhoff 2012). In both types, building codes tend to be inherently abstracted into followable steps. It usually relies on the concise technical execution of the specified models leading to standard practices and standardised materials. Being typical, standardised, and replicable, building codes narrowed the use of materials or building components to few and controllable variables and techniques such as reinforced concrete.

In contrast, building practices based on local and unengineered materials were of less interest for new buildings. The knowledge and use of traditional or vernacular building elements have been excluded or limited to restoration and rehabilitation of the old structures. Such differentiation makes building codes one of the manifestations of the divorce between the past and the future and the countable the uncountable in the building industry. The recent recognition of vernacular materials and practices in construction has led to re-questioning codes as a contested area between building industries and state policies on the one hand and between innovation and standard production on the other. Current calls for an inclusion of vernacular construction demand codifying its existing materials, components, and practices. However, this testing and codifying process is a resource- and time-consuming; it usually requires a strong political will (Harries and Sharma 2019). These are factors that hinder the efforts to include vernacular architecture as a contributor to the building industry.

Nevertheless, this hindrance is usually overruled by practicality. Thin-tile vaulted stairs in Spain are an excellent example of how a vernacular technique survives building code’s exclusion. The Spanish Building Code does not recognise thin-tile vault for ceilings or stairs. In practice, thin-tile stairs are widely used in Spain in restoration and new construction alike. The rapid formwork free construction elbows out reinforced concrete stairs. Usually, when the builders finish their stairs, they will have to make a load-test of 300-400 kg point load and around 1000 kg distributed load on the vaulted stairs with sandbags, the stairs and the test are described in the report of building permissions. In some instances, architects require a steel reinforcement of the vault or use the vault as a mould for reinforced concrete casting (Gomis 2019). However, the method and geometry of the vault are all left to the builder’s experience. Here, there is flexibility and an acceptance of the builder’s experience in ‘how’ to build; verification is oriented on ‘what’ the builder built.

During times of economic crises, the scarcity of standardised materials motivates such flexibility. One of the earliest codes of earth construction, a very disputed material for codes, was made in Germany in 1944. The German Earth Building Code was issued during the last year of the Second World War under the pressure of shelters need and the destruction of material factories (Hall, Lindsay, and Krayenhoff 2012, 74). The code was kept as a draft, and only part of it came into force. In the 1970s, earth building disappeared again, and the code
was withdrawn in 1971. This and other instances of resorting to what is in hand at an institutionalised level triggers a two-folded question: How can scarcity provoke jumping over standardised construction for the sake of using local methods of building? How could this return be rooted in practice when limitations are elevated?

This question is crucial in thin-tile construction and in vaulting in general, as it relies on vernacular knowledge and on-site conditions. There are two cases of vaulting that can be studied and compared concerning the use of vaults in construction policy. The first is in Cuba right after the revolution; the second in Syria during the years of sanctions in the 1980s. In both instances, the state facilitated the use of vaults for housing and other projects as steel was not available. Also, in the two cases, the use of vault was momentary and did not prolong in the long-term; it was abandoned as soon as resources were available again. The two case studies’ learnings will form a guideline to how policy approaches to thin-tile vaulting can be introduced in contemporary construction.

This historical study is based on archival research and new data about vaulting projects in both countries. The archives are supported by interviews with architects and engineers who participated in the projects, alongside typology analysis from aerial photos. As a result, this section examines the urban, architectural, and constructional aspects of several vaulted buildings, with notes about modifications and transformation in these structures since they were first built.

Drawing and digital modelling is the lead methodology that interrogates the archival findings. The methodology starts with modelling each vault found in texts or drawings during the research. The drawings are then supplemented with notes highlighting the time and location of construction, geometry, materials, and technique. New relationships between different buildings and vaults start to emerge unveiling narratives that are otherwise hard to find through modelling. The output models also simplified the story about the vaults in Cuba and Syria, resulting in a comprehensive infographic about both cases (Figure 47, Figure 57). Visual modelling was also used to superimpose drawings on buildings to verify if regulations were followed. Finally, modelling has also offered perspectives that are not usually shown in pictures, allowing for new comparisons between the shells.
2.2 Vaults in Cuba after the Revolution, Beyond the Art Schools

2.2.1 Introduction: Context

Similar to other facets of Cuban history, the year 1959 marked a rupture in construction approaches, including the questions of “how” and “what” to build for the country. The first period after the Revolution was particularly vibrant. A search for methods of construction began, albeit in a highly constrained context. The country was undergoing an economic crisis and an embargo resulting in a severe lack of resources. Systems of governance and administration were unstable, shifting between centralisation and diversification of governmental entities. The Revolutionary government set a difficult mission of eradicating illiteracy and inadequate housing, an objective that necessitated mass production of new houses and schools. All this took place in tandem with nationalising construction companies, many of which were North American, and an outflow of architects working for the toppled regime. This context of tight constraints and high hopes prompted a structural and provocative interrogation and criticism of existing and aspirational construction models in the country. The process of questioning resulted in extensive and systematic experimentation of techniques, materials, and fabrication of building elements. Cuban architects and engineers embarked on collating an inventory of construction methods with the potential for nationwide application. Vaults of thin-tiles and bricks were on the top of the list. Contrary to dominant scholarly claims, which will be detailed in the next section, these inventories reveal that Cuban architects in centres of technical investigations looked closely at thin-tile vault techniques as a possible method for constructing shells and slabs.

Recent research has revealed thin-tile vaulting transfer cases to central Europe, specifically Germany and Belgium, during the first half of the twentieth century (Huerta 2017; Fuentes and Iné 2019). Architects, engineers, and construction companies introduced and sometimes patented the light and fast building technique. However, thin-tile vault’s largest leap was made across the Atlantic to North and South America in the eighteenth and nineteenth centuries. Studies of thin-tile vaults in the Americas present varied cases. The oldest is Fílar Domingo de Peters, a Valencian missionary and master mason who used the technique in his buildings in Colombia in the late 18th and early 19th century (Ochsendorf 2010). The most salient case of transfer took place in North America by the Valencian architect Rafael Guastavino (1842-1908), who arrived in New York in 1881 and started a company with his son Rafael Guastavino Jr. (1872-1950) that would build more than 1000 vaults for projects in North America (Collins 1968; Ochsendorf 2010). In South America, thin-tile vaulting took a different turn due to the need for material rationalisation and the search for new constructional applications. It sprung from its vernacular form into experimentations for new construction methods, combining the expressive and the utilitarian: the design-led and the labour-led. During the second half of the twentieth century, ceramic shells were built for large-span warehouses, low-cost housing, and prefabricated systems in Uruguay, Argentina, Mexico, and Brazil. The work of the Catalan architect Antoni Bonet i Castellana (1913-1989) with Eladio Dieste (1917-2000) in Berlingieri house (1947) contributed to the formation of Dieste’s unprecedented oeuvre of reinforced masonry (Anderson 2004). The Argentinean architect Eduardo Sacriste (1905-1999) was familiar with thin-tile vaults in Spain and Argentina, he developed several constructions and vaulted prefabrication solutions that he implemented in Casa Carriera (1961) (Sacriste, Kechichian, and Mackintosh 1977). Many other vaulted examples can be traced in the work of Francisco Pizano (1926 - 2018) and Alvaro Ortega (1920-1991) in Colombia, Rodrigo Lefevre (1938) in Brazil, and Carlos González Lobo (1939) in Mexico, and Mario Kalemkerian in Uruguay (Muñoz and Fernández 2014; Medina, García, and Rodríguez 2019). The crucial value of these structures stems not only from their innovative forms but also from the adaptation of the technique to respond to the mass use of vaults within contexts of scarcity.
2.2.2 Vaulting in Cuba

Shells before the Revolution (1950-1959)

Vaults in modern Cuban architecture started with the spread of reinforced concrete shells in Latin America during the early 1950s, a period that is characterised by the shift to modern code while searching for a regional interpretation of architectural expression (Luis Rodriguez 2015; Gómez 2016; Moreyra Garlock and Glisic 2020). Between 1955 and 1958, a group of architects led by Paul Lester Wiener (1895–1967) and Josep Lluís Sert (1902–1983) made an urban plan for Havana, famously known as Plan Piloto (Timothy. Hyde 2012, 139–76). Vaulted houses were proposed in Quinta Palatino, a typical neighbourhood sector of Plan Piloto. The houses were designed in 1954, with Sert and Wiener’s collaborators Nicolás Arroyo (1917–2008) and Gabriela Menéndez (1942–2008) (Timothy. Hyde 2012, 170–72). Another vaulted housing project was the beachfront Cabañas Jibacoa of Antonio Quintana Simonetti (1919–1993), built in 1959 (Bergdoll et al. 2015, 196).

However, thin concrete shells were celebrated more in public buildings than in houses. The earliest and best known are those of the Arcos de Cristal (Crystal Arches) in the Tropicana Cabaret in Havana by Max Borges Jr (1918 - 2009) in 1951. Borges Jr. is known for his extensive use of expressive shells inside and outside Cuba, collaborating with Felix Candela in many of them, including the flower shop Antilla (1955) and Nuñez Bank (1957) (Moreyra Garlock and Glisic 2020). Candela was by then recognised for his revolutionary shell geometry and construction. In 1957, he was also invited to be involved in Wiener and Sert’s unbuilt presidential palace of Fulgencio Batista known as Palacio de las Palmas. The architects’ design included a corrugated ceiling composed of multiple Hyperbolic Paraboloid Umbrellas (or “palms”, hence the name) (Timothy. Hyde 2012, 276). Shells represented a formal interpretation of the regional identity of Cuban architecture. The novelty of concrete as a new material that made solid and robust but thin and organic structures contributed to the appreciation of thin concrete shells in the 1950s (Loomis 1999, 8; Timothy. Hyde 2012, 276; Luis Rodriguez 2015).

National Art Schools in Havana

For thin-tile vault examples in Cuba, scholars usually draw on one project: the exquisite National Art Schools, Escuelas Nacionales de Arte (ENA), in the west of Havana. Unlike the concrete shell projects, the schools were born of and cherished as a Revolution product. The use of ceramic as a local material was another layer of a regionalist approach that considers the locality of material and the expression of the form.

In 1961, right after the revolution takeover, Fidel Castro envisioned the Cuban Art Schools that would revolutionise art education to represent the Cuban Revolution as a national and universal message (Loomis 1999, 19). The project was led by the Cuban architect Ricardo Porro (1925-2014), who collaborated with two Italian architects living in Cuba and supporting the Revolution: Roberto Gottardi (1927-2017) and Vittorio Garatti (1927-). Located in a formerly elite golf club in Cubanacan, the site had five schools. Porro designed the School of Modern Dance and the School of Plastic Arts. Garatti designed the School of Music and the School of Ballet, and Gottardi designed the School of Theatre. The schools are characterised by extensive use of ceramic tiles and bricks placed in curves of shells integrated with the natural landscape (Juanas, José, and Rueda Jiménez 2013).

The schools’ architects framed the use of thin-tile vaulting as a response to the scarcity of materials for concrete (Loomis 1999, 25). Builders were trained, students of architecture worked with the leading architects; the schools’ design and construction had a collective and enthusiastic start in 1961 but stopped after four years. Only the schools by Porro were completed, with the rest were abandoned. The main explanation of this abandonment is that the political and cultural acceptance of those craft-produced structures began to be challenged by a wave...
of prefabrication and the concept of building for the masses (Loomis 1999, 117; Segre 1970, 83). The schools eroded as an idea but remained as unfinished buildings. After the school’s construction abandonment, they were always referenced as the projects of explorations, expressions, and individuality. Such rhetoric appears in Roberto Segre’s text about the school in his book Arquitectura y urbanismo de la Revolución Cubana in 1989. Before Segre, the work of the Generation of the 80s used the school as an example to argue against the Cuban prefabrication systems (Segre 1989, 123; Loomis 1999, 151). It was not until 1982, when Hurricane Alberto flooded and damaged the schools, that the schools came back into focus. This new interest was fuelled by the work of Generation of the 1980s, a Cuban architectural movement that covered the schools’ architecture and defended it with writings and exhibitions.

Since then, scholarship on the Art Schools points to their abandonment by the political changes in construction policies. Roberto Segre used the schools as an example of the two contesting approaches to Cuba’s architecture after the Revolution. One adopts technological advances, represented in Fernando Salina’s inclination to prefabrication, and one of the works of Porro in the Art Schools that advocated the artistic and aesthetic values in design (Segre 2003, 34). Within this political change, a second reason to abandon the schools’ project is the alleged mistrust and lack of knowledge about thin-tile vaulting amongst workers in the Ministry of the Public Works (MINOP), which was renamed as Ministry of Construction (MICONS) in 1963 (Loomis 1999, 112; Huerta 2003).

This latter claim is questionable for two reasons. First, it mistakenly suggests that thin-tile vaulting was a novelty in Cuba’s architecture, and the MICONS did not know about the technique. In fact, thin-tile vaulted buildings and builders existed in Cuba before the Art Schools. In 1954 the architect, Abel Fernández Simón mentioned rectangular tiles called Catalan tiles or tiles of Gerona, which was used extensively in the construction of stairs and terraces (Toraya, Santos, and Valdés 2001, 50). Housing blocks in the old city of Havana abound with vaulted stairs and barrel vaults on beams known as revoltones, not to mention public buildings and churches. Many tile vaulted stairs and ceilings are now being restored by builders and apprentices from the vocational school, Escuela Taller Gaspar Melchor de Jovellanos, and led by the Office of the Historian of the City of Havana. One of the latest restored stairs is located at 360 San Ignacio, currently accommodating the office of the historian, which is an 1871 commerce building by José Toraya, renovated in 1921. The Escuela Taller also restored churches. In 2008, the historian’s office also worked on the restoration of the Cathedral of Matanzas, built in 1735 and restored in 1912, whose vaults were thin-tile vaults and were restored with the same technique (Pedro 2018; HABANA RADIO 2014).

Second, the anecdote in which thin-tile vaulting was made part of the schools’ construction ambiguously mentions the Ministry of Construction but without any elaboration. Studies about the schools refer to a central figure, a Catalan builder named Gumersindo, who was building a vault in the Ministry of Construction’s courtyard. One of the schools’ architects (some sources refer to Porro while other states it is Garatti) found the man in the courtyard of MICONS and decided to engage him for building the schools (Loomis 1999; F. García 2008). Training of Cuban builders by Gumersindo took place in the golf course in Cubacan. However, no studies were made to explain the existence of thin-tile vault prototypes in the courtyard of MICONS or the reasons behind having a thin-tile vault maker building a stair at the Ministry. These gaps initiated this research, alongside questions springing from the author’s practice of designing and building thin-tile vaults with Spanish artisans. The schools exhibit complex structures and geometries that would necessitate systematic research and collaboration between architects, engineers, and builders. If the process of designing the schools is now well explained, a lot is yet to be said about how they were built.
In this study, I take a closer look at the courtyard of MICONS, a look that is made possible by scrutinising primary and secondary sources, mainly MICONS publications between 1959 and 1965, and interviews with architects and engineers who were assigned to work on investigating the theme of ceramics in construction during this period.

Most importantly, this research focuses on a rarely examined photographic archive that I found in the Documentation Centre (Restaura) at the Office of the Historian of the City of Havana. The archive originally belongs to the Centre of Technical Investigation at MICONS, elaborated on by Juan de las Cuevas Toraya. The archive and the publications of the Centre of Technical investigation are rarely associated with thin-tile vaulting. This is due to the predominance of the Art Schools in thin-tile vault studies about Cuba. The story of schools offers attractive cultural, structural and political complexities for researchers to explore.
Chapter 02

Since 1980, the project has been a debated subject among scholars interested in modern Cuban architecture and architect-restorers interested in finishing the schools. The ruin alike and dispersed shells of the unfinished structures have contributed to magnifying, sometimes romanticising, the meaning of their architecture and the choice of materials, including thin-tile vaults. The archives and pictures have led to interviews and site visits, all offering access to a complex and evolving building strategy of experiments that were later translated into buildings. The research adopts drawing and digital modelling as a methodology to interrogate the archival findings from regulation tables and pictures of housing blocks.

The collected archives and the methodological approach of modelling reveal that while ENA’s enthusiasts usually accuse MICONS of ignorance about thin-tile vaults, the Ministry conducted an in-depth series of investigations for both reinforced and unreinforced ceramic shells. Shells were employed beyond the Art Schools to nationwide use in housing blocks, schools, recreational and industrial buildings.

While less monumental, these projects were no less significant. The importance of their study stems from three primary reasons. First, a survey of thin-tile vaulted projects in Cuba consolidates a better understanding of the Art Schools and the use and adaptation of ceramic vaults after the Revolution. Second, because it was institutionalised and used in projects by MICONS, thin-tile vaulting as a technique cannot be central in the dispute between the architects in the schools and their counterparts in MICONS (Loomis 1999, 112, Paradiso 2016a). Instead, one can shift the discussion from what is believed to be MICONS’ mistrust in the technique to a mistrust in the application and the expressive formalist approach, evident in the schools’ structures. Lastly, the study of a state-led initiative to investigate thin-tile vaults nuances the over-contrasted image of traditional versus prefabrication construction in Cuba after the Revolution.

2.2.3 Early Experiments

The Revolution marked a pivotal change in Cuban architecture and construction. The scope of the production of the built environment had drastically widened. Many leading practitioners and architects left the country to the U.S or Europe. Architectural students, mentees, and young architects entered on the heels of their fleeing teachers. Foreign architects came to Cuba from Latin America and Europe (International Union of Architects 1963, 41; Zardoya Loureda 2015).

The housing budget doubled between 1959-1960, many investigation entities were created for rural, urban, and self-built housing. The regional, rural, and urban planning was done in the Department of planning (Departamento de Planificación Física) in MINOP. For the construction of new rural and urban housing units, three separate governmental entities were created: Instituto Nacional de Ahorros y Viviendas (INAV) in 1959, Viviendas Campesinas in 1960, and Dirección de Viviendas Urbanas in 1961. To rehabilitate existing houses, help for inhabitant was provided through the program Ayuda Mutua y de Esfuerzo Propio, which was part of the 1959 plan to eliminate unhealthy urban neighbourhoods (International Union of Architects 1963, 35; Hernández and Loureda 2015, 39).

Schools also doubled in Cuba after the Revolution, and MICONS had teams dedicated to designing schools. In Cuba, the year 1960 was pronounced the year of education, illiteracy was eliminated for more than one million persons, most of whom were in remote villages. School construction and repair was partially made by the Ministry of education (Zardoya Loureda 2015, 9).
Policy Approaches to Thin-tile Vaulting

Figure 27 A. Left: Juan Campos (Architect) and Alfredo Perez (Engineer), first brick vaults experiments after the revolution, Azorín Ceramic Factory, Camagüey, 1960 (Juan de las Cuevas Toraya, Restaura). B. Right: another experiment in Santiago de Cuba, 1960. (Juan de las Cuevas Toraya, Restaura).

Figure 28 Juan Campos, Cabañas in Santa Lucía, Camagüey, 1960 (Juan de las Cuevas Toraya, Restaura).
Under these entities, architects, engineers and students were assigned specific topics in the building industry, such as ceramics, concrete casting, plumbing, industrial plants (Rolando 2018). Because the groups were small and dispersed across governmental bodies, architects found freedom from the restrictive processes of codes, justification, and centralisation. Their interpretation of how a building should be made was accompanied by their vision of what the architecture of a building should offer— a pattern that would change in later periods of centralisation.

In their initial attempts to work with the Cuban resources at hand, it was natural for architects working on ceramic to head to Camagüey, the central-eastern province with a long brick-making tradition. In March 1960, two collaborators from the ceramic investigation unit, the architect Juan Campos Almanza (1930 – 2007) and the engineer Alfredo Pérez, built the first test of a brick vault in Cuba after the Revolution (Figure 2a) (Cerámica Armada 1962, 2,76). The test was made in a then famous brick and ceramic factory called Azorín near Camagüey. The factory was of family Azorín before the Revolution, it was expropriated in 1960 to be called Antonio Suárez Domínguez.

The bird-like double vaults were built with bricks on sliding formwork. Campos implemented the test in his design of beachfront houses (cabañas) in Santa Lucía, north of Camagüey. This first vaulted project in Cuba after the Revolution took only 40 days to build (Figure 3) (Cerámica Convencional 1965, 2–4). The early tests highlight an immediate interest in Cuba’s established ceramic industry, expropriated and governed by the state. Factories were needed to continue producing bricks for construction in Cuba (Rolando 2018). However, finding new alternative material for vaulting was also important. Later in 1960, another vault test took place in Santiago de Cuba but was for cement, not terracotta brick vaults (Figure 2b).

2.2.4 The Seed: el Patio de MICONS

In 1961, the early dispersed investigations on materials and construction across the country were gathered under the direct supervision of MICONS in the Center of Technical Investigation (Dirección de Investigaciones Técnicas), led by Hugo d’Acosta Calheiros (1932-2010). In December 1960, offices for the centre were built behind the MICONS building (Figure 4). The two-story office building itself has barrel cement block vaults on the upper floor. The experiments and construction tests took place in the courtyard between the ministry building and the new office building, famously called el patio de MICONS. Starting from 1960 and until its relocation in East Havana in 1965, the centre’s work incorporated systematic ceramic experimentation for structural building elements. That included unreinforced vaults (Cerámica convencional), reinforced bricks and tiles structures (Cerámica armada), and flat ceramic panels for walls (Paneles) (Cerámica Convencional 1965; Cerámica Armada 1962).

Campos led the architectural team in the investigations on ceramics. The architect is known for the design and construction of the Cuban Pavillion in La Rampa with the engineer Maximino Isoba in 1963, but his contribution to the investigation and construction of vaulted buildings is never mentioned. Following graduation in 1956, Campos joined the Ministry of Construction after the Revolution, where he worked in the Department of Technical Investigations; then left Cuba for Miami in the late 1980s. Most of his work on ceramic experimentation was made between 1960-1962 and published in reports by MICONS between 1962 and 1965. The work of many investigations, including the one of thin-tile vault, was published in 1965, which could be considered the closure of five years of diverse research and opening a new phase of investigations on reinforced concrete. The publications by MICONS (Figure 5) explain in detail the ceramic shells research, namely the reasons, labour, tools, materials, load tests, structures, typologies of forms, and results with built examples of vaults.
Reasons

From the outset, MICONS publications on ceramic construction acknowledge the "conventionality" of the use of brick and tile vaults in contrast to the "futurist" approach of prefabricated reinforced bricks and concrete. The justification for the use of fired brick was the lack of steel to reinforce and wood to make concrete formwork. However, a pertinent reason was the needed social and economic support to the brick industry in Cuba. Aspects like the aesthetic and environmental performance of vaulted spaces were not mentioned as reasons, and they were more as observations than systematic testing. In fact, later reports in 1965 criticised brick vaults for their poor isolation and waterproofing. ("Construcciones Escolares" 1965). There was a fear of an imminent loss of this knowledge, caused by the emigration of many builders and owners of ceramic industries after the nationalisation of many factories and workshop.

In addition to the nationalisation, there was a transition from small scale to large scale production. Small farmers' land was concentrated in cooperatives or large state farms. Artisans abandoned their small workshops to be concentrated in large industries called "consolidated". In the case of construction, small artisan production workshops were replaced by large industrialised production plants. This was reflected in 1963 reports about Cuba’s construction (International Union of Architects 1963, 41).

Therefore, the historical role of brick construction in Cuban architecture was pressing. The report Cerámica convencional framed the brick industry as being "...known for many centuries by tradition; now it is losing its secrets when discontinued and replaced by more practical and less noble methods. Our interest in using all the labour force and methods, as well as finding this historical justification, led us to investigate the artisanal technique of brick for roofs and slabs." (Cerámica Convencional 1965, 3).

Tools and Labour

The experimental work on tile and brick vaults was accompanied by training of labour. A school for tilers (rasilleros) was organised in the courtyard to build experiments. The training was extended to actual projects around Cuba so that "...while the research staff were experimenting, they were also training groups working on them." (Cerámica Convencional 1965, 3).

However, workshops in project sites were different from the central one in the courtyard. The training in a project site, such as in the Art Schools, was more technique practice, where tens of workers built 2 to 3-meter span arches to master the tools and movements. This was not the case in the courtyard, where training explored new possible typologies, materials, and reinforcement methods, necessitating an inevitable and close collaboration between builders and designers for the making, testing, and observing of the structures (Figure 6).

MICONS’ reports highlight an implicit relationship between tools and skill. Brick vaults need full shuttering, whereas tile vaults need little temporary support but greater skill. Furthermore, a changing labour/tool relationship is linked to the builder’s learning progress, "...work was carried out with full shuttering first, then simple sliding wooden formwork, then with formworks and strings, and finally building in the air". The formwork systems with which the Cubans worked were very similar to ones in Spain in terms of using wood frames, strings, and wedges for centring and decentring seen in the books of Moya and Truño (Moya Blanco 1947; Truño i Rusiñol et al. 2004; Cerámica Convencional 1965, 3). Finally, labour relation to the time was quantified: 1 square meter of a brick vault with the second layer of tile vault will need 27 bricks, 27 tiles, 0.03 m³ of wood for shuttering, 4 kg of rapid cement, 0.05m³ of mortar, and one and half hour of one labourer’s time (Cerámica Convencional 1965, 39).
Chapter 02

Figure 29 Office building in the back of the Ministry of Construction, 1960 (Juan de las Cuevas Toraya, Restaura).

Figure 30 MICONS, Publications of the Department for Technical Investigation, 1960-1965 (Authors photo)
Materials

MICONS reports on ceramic construction emphasised the reliance on local resources. Brick production in Cuba, often concentrated in the central and far western part of the island, had a good reputation among architects and engineers. While Cuban brick factories continued to make bricks for the Revolution in the 1960s, MICONS architects and engineers realised the need to activate their architecture role in Cuba. Samuel Rolando stated that “I repeatedly called within the Ministry of Construction for the use of fired ceramics as it is essential to produce high-quality housing and buildings... it was not only about vaults and domes, but also about walls, floors, and window frames, made traditionally or prefabricated” (Rolando 2018).

The bricks and the tiles used in experiments and construction existed in the Cuban construction market, often used for walls or ceilings. The lengths and widths of the three standard Cuban ceramic units are 140 by 280, 135 by 270, or 200 by 200mm, the difference between the tile and the brick is determined by thickness: tiles are 30 to 50 mm while bricks are 100 to 140 mm thick.

Builders used hollow and solid blocks, with the condition that any brick must have an average compressive strength of ~1,500 psi (~10 MPa), measured from at least five blocks. Some arches and vaults were also built from voided hexagonal blocks traditionally used, among other shapes of ceramic bricks known as Celosía, as permeable or decorative surfaces in walls facades (Cerámica Convencional 1965, 52). The fast setting mortar used in the construction of the thin-tile vaults was plaster of Paris mixed with cement in a 3:1 ratio. The mortar for the additional thin-tile layers was cement and sand in a 1:3 or 1:2 ratio. The mortar of the exterior finishing of the vaults is often made up of cement and lime to seal the vaults to avoid water infiltration (Cerámica Convencional 1965, 15). The only two reinforcement examples in the pamphlet of Cerámica Convencional are a flat slab construction where the ceramic’s role was as a mould for the reinforced concrete slab and reinforced brick panels prefabricated on-site from hollow ceramic making them lightweight for the labourer to lift and assemble. Reeds were also mentioned as reinforcement for ceramic, without further elaboration, tables, or drawings (Cerámica Convencional 1965, 2).

Tiles and bricks were also used in reinforced shells and slabs, which was a departure from the traditional vaults method in Cuba and was published separately in a pamphlet called Cerámica Armada. Reinforced Masonry in the Ibero-American architecture went hand in hand with the development of concrete construction. During the 1950s and 1960s. Dieste’s reinforced ruled surfaces and Gaussian vaults were introduced in South America. Luis Moya used reinforced ceramic for his hyperbolic parabolic in the Chapel of Santa Maria del Pilar College (1956). Eduardo Torroja’s design for the Pont de Suert church incorporated reinforced ceramic shells (1952) (Mosteiro 1996; Ochsendorf and Bernardo 2003).

Load Tests and Structural Analysis

After the vault construction, load tests were conducted using cement blocks of 31 kg. The tests were made for both uniform and concentrated symmetric and asymmetric loads (Figure 7). The results were observed in three different categories: collapse, breakage or cracks, and resistance. The results were modelled and registered. Most of the repeated load tests were for small-span barrel vaults.
Figure 31 Tile-vault different training styles, top: training in the school of arts (Photo courtesy: Roberto Gottardi), and bottom: training in the courtyard of MICON, 1961 (Juan de las Cuevas Toraya, Restaura).

Figure 32 Tile-vault: symmetrical and asymmetrical load tests, 1961 (Juan de las Cuevas Toraya, Restaura).
The load tests were contrasted with the vaults’ structural analysis made by rules of thumb, fundamental equations, and form-verification using graphic statics. In the vault’s structural analysis, the equations are 1) chord and point of a circle, 2) the total load for 1 m strips of the vault, and 3) the Goldenhorn equation for the minimum thickness of the vault. The Goldenhorn equation is from the study of the Argentinean engineer Simon Goldenhorn (Goldenhorn 1960, Cerámica Convencional 1965, 43–45).

After defining the span and height, graphic statics was used to modify the vault’s shape and thickness to maintain the line of thrust in the middle third of the vault, usually resulting in a catenary section. In vaults with large spans, mainly larger than 6 m, the thickness change was expressed in the number of layers decreasing towards the shell’s upper part.

Constructability and Typologies of Form

Two complementary strands of research can be noted in the shell experiments in the courtyard of MICONS. The first has to do with the geometric possibilities of unreinforced shell structures, while the second is about the tools and formwork used to realise such geometries. The team in the courtyard had two families of vaults: singly- and doubly-curved surfaces. One can imagine that the relationship between the formwork use and the vault’s span is relatively straightforward: the less span, the less formwork. However, studying the courtyard experiments suggests that such a linear correlation is not accurate. Formwork has more to do with geometry’s nature as single or double curvature rather than the size. Barrel vaults of bricks and tiles were usually built over a robust shuttering, which incorporated three advantages. First, the finishing of the vaults in the interior was part of the construction. Second, full shuttering helps moderately skilled labour. And finally, vaults can be identical for their mass production.

Notwithstanding those advantages, the objective in using full formwork for barrel vaults is their nature as singly-curved surfaces, as it is hard to place tiles or bricks in the upper parts of the shell for the lack of the three-dimensional curvature.

Campos and his team had a clear incentive to understand the behaviours and potentials of doubly curved surfaces in reducing the use of formwork materials and spanning better to cover large spaces. The change from single to double curvature happens when the vault span exceeds 8 meters, and doubly curved surfaces become advantageous for the vault’s stability and constructability. Drawing the instruction of using formwork suggests that when a vault is more than 8 meters, two formworks should be placed along the curve, forming a rail on which a sliding frame runs, converting the structure from barrel to sail vault (Figure 8) (Cerámica Convencional 1965, 39).

These structures were built in the patio with formwork minimally placed in the edge arches (Figure 9). The simplest doubly-curved structure built in the courtyard was a 4 x 4 m sail tile-vault on a ring beam (Figure 10). Like all small vaults and arches, the two-layer vault was load tested. The second was also a sail vault covering a 6 x 6 m square but sprung from buttresses instead of a ring beam. To this vault, the designers added eaves (aleros) that fly from the edges as counter-curves, the lip-like shape of the eaves cantilevering more in the middle than in the corners (Figure 10).
Figure 33 From single to double curvature by adding a formwork on the sides, interpreted from the guide of building vaults in Ceramica Convencional.

Figure 34: MICONS, drawings of some of the vaults realised in the Courtyard (Ceramica Convencional 1965).
The 6 x 6 m base was also used for exploring an inverted paraboloid hyperbolic, which is simply an upside-down version of Candela's concrete umbrellas. If we can place domes as a subcategory in the family of the doubly-curved surfaces tested in the courtyard, the paraboloid hyperbolic would fit better in this category than in one of the vaults. Another more geometrically pronounced dome was a corrugated radial vaults surface, called *jardinera*, that sat on six pillars shaping a hexagonal dome (Figure 10).

The largest doubly-curved structure that existed in the courtyard of MICONS was a 15-meter sail tile-vault. The span of 15 m is the maximum seen in the investigation's tables about vault characteristics and specification. This shell was built with side and diagonal formwork. Similar to the small 6 x 6 version, the sail vaults had cantilevering *aleros* but with less proportional projection and many more layers. There were six layers of tiles at the edges and 2 in the centre. The buttresses receiving the vaults were open, visually light and elegant, and made of vertical brick elements with angled support of reinforced concrete tied by invisible underground tension rods.

This specific sail vault structure serves as an excellent example of structural efficiency and material optimisation represented using catenary sections, different layers of tiles, and lightened substructure. By design and experiment from the investigation group of Campos, the 15 m sail vault could achieve this efficiency. The only structures of a thin-tiled surface without concrete ribs and with greater span in the Art Schools are the workshops' domes in the School of Plastic Arts by Ricardo Porro. Figure (11) shows all the built vaults drawn from images, documents, and illustrations.

For standardisation of vaults, MICONS' technical investigation team worked on small and mid-span singly curved vaults for houses, beach houses, schools and small outdoor pavilions. They channelled the standardisation through four tables, presented in the pamphlet *Ceramica Convencional* for architects, engineers and builders to use for vaulted roofs.

The tables indicate: 1) vault span to rise ratio, 2) section and layers details, 3) elements such as tension rods and ring beams, 4) details of moving formwork and guidework. All vaults in the tables have a parabolic section. The curvature is determined by a span to height ratio of 1/5; hence vertices are given to find the catenary section according to the desired span of 3, 3.5, 4, 5...15 meters (Figure 12). After finding the vault curve, the span also determines three more elements: the unit being tile or brick, the layers, and the detail of rib. These elements are explained in the forms of sections of the details. Formwork tables are more suggestive of the shape and construction of the wooden formwork. However, observing the construction of the large 15 m span vault in the courtyard suggests that the drawings of vault formwork were rigorously followed (Figure 13).

The regulation tables were used to produce many vaulted projects in Cuba and hence are equally applicable today to speculate on the construction details of these buildings. For example, knowing that the main span for rectangular rooms in rural and urban houses is 3 to 4 m, one can reasonably infer that the barrel vaults of these rooms are either one brick and one tile layer three tile layers. For vaults between 10 and 15 meters, one can infer that five layers of tiles would have been used with tension rods and ribs that repeat along the section with a spacing equal to the span (Figure 14). Indeed, other MICONS pamphlets confirm the use of the table in construction. The description states that catenary sections were used in one about urban housing blocks, and vaults were one layer of brick and one layer of tiles (Viviendas Urbanas 1964).
Figure 35: MICONS, photos of vaults realized in the Courtyard (Ceramica Convencional 1965 and Restaura).
Figure 36: MICONS, all unreinforced tile- and brick vaults that were built in the courtyard.
Figure 37: Table for Parabolic vaults, note the table of spans, thickness, and the details of layers and stiffening arches (Ceramica Convencional, 1965).
Figure 38. Table for Tile-vault formwork, bracing, and details based on span (Ceramica Convencional, 1965).
2.2.5 Systemising Vaults

The experiment in the courtyard of MICONS had two families of vaults: Small to mid-size single curvature vaults and mid to large doubly curved vaults. Large span vaults were not meant for a load test-to-collapse like the small ones but were more proof of how large vaults can be built. Large vaults were kept in the courtyard. Images from later years of the courtyard show that the 15 m sail vaults were converted into a big room annexed to the Ministry’s building (D’Acosta 1964, 52). Here we can observe the discrepancy between the work on vaults led by MICONS and the architects’ work in the Art Schools. Campos and his team were more interested in vaults’ national-scale application by systemising their production and design for repetition, modularity, and composition. The Art Schools’ architects approached thin-tile vaulting from a geometrical understanding, where the vault as an element is expressive and unique, making it hard to be systemised for production. The clearest example of this discrepancy is the corrugated dome in the courtyard of MICONS. The 9 m diameter structure has appeared in publications about the Art Schools where it was used to explain how Gumersindo showcased tile vault to personnel in MICONS (Loomis 1999, 33; Garatti 2016, 87). However, precise drawings of sections, plans, and perspectives with details of construction suggest that the Jardinera has been thoroughly drafted, if not designed, by workers of MICONS. Whoever built the dome had no intention to study it as a systemised construction rigorously, nor was it subject to any load-test, nor did it impact the systematisation of vault construction in the study of the MICONS team (Cerámica Convencional 1965, 38). It was realised to explore the possibility of the craft of tile vaults to produce complex structures that were only imagined as an individual element or pavilion. However, while briefly mentioned in the studies of Campos, the dome did have an impact on the design of the schools and reappeared in their language of domes and vaults. This impact became clear during the digital modelling of this dome using the schematic plans and sections in the MICONS report (Figure 15). The digital model offered the possibility of understanding the structure from different angles that archival pictures did not. The geometric articulation of this structure was influential on the forms the main halls in Porro’s School of Dance and the unbuilt central hall of Garatti’s School of Music. Both domes are corrugated but with reinforced concrete ribs that were introduced in the intersection of the vaults’ surfaces.

Campos and his team’s investigation supported the use of tile vaults in construction. They were open to pushing the boundary of the design-led geometry of vaults for playgrounds and pavilions. However, their focus was on having rigorous guidance for labour-led systemised construction of simple elements. Most vaults were designed to be repeatedly applied for the construction of houses and schools in a conventional or partially prefabricated manner. Their goal was realised. Many vaulted projects were built in Cuba, and many survive in current use today.

2.2.6 Vaults in Cuban Buildings

One model, many times

Parallel to thematic investigation in construction after the Revolution was implementing prototypes for buildings in different locations in Cuba. These buildings were made with on-site construction but with modular elements that were also prefabricated on-site. This early thinking of modular design and on-site prefabrication for building components, called semi-prefabrication, has resulted in a much richer body of methods than what came afterwards with full prefabrication industrialised building manufacturing.
Figure 39 Verifying the implementation of formwork standardization. (Authors’ drawing over an image from Restaura)

Figure 40 Left: Ricardo Porro, School of Modern Dance, Havana 1961-1964 [Paolo Gasparini. Courtesy of John A. Loomis]. Right: Jardinería test model in the courtyard of MICONS (Author’s drawing)
An example of modular design thinking is the 1961 prototype of the circular market by Frank Martinez, whose variations were built in several locations in the country. Depending on space and budget constraints, some markets were only half circles while others are complete, forming open courtyards in their centres (Zardoya Loureda 2015, 8). This method offered an exchange between investigation and implementation within MICONS. After the investigation team proposed a building prototype, other architects took the seed model to implement it. This resulted in various architectural solutions for the same structural elements. For example, while the vaults were the same for a housing block, the walls, spaces, and facades differed among the repeated projects.

**Housing**

Being delivered by the State, the housing supply in Cuba right after the Revolution was channelled via several entities. One of the most recognised paths was the Instituto Nacional de Ahorro y Viviendas (INAV), a mere continuation of the conventional construction approach before the Revolution. INAV interests lay more in delivering high-quality houses than the inquiry and experimentation with mass production of houses for Cuba (Hernández and Loureda 2015). Parallel to that path was the Department of Houses and Other Buildings (Departemento de Viviendas y Otros Edificios) at the d'Acotsa's Center of Technical Investigation. The Department's inquiry concerned economy, applicability, and advanced construction technology, and its criteria were about cost, time of construction, and manufacturing and maintenance methods. A team also headed by Campos initiated a pilot project of housing blocks in Altahabana, south of the Capital. In the housing project, Campos started to translate his work at the Center of Technical Investigation into buildings.

The Department of Houses and Other Buildings' work was also published in 1964 by the centre of technical investigation (Viviendas Urbanas 1964). The report, called Urban Housing (Viviendas Urbanas), presents the work in Altahabana on seven experimental buildings that later became models for diverse housing projects in Cuba between 1961-1964. All seven buildings had three stories, with symmetrical apartments on each floor. The structural elements in the seven buildings are the load-bearing walls, beams, and prefabricated slab panels. The investigation examined the composition and articulation of these elements, the details where they meet, and their production method. This examination had implications on the general design of the apartments, spaces of living, areas of services, the openness of plans, and furniture, and all these elements were part of the discussions in all experiments. Experiment 1, 2 and 3 had load-bearing walls parallel to the facades and prefabricated flat concrete panels placed on transversal beams. It is not until experiment 4 that vaults started to appear (Figure 16). The use of vaults was derived from the intention to incorporate the ceramic material in the building's structure. The 1.5 m span vaults were only built for the ceiling on the top floor, as the first and second-floor apartments had prefabricated flat brick panels on beams. This first urban housing block with vaults was generalised and built in Havana and Manzanillo in eastern Cuba. Such deployment was not only because of the efficiency in cost, represented in the use of certain prefabricated elements alongside on-site construction, but also the architectural approach of the flexibly partitioned living spaces (Viviendas Urbanas 1964, 32–42).

A turning point happened in the apartment layout of experiment 5 and 6, in which the direction of load-bearing changed from parallel to the facade to perpendicular, making spaces for three 3.5 meter wide bays for each apartment (Figure 16). This change created a flexible and large daily living area. After the timid introduction of 1.5 m span vaults in the previous experiment, the vaults now span 3.5 m. Again, vaults were only used for the last floor, with prefabricated panels in lower stories. The vaults were made of bricks using a sliding formwork to make one layer of brick and one layer of tiles; this solution corresponds to the table of vaults detail concerning the span. All vaults in the buildings have parabolic sections (Viviendas Urbanas 1964, 71).
Experiment 5 failed on cost inefficiency resulting from making the service space indoors, which added extra cost for fixtures and plumbing. The inefficiency was obviated in Experiment 6, which formed the seed that Campos and his team gave to architects in MICONs to use in Cuba’s housing projects. The basic configuration of the housing block comprises a staircase with a permeable facade leading to two apartments on every level. Each apartment is a three-bay of load-bearing walls of living area, service area, and sleeping areas. The promoted advantages in the vaulted urban housing model were bricks instead of concrete and the easy draining of water in the rainy Cuban climate. The research team saw an advantage in using vaults in urban housing projects for water drainage in the roof. The prefabricated wing beams *aleros* were also equipped with water channels for drainage and treated with lime cement for their impermeability (Viviendas Urbanas 1964, 46). From the experiment in Altahabana, architects of MICONs used experiment 6 to generalise and repeat throughout the country. The apartment plans and structures were kept similar, but variations were introduced in window details, the staircase location, facade openings, and the construction methods used to erect the buildings. Three main areas in the Capital were developed with this typology. In Vedado 24 (between 13 and 15), the architect A. Cauto Ramos used the vaulted typology with the same construction tools of brick vaults and sliding formwork (Figure 17). In Plaza de la Revolución, 24 housing units were built by the architect Angel Cuervo, but the vaults were built on full wood shuttering (Figure 17).

The third location of vaulted urban houses in Havana is in Ciudad de la Construcción (Figure 17). Located in the south of Havana, the development is imagined to host 21,424 inhabitants in conditions that are similar, if not better, to the luxurious private housing developments that used to happen in Cuba before the Revolution. The planners and architects believed that public housing programs could offer the same for everyone; the project’s description used the 1955 La Hague declaration of IUA about housing being a right. The early description of the project in 1960 boasted about the 90% unbuilt open area in the projects such as parks, playgrounds, and public areas, surpassing the 87% average in the luxurious private housing development in Cuba before the Revolution (MINOP 1960).

The project was initiated in 1960 before MICONs established the investigation on vaults, with the original proposal lacking vaults completely. By introducing the house as a right and not a privilege, the project was imagined as a “city” for builders that challenged the capitalist approach in architecture by proposing a public housing project with high-end quality apartments and urban areas. The ambitious plans by Antonio Quintana showed two housing typologies: one-story semi-detached houses and multi-storey apartment buildings. The plans also had educational facilities for both schools and construction training centres for workers, and sport and service zones. This extension of mega planning from before the Revolution was evident in some projects after the Revolution, such as Ciudad de la Construcción, the first neighbourhood (*unidad vecinal*) in East Havana and the educational city Ciudad Libertad.

However, the plans and the concept of luxurious public houses went through serious reconsideration, and criticism resulted in severe cuts to the project’s budget. Samuel Rolando was the site architect for this project, working for Quintana. He recalls that just before starting with the construction using the original plans, Ernesto (Che) Guevara has asked for an immediate meeting with Quintana to discuss reducing both the areas and the costs and increases the number of apartments. Quintana and his designing team had to redesign the units; they introduced the vaults in many buildings’ design (Rolando 2018). Plans and the design had to be redone in 1961, and vaults were introduced as part of the cost reduction procedures, following the structural solutions investigated in Altahabana.
In Quintana’s vaulted housing blocks, the ground floor is an open public space with load-bearing walls supporting catenary arches. Staircases are projected outside the building, avoiding building a specific bay for a staircase area, and vaults are added in the upper story. Vaults were also used in row houses and primary school buildings (Figure 17). All vaults in the project are brick vaults with a catenary section. From the 200-hectare area of the original plan, only 16 hectares were built between 1961 and 1964. The completion of this first (and final) phase was celebrated in the Congress of Construction in Havana in October 1964.
Figure 42: Various architects, vaulted housing, Havana, 1961-1965 (Juan de las Cuevas, Toraya, Restaura)
The one-story and vaulted row houses in the Ciudad de la Construcción are not the first of this kind. The earliest rural vaulted houses were in Alamar in East Havana, where about 400 houses were built by MICONS, designed by Enrique Cano (Figure 17). Alamar houses are made of eight typologies, six of which are vaulted and two with reinforced concrete slabs. In the vaulted typologies, three are individual, and three are semi-detached or duplex. Similar to the approach in the Ciudad de la Construcción, the urban and architectural solutions were tailored for high standards of urban housing, including vaulted covered areas for parking, unfenced front gardens, and extensive back gardens. Part of the area of Alamar was later designated for foreign experts and engineers of exchange programs in Cuba, hence the popular name of the zone as Houses of the Russians (Casa de los Rusos). The houses also served as student's residence in the early 70s being part of a university branch of Polytechnic José Antonio Echeverría (CUJAE) in Alamar. In the late 1990s and early 2000s, the individual vaulted houses served as temporary accommodation for those in the list for accommodation in the large housing blocks in the area.

The vaults in the houses are all made of brick and cement over full modular shuttering. The vault substructure is ring beams and load-bearing walls. Two houses are different from anything else in Alamar (Figure 17). Perhaps as an extension to the bird-like vault experiment by Campos in Camagüey, the two houses have similar vaults. The houses' design is included as an annexe in the 1964 publication of MICONS called 'Viviendas Rurales'. The bird-like vaults in Alamar's two houses were justified to eliminate the load-bearing walls, "so the vault reaches the ground and integrates the ceiling the wall". The summarised advantages and preconditions of this way of building are "the availability of labour, the minimum use of wood in the shuttering, the prefabricated mould, the savings in cement, and the eliminated use of steel." (Viviendas Rurales 1964).

**Schools**

The emphasis on educational progress in Cuba after the Revolution was also of great interest. More than 250,000 schools were built in Cuba between 1961 and 1964. Schools had doubled in Cuba from 1957 to 1964. In addition to the conventional education of primary and secondary program. Cuba has introduced many other preschools, pre-university, vocational training, and childcare centres called Círculo Infantil. The latter was made to help women reduce their maternity leaves, maximising their working time and participation in public work (Zardoya Loureda 2015).

This demand for new facilities also translated into an investigation to build schools with fast, off-site and mass production systems that prompted modularity in designing and constructing educational facilities. Like housing, the early models of schools offered generous design autonomy, an approach that would later be replaced with a much narrower understanding that focused on industrialised elements. Ceramic materials and structures were also part of investigations into school construction from the outset.

The earliest vaulted education facility was a childcare centre in Havana designed by Marta Ontiveros (Figure 18). The building has a U-shaped plan with tile vaults over beams. Both architecture and structure in this building were subjects of experimentation. For primary schools, one of the most pronounced vaulted school models was the one developed by Mario Girona (1924-2008) of 7-14-21 classroom expansion (Figure 18). Primary education in Cuba has six grades and one preschool level, hence the number 7 forms the modularity base. Five long parallel rectangular bays bring about the primary school model with barrel vaults resting on their load-bearing walls, following the unit’s long direction. Two bays in the middle are voided with a courtyard for outdoor classrooms.
Many schools with this model were built across the country. In Havana, the highest concentration of vaulted schools is in the western extension in Marianao where more than five schools can be found today. The schools of Marianao are among the earliest developed with vaults and had an essential impact on the repetition of the model in the rest of the country. However, the model was criticised for having large rooms, poor orientation, and open circulation areas ("Construcciones Escolares" 1965). Another improved model, mostly used for secondary schools, arranges the vaults perpendicularly around a central courtyard, allowing beams and vaults to project from the exterior walls and shape a covered movement area. In this model, classrooms were smaller, and the vaults were shorter, reducing the probability of suffering cracks due to the long extrusions. This design has been reported in Ceramica Convencional as the work of Dorta Duque. The architect could be Jorge Dorta-Duque, whom Fidel Castro has assigned to the program Changing Quarteles into Educational Cities (Convertir Cuarteles en Escuelas), but the architect left the country after a short period (Dorta-Duque n.d.).
work on architecture for education continued under Josefina Rebellón in MINOP, who also designed and built vaulted secondary schools with similar typology in Minas, Camagüey (Figure 43) (Hernández and Loureda 2015, 70).

In 1965, a report about the construction of schools in Cuba recognised the widespread use of vaults in school construction on the island ("Construcciones Escolares" 1965). However, the report also identified several problems with the vaulted school typologies. Vaults were criticised for being used without sufficient experience in their construction, being used without good waterproofing, associated acoustic problems, being unable to cantilever and, therefore, unable to make covered outdoor passages and suffer from cracks. This litany of criticism was usually put in comparison with the advantages of vaults in buildings for education, articulated as the scarcity of materials, the construction with people from the neighbourhood, and the possible application of different materials such as concrete, brick, or tile for the same geometrical solution.

The sixth tile-vault school in Havana

One of the Cuban Revolution’s first missions was the transformation of military camps and barracks into educational facilities. In addition to thirty-some small Quarteles, six large military camps were studied to become cities of schools and institutions, including the Columbia Camp in the west part of the city near Marianao (International Union of Architects 1963; Zardoya Loureda 2015, 5,19). The camp was named Cuidad Libertad (Liberty City) and was planned to accommodate schools and recreational areas for 8000 students. Many of the existing structures were rehabilitated for those purposes, most of which were roofed using shells of concrete or bricks.

Figure 44 Josefina Rebellón, pre-University Centre, Ciudad Libertad, Havana 1961-1962 (Drawings from Restaura, images from Arquitectura Cuba (334) 1965).
In Ciudad Libertad, just 2 kilometres away from the National Art Schools site, another educational centre was built with tile vaults, standing in the landscape of the former Quartel. A pre-university institute was designed and built in 1961, the same period in which the art schools were under construction (Figure 18).

The building was designed by Josefina Rebellón, a third-year architecture student at the time, and she recalls: "most of us were students or newly graduated architects, the practising architects left the country" (Rebellón 2018). Rebellón was left with the challenge of the design of the project and the task that it should be finished in five months. Half of the 4500 square meter footprint building is tile vaulted; the other half was made with concrete slabs. The building was divided into three sections, two sections are vaulted rooms arranged circularly, and one is a linear two-story classroom that lies between the two circles (Figure 18). The division was made to reduce construction time by phases, first the classroom, second the block of laboratories, and finally the large seminar rooms and library. Workers experienced in tile vaulting were brought from MICONS courtyard.

Originally, all three sections were designed to have vaults, but the Ministry did not give as many thin-tile vault masons as needed to finish the project on time. The architect was left to use reinforced concrete flat slabs for the central linear section of the classrooms (Rebellón 2018). With this decision, the project carried on without the extensive use of skilled thin-tile vault labour and, in January 1962, the project was inaugurated on schedule (Figure 19). The 2500 square meter vaulted area is the nucleus of large teaching seminar halls and laboratories. These spaces have conical vaults with sequences of catenary-section arches. Most vaults have two layers of tiles of 120 x 240 mm with a thickness of about 30 - 40 mm. The largest vault has a 10 x 5 m span. The smaller vaults’ span is 5 m decreasing to 3 m. All vaults spring from beams that shape the intersection between the conical vaults. Each joint between the beam and vault has an extra layer of tiles that protects the joint from rain. The vaults continue in outdoor spaces, making them part of the landscape of the building. The facades’ openings were made with voided decorative ceramic block, called celosia, which enhanced its visual and functional permeability and integration with the green landscape of the site.

In this project, Rebellón did stray far away from many standardised elements of vault research. The elements of reinforced concrete beams, tile vaults, and ceramic facade treatment are very similar to, for example, the housing blocks of Angel Cuervo in Plaza de la Revolucion. However, Rebellón’s pre-university structure presents an understanding of such modular systems’ flexibility in the vault component. The change from barrel to the conical vault was possible because it is the only on-site construction element; hence it can be pushed by design for more complex geometries that can still be built quickly.

Other Constructions

In addition to schools and houses, vaults were also used for public projects such as factories, beachfront hotels, restaurants, and cooperative centres. The hotels in Playa Giron and Playa Ancón belong to another seed model employed in many Cuban beaches, which comprises one storey vaulted building (Figure 20). The hotel in Ancón is now being demolished to be replaced with a new building, and an outdoor vaulted canopy is the only structure left on the site. Cooperative cafeterias were also made in two vaulted models distributed on the island: the first is a pavilion of six half-circle barrel vaults on two parallel beams, a small block for services and storage at the back of the pavilion. This model can be found in the cooperative cafeteria in Ciego de Ávila and Granma. The second model is a much larger cafeteria in El Rosario in Pinar del Río, comprised of four vaulted bays of about 8 m span for each vault. One of the vaults is truncated and covers a terrace. Two closed service zones are built under the pavilion. Today, the cooperative cafeteria is almost in ruin from abandonment.
2.2.7 Vaults in the Cuban Centralised Industry for Construction

Improved Traditional Building

In September 1961, the construction of the School of Arts commenced. It lasted four years until it was suspended, and the schools were officially opened. Studies about the Art Schools frame the incompletion of the schools, and the criticism levelled several key-concepts, one of those is the shift from traditional building methods, including thin-tile vaults, to imported prefabrication methods. Segre and Coyula associate the adoption of the Soviet model of prefabrication with the destruction caused by Hurricane Flora in 1963 when the government of the Soviet Union offered a prefabrication plant to Cuba (Segre 2003, 33; Coyula 2011, 59). However, prefabrication was not merely imported from the Soviet Union, it was developed in Cuba before, during, and after the establishment of the Soviet Plant.

However, the vaulted projects of MICONS offer a more precise and nuanced understanding of the role of vaults and their relationship to prefabrication during the first half of the 1960s. One cannot suggest that MICONS mistrusted vaulting, as it was on its research and implementation agenda in many parts of the island. Vaults were not abruptly placed as the extreme opposite of prefabrication, nor were many elements inherited from Cuba’s conventional construction before the Revolution. Indeed, the path towards a form of industrialisation of construction started as early as 1960, but without disregarding the path of conventional prerevolution construction, called tradicional, as it continued in the work of INAV (Hernández and González 2015, 6). During the vibrant period 1960-1965, MICONS intertwined these two paths to hybridise building manufacture and on-site construction.
As a result, between prefabricado and tradicional, there was an interesting category called improved traditional (tradicional mejorado). The improved traditional construction is known for providing flexible concrete plate systems such as Pepsa and folded plates, but vaults are rarely mentioned to be part of it. Most of MICONS projects with vaults were placed in this category. In the report vivienda urbana, the improved traditional was defined as "a construction system that combines the traditional and the semi-prefabricated." (Viviendas Urbanas 1964, 65). One can define the improved traditional by the scale and number of the prefabricated elements, but a better definition is conveyed by saying it is prefabrication without huge mechanisation, it depends on the skill of labour not the potency of a crane.

Within efforts of using traditional and industrialised methods were combined with building regulations for construction. However, there was a flexible understanding of regulations as resources and labour skill varied in different regions. MICONS architects realised that "prefabrication starts with the codifying of the construction and ends with systems. All this should take into consideration the local materials, resources, and social factors of the society." ("Resoluciones Finales del VII Congreso de la ULA" 1964, 23). The technical reports about vaults were also documents toward codifying of vaults. However, what was systemised, in fact, is the formwork. The vault itself was not of interest to mechanisation or codifying as it relies entirely on the labour hand.

This construction approach considers local labour and materials and integrates them into the design thinking of prefabrication. The result is rules of building for components that can be made on site. Another result is lightweight and easily transportable components for concrete slabs and beams, while walls were made locally with bricks. This type of hybrid and design-oriented prefabrication would change after 1965 with total centralisation of construction. Reflections on centralised construction in Cuba started during the 1963 congress of the International Union of Architects (UIA) in Havana.

**UIA 1963- A Moment for Assessment**

The years 1963-1965 marked a phase of reflection on the first years of construction and investigation into building in Cuba after the Revolution. The International Union of Architects (UIA) congress took place in Havana in 1963 under the theme Architecture in Developing Countries (La Arquitectura en los Países en Vía de Desarrollo). The conference offered a pause-to-reflect moment, in which it was stated that a rigorous and critical analysis of the architecture of the early period after the Revolution (from 1960 to 1963) was needed. The analysis was summarised in the conference proceedings and a special issue in 1964 of Arquitectura Cuba and was designated to extend the conference's discussion. Likewise, and until 1965, reflective articles continued in the journal, alongside reports from conferences such as the National Seminar of Housing and Congress of Construction, both held in October 1964.

Looking at the previously mentioned reports, Cuban architects considered those early stages in which vaults were investigated as a temporary phase towards a comprehensive solution to construction problems in Cuba. In this phase, a confession was also made about the ambition of Cuban architects as bigger than the reality. This was expressed in the speech of Castro at UIA in Cuba where he said that "our aspiration [to provide houses for the people] is limited by the capacity of our construction industry." ("Discurso del Dr. Fidel Castro en la Clausura del VII Congreso de la UIA" 1964, 44). While the massive need for housing was considered as a right, the method of production had to change, as housing is not the result of small isolated constructions as in the way architecture traditionally happens, especially with a scarcity of materials and labour ("Sesiones de Trabajo del VII Congreso" 1964, 21).
The absence of a workforce and materials resulted in a budget difference between proposals and realisations, a problem translated in Castro’s words: “We must confess that we were also rather subjective at the beginning. During the first years of the Revolution, we often confused reality with desire” (“Discurso del Dr. Fidel Castro en la Clausura del VII Congreso de la UIA” 1964, 44, 69).

The solution was imagined in centralising the construction within the State. The small groups of investigations that were working on housing, rural housing, and construction were later merged with the MICONS. Under the goal: “total mechanisation of construction”, the mix of industrial building components and production centralisation was a way to recalibrate need and production (International Union of Architects 1963, 100). Furthermore, the total industrialisation of construction had an ideological aspect regarding the worker’s role and the role of the architect. The report from UIA 1963 stated that while Revolution changed the scope of the role and architects’ clientele, the tools and models of practice remained similar (International Union of Architects 1963, 85).

The change of the tools is in the mechanisation of the construction that “…will represent a change of scale in all aspects of [the architect’s] work. The projects will not be based on small elements such as the cement block and the traditional brick but taking into account the possible ideas that allow grand elements and panels… The new structuring of the society’s life will produce the role of the joint architecture as one of the main features of our architect in this stage.” (International Union of Architects 1963, 99).

Thus, the Revolution’s mechanised architecture was seen to offer an ‘opportunity’ and a ‘goal’ to explore new possibilities, similar to today’s big scale 3-dimensional printing of buildings and robotic construction. These social, economic and technical conditions posed: “a historical challenge to architects: create a new architectural and human language in an epoch when the architect for the first time delivers his work to the whole society” (International Union of Architects 1963, 86).

This universality of construction carried a veiled rethinking, if not a criticism, of the ‘traditional’ and ‘improved traditional’ construction. The improved traditional method was analysed thoroughly, for it was a fruit of the Revolution. After recognising its positive role in the early phase, claims declared the improved traditional construction’s insufficiency for nationwide use. The reasons given included the uneven distribution of building skills on the island and the lengthy construction site period. It was an accepted category of construction but a transitional one. In 1965, Hugo d’Acosta wrote in Arquitectura Cuba a summary of the office of technical investigation where he phased Cuba’s construction in three eras: the past construction of capitalism, the present investigation of possibilities, and the future application of selected possibilities. The vaults’ work was timidly mentioned in d’Acosta’s review, where he stated that some ceramic work was done for schools and houses.

In contrast to that was the work on systems prefabricated concrete (D’Acosta 1964). In d’Acosta’s list of future building techniques and task, vaults were not included. He stated that the improved traditional was set to be concluded in 1964, and full industrialisation would start (D’Acosta 1964). This acknowledgement about the role of vaults in similar construction in the period 1960-1963 suggests that perhaps it was not mistrust in vaults that led to their decline but the over trust in prefabricated concrete.
Post-amnesia: Vaults in Cuba after the 1960s

The work in the Department of Technical Investigations shows more shades in MICONS’s approach to construction that defies the over-contrast between the battling technical and artistic approaches in Cuba in the 1960s, a story that has been told by scholars including Juan de las Cuevas Toraya and Roberto Segre (Segre 1989, 30–31; Toraya, Santos, and Valdés 2001, 283). The Department did work intensively on vaults, but the investigation was forgotten or omitted. Segre and Toraya justified the creation of technical investigation as the first attempts of MICONS to industrialise the construction in Cuba, without any elaborate about the work of vaults or reinforced ceramics (Segre 1989, 254; Toraya, Santos, and Valdés 2001, 284).

This amnesia has affected the approach to vaults in Cuba in later years. In the 1990s and early 2000s, during the economic crises in Cuba known as the special period, construction materials became scarce again. Vaults reappeared in buildings known as ‘Movimiento de viviendas de bajo consumo material y energético’ Vaults, made with earthen thin-tiles instead of terracotta, were considered alternative technology for construction. Unlike the work in the 1960s, the new earthen tiles initiative was not thoroughly investigated structurally and architecturally.

Furthermore, the movement and the buildings did not have any mention or references to the work of MICONS on vaults only thirty years before the 90s economic crisis with similar circumstances. Unlike the buildings in the 60s, the 90s vaulted buildings were criticised for the low quality of material and construction (Couret 2009, 87; Coyula 2009, 26). The same centre of the technical investigation direction, now located in east Havana, has a slab system solution with thin-tile vaults but from stabilised earth, joined with cement over a sliding mould (Gálligo 2005; Bocalandro 2018). Today, the only construction of thin-tile vaults is linked to restoration projects in Cuba, directed by the vocational school Gazpar Mechlor Escuela Taller, a school annexed to the historian’s office Havana. Workers and engineers in the school had no associations with the work of Juan Campos in the 60s. Thin-tile vaulting started in 2000 with a workshop between Extremadura (Spain) and Havana, now vaulting is part of the program and has produced many buildings such as the Orthodox and Russian churches in the Old City of Havana (Al Asali 2016; Pedro 2018).

2.2.8 Discussion:

This study adds to the expanding research on thin-tile vaulting history in the Americas. Recent studies have shown architects, engineers and contractors transferring the technique to Germany and Belgium, usually patenting it with some modifications (Huerta 2017; Fuentes and Ine 2019). However, this study in Cuba presents a unique case where the state is behind the use of thin-tile vaulting’s documentation and experimentation. Possible future work would compare the mentioned examples as they all strived to industrialise tile vaulting construction. Construction during the first five years after the Cuban Revolution exemplifies an exceptional phase of intertwining a technical futuristic vision with scarcity-driven reality in building. The period was equally exceptional for brick and tile vaults when there was a systematic investigation envisioning them as part of an extensive list of building components for the first time.
The architect Juan Campos Almanza had an essential role in investigating and implementing vaulted buildings for MICONS. Having made the initial proof of concept investigation in 1960, he became the head of the teams in the Management of Technical Investigation, exploring traditional and reinforced ceramics and building the first vaulted urban housing in Altahabana (Figure 21).

Campos and his team brought bricks to projects of MICONS buildings, including the Art Schools in Cubacan. However, the team’s approach to using bricks and vaults in the Art Schools was different from any other MICONS projects. They pushed the materials and building techniques to new levels of geometrical explorations.
Notwithstanding the unique and innovative geometries, the construction and structural approach were not optimal; many of the shells used tile vaults to fill between extensive reinforced concrete nerves or beams, or have additional redundant substructures (Douglas et al. 2020). The schools’ inefficient structural use of tile vault was signalled in the 1970s by Eladio Dieste during his visit to the school (Segre 1989, 119).

Furthermore, although some vaults followed modular units in some of the school’s structures, many other vaults were individual elements. In contrast to the Art Schools, the architects in MICONS were interested in rationalisation: they explored the vaults’ modularity and the compositions generated from the repetition of one unit. This had implications for the ease and productivity in construction; singly curved structures could build...
with moulds or light formwork many times. The use of this modularity with formwork facilitated the engagement of unskilled workers to participate in the construction. Although not as architecturally and geometrically exceptional as the Art Schools, vaulted houses and schools were possible because there were reduced to repetitive and easy-to-build elements (Figure 22).

Between these extremes lies the example of the sixth thin-tile vaulted school in Havana by Josefina Rebellón, where a negotiation happened not only between the architect and the labour from MICONS, but also between the geometry and repetition in tile vaulting (Figure 22). The design made by a then-third-year architecture student uses the same MICONS elements, the prefabricated beam, the load-bearing walls or columns, and the vault. However, and because the vault is an in-situ construction, the repetition of the vaulted unit was possible to arrange as a segment of a circle, with the vaults made into conic shapes but remaining singly curved. With this articulation the architect managed to build the schools in five months as planned, compromising that part of it was flat-slab concrete for the lack of thin-tile vault builders. Today, like Rebellon’s school, many shells in Cuba are believed to be concrete shells but need to be examined; this research reveals that brick vaults were strongly present in MICONS projects but have been overshadowed and forgotten.

In recent years, efforts are taking place to protect and restore the National Art Schools in Cuba ("Keeping It Modern: Grants Awarded 2018 (Getty Foundation)" n.d.). The finding of this large body of brick buildings discussed here aligns with this effort as it reveals that the construction and structural language of the schools is shared with many other instances of Cuban architecture of that era. Similarly, the study calls to expand the design venture on the Art Schools beyond their singularity as monuments and consider them a reflection of a movement that produced many structures currently in need of documentation – a possible future work on Cuban vaulting history.

This study on the vaults in Cuba has examined the standardisation of thin-tile vaults as part of the state-led building strategy. The early improved traditional model of modular semi-prefabrication of light elements combined with the in-situ craft-based building was successful but conditioned with non-centralised government. The centralisation of building did not allow such a combination of craft and manufacture whose result is hard to be abstracted, coded, and decontextualised.

What the Cuban architect called improved traditional model is still relevant in tackling current construction challenges. The environmental emergency is driving efforts to use technology in construction for reasons related to resources and materials. What makes the improved traditional model important is that it uses technology not to produce building elements but to improve the dialogue between site conditions and builders’ skill. It is a model that concerns the accessibility of builder to technology and not replacing builders with technology. The improved traditional model combines two extremes in design, the scarcity of resources and the abundance of solutions.

Finally, the contribution of this section is also methodological. Using drawing and modelling and being aware of the construction technique in hand have been indispensable in making this piece. The work has constructed new elements and relationships in the Cuban vault’s genealogical tree (Figure 22). In this tree, almost every vault found in the archives is drawn and positioned in its temporal, geographical and geometrical conditions. Drawing and modelling become tools to understand and communicate simultaneously.
2.3 Vaulting in Syria: The Case of Al-Sharqyat in Damascus 1980.

2.3.1 Introduction

The second half of the 1980s in Syria was economically challenging. With the 1979 sanctions from the United States escalating in the 1980s alongside regional and internal strife, building materials became scarce (Human Rights Watch 1989; Perthes 1992; Sinjab 2008). Syrian cement factories were functioning, but steel was hard to find as an imported material, making reinforced concrete expensive. Builders and architects were forced to navigate new building methods and pushed the whole system of architectural thinking towards new boundaries, most of which were infused with a regionalist approach that claimed traditional construction as a solution.

Among many initiatives, one large-scale project was central in the 1980s movement of locally resourced construction. Al-Sharqyat, which means “the Orientals”, was part of a state-led housing project directed by the Military Housing Association (Milihouse). The project aimed at providing steel-free housing as part of the then newly built villages outside Damascus and Aleppo. Specific zones in these villages were designated for single-family houses a la Oriental, an expression that architects in Milihouse used to describe houses with vaults. By forgoing steel, the construction of the houses had to rely on compression-only structures. Barrel vaults of different sizes sat on load-bearing walls with arched windows and doors. After experimenting with different housing typologies, one prototype was generalised and repeated. In Al Sharqyat, vaults were not only a technical solution but also claimed as a representation of “rural” building in Syria. During the 1980s, when Al-Sharqyat was being built, vaulted housing was a debated theme in the region, usually promoted through the architecture of prominent figures such as Hasan Fathy and Nader Khalili. However, examining the Al Sharqyat case shifts the discussion towards vaulted housing in state-led projects at large scales and during times of scarcity.

The case has been previously presented in two studies about the use of crafts, vaults, and locally resourced construction in Syria (Abed 1988; Mousally 1988). The studies were made during the initial period of Al Sharqyat, during which the expectations were high. As this paper will show, this situation did not extend throughout the project’s construction, and vaults became a rather burden than a solution. Hence, there is a need for an updated and detailed study on key-factors, ideas, and persons involved in the project and the current status of vaults.

While this case study focuses on these two aspects, it also tries to uncover some elements in modern Syrian architecture, which little has been written about.

Global Context: Regionalism and Vaulting

In the early 1980s, the faculty of architecture became an independent department in Damascus university—twenty years after it was first constituted as part of the Fine Arts Faculty and then the Engineering Faculty. Teachers and students were influenced by global discussions on the significance of regionalist and vernacular construction. However, the influence did not come from writings or studies such as those of Rudofsky (1964) and Frampton (1983) but projects happening in the Middle East, specifically the work on Nader Khalili in Iran and Hasan Fathy in Egypt (Mousally 1988; Ahmar 2018). The experiences of Fathy found echoes in the architectural discourse among Syrian architecture students. By the 1980s, Fathy had built many of his mud-brick projects and written his book “Architecture of the Poor”. Also, by 1980, Fathy had been awarded the Aga Khan Award for Architectural Achievement, making his work yet more visible. Some graduation projects were directly impacted by Fathy’s work and his argument about designing with and not against climate. Nasser Rabbat’s graduation
project, conducted in 1979, was about a rural housing and solar power. Rabbat acknowledged that his inspiration for his project came directly from reading Fathy’s books (Al Araby tv 2018).

However, the discussions about local building had another, less examined, face. One that is utilitarian and pragmatically advocates the rationalisation of materials. This aspect is rooted in the severe scarcity of resources in Syria because of the escalating economic crisis due to the sanctions and inadequate economic measures (Abed 1988, 36). Within this context, initiatives of locally sourced buildings started from individual architects looking for alternatives to reinforced concrete for houses in villages, farms, and other projects outside major cities. In Aleppo in the early 1980s, the architect Rabie Dahman, then the head of the heritage department in Milihouse, built a brick dome in a mosque in Hama using light formwork of wooden blades using 200 mm thick terracotta hollow bricks. Dahman used a 150 mm thick cement bricks in a smaller project to make folded groin vaults that spring from concrete pillars to build his own house (Figure 48).

In Damascus, Khaled Al Fahham built a small house with mortared stone vaults using light volcanic stones on rubble concrete walls and left without finishing (Figure 48). The architects framed the house as a modern rural house which is proposed as the result of the "current skill and quality of work in the absence of technology" to prevent "chaotic import of urban houses into the countryside" (Mousally 1988, 80). A larger project was an industrial and agricultural facility near Damascus called Al Khaldiyah Farm (the Arab Association for Agricultural Technology) built by Abd Alfattah Iyaso, Andre Mashaqa and Amer Mouselly. The facility is 826 m2 and a poultry farming hall and a guardhouse. The project’s vaults were essential and geometrically more elaborate than the previous two examples, with crossed vaults and intersected domes. The architects used terracotta bricks, a new material in Syrian architecture which was first produced in the early 1980s (Figure 48). The architects compared their terracotta vault and reinforced construction of large span, concluding an almost 50% cost reduction (Mousally 1988, 86–87).

Another relevant experience is this of the Muhanna brothers, who worked extensively on developing vaulted houses from the traditional knowledge of basalt stonemasons, their most well-known work is the Aga Khan 1990-1992 Cycle awarded public schools that were built with the same system (Figure 49). Unlike the other experimental project, Muhanna’s series of houses in the south of Syria was finely detailed and supplemented with material studies in vaults. To minimise the use of cement, uncut but naturally thin basalt stone called Raqraq was added to the soffit of the vaults (Steele 1992, 157–62; Mouhanna 2018). Unlike the previous projects, the Muhanna brothers invested in the already existing knowledge of stone masonry in the south of Syria. The brothers’ research on vaults directly connected with Milihouse, where they build military hangers and dorms in the country (Mouhanna 2018).

Local Context: Urban and Rural Housing

Although initially proposed for both urban and rural housing buildings, vaults were rapidly associated with rural housing (Jolha and Jolha 1984). When the theme of low-cost housing was debated, a clear distinction was made between rural housing and urban public housing.

Public urban housing was always proposed as mid-rise high-density buildings that should mitigate informal settlement expansion around major cities of Syria. Urban housing construction was outlined as standardised made by prefabricated elements of steel and reinforced concrete (Jolha and Jolha 1984).
Figure 48 Late 80s experiments with vaults in Syria. Source: (Mousally 1988)
In contrast to that scheme, rural housing was proposed due to local material and labour, a house should be shaped from what exists on the site, built by its residents, and have large outdoor spaces for agricultural or animal-related activities. In this distinction, the discussion about the rural houses in Syria infused the rural housing with a cultural significance that was utterly ignored in the urban scheme. But instead of examining the existing vernacular architecture in Syrian villages, a "new vernacular" was proposed. Studies of typologies of traditional Syrian houses were conducted for documentation purposes, such as Aljundi (1984) addressing the dome houses in northern Syria. The new vernacular introduced new materials and applications for suitable low-cost housing based on durability, thermal isolation, and services (Jolha and Jolha 1984). Entities like Milihouse and individual architects criticised the bad quality and low durability of traditional natural materials. This resulted in a new architectural language unrelated to any traditional or vernacular architecture in Syria, although otherwise was claimed.

 Vaults were central to this approach, aligned with the 1980s model of "appropriate local architecture" endeavoured by Fathy in the Middle East. However, while Fathy's vault was mainly formwork-free made with mud bricks, its adoption in Syria required shuttering and was built using different materials of stone, terracotta bricks, and cement bricks. Moreover, in many Syrian regions, vaults are not typical for houses and only exist in public and religious buildings such as Souks, Mosques, and Hammams. In contrast to Fathy's proposal of vaults as a solution for rural and environmentally sensible housing, the vaults in Syria stood out merely for their romanticised geometry. Therefore, there is more in choosing a rural housing theme to propose the "new vernacular" than looking for the acclaimed restoration of architectural identity. The lack of regulations in villages made it easier for vaults to be applied in Syria's construction industry. This jump over regulations was made...
thanks to overcharging the rural with emotions about pre-industrial society. Cities were imagined strictly ‘modern’, villages were imagined loosely ‘traditional’.

2.3.2 "Urban Villages"

The period between 1975-1995 was vibrant in making outskirt urban zones in Syria. Some of those housing projects were thematic, linked to a specific association of workers in public sectors such as doctors and engineers, other projects were associated with income level being low, middle, or high (Al Salti 1997). During this outburst of new suburbs, construction entities, which were all governmental, had a centralised role in the planning and construction. Many decisions about land-use, materials, and housing typologies were decided internally within these entities. This resulted in comprehensive planning that determined not only regulations but also the design of all the buildings inside the new suburb, including housing blocks, individual houses, and public buildings. Being proposed as a solution to the informal and non-homogenous construction of housing, these governmental entities enjoyed the ultimate power to regulate and interfere in the nature and purposes of housing projects in Syria during the 80s. While monopolising the housing market, this power made it possible for changes and materials during the construction without referring to the general Syrian building regulations.

The northwest outskirts of Damascus were one of the earliest zones to witness those mass housing construction. What used to be villages in the road to Beirut, such as Dummar and Qudsyah, were planned to become satellite towns annexed to the Capital. Land located in Dimas, 18km northwest of Damascus, was designated to be a village for architects and engineers working in the public sectors. The project was initiated in 1980 with a scope of building 180 houses (Al Salti 1997). Being a governmental project, Milihouse was responsible for the construction of the houses.

By 1982, after the completion of Phase I, the project was not successful. The villages were remote and with little public transport or medical and educational services. Houses were dispersed, and the streets looked empty. Furthermore, the country was struggling to keep foreign currency in Syria because of the sanctions. To solve these villages’ problem, Milihouse director Khalil Bahloul changed the size and scope of the project, including the one in Dimas, to became a suburbs of summer houses for Syrian expat living outside the country (Abaza 2017). The houses were proposed as "villas" so that expat will have similar standards to their houses in their countries of residency (Figure 50).

The villas in Dimas, now called Qura Al Asad, could only be bought with US dollars, bringing the much needed foreign money back to the country (Al Salti 1997). During 1983, Phase II in Qura Al Asad was planned to become 77.25 hectares, 70% of which was designated as housing zones (Figure 50). Five islands formed the land and with the expectancy of the life span of 32 years for houses (Milihouse EST, n.d.). Qura Al Asad was one of ten new suburbs around Syrian cities for expatriates to shop in. While initially imagined as a mid-cost housing project for workers in the public sector, the houses in Dimas became a luxurious seasonal village for wealthy Syrians living abroad. The market of the project improved, and another two patches were added to the urban plans. A considerable extension of 4000 Hectares was made in 1985, forming an additional four villages next to the first one. To encourage living in the newly built suburb, Milihouse wanted to restore the mid-cost housing in the project (Al Salti 1997). Houses were given for free to the architects and engineers to reduce the cost by selecting materials and quality of finishing. Milihouse architects were given lands next to phase II to design, build, and own a vaulted house.
2.3.3 Milihouse Vaults: Early Experiments

Starting from the mid-1970s, the industry of building material in the country started to investigate natural resources for the building industry (Al Hasan and Al Salti 1983, 4). A report by the association of geology and mineral in 1977 led to producing sand-lime bricks and gypsum bricks. The Association of Cement and Building Materials also developed bricks from concrete and basalt stone and pumice stone for concrete mixtures. In 1979, Milihouse became more interested in fired clay brick and its potential industry in the country, which is not vastly used in traditional architecture in Syria. Pilot reports from Milihouse encouraged investing in fired clay. In the early 1980s, locations near lakes and riverbeds were selected to establish fired clay kilns. The closest to Damascus was in Adra (Al Hasan and Al Salti 1983; Jolha and Jolha 1984).

Being the producer of the material, the work on fired clay was encouraged by Milihouse. However, the first introduction of vaults construction did not use clay bricks but tubes and was not made in Milihouse. In Damas Expo 1981, and under the supervision of the architect Abdul Rauf Al Kasm, the prime minister at the time, a group of architects and engineers from Damascus University proposed two typologies of vaulted houses with terracotta tubes, an individual one storey house with parabolic vaults; and a multiple storey vaulted system for mid-rise vaulted buildings (Figure 51). The tubes and machines were designed and engineered inside the country. The technical specification of the tube and the machine was led by Rafee Mouhanna, one of the Mouhanna brothers who would later become leaders in vault construction using basalt stone in the south of Syria (Mouhanna 2018).

The house experiment received much attention from those interested in low-cost housing construction, including Milihouse (Abaza 2017). The association adopted the experiment and took it further in constructing two sites near the fired brick factory in Adraa. Alaaadin Al Salti, then the head of the construction department in Milihouse, started the construction with a team of architects. However, after unsuccessful preliminary experiments with tubes, the team replaced the tubes with extruded terracotta bricks for load-bearing walls and flat ceilings. The second alternative material was sandstone "Kafar Hawwar", which is light and easy to cut. The stone was used for building the headquarters of the Milihouse in Adraa whose parabolic vaults were heavily inspired by the house in Damas Expo 1981 (Figure 51, Figure 52). Nine bays of parallel vaults sat next to each other with a central void in the composition as a courtyard (Figure 52). The walls were 2.1m high, with beams of reinforced concrete on the top supporting the parabolic vaults. The use of stone was not arbitrary, but to keep quarry and masonry workshops working during the sanctions (Abed 1988, 36).

However, the material, called by Milihouse as industrialised cut stone, was three times more expensive than cement blocks (Al Hasan and Al Salti 1983, 14). Stone requires low-tolerance construction where joined, and edges need to be cut with high precision. Lacking this precision resulted in problems in the detailing of the building, waterproofing, and coursing. What saved the cost of the project, however, was the absence of imported steel for reinforcement. The use of load-bearing vaults kept the project’s cost slightly under the cost of standard reinforced concrete and cement block construction (Al Hasan and Al Salti 1983, 14). It was the vault’s geometry that reduced the cost of the building and not the material of the vault.
2.3.4 Milihouse Vaults: Pilot Projects

During Milihouse vaulting experiments, the concept of mid-cost housing in Dimas was also finding its way towards implementation. The team of Milihouse architects started working on typologies for low-cost vaulted houses (Abaza 2017). Starting from 1986, vaulted houses started to appear in the project’s southern strip of Phase I (Figure 50E). The plan produced for this period shows five vaulted typologies to be generalised for the remaining land in phase I. Three typologies are similar to the one-story U-shaped house, one typology with three parallel vaults, and one with two stories vaulted villa. The architects in this phase used a wide range of materials, including cement blocks, uncut stones, and terracotta bricks (Figure 53). However, building the early prototypes was not an easy task, and it was mostly based on a trial-and-error process. Some vaults collapsed for lacking a supporting substructure in the house to contain the lateral forces (Khayat 2018). Engineering consultants advised Milihouse team to use beams or buttresses in the load-bearing walls, Milihouse team started to add excessive structures. Some vaults had placed both buttresses and ring beams. This excessive use of supporting structure not only shows that the team had no clear understanding of the structural design and behaviour of vaults but also made the cost of the houses higher than expected.
Figure 51 Damascus Expo 1981 (Archive of Maen Abaza).
Figure 52 Milihouse Experimental Stone Building in Adra. The size of stone units is 400,200,200 mm for walls and 400,100,100 mm for vaults. (Al Hasan and Al Salti 1983).

Figure 53 The first vaulted houses in Al Sharqyat (Mousally 1988).

Interior of villas under construction in Sharqyat, 1988
Two stories villas under construction in Sharqyat, 1988

Figure S3 The first vaulted houses in Al Sharqyat (Mousally 1988).
Labour on-site had never worked previously with vaults, which necessitated a close collaboration between architects and builders for a collective effort to rectify construction faults. The work in the early vaults was carried out using a sliding formwork. However, because the labourers were not skilled, the miscalibration of the formwork in every slide resulted in a discontinuous surface of the vault (Abed 1988, 43). Plastering the vaults' interior surface was yet another challenge that increased the cost of the house. The formwork problem was solved by introducing a full steel formwork with steel rebar but resulted in difficulties where vaults intersect.

The 65 vaulted houses initiative was about to stop as it was not as efficient as imagined (Mousally 1988, 87). However, the response to these construction challenges was a simplification of design that compromised the houses' architectural and constructional quality. For example, a prototype of two stories house with domes and vaults was never generalised (Figure 54). Instead, most of the houses were L shape one storey building.

### 2.3.5 Milihouse Vaults: Application

Starting from 1987, a trend of commercial buying and selling appeared when the location got better connected with Damascus by a regular bus line, and the village started to become more inhabited (Ahmar 2018). The vaulted mid-cost housing scheme was maintained and expanded within the plan. However, the vaulted housing typologies' diversity in the pilot project was more ambitious than the real work in Phase IV. In 1990, Milihouse unified Phase IV’s different houses typologies of row-housing, two stories vaulted houses, and separate vaulted villas; all became one storey vaulted housing for low-cost construction. The houses were officially designated to workers in Milihouse on 10 July 1987.

The current examination of the village's houses shows only one prototype called (87-99-B-1) was used for all 200 houses. The chosen prototype is one storey and has a U shape plan with barrel vaults formed a courtyard in the centre. The house's total area was 135 m² with a plot of an average area of 1200 m². In 1992 as-built plan, the prototype (87-99-B-1) appears in all Phase IV under the name Sharqyat while all experimental vaulted typologies in Phase I were categorized as individual villas.

Another simplification accompanied the simplification in urban typologies in the prototype’s geometry and construction materials. Original plans show domes sticking out from the flat roof but were not built in the construction. Buttresses were eliminated and replaced with reinforced concrete ring beams. Vaults' intersections were avoided. For example, in the case of two perpendicular vaults, one of the vaults had to stop before intersecting with the other vaults; an interior wall would need to be extended to cap the truncated vault. Also, to avoid vault intersections, a flat roof corridor is positioned between two perpendicular vaults forming a small entrance vault. Arches in openings were replaced with rectangular openings with lintels. Material wise, terracotta bricks, the main reason why Milihouse initiated vaulted houses, were replaced with CMU blocks in both vaults and walls. Only a layer of terracotta roof cladding was added to the vault (Figure 55).

### 2.3.6 Al Sharqyat Today

By 1995, 270 vaulted houses were built in Qura Al Asad, many were allocated to Milihouse workers, sold to expats or brokers, or never used and hence in ruins today. While some early projects are considered individual villas, 200 typical houses are now called Sharqyat or Qawsyat (arched) villas.
Figure 54 Vaulted houses prototypes in Al Sharqyat.

These houses’ structures and materials are popularly known to be of bad quality, including the load-bearing 400mm thick walls made from two layers of CMU blocks and 300mm thick vaults made from CMU blocks and 100mm cement cladding.

By 2000, the vaulted houses in Al Sharqyat were bought for their location. It became a cheap option in an expensive area. This trend escalated after 2000, and the houses became famous for families owning cars to commute to Damascus. Today, ‘Al Sharqyat is one of the most expensive developments in Qura Al Asad. The reason is the location and not the design. The prices of the houses are connected with the material market. Massive reformation of the houses is essential, which can be an additional 30% of the property price.’ (Al Asadi 2018). For the house rehabilitation, the most common first step of those buying vaulted houses is to redo the plastering work; walls are clad with stone or mortar and vaults with terracotta tiles with particular attention to seal the vaults connection with the wall to avoid any water leakage under heavy rain.

While vaults have helped in limiting vertical expansions in the villas, horizontal expansion is widespread. In fact, most of those who bought vaulted villas in Qura Al Asad were looking for a spacious garden. The garden guaranteed a horizontal expansion of the house, additional facilities, and a swimming pool. Most of these elements were added after buying the house. From aerial photos and interviews and site visits, it can be inferred that the horizontal expansion of the house starts with annexed the courtyard by adding a flat ceiling to cover it. Space is then changed to become a saloon or the main living room. The flat ceiling of the added saloon permits another storey to be constructed, which is the case in many expansions. A third house extension adds a bay of rooms closing the U shaped’s open side, converting it into a box, or replacing on vaulted side of the house with a two-storey house (Figure 55, Figure 56).
Figure 55 Prototype 1990: Simplifications and residents’ interventions.
Figure 56 Houses in Al Sharqyat today.

From ruins to villas: current versions of Al Sharqyat houses.

Vaulted house without cladding, showing the original materials used by Millhouse in 1990s.

Interior views of vaults.

Figure 56 Houses in Al Sharqyat today.
Figure 57 Genealogy of Milhouse Vaults timeline in Milhouse projects.
In the interior, vaults in small rooms are usually kept, for they can offer additional floor areas with mezzanines and storages. In the main large living room, interior renovation could include painting the vault or, in many cases, vaults become hidden with false ceiling to reduce the space which needs more energy to be heated or air-conditioned—ironically a thermal problem that the vaults are intended to solve (Al Asadi 2018; Ahmar 2018). False ceiling solutions vary from a simple flat ceiling stepping surface to an imitation of pitched wood’s interior. In general, vaults are kept by the residence, and it is an accepted character of the house, but their annotation to traditional rural housing is replaced with a pseudo touristic one of houses with swimming pools and extensive gardens, an expensive retreat from the busy life of the capital.

2.3.7 Discussion: Vaulting from Processes to Products

The story of the vaulted housing in Syrian during the 1980s resembles a temporary response to steel scarcity. This response started with individual architects experimenting with houses in the city’s outskirt. Soon, these experiments found echoes in the centralised governmental construction entity (Milihouse) and were adopted to construct two new villages, one of them in Dimas, called Al Sharqyat.

The experiments and the construction of Al Sharqyat reveal two essential elements in the state’s policy toward vaults. The first is the geometry, and the second is the material (Figure 57Figure 58). When the project was made of individual experiments at early stages, Milihouse did not have to deal with the challenges of large-scale implementations. Geometries were aligned to structural efficiency, and parabolic sections were adopted. However, parabolic vaults became barrel vaults when houses started to look like mass products. This has led to simplifications of the house geometries, two-story houses were eliminated, and arched windows and doors became rectangular with lintels. To avoid any laborious detailing of beams, buttresses and ribs, intersecting vaults were avoided, and flat concrete ceilings started to be addressed again in the design.

Material wise, the diverse and rich experiments in the early stages using options like terracotta tubes, light stone and fired clay bricks were replaced with concrete blocks on mass construction of the vaulting houses. Not only was the material of low quality, but it also was used without addressing the possible problems resulting from their use, such as water leakage and bad thermal isolation. Some of the houses were left without rendering, showing cement block vaults and walls exposed. While the houses were finally mid-cost, their final geometry and materials became architecturally and functionally deficient, residences of these houses’ residences had to make changes in their design. Today, the value of these houses in their original condition is meagre, but the land of the house is one of the most expensive in the developments around the capital.

Al Sharqyat shows a case where vaults were symbolised as elements of traditions. But this symbolising was voided as no investment or research included any existing local building traditions in Syria. The architects of Al Sharqyat were avoiding any geometrical or material challenges pose by the vaults. Unlike the case of Al Shaqyat, this dialogue with vault makers did happen at projects of architects such as the Muhanna Brothers. Houses build through this dialogue were more successful in spatial and material quality. This suggests that although approached as an industry, large-scale production of crafted building components is conditioned with the close collaboration with traditional builders and the investment of their knowledge to confront and work with the complexity inherited in crafts instead of eliminating it altogether.
Chapter 02

2.4 Conclusion: Construction Policies in Thin-tile Vaulting

The historical study of vaults in Cuba and Syria offers an insight into how material limitations at national scales trigger a search for alternative, usually neglected, solutions (Table 2). In both Cuba and Syria, vaults were proposed as a solution to build without steel. But the adoption of vaults had to go through a period of experimentation in which architects and engineers tried to convert their constructions into a systematic process. While systemising vaults was evident in five years of research in Cuba, research on vaults in the Syrian case was more sporadic and limited to isolated projects. Similarly, in contrast to the case of Al Sharqyat in Syria, the move from experiments to applications in the Cuban case was carefully phased. Campos Almanza’s team offered several vaulting solutions using bricks or tiles, full shuttering or light formwork. Vaults were codified, but their use was open and flexible. In Syria, only one vaulting typology, the barrel vault, was examined and disseminated (Table 3).

While initially adopted to substitute steel construction, the reasons why vaults did not continue after a short and vibrant period differs between the two cases. In Cuba, it was the centralisation of construction policy that narrowed down buildings to a few controllable elements. The improved traditional model, a modular semi-prefabrication of light elements combined with in-situ craft-based building, was successful when the research was centralised but not construction. The centralisation of construction processes did not allow combining manufacture and craft as the latter was hard to be abstracted, coded, and decontextualised.

In Syria, the association of vaults to a ‘regional architecture’ that restores the ‘architectural identity’ seems more an excuse, if not a cliché, to convert vaults from craft to products of forms that do not align with or feed on the traditional or vernacular. Vaults and arches were used to draw a universal image of Syrian rural architecture, an image that is vacuumed from its locality.

The two cases raise questions about the ability of a large governmental entity to approach a construction that relies heavily on-site conditions. Standardisation and codifying of building practices in state-led construction pose challenges on craft-based construction because of its large margins of uncontrolled processes. Construction policies cannot rely on the historical trust between the master builder and the designer (in many instances, they were the same person) and traditional site verification methods such as on-site load testing.

This rejection is challenged when vaults are posed as an emergency case of construction under economic constraints, the exceptionality of the circumstances did give the freedom to consider nonstandard solutions. These periods teach us that the implementation of vaults in state-led policies should engender a process that mitigates standardisation, requiring an accumulative investigation and cycles of learning. This process is conditioned with the partnership with master builders of these crafts. Hence, the work in Cuba was successful in producing building elements with a deep understanding of their design and implementation, whereas the case in Syria seemed to lack and avoid this depth.

Can the environmental emergency now be also considered an exceptional period in building codes? Efforts to include all possible low-carbon solutions are taking place globally. Integrating building craft is one crucial way. A way to push the discussion of construction policies to building craft is a must.
General Information

Number of Projects
- More than 50 in Cuba
- 2 (large development) in Syria

Entity
- Ministry of Construction in Cuba
- Military Housing Association in Syria

Labour From
- Labour associated to MICONS in Cuba
- Labour Associated to Milhouse in Syria

Design lead
- Juan Campos Almanza (Architect) in Cuba
- Alaadin Al Salti (Engineer) in Syria

Design and vault Geometry

Reasons to adopt vaults
- Scarcity of steel and wood in Cuba
- Distribution of labour in Cuba
- Scarcity of wood in Syria
- Searching for regional architecture in Syria

Housing Typology
- Urban, Rural, Resort in Cuba
- Rural only in Syria

Design development
- Standardisation of vaults in Cuba
- Experimentation in housing building in Cuba
- Simplifications of geometry in Syria
- Reducing cost with low-quality materials in Syria

Resources
- Traditional Ceramic Bricks in Cuba
- Newly introduced ceramic bricks & tubes in Syria
- Cement blocks in Syria

Reasons to abandon vaults
- Systemised construction for the masses in Cuba
- Centralising construction policy in Cuba
- Vaults are only useable in rural zones in Syria
- Vaults are hard to build in Syria

Current status of buildings
- All still in place in Cuba
- Appreciated by the residents in Cuba
- Many villas are being demolished in Syria
- Reputation of bad quality in Syria

Table 2 Summary Vaults in Cuba and Syria

<table>
<thead>
<tr>
<th>Design Key</th>
<th>Structure</th>
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<tbody>
<tr>
<td>Type</td>
<td>Sub struct</td>
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<td>Multi-storey</td>
</tr>
<tr>
<td>Syria</td>
<td>Multi-storey</td>
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<td>Materials</td>
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<tr>
<td>Cuba</td>
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<td>Syria</td>
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Table 3 Vaults in Cuba and Syria in Comparison with traditional vaults in Spain
2.4.1 Integrating craft in construction policies

Figure 58 shows the formal and regular construction policy from material supply to measuring building performance. It is noted that the process is phased in cycles of verifications and development to ensure the applicability and suitability of materials, individual building components, construction, and buildings’ performance. However, it is also noted that the process is linear, broken into small and confined cycles with established specialisations that range from material sciences to building energy engineering.

Because craft construction spans between all these disciplines, it requires an infrastructure that should accommodate two conceptual zones (Figure 59). The first is a collaboration and dialogue zone where master builders and artisans are included in the design development and can perform and build models for components to be testing against loads, construction, and performance, exemplified in the activities made at the courtyard of the Ministry of Construction in Cuba. The second is a verification and learning zone where the application of craft is thoroughly observed and documented in on-site construction; an excellent example of this cycle is the project in Altahabana.

However, to integrate craft-based construction within these two cyclic-flows, essential critical conditions need to be fulfilled. The first is the engagement with already established material and resource supply; the second is the master-builders existence both conceptually and operationally. The third is to accommodate and tolerate variations in on-site construction. Finally, the on-site construction itself should allow for testing and adaptation.
Investing in existing supply chains
Like any industry, craft-based construction requires a supply chain of materials. In Cuba, the existence of brick factories in the country was one of the main reasons for the use of vaults. In Syria, the establishment of these factories triggered experiments in vaulting. When the Syrian architects decided to use cement blocks, no efforts were made to understand the impact of their use and how it can be addressed in the design and the construction of the vaults. This has resulted in many structural and construction problems related to the durability and efficiency of vaults. Finding alternative local material to establish a construction craft is not only crucial but also has implications that might change the very nature of the craft at hand.

Capacity building
The skill of labour and design infrastructure is essential. In Cuba, the success in the experiments and the projects were possible thanks to the establishment of the schools of vault builders. The absence of such an entity in Syria led to many failures during the projects. To tolerate unskilled construction, full formworks were introduced, contradicting the main reasons behind using the vaults.

Error-friendly Systems
Drawing on the notion of non-centralised and error-friendly systems, discussed in section 1.2.3 (Manzini 2012). Error-friendly systems can tolerate a threshold of faults without a catastrophic failure of the system; it relies on the verifications of essential components and the distribution of expertise in all levels of the system. In the
Cuban case, this system is represented in the improved traditional vault model, where it fuses standardised elements with on-site construction. The process on-site might not be a clean assembly of building components, but it also provided a margin of flexibility to adjust and calibrate the prefabricated elements, which might be handmade. However, such flexibility is conditioned with skilled labour.

Research and on-site verifications

In construction sites where craft-like vaulting is central, the extension of lab testing into the site application is inevitable. Building components in industrialised construction are mostly verified and coded in the construction market, but on-site craft needs additional verification and assessment in the making. In the early application of vaults in real projects in Altahabana the architects observed the cost implications, the time needed for construction, and functionality of the designed spaces. The extensive documentation during this phase was crucial for generalising the vaulted solutions for houses in Cuba. Experiments were sequential, numbered and phased from Experiment 1 to Experiment 6. This accumulating knowledge was not addressed during the construction of Al Sharqyat in Syria where each architect designed and built a house without being part of collective learning towards finding optimal solutions.
Chapter 3
Training Approaches to Thin-tile Vaulting

Craft Training in Thin-tile Vaulting in Rwanda, Jordan, and Spain

As a building craft, thin-tile vaulting requires practical knowledge. Such knowledge was exchanged within established modes of trades, like many other traditional construction techniques. Historically, architects and master builders were taught in workshops and art schools to design and build vaults. Today, thin-tile vaulting is regaining trust as a viable solution in contemporary construction (M. H. Ramage 2007; M. H. Ramage, Ochsendorf, and Rich 2010; M. Ramage et al. 2019; Davis and Block 2012a). However, the historical model of training of a master-apprentice is being replaced with experimental and project-specific training programmes, some of which introduce the techniques to new regions and cultures. Challenges of time, site conditions, and the adaptation of the technique to local construction become intrinsic to learning. This chapter will examine these challenges in three thin-tile vault training programmes in Rwanda, Jordan, and Spain.

To examine how thin-tile training is both planned and practised as pedagogy, the study draws on two social learning theories. The first is Basil Bernstein’s social learning theory which will define and describe the trainers’ strategies. The second is the situated learning theory by Jean Lave and Etienne Wenger (1991), which explores how training is connected to each project’s social and economic context. The two converge to forge a training model that considers site and design limitation. Finally, the chapter will project the lessons learned from thin-tile vaulting training on architecture education. The project at its core is an ethnographic study. However, it approaches ethnographical methods by “making” and “drawing” as the driving techniques of data gathering and analysis. Therefore, the chapter also contributes to studies about the visual ethnographic methodologies.
3.1 Historical Background

Because it is a building technique that relies on skill, cultivating skill within a team of thin-tile builders is one of its preconditions. In fact, the earliest document about thin-tile vaulting, a letter of King Peter IV of Aragon in 1382, is about sending builders and architects from Aragon to Valencia to ‘learn’ the technique (Ochsendorf 2010). Since Peter IV’s letter, learning thin-tile has taken place in different locations and cultures. It entailed structural mastery, practising a craft, or gaining a profession.

In Spain before industrialised construction, training of thin-tile vaulting took places within two entities. The first is the traditional form of learning inside the craft systems and hierarchies. Within families of trades, a tile-vault learner used to be an apprentice working with the master until gaining independence. The other form of traditional training is institutionalised within formal and recognised schools of art. During the nineteenth century, learning tile vaulting was conditioned with attendance to a three-years of training. The training included teaching students how to design, calculate, and build tile vaults at the school of art (Escuela de las Tres Nobles Artes) (Bassegoda Musté and Bassegoda Nonell 1947, 3). It continued until the first decades of the twentieth century, influencing the teaching of architecture and construction schools during the Catalan Modernisme (Bassegoda Musté and Bassegoda Nonell 1947, 4).

The existence of the technique as part of the construction culture in Spain influenced the country’s renowned structural designers such as Eduardo Torroja, Miguel Fisac, and Luis Moya. David P. Billington mentions how Spanish structural designers were ‘...stimulated by local artisan tradition of laminated tile vaults...’ (Billington 1985, 173). Torroja’s work, in particular, is a clear example of this association; he used thin-tile vaulting as formwork for reinforced concrete shells for urban and architectural structures (Ochsendorf and Bernardo 2003).

Starting from the 1950s, when the concrete construction eclipsed thin-tile vaulting, builders’ training ceased to be officially formalised. Angle Truño, for example, lamented the poorly executed vaults accusing those who build them of degrading the legacy of vaulting (Truño i Rusiñol et al. 2004, 7). Since then, the knowledge was sustained within the vernacular architecture and restoration projects in thin-tile vaulting.

Knowledge in the previous transmission is passed down through generations of builders and intertwined with craft; the tradition and identity of building is part of sustaining the knowledge. Another transmission is when knowledge exchange happens between regions, and location, not time, is the context. At the beginning of the twentieth century, the Madrilenian architect and craft enthusiast Juan Bautista Lázaro brought many thin-tile vault builders with their families from Valencia and Catalonia to the Capital. Those builders made possible many of his celebrated residential and religious projects (Mosteiro 1996, 231–32). Thin-tile vaults continued in Madrid after Lázaro. The technique was crucial in the construction around Madrid fifty years after the Spanish civil war (Figure 60) (Mosteiro 1992). Luis Moya Blanco worked with the descendants of the Catalan workers to build exemplar thin-tile vaults for many of his projects, including the Museum of América, the University of Zamora, and the Church of San Agustín (Figure 61) (Mosteiro 1996).

Another exemplary transfer of the technique is Rafael Guastavino’s work and his son Guastavino Jr. who took thin-tile vaulting to the United States. The current archives about Guastavino Company do not offer much about the training or resourcing of labour. The answers to whether Guastavino trained unskilled builders to thin-tile vault or recruited builders from Spanish immigrants remains unknown. But what can be indeed known is that he had highly-skilled workers. When reviewing the ‘labour’ aspect in the Guastavino archives, I could find only one indication of his workers’ skill in the construction of the Capitol of Minnesota. In the correspondence
between Guastavino and Cass Gilbert, the architect of the Capitol, there were 4533 sq. ft. (421 sq. m.) to be built under ten days by four builders; this results in an intensive work of about 9.2 sq. m. per builder per day—a 3 by 3 meters room. The four workers were under the supervision of Guastavino Jr., the picture of the four men also shows a formwork for the Capitol’s dome under construction (Figure 62) (Parks 2012, 15).

Another historical example where training to the thin-tile vault was made clear is the National Schools of Art in Cuba, which was thoroughly examined in the last chapter. However, it is helpful to re-mention how the previous chapter depicted two types of training in Cuba between 1961 and 1965. At research centres in the ministry of construction, the training was more a collaboration between architects and builders for experimental and testing purposes. At projects’ sites, training was directed for unskilled builders to learn the technique and use it in the project. The example of thin-tile vaulting in Cuba shows the duality of design and technique learning in thin-tile vault training.

Since the 1970s, thin-tile vaulting was treated as a lost craft (Moreno-Navarro 2005). However, what was lost indeed was not the construction of vaults but incorporated such elements in architecture. In vernacular and informal architecture, thin-tile stairs in specific kept the tradition alive. Vaulted stairs persisted in Spain’s many regions, beating concrete stairs in efficiency in time and materials, and elegance in design and construction. By the time the architecture historian lamented the disappearance of thin-tile vaulting in Spain, builders in the Spanish Levant and the Catalan region were building tile stairs daily (Moreno-Navarro 2005, 68). It was the formal architecture that lost interest in building thin-tile vaults and not the opposite.

Nonetheless, many stair builders did not know that they could also build other vaulted geometries (Gomis 2019). The master vault maker Salvador Gomis. Gomis started his apprenticeship in building vaulted stairs in 1995. Ten years later, he built his first barrel vault in the Monastery of Santa María de la Valldigna (Gomis 2019). Since then, he became one of the few vaulting masters in Spain and participated in the construction and restoration of projects, including the Pantheon of the Soriano Manzanet Family (Camilla Mileto and López-Manzanares 2016).

In addition to stairs, restoration builders and building artisans also were part of sustaining the knowledge. Artisan-restorers, who primarily work with plaster, are familiar with repairing and replacing thin-tile vaults in Spain’s historic buildings. Their knowledge was also vital in the recent revival of thin-tile vaults. The master restorer Carlos Martin Jimenez had worked intensively in many restoration projects in Alcala de Henares before starting to work on new vaulted projects such as the winery of Valdemonja in Valladolid as well as the droneport prototype, designed by Norman Foster and built during the Venice Biennale in 2016. Another artisan is Jordi Domenech I Burnet, who is a descendant of a family of construction trades. Jordi has been working on building thin-tile vaults in Catalonia, twinning the technique with other elements from the Catalan Modernisme such as stonework, coloured glass (Claraboies), and ceramic work (Trencadís) (Al Asali 2016).

This vernacular knowledge in Spain was a source to transfer the technique to new geographies. The first tile-vaulted project in the UK and outside Spain in the twenty-first century is the Pines Calyx centre in Kent. To build the dome in the project, the builders and architects received a Spanish builder from Extremadura Spain (M. H. Ramage 2007). The Spanish builders worked with the team to realise the dome, then one of the masons (Sarah Pennal) in the team built the vaulted stairs in the centre. James Bellamy was also trained during Pines Calyx and became a trainer himself. His role was essential in realising two thin-tile vaulted projects in South Africa and Rwanda, both are examples of a low-cost and locally resourced construction.
Figure 60 Construction of Post-war village Villanueva de la Cañada (Churtichaga and Llanos 2001)

Figure 61 Construction of Universidad Laboral de Zamora by Luis Moya (Méndez and González Fueyo 2009)

Figure 62 Guastavinos' workers are building a dome in the Capitol of Minnesota (Photograph by the author, Guastavino Fireproof Construction Company architectural records, 1866-1985, Avery Architectural & Fine Arts Library, Columbia University)
The team from Extremadura was also involved in a workshop of training and construction of thin-tile vaults in Cuba in 2000, led by the architect Manuel Fortea Luna (Al Asali 2016). The workshop in 2000 was converted into a yearly training program in the vocational training school Gaspar Melchor in old Havana. The school prepares several thin-tile vault makers and employs them to restore old vaults and stairs in Cuba.

Since the mentioned early examples, the interest in thin-tile vaults kept increasing and producing many forms of documenting the learning, such as reports of materials and time, technical notes, and design guidelines. Recent examples are derived from texts of buildings (M. H. Ramage 2006), being trained by a master builder (P. Becker and Anderson 2004), or experimentation (Davis 2010).

In practice, builders and architects undergo short courses of thin-tile vaulting, which some schools of construction offer in Spain (Al Asali 2016). Since 2010, schools of Architecture in Madrid, Valencia, Alcala de Henares, and Barcelona have conducted short workshops within their curriculum of architectural education (Fuentes and Huerta 2014, “VIII Taller de Bóvedas Tabicadas – MUPAAC” 2020). More vocational-alike summer schools also offer one-week workshops such as Taller de Boveda in Guadalajara and Escuela Origin in Catalonia, and Homo Faber in León (“Origens Escola Taller de Bioconstrucció | Escola Taller de Bioconstrucció” 2020, “Homo Faber - Rehabilitación de Edificios y Cursos de Oficios” 2020). Trainers of vaults in these workshops are primarily professionals and master builders working on restoration projects or vaulted stairs specialists.

### 3.1.1 Research Questions

Studying the history of thin-tile vaulting shows the importance of the know-how to develop, sustain, and revive the technique. It reveals, however, different approaches to the duality of design and construction. There are two main formats of learning and teaching in thin-tile vaulting— one that focuses on profession and technique, and one that focuses on design and analysis. Teaching a thin-tile vaulting apprentice with a prospect of developing a career as a master-builder is different from training for a specific application without expectations for long-term implications. The former entails understanding the geometrical, material, and structural properties of vaulted elements. The latter is about a structure that needs to be built with supervisions from the leading designer or master craftsperson. The difference between the two is summed up into the builder’s ability, or lack thereof, to move between technique and design.

Today, the transfer of thin-tile vaulting is less about passing down and more about passing on. Short, concise training workshops are prevalent, in contrast to the master-apprentice model. This prompts the following questions: How can thin-tile vaulting, as an example of a construction craft, be situated in the construction industry? How can the shift between design and technique in thin-tile vault training respond to site, social, and economic needs and challenges? How can today’s short and in-focus learning of thin-tile vaulting offer builders’ preparation for further autonomous thin-tile applications?

### 3.1.2 Theoretical Framework

The theoretical framework used in this examination aims at illustrating a clear description of 1) the content: the transmission of knowledge through activities, 2) the context: the experience of the trainees, and 3) the relationship between the two. Two main theories will be used to examine the content and context. The first is the Sociological Theory in education developed by Basil Bernstein, and the second is the Situated Learning Theory by Jean Lave and Etienne Wenger (Bernstein 2003, 147–77; Lave 1991, Lave and Wenger 1991).
The content of learning

Bernstein’s sociological theory explains pedagogical practices in two discourses. The first is a discourse of order on “what” we regulate the transmission of knowledge based on the dominant values of society, and the second is a discourse of competence exemplified by the “how” we transmit as knowledge (Sadovnik 1991, 50). To understand how these discourses function in pedagogical practice, Bernstein uses ‘classification’ and ‘framing’ to code the relationships between subjects, spaces, and activities in education (Bernstein 2003, 158).

Classification and framing do not describe the content or activities of learning, they illustrate the permeability and the degree boundaries between them. Classification focuses on the subjects taught and the boundary between them; it is the educational system setting or releasing divisions between different subjects. Framing refers to the practice of education and the role of the teacher in structuring the learning activities. The two boundary sets of classification and framing are independent, a teaching practice can have strong classification but weak framing, for example. With this theoretical framework, Bernstein explains two curricula: ‘collection’, whose classification and framing are strong, and ‘integrated’, whose classification and framing are weak.

Positioning any educational practice on the scale between the two helped Bernstein explain how education reflects societies’ values and practices (Bernstein 2003, 160–62). As most of Bernstein’s work, the framework combines conceptual visualisation with empirical investigation; algebraic symbols deduce observations into comparable diagrams. The strength and weakness of boundaries are described as (+) and (-) proceeding the letter of either classification (C) or framing (F). With these codes in hand, the tool also captures how framing, represented in evaluation and examination procedures, changes during the teaching.

Bernstein’s framework (Figure 63) is relevant to the inquiry on training practices of thin-tile vaulting. It first set up an explicit scene of the otherwise hard to describe training strategies. There was no clear document in all examined training programmes that is prepared as an approach to pedagogy. All the training sessions were applied based on the estimation and previous experience of the training. The classification and framing scale can be used as an alternative to depict the pedagogy and curriculum a posteriori based on observations of the training and interviews with trainers. The framework is also helpful because it involves an empirical analysis of data.

The context of learning

Bernstein framework is conducive to mapping the content of learning. However, it falls short in showing how the content is translated into the experience of the learner. Understanding the relationship of the context within the reflections of the trainees will be examined by drawing on theories of social practice in education. Social practice in learning is rooted in the exchange between craft studies and education studies during the 80s and 90s (Gamble 2004, 12; Lave and Gomes 2019, 34). The observation of non-systemised learning exemplified in the master-apprentice relationship in craft has been influential in shaping a context-oriented theory (Lave and Gomes 2019, 34). Lave and Wenger’s work on the curriculum of learning, instead of teaching, is constituted around the observation of craft schools and tailor’s workshops (Lave and Wenger 1991).

Developing the social practice theory in education was set to forgo the divisions between formal/informal learning and classroom/non-classroom learning (Lave and Wenger 1991, 97). Instead, the site’s specific condition and context for learning as collective activities made “situated learning” central to the social practice theory in learning. Situated learning shifts the focus of education from being the cognitive processes of individuals into a collective engagement. Lave and Wenger introduced the term to explain how newcomers’ identities engage as a community where learning is always reconstructed through their everyday interactions, motivated by desires.
to become experts. This community is called a Community of Practice, defined by Wenger as ‘groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly’ (Wenger 2011, 1).

Since the 1990s, situated learning entered adult education studies, including vocational training, and the attention to context was brought to the fore (Gamble 2004, 5). Situated learning is not a pedagogical strategy but a way to understand learning. The three pillars of the framework can be drawn from Wenger’s definition of a community of practice being constructed by domains, community, and practices. Domain in the framework is the learned technique (thin-tile vaulting). Community is the groups of trainees and the institution in which they work. Practice is the expectation of the technique on a personal and collective level.

Combining the two theories and the relationship between them will cover both strategies and impacts of learning. This gives us an answer to how thin-tile vaulting training takes place in different contexts and its impact on communities of practices and ways to sustain it after the training. With this in hand, the framework will comprise: 1) a list of an analysis of the content and context of training (Table 4) and 2) a plot to explain how the two evolve in training (Figure 63).

<table>
<thead>
<tr>
<th>Curriculum Classification</th>
<th>Strong</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Separated task and activities</td>
<td>- Integrated tasks in activities</td>
<td></td>
</tr>
<tr>
<td>+ Separated theory and practice</td>
<td>- Integrated theory and practice</td>
<td></td>
</tr>
<tr>
<td>+ Strict selection of specialization</td>
<td>- Loose selection of specialization</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Framing Classification</th>
<th>Strong</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Included input from other specialisations</td>
<td>- Excluded input from other specialisations</td>
<td></td>
</tr>
<tr>
<td>+ Strict sequencing and pacing</td>
<td>- Easy sequencing and pacing</td>
<td></td>
</tr>
<tr>
<td>+ Firm evaluation criteria</td>
<td>- Organic evaluation criteria</td>
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<table>
<thead>
<tr>
<th>Context Practice</th>
<th>Profession</th>
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</thead>
<tbody>
<tr>
<td>Future market estimation</td>
<td></td>
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<tr>
<td>Alternatives materials in the local market</td>
<td></td>
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<tr>
<td>Starting own business</td>
<td></td>
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<tr>
<td>Work relief</td>
<td></td>
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<tr>
<td>Cash for work</td>
<td></td>
</tr>
<tr>
<td>Focus on the project’s material only</td>
<td></td>
</tr>
<tr>
<td>Preparation for similar jobs</td>
<td></td>
</tr>
<tr>
<td>Community</td>
<td></td>
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<tr>
<td>Self-structured</td>
<td></td>
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<tr>
<td>Internal organization</td>
<td></td>
</tr>
<tr>
<td>Extended decision making</td>
<td></td>
</tr>
<tr>
<td>Skill for the future</td>
<td></td>
</tr>
<tr>
<td>Cultivated</td>
<td></td>
</tr>
<tr>
<td>External organisation</td>
<td></td>
</tr>
<tr>
<td>Limited decision making</td>
<td></td>
</tr>
<tr>
<td>Domain</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td></td>
</tr>
<tr>
<td>Placing the tile</td>
<td></td>
</tr>
<tr>
<td>Curvature estimation</td>
<td></td>
</tr>
<tr>
<td>Typologies of vaults</td>
<td></td>
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<tr>
<td>Technique</td>
<td></td>
</tr>
<tr>
<td>Plaster setting time</td>
<td></td>
</tr>
<tr>
<td>Clean construction</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Theoretical Framework: Content and Context List for Analysis
Figure 63: Left: Coding Learning Discourses by Classification and Framing. Adopted from Basil Bernstein 2003. Right: Context of training in terms of domain, practice, and community.

Figure 64: Context and modes of training. Left: top-down training for tasks. Right: Bottom-up training for values.

### 3.2 Methodology

#### 3.2.1 Ethnography and Observation

At its core, this is an ethnographic study on education. It comprises direct observations and participation of three training programs in different locations and contexts. Ethnography is defined as "the study of social interactions, behaviours, and perceptions that occur within groups, teams, organisations, and communities." (Reeves, Kuper, and Hodges 2008). It allows for rich insight into and about a specific subject by constructing and comparing meanings of its activities and viewpoints (LeCompte and Schensul 2010, 1). Ethnographic studies surged in the
1970s and 1980s when the dynamics of the learning environment became crucial in education studies; such methodologies were essential in the emergence of new theories in which the classroom was reconceptualised as an active player in the learning process (Grenfell 2012, 7–8).

The proposed qualitative driven method is germane to the nature of this study on training programmes. Thin-tile vaulting training usually involves only a few people (from 10 to 20); it does not regularly allow for extensive numerical data collections and analysis. In fact, this research had the good fortune to witness three thin-tile vaulting workshops between 2017-2019, all of which led to full-scale construction of the buildings. Adopting direct interactions and observations facilitates the inclusion of many physical and social details that otherwise would have been disregarded. The observations concern the activity (training), subject (the structure), and participants’ views and reflections. Tools from ethnographic studies are crucial to unpack the complexity of actors and systemise data collection and analysis.

However, drawing on the history of ethnographic studies, it is criticised for being a product of power and control the observer exercises within the observation (Gobo and Molle 2008, 1–3). Similarly, such methodology usually risks favouring the observer’s viewpoint over the observed subject (Domingo 2003). In simple terms, the observers search for what they want to find. Both criticisms require nuancing the role of the observer and the position of the study.

To position my role in the observations, I will state my participation in each examined project. In Rwanda, I was not the designer or lead site architect of the project. I developed the guidework design and built them with carpenters, which is not part of this study. In Jordan, I was a consultant for the architects’ structural design and materials, and I collaborated on the curriculum of thin-tile vault training and translated it from Spanish to Arabic. In Spain, I was the pavilion designer, and I collaborated on the curriculum in which I also taught two lectures on materials, calculations, and construction. However, in all three workshops, I was not the leading trainer, and I was only an observer with informal discussions with other participants, especially at the beginning of the workshops.

I am familiar with the technique of thin-tile vaulting. I learned the technique in 2015-2016 through several trips to Spain, where I attended two workshops in Madrid and Catalonia. My learning in the workshops was introductory. I had the chance to gain more insights into thin-tile building through building side by side with thin-tile vault master builders.

3.2.2 Design Tools as Tools for Observation

Because of the interest in design as a practice, the proposed methodology incorporates design tools. Ethnography studies define nine observational dimensions: Space, actor, activity, object, act, event, time, goal, and feeling (Reeves et al. 2013; Spradley 2016). Here, spatial elements in the observed dimensions are instantly recognised, such as space and object. In addition to the essential techniques of observation, interviews, and questionnaire, the analysis dwells in design and design tools as the primary vehicle to observe, interact, and analyse. The study borrows tools from design and implements them as methodological techniques. The tools are drawing, mapping, and making.

The first use of these techniques is within the training to observe the interaction between and with participants. In other words, it is co-drawing, co-mapping, and co-making. Sketching with participants while talking led not only to physical findings but also to profound discussions using line-work in addition to word-work (Figure 65)
Drawing is one of the most used communication methods between builders, usually exercised with a stick and sand. That said, using a notebook and pen implies more officiality to the sketch and permanency. The consequences were that participants had to make, sometimes, careful thinking before drawing or before asking me to draw what they are thinking, sometimes requiring several iterations until approved. Co-sketching was not about perfecting the technique of drawing or copying a scene into a notebook. Co-sketching here was about extending design ideas and construction obstacle or solutions.

The second use of drawing and mapping happens after the training in what is called “concentrated seeing” (Heath, Chapman, and Sketchers 2018). In this case, sketching is a process that makes, within iterations of drawing and writing, reflections that are hard to make using only textual and key-word analysis. Reflective mapping was used to describe the spatial articulation of the training (Figure 66). The trainers, trainees, watchers, the building and myself as the observer are all drawn in a plan diagram. The map of the training illustrates hierarchies, sizes of working groups, the link to the building and materials. All maps were then translated into diagrams about the training spaces, facilitating comparisons between the three pieces of training.

Non-textual observation and exploration are recently increasing in ethnographic studies (Pink 2007). It is usually framed by its power to force observers to change their habits (Heath, Chapman, and Sketchers 2018). In this research, making is central and part of design and research practice; it is a tool with which I am familiar. It, therefore, does not merely imply freshness to the methodology, but it is systematically used as a tool to both understand and communicate. Table 5 summarises the techniques and observational tools in the research.

<table>
<thead>
<tr>
<th>Type of Observation</th>
<th>Technique</th>
<th>During training</th>
<th>Outside training</th>
<th>Off-site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textural Observation</td>
<td>Notes from Observations</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Interviews</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual Observation</td>
<td>Mapping</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Sketching with builders</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tacit Observation</td>
<td>Visual observation of the vaults</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Building with builders</td>
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</tbody>
</table>

Table 5 Methodological framework: Observations and techniques
Training Approaches to Thin-tile Vaulting

Figure 65 Making and Drawing with Builders, Rwanda.

Figure 66 Mapping Training Space, Rwanda.

Figure 67 Development of Materials and structures in Rwanda by trainees
3.3 Case Studies: Rwanda, Jordan, and Spain

3.3.1 Rwanda Cricket Stadium

Located in the outskirt of Kigali, Rwanda Cricket Stadium is a three-vaults pavilion that houses players’ facilities and space for spectacles. Designed by Light Earth Designs (LED), the vaults were built using stabilised earth tiles and local labour. The stadium celebrates local Rwandan communities through sport, an initiative led by Rwanda Cricket and the Cricket Builds Hope Foundations. (Figure 68). Following the initiative’s goals of empowering the local economy, the pavilion vaults are designed to be resources and built locally. Stabilised soil tiles were hand pressed, air-dried and used for vaults alongside geogrid reinforcement for seismic stabilisation (M. Ramage et al. 2019). Workers were trained to produce the tiles and build the vaults. For the tiles’ production, mechanised presses and pan mixers were provided by the South African Company Hydraform (“Hydraform – Brick & Block Making Machines” n.d.). The company led the training of local workers in Rwanda on the making and the tiles. For the vaults’ construction, a one-week training program was led by James Bellamy and followed by the full-scale construction. The training for both the tiles production and the vaulting took place among the workers of the contracted construction company ROKO. The company selected 20 brick-layering experts and builders for the training.

Training description

For building the three large-span vaults, a set of formworks and guidework was made for the builders to use in the construction. Full formwork was made for each vault’s edge arches, guidework was placed in the web to visualise the sail geometry of the vaults, carpenters and scaffolders installed both while the workshop of thin-tile vaulting took place on-site. No builder trainees were involved in the making of the formwork. James Bellamy, the trainer in the construction, is a builder with extensive experience in earth construction. He was part of the Pines Calyx Centre’s construction in the UK, where he was in the team building the rammed earth walls (M. H. Ramage 2007). He then participated in the thin-tile vault construction learning from Máximo Portal and Fernando Marin, both Spanish vault builders. James led the construction of the Mapungubwe Interpretation Centre, his role in Rwanda was also to train the local builders to make the vault. The extensive experience of his previous project in South Africa gave him an insight into what the training in Rwanda should be. After selecting builders by ROKO, the one-week training had two main strategies; the first was decomposing thin-tile vaulting into its constituent materials, namely gypsum, tiles, cement, geogrid. The training introduced each material and the reasons behind using it in the vaults. The second strategy was to work with these materials from small to large elements incrementally.

After a general introduction to the vaults and their materials, trainees were instructed first to join two tiles with plaster (Figure 69). Several iterations of this exercise aimed at bringing the trainees attention not to waste the fast setting mortar. Understanding the mortar behaviours was the first challenge, the second was contrasting the vaulted geometry to the habitual construction of brick walls. According to James Bellamy, “good brick wall builders are not necessarily good vault makers”. Therefore, joining tiles at an angle was in the core of the workshop right from the outset. These two challenges, the plaster setting time and the joining of tiles at an angle converged into building catenary vaults on walls. The training then moved to adding more layers and installing the geogrid between them (Figure 70).
Figure 68 Rwanda Cricket Stadium, Kigali, Rwanda. (Light Earth Designs 2019)
The workshop activities were not many but with multiple iterations. After the workshop, builders with the trainers started to work directly but carefully on the vaults. The vaults construction starts with the arches on the edges whose shuttering is full, working on full shuttering allowed a transitional period between the training on small scale elements and vaulting a 7-meter span vault (Figure 71). This transitional work proved very beneficial to gain confidence in their work. After working on the arches, the construction of the vault started. Following the guidework, six groups of twos, a vault maker and a plaster mixer, were placed in the four corners and the long edges' central location. The vault makers' work had to be orchestrated by a supervisor to guarantee following the guidework's geometry, having a clean tile pattern, and ensuring the vault's corners are being built in tandem (Figure 72).

The building of the first arches and vaults was also an evaluation process that is discrete and organic. Builders who felt less comfortable with the vaulting were assigned to mix plaster or add more cement layers. A mix between self-organisation and instruction by the trainer and the site engineer resulted in groups of vault makers, plaster mixers, other layers and geogrid builders. James left the project during the second vault's construction, but he made sure to find a replacement. Salem, a chief builder, supervised the remaining building and directly coordinated any reports or incidents with James and the site engineers. The training dynamics have completely changed the workflow from being entirely reliant on the trainer’s decisions to form an autonomous system of builders and supervisors with reports about the process. Vaults stopped from being uncompromisable structures.

**Training Content**

**Classification**

There was no clear document that described the activities and tasks in the training of the workshop. However, strong classification and framing flagged the training in Rwanda with a clear structure of the curriculum and a solid focus on building the project’s vaults. The training had no in-depth introduction to the structural design approaches. Instead, all training activities had a clear objective: understanding plaster-setting time, cutting the tile, positioning the tiles and so on. Hence there was little space for the trainees to experiments within the time of the program. Another indication of robust classification is that the training was directed strictly to those with a background and experience in building technique. In summary, the training had barriers between theory and practice, tasks and activities, skilled and unskilled labour.

**Framing**

**Framing during Workshop**

The workshop started with strong framing. The workspace between the trainees and trainers were structured, James in the front and trainees standing in a straight line looking at him (Figure 73). Pacing and sequencing were critical to elevate the skill of tiling. Although there were no clear evaluation criteria, skilled labourers were signalled through the process to be later chosen for the following tasks. No knowledge or experience from outside the domain of vaulting was explored in the workshop. On the contrary, builders were repeatedly advised to unlearn their skill of wall construction as it is very different from vaulting.
Framing during Construction of the project

Amid the construction of the vaults, the framing changed. Strict and robust framing started to loosen, and more areas of self-development were given to the builders. After rigorous induction, James started to allow for the builders’ experience to add to the training when relevant, stating that although the training started with one way of mixing, “...builders might know many ways of mixing and adding gypsum”. What mattered is getting the overall construction rhythm and direction right. This change was noted from moving from small steps to the overall understanding of construction.

Builder 5: Maybe the easiest way to explain this is: gypsum was hard then easy, curvature was easy then hard.

Builder 1: the basics are simple, the overall thing is complicated.

During the beginning of the full-scale construction, the trainer worked on the same elements as the builders; sequencing and pacing was no more a training schedule but a construction program. The Head of masons was given deadlines but without interfering with their internal organization between the builders. The only framing aspect that sustained its strength during the construction is the separation between vault construction and other building activities, including at a spatial level. Builders adding more layers to the vaults were outside in contrast to builders placing the tiles from inside. Little communication was seen between the two.

Builder 4- Closing the vault is always the hardest part because all the four corners must collaborate and work together and with the ones outside the vault. It is hard.

Training Context

At the beginning of the workshop, learning of thin-tile vaulting was coined as structured activities; completing the three vaults was the central motivation for all trainees. No discussions or objectives were given to the prospects of learning the technique other than “having a new skill of our builders”. Builders were interested in the vaults’ appearance and the way they will look when they are built. However, before the actual construction, many have expressed doubts about their ability and technique. At the community level, a top-down hierarchy was noticed in decision making and phasing the work. This resulted not only from site hierarchies but also from the reliance on the trainer’s experience. Finally, at a design level, the trainees had little interests in exploring vaults typologies.

However, this task-orient trend had changed as the project progressed towards completion. The dynamics between the builders became fluid. Small groups of builders were formed inside the large group and distributed at the corners of the vaults. Although each group had a specific zone in the vaults, there was an exchange of opinions and instructions. Decision making was still in the hand of the supervisor, Salem. But the builder’s opinion was starting to be influential. In one incident during the construction, I noted in my observation:

Today, Salem noted the curvature of the vault at one side is off. The discussion was whether they should continue and correct the curvature while building, which will result in a bulge or cut the tile and redo it again. This is very typical in thin-tile vaulting. One builder was enthusiastic and said that he will do it fast because he knows now how to do it. Salem agreed on redoing the curve.
Chapter 03

Figure 69 RCS Training 01 Joining Two Tiles.

Figure 70 RCS Training 02 Building Small Vaults.
Figure 71 RCS Building the Edge Arches.

Figure 72 RCS Construction of Vaults.
One of the most vivid examples of how the trained team was able to self-organise was when they trained other people.

Builder 4: I was not part of the training. I joined the team afterwards to do plastering. But I wanted to build the vault too. I tried the technique on one side of the scaffold for some time. But then my trained friends were very confident, and they started to correct what I was doing. Little by little. Now I am part of the team; there is no difference between me and anyone who took the first training.

The conclusion of the project brought a "what next" to the fore. Workers split in their answers. While many wished for building a similar project in the future, a few builders started to look for ways to make vaults in their houses. Two main obstacles hindered moving forward, the availability of the materials for tiles and geogrids and the understanding of how to design a vault for their spaces. Some workers tried casting concrete tiles to make the vaults, but the geogrid replacement was still hard to find.

Figure 73 Spaces and organisation of training and construction of RCS. Both in the training and the construction, the trainer is at the centre of the space with training working around him or looking at him while demonstrating the work.
Rwanda Cricket Stadium: Summary of Training Analysis

### Content in Training

#### Classification

| Theory/Practice | + | Structural design was not part of the training, only roles of thumb of catenary curves |
| Activities/Tasks | + | All activity had a clear objective; there was always a goal to achieve during each activity. |
| Specialisation | + | Participants were carefully selected from building background profession within the company. |

#### Framing

| Trainer/Trainee Relationship | + | The distance was maintained between trainees and trainers inside the construction activities |
| Sequencing/Pacing/Evaluation | + | Although there were no clear evaluation criteria, strong sequencing took place in the training as participants showing skill in work were appointed as masters |
| Inside/Outside Knowledge | + | Outside knowledge was not incorporated in the training, tiling and brick layering were not important to how the training was provided |

### Content in Full-scale Construction

#### Classification

| Theory/Practice | + | The theory was not introduced or concluded at the end of the training |
| Activities/Tasks | + | The activity was always oriented around the construction of the project itself |
| Specialisation | - | Specialisation was overruled by those who proved to be skilful while building |

#### Framing

| Trainer/Trainee Relationship | - | Trainers participated in the construction of the vaults with the trainees |
| Sequencing/Pacing/Evaluation | - | During the project, pacing and sequencing were not based on training evaluation but logistics in construction such as material availability, modification in design, etc. |
| Inside/Outside Knowledge | + | Outside knowledge was not incorporated in the construction of the project |

### Context in Training

#### Practice (Work relief vs Profession)

| Market/Employment | - | The training was done within a construction company with in-house builders |
| Development/Adaptation to local mat | - | Trainees were interested in the adaptation of the technique to materials and functions other than the project |
| Goal/usability of the technique self-building | - | Builders were interested in the vaults' appearance; vaulting was more considered as tiling than structural craftsmanship |

#### Community (Cultivated vs Self-structured)

| Organisation/External/Internal | - | The organisation was completely external as the construction company selected the participants |
| Decision making/Extended-limited | - | Trainer and site engineers instructed the decision making of the vault and technique construction |
| Boundaries/On-site-off-site | - | There were no collective ideas developed between participants outside the construction site. All were employees in the construction company |
Domain (Technique vs Design)

| Tile placing / speed / precision | Speed and clean construction were essential in training, but the position and inclination of the tile was not as essential. |
| Curvature formwork / no formwork | The training incorporated working with formwork, and the first phase of the project was building arches over full shuttering. |
| Geometry / typologies / tile patterns | Patterns of tiles were studied in training, geometries of vaults other than catenary arches were not explored. |

Context in Full-scale Construction

Practice (Work relief vs Profession)

| Market / Employment | Trainees discussed possible application of the vaulting but only possible through similar projects. |
| Development / Adaptation to local mat | Builders were looking for cheaper and locally available alternatives to CEB and geogrids to apply vaulting outside the project. |
| Goal/usability of the technique self-building | Builders were discussing applying the technique for their structures and houses, such as gates and small storages. |

Community (Cultivated vs Self-structured)

| Organisation | As the project progressed, the team found new dynamics of self-organisation within the company. |
| External / Internal | Head of builders took care of the progress of the vault and affected the decision making in the construction of the vaults among engineers and architects. |
| Decision making | There were no collective ideas developed between participants outside the construction site. All were employees in the construction company. |

Domain (Technique vs Design)

| Tile placing / speed / precision | Like in training, attention was given to the speed, and clean construction, the wrong placing of tiles was avoided by practice or corrected by cutting and replacing the tiles. |
| Curvature formwork / no formwork | Some of the guidework were eliminated during the construction of the vaults to give freedom to builders to build faster as they dominated the curvature estimation. |
| Geometry / typologies / tile patterns | The geometry of the project's vault was believed to be the only geometry, no other typologies of vaults were studied or introduced. |

Figure 74 Positive development of training in RCS from tasks with strong classifications and framing (left) to values with weak framing (right). The development was noted by self-organisation and a better understanding of vault's design among builders.
Discussion

The RCS shows a particular scenario of thin-tile training in an already established practice represented in the construction company ROKO (Figure 74). This specificity facilitated the otherwise complicated procedures of recruiting labour. The company has its already established structure that regulates payment, selection, and assignment of tasks. Training in this context is more of a consultation or a boost to the skills ROKO’s workers. That said, training within a construction company has many downsides. Being in an overwhelmingly large company, the trainees were mere recipients with little reflections on their learning or how it could impact their lives. It was towards the end of the project that the trainees discussed what to do with their skill.

Furthermore, the enthusiasm towards learning the technique was noticed only in the circles of the builders. The middle management showed less interest and more doubts in the technique than the workers. The construction of the vaults necessitated a different flow of resources and decisions than the typical procedures. The project’s risk from the middle management’s perspective entails uncertainty, as explained by the project manager:

The difference with this [thin-tile vault] structure is the number of key-elements and the risk involved in those compared to a normal structure the ROKO usually build, which is concrete and steel.

You will need to have accurate cost information about what is required to produce tiles to the right quality and labour to the right quality.

These reflections unveils how established construction and business models do not welcome alterations in the way they work. On many occasions, site and material managers reduced the project to “a complicated shape”. As a result, middle management was less engaged in the training and the construction of the vaults. James was aware of the complexity of overseeing thin-tile construction, giving the “too many components involved” such as the vault’s curvature, the number of layers, and the substructures. For him, the transfer is about the ‘confidence’ that is developed during the training. “You need to find the key people that will build the vault”. Finding the key people to build the vault challenges the characterisation of skilled and unskilled labour, especially within a construction company with an established hierarchy. A skilled mason who excels in building straight walls, for example, might not master the technique as well as a novice one, leading to a change in the roles, which is challenging organisation and social wise. This necessitates an extra skill to mediate not only between builders but also between them and their employer. Being involved in the sites’ dynamic means also being aware of the social and cultural elements described in James’s words as “part of the story of forming a building.”

For those key-builders, thin-tile vaulting was a new quality to have within ROKKS, an advantage, a reason to verify and validate their work and profession. Discussion towards the end of the workshops showed how they consider themselves agile builders.

Builder 5: Thin-tile vault builder must have an awareness of everything; he should take everything into consideration.

Builder 6: Being good in this construction is not about the technical part, it is about the logic of foreseeing problems and solving them before they happen.

That has been said, final discussions with who became good thin-tile vaulting builders showed that they were very interested in learning not only the technique but also how to design the vaults and make its relevant formwork.
Builder 1: I still do not know how and why the six layers of the vault at the bottom become three layers at the top? Is it not better to be thicker? Is this about the design?

Builder 2: I want to know how you did the formwork. I know how to make formwork in concrete, but this is different.

This wish to learn was a wish to adopt thin-tile vault for their homes. It was hard to imagine any other geometry than the one they built, which they kept associating with landmark projects only and not housing. The lack of specific materials was another limitation to using thin-tile vaults for self-built houses

Builder 1: I would build a vault in my house, but where would I find geogrids? I never saw here in Rwanda. I understand that without geogrids, the vaults will collapse when an earthquake happens. Without geogrids, I cannot build a vault.

Builder 7: the vaults are faster and cheaper to build than concrete shells for sure, but the problem is the materials. I really do not know where to get gypsum and how much it costs.

Workers in ROKO can build more vaults. However, this unlikely to happen outside a construction project similar to RCS. Drawing on his experience in Mapungubwe, James expressed little confidence in making thin-tile vaulting part of South Africa or Rwanda’s local construction technique. When asked about the application for self-building of houses in South Africa. He stated

We tried to look at house’s design to pass on and replicate the knowledge. But without the [vault’s] design part of it, they did not pick that.

James was aware that in-situ simple form-finding tools such as hanging chains could help understanding vaults geometry, but the applicability is related to economy and availability of materials.

We taught the locals how to put roofs on their houses; they like the idea, but it was far-fetched, and the way it is done there would become very expensive.

The social and economic circumstances limited any autonomous use of thin-tile vaulting without being part of a construction company’s project. Both the trainer and the design lead team were aware of these realities from the previous similar project they did in Mapungubwe (Splaingard 2016). They state clearly that any skill transfer of thin-tile vaulting is aimed at constructing this project and similar possible projects that ROKO might work on in the future.

In conclusion, Rwanda Cricket Stadium’s training had a strong classification, with framing starting very strong and ending weaker (Figure 74). The context of this learning shows a positive engagement among the workers translated into an excellent understanding of building a vault but lacking a holistic approach for design and geometry, hindered by both the economic and hierarchical driving powers in the construction site.
3.3.2 Azraq Refugee Schools in Jordan

Azraq is a village in the south of Jordan whose surroundings hosts the second-largest refugee camps in Jordan after Zaatari. The village itself hosted 15,000 refugees in 2018, half of whom are children. Emergency Architecture and Human Right (EAHR), in partnership with South Azraq Women’s Association (SAWA) and the Syrian Fund, embarked on the task of building a school for refugee children in the village (Figure 75). The school was imagined to be built by local workers and refugees living in the village. The design and construction strategy aimed for a locally resourced construction, using soil from the site to fabricate compressed earth blocks (CEB). The proposed labour-intensive construction aimed at minimising the use of large construction machines and maximising labourers’ work, allowing for financial support for refugees by temporary employment.

The school’s design accommodated four rectangular units with patios. All four units had barrel thin-tile vaulting as a ceiling, two had a dome in the second floor resulting in six classrooms (Figure 75). I worked with EAHR as a consultant to facilitate training construction of the project’s vaults and domes. The barrel 1.2-meter-wide barrel vaults were designed to have two layers of thin-tile vaulting on which light volcanic stones and concrete were used for the infill (Rashad 2019). The 6-meter span domes were proposed to have four layers of thin-tile vaulting.

Training description:

In collaboration with the Spanish thin-tile vault builders Salvador Gomis Aviñó and Jesus Gomis Aviñó, the training in Azraq village was programmed to happen in two weeks. My part in the training was to translate the training from Spanish to Arabic and give the trainers feedback and reflections from participants. The participants in the training were Syrian refugees and Jordanians who also worked on-site making bricks. The training started with an explanation of thin-tile vaulting construction and the role of plaster mixing in minimizing wasting material and time. A training exercise was made using the barrel vault formwork (Figure 76). Many workers in the site participated in the first building activity, and some expressed their wish to learn the technique. The first activity in training also served the site architects to see the process and the time needed for construction. During this training, four workers and four helpers were chosen for the construction of the barrel vaults.

A second phase was made with the eight trainees. First, they built a 1/1 mock-up of one of the ceiling barrel vault, then a 1/4 mock-up of the dome with two layers (Figure 77). The training in this stage focused only on the building technique without mentioning design or structures aspects. The training in this stage had several iterations of trial and error. The barrel vault, for example, collapsed once because of adding tiles and cement for the second layer on one side only. Trainers build the vault again, adding the second layer more homogeneously and with plaster of Paris instead of cement.

The original training plan aimed at having one classroom and half a dome built under the direct supervision of the trainers. However, due to a project’s schedule delay, the substructures were not ready for vaulting activity during the time of the training. The project construction started one week after the trainers left the site. The barrel vault construction started with little difficulty, but it continued faster while progressing (Figure 78). The eight builders were made into four groups of twos, one plaster mixers, and one vault builder.
Figure 75 Azraq School for Refugees. (EAHR 2018)
The use of the formwork was necessary because of the vault’s shallow curvature geometry. Tiles were challenging to be placed with plaster only; temporary support was a must. Each classroom had 5 bays of 12m barrel vault that extrudes 6 meters. Each classroom needed about five days to be vaulted and one to two days filled with concrete and pumice. After the construction of all four barrel-vaulted slabs, the building of domes commenced. However, due to the inadequate and inconsistent quality of several patches of tiles, the dome’s construction needed to be done at a meagre pace. All layers needed to be built together, allowing time for the cement to cure (Figure 79). The two-dome construction resulted in a complex construction that was hard to tackle by the trained builders on the site. The decision to solve the problem was to use full shuttering of wood and add a layer of reinforced concrete to the dome’s layers.

**Training Content**

**Classification**
The workshop in Jordan had two stages: the training led by thin-tile vaulting experts and the construction led by (EAHR) architects on the site. Unlike the other examined cases of thin-tile vaulting, there was no overlap between the workshop and training and the project’s full-scale construction, as trainers left the site before the latter commenced. In both training and full-scale construction, the workshop’s preparation and activities present learning subjects with strong boundaries between them. The workshop focused only on vaulting and did not integrate any learning on the design of shells. All workshop’s activities had a clear task and objectives with little area to experiment or train. Although all builders were refugees and local working on producing the compressed earth blocks, priority was given to those with experience in construction (Figure 80).

**Framing**

**Framing during Workshop**
The workshop had very loose training pacing with time opened for reflections and comments. Because some trainees had previous experience in building, outside knowledge could take place. Builders could use whatever tools and techniques to finish the vault; no clear indication was given to use specific tools. The space between the builders and trainers had no divisions in all training activities (Figure 80). The evaluation criteria for vaulting and trainees were spontaneous. At the beginning of the workshop, those who felt they do not want to engage in the learning and construction of the vault could withdraw and go back to produce earth blocks. Workers on site were recommending who could be good at this construction, nominating those who did well in producing the tiles as I note:

Groups of two started to work with trainers. Some liked and worked well with the technique, other were not as enthusiastic. Many were suggesting that Ammar as a trainee, a young Syrian who was doing very well in producing tiles.

The loose framing in this phase has resulted in high aspiration to learn a new construction method that could be an advantage in the local construction market. However, a more immediate reason for workers to participate is to prove their validity and guarantee their employment. While it looked promising then, this loose framing had consequences in the construction of the project.

**Framing during Construction**
In the construction of the schools in Jordan, a drastic contrast between the training and the construction could be noted. By the time the trainees were on the scaffold to vault the first classroom, they were treated as professionals and experts.
Figure 76 Training 01 Building Small Barrel Vaults.

Figure 77 Training 2 Building Mock-ups for Project's Vaults.
Figure 78 Building Small Barrel Vault.

Figure 79 Construction of the Dome. (2018 EARH)
Pacing and evolution were taken very seriously, and no margins for error were tolerated. This was because of the project pressing deadline. The hierarchal interaction replaced the absence of the trainer in the construction. Site architects with little knowledge about the dynamics of labour and construction in thin-tile vaulting led the vaulting. However, the work on the barrel vault was not a real problem for the builders who were able to make the vaults without real complications. They also did some alteration to the construction for a better looking and faster vaulting.

In the first classroom: we started with the running bond coursing; we chose this coursing because it was better on the training. But in the building of the classroom, it resulted problematic for the half tiles are breaking while we change the formwork resulting in more time to work and errors in coursing.

In the second classroom: the workers did new coursing, sequences of arches, the vaults are looking much better, and the tiles are not cracking during the construction.

The incremental change to a stricter framing has resulted in continuous stress among the builders. However, the participant’s internal social structure played an essential role in regulating this stress (Figure 81).

Training Context
Building the school in Azraq took place in complex social and economic circumstances. The construction site has refugees who were working on a basis known as cash-for-work; any other format of labour was very hard for refugees to access. Local Jordanian workers were also on the site. The site, therefore, illustrates an area of contested interaction between refugees and local workers on the one hand and between all workers and site architects on the other.

Workers with refugee status are Syrians; most of them are from two villages, Al Quaryatayn and Mheen, located between Homs and Damascus. Workers are either neighbours or come from the same family. The extension of the family’s hierarchy in work was evident. Early training of thin-tile vaulting had about five young builders. Good vault builders they were, but they called for the participation of an older person who was able to lead the construction, not only technically but also socially, as a respected member among his family members.

Refugee builders made many connections of the thin-tile construction to their home villages. The workers’ original villages have mud houses, a relationship between the compressed earth blocks and the sun-dried adobe was discussed between them and the trainers. The inconsistent quality of the compressed earth tiles has contributed to mistrusting the material, usually comparing it to the bulky and sturdy adobe of Syria’s mud villages.

Salvador, the leading trainer, noted that they have to know not only how to thin-tile but many other things that he calls

The tiles are not as strong as fire clay tiles that we use in Spain, so we need to treat this construction more carefully. First, we will have to know how to prepare a good mortar for the second layers. In some cases, we even have to do the second layer with plaster of Paris. We also must learn how to decentre the formwork without breaking the tiles. So we might have simple barrel vaults, but the elements in it are crucial.

This was also reflected in the trainees’ reflections on the process

Builder 02: The training was introductory, but I wish we had more time with Salvador to work on the material mixes for the tiles and the mortar.
Builder 03: I really like the technique; it will work but only if the materials were better and stronger. I think if we change the material to fired blocks, we will do a much better job.

The work on the vaulting started to become a burden instead of a privilege to the trainees. When the full-scale construction started and framing became strict, the curiosity to learn was outweighed by the commitment to build. Decision making of what and how to build was now part of the project program. New builders enter the project as contractors who were not part of the training. What had started as catering for a small community of individuals was overwhelmed with site hierarchy and social structures.

Figure 80 Spaces and organisation of training and construction of the Azraq school for refugees in Jordan. No boundaries of clear structure can be noted (especially in phase 2). No trainers were in the space during full-scale construction.
Azraq Refugees School in Jordan: Summary of Training Analysis

Content in Training

Classification

Theory/ Practice: The theory was not part of the training. Instead, the work was focusing on the two geometries of the vaults.

Activities/ Tasks: Activities were open to participants to try out their skill in layering the tiles on moulds without the need to finish the element from A to Z.

Specialisation: No criteria of who participate were set, some preferences were given to those with some building activities, but the selection was based on short training for selection.

Framing

Trainer / Trainee: The distance was maintained between trainees and trainers inside the construction activities.

Sequencing / Pacing / Evaluation: Very loose pacing in training with time opened for reflections and comments.

Inside/outside Knowledge: Outside knowledge was allowed to take place in the training where trainers were allowed to use whatever tools and techniques to add the tiles.

Content in Full-Scale Construction

Classification

Theory/ Practice: The work on the project was only focusing on the techniques.

Activities/ Tasks: The project tasks were clear, and the margin to practice until completing to vaults was not possible.

Specialisation: Those who were trained but had no previous building activities were replaced with concrete builders to speed up the construction of the project.

Framing

Trainer / Trainee: The trainer left the site after the training without participating in the construction of the vault.

Sequencing / Pacing / Evaluation: During the project, strong sequencing was made, and time was very important for builders to meet targets; evaluation was made with explicit rules.

Inside/outside Knowledge: Outside knowledge was not incorporated in the construction of the project.

Context in Training

Practice (Work relief vs Profession)

Market / Employment: The work with the participant was set as training for a new profession where the trainees can develop a self-supporting job.

Development / Adaptation to local mat: The work in the training was incorporating an investigation of different materials that can be found locally to support further work during and after the project.

Goal/usability of the technique self-building: Participants in the training were also working in the production of the compressed earth blocks; the work incorporated producing your material and build with it.

Community (Cultivated vs Self-structured)

Organisation: Although there was a selection process of participants, some freedom was given to those interested in the training.

External / Internal Decision making: Decision making of what and how to build in training was systemised.

Extended-limited Boundaries: Groups of the participants were all refugees from two adjoining villages in Syria who reside in Azraq; they were families and friends.
Training Approaches to Thin-tile Vaulting

**Domain (Technique vs Design)**

- **Tile placing / speed / precision**
  - Speed and clean construction were essential in training, the position of placing the tile was not as essential.

- **Curvature formwork / no formwork**
  - The training incorporated working with formwork, and the first phase of the project was building arches over full shuttering.

- **Geometry / typologies / tile patterns**
  - Patterns of tiles were studied in the training, geometry of vaults were not.

**Context in Full-scale Construction**

**Practice (Work relief vs Profession)**

- **Market / Employment**
  - Complications in the project’s administration developed a sense of rejection towards the technique as possible permanent work.

- **Development / Adaptation to local mat**
  - In the construction, the focus was always on the compressed earth blocks.

- **Goal/usability of the technique self-building**
  - The state of refugees was also essential in the rejection to adopt the technique in building their houses.

**Community (Cultivated vs Self-structured)**

- **Organisation External / Internal**
  - The untrained external contractor was brought to the project.

- **Decision making Extended- limited**
  - Decision making in building and organisation was all done by the site architects.

- **Boundaries On-site- off-site**
  - The introduction of construction contractor was resulted in a group of the trainees to leave vaulting and go back to block making.

**Domain (Technique vs Design)**

- **Tile placing / speed / precision**
  - Attention was given to the speed and clean construction, wrong placing of tiles avoided by practice or corrected by cutting the vault and replacing.

- **Curvature formwork / no formwork**
  - Most vaults had very formwork for workers to follow. Domes had full shuttering.

- **Geometry / typologies / tile patterns**
  - Discussion about the geometry of vaults focused on vaults in the project, no other vaults were given or studies by the builders.

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**Figure 81** Negative development of training in the Azraq school from (value) of a craft training with weak framing to (task) training in full-scale construction with strong framing.

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123
Discussion

The training and working environment in Azraq exhibit a high complexity in the site’s contested practices. In an exceptional working process where the budget was directed to local workers and refugees. We have two groups of nationalities, two types of contracting (constructor for walls and by day freelancers for making tiles). This results in extreme effort to build the project and much time being spent on arrangement and organization. The project did not have a leading contractor or a construction entity that regulates the work between builders, forming difficulties in committing to the laborious work of thin-tile vaulting in the long term. Two of the trained builders left the site because they found a job with better conditions in another organization.

Within this context, the thin-tile vaulting training was explicitly introduced to workers as a new skill that might help them financially support themselves. However, the Syrian refugees’ aim to work on vaulting comes is more connected to their original villages than their aspiration to the future. In the middle of the training, when a discussion was opened about using the technique after the project, all refugees refuted any possible applications in their houses or as a profession.

Builder 01: I do not think this construction or anything else can help me here. I can not own a house, so why would I build my house myself? It is hard to work autonomously; I will always be an employee. If we were in Syria, I would even borrow the machine that compresses earth for a while and build some stuff with from what we learned. I could also try to do it with mud. But all this is not possible here in the asylum.

A concise and robust training curriculum would serve the craft training programs (Gamble 2004, 134). However, the abrupt shift from weak to strong framing led to a negative impact on the practising community (Figure 81). Moving forward with the construction of the dome was specifically problematic. The construction over a full shuttering in the dome represented a failure in using thin-tile vaulting where skill is replaced with formwork.

The trained builders in the project of Azraq are unlikely to build with thin-tile vaulting. This is a result of two reasons. The first is the trainees’ economic and social conditions as refugees who are unable to easily establish their own business, be employed, or own a house. Thin-tile vaulting only offered a cash-for-living and a work relief program to temporary pay the builders. The second is about the abrupt change in framing, the training did not support the construction as planned. Instead, they were treated as experts and were expected to perform and such
3.3.3 Santa Pola Cultural Centre in Spain

The Centre of the Art and Culture in Santa Pola (Alicante) is a community centre that hosts events and activities related to art, music, and literature. The centre is a 1912 two-storey family house with a large garden surrounding it, owned by the poet Maribel Lopez and her family. They donated the house to the municipality for art residency and exhibitions. The garden’s rehabilitation and space are used by municipal vocational school (SERVEF). Construction training programs such as masonry, painting, and plumbing occur in the garden to fix or supply it with new facilities. The house’s rehabilitation program suggests a pavilion for a performance stage and a small seating area in the back garden. I was asked to design the pavilion, considering that it will be built as part of the vocational training program, and students will build it with the trainer.

Being a workshop and a pavilion, the thin-tile vaults needed to accommodate the program of the two. The vault’s construction needed to be customised; trainees with low-skill in thin-tile vaulting should still be part of the construction. The design has a triangular plan with three vaults at the edges. Each vault is a sequence of catenary arches formed with a hanging chain, the arches sweep over a curved base generating a simultaneous change in the height as they open or close. The result is a doubly-curved catenary vault, two of which intersect at the base (Figure 82). The agglomeration of the three vaults has a compositional complexity. However, vaults’ construction is easy given the modularity and use of a sequence of catenary arches.

Training description

Centres for vocational training in Spain runs extended training programs as part of the national and regional employment plan for young persons. The training in Santa Pola is both diverse and general. It offers many building skills during nine months-long programs with participants between 20 and 30 years. One of the training activities was thin-tile vault. The activity was led by thin-tile master-builder. The training strategy integrated design in the thin-tile construction. The workshop included theory sessions and discussion about vaulting during and after the construction. Likewise, the workshop integrated margins of trying then applying. The two had a clear objective, building the pavilion.

To kick-start the workshop with activities that the trainees are already familiar with, the vaults’ curved foundations were built with bricks and plaster (Figure 83). The workshop introduced the project and explained the pavilion geometry using 3d printed models and sketches (Figure 85). Theory sessions took place after midday breaks and early morning. The sessions explained lines of thrusts in load-bearing vaulting, graphic statics and simple construction methods, typologies of vaults and domes and the available tools and guidework to build them. All these sessions were also hands-on, using chains, strings, and small blocks. In the sessions towards the end of the workshop, attention was given to questions related to the pavilion.

Although many options were explored in the teaching sessions, the practice aimed at providing the trainees with the simplest on-site method to build a vault when needed. Therefore, the practical side of the thin-tile vaulting was the construction of the pavilion itself. The trainer used a chain and wooden boards to both form-find the vault section and use the board as formwork (Figure 83). After tracing the hanging chain on wood and flipping the board, the board serves as a wall on which the tiles can be placed with plaster of Paris. After building several arches, the board can be removed and used to build another vault (Figure 84).
Figure 82 Santa Pola Pavilion Cultural Centre, 2019.
The 12 participants of the workshop worked collectively on the making and installation of the formwork. However, the building itself was formatted in two parallel activities: the first was the central construction of the pavilion in which the trainers led the construction. Trainees were observing and helping in material preparations, plaster mixing, and adding cement and more layers to the vaults. Because the group of trainees is small, the interaction with the builders in the pavilion was very vibrant with questions and comments. The second activity was in the nearby area where participants teamed to two to replicate the construction of the pavilion but at a smaller scale (Figure 85, Figure 86). They built 1.2-meter span arches with rips on the top, a mock-up of a thin-tile vault slab system that is found abundantly in the traditional construction in the region (Figure 87). The small arches' construction was lightly supervised; students tried to apply what they are learning from the large structures with a margin for trial and error. They were also allowed to experiment with their structures.

Training Content

Classification

Weak classification themed the training workshop in Santa Pola. No strong boundaries between the subjects of learning were formalised. How to design and how to build were both intertwined with no advantage given to any of them. Indeed, the short-term workshop and the construction of the pavilion was about finding simple methods to transfer site and material limitation into a solution. The training program did not have a clear differentiation between the activities and the tasks. Although the completion of the pavilion was a requirement, it was the trainers who were subject to conclude its construction and not the participants. Salvador Gomis was supportive of this approach, stating that

It is easier if I finish it, we will do that collectively of course, but in case there will be any problems, I will solve them with them, it is my responsibility.

Trainee’s practice on the small arches was not the main task of the workshop. However, it opened a possibility for experimentation and interpretation of the thin-tile building by small teams of trainees. Finally, many participants of the workshop had no background in construction other than the skills they learn in the unemployment program, making minimal boundaries between specializations.

Framing

Framing during Workshop

Although the activities of the workshops’ sessions were structured, the overall framing was left to grow with the interests of participants. Outside knowledge and experience from previous training, such as masonry and brick layering, were present in the discussion about the vaults. The subject of sustainability and materials was very prominent. This comprehensive discussion allowed for talking about more vaulting technique and associating or contrasting them with thin-tile vaulting.

The exposure to other methods to build than thin-tile vaulting was thoroughly discussed with students in class today. The Mexican technique, *ladrillo recargado*, in particular was of huge interests which we explored using boxes of orange juice to explain how the inclination of the brick along the bed can revoke the use of formwork.
Figure 83 Training making the Foundation and Formwork of the Pavilion.

Figure 84 Construction of the Pavilion
Training Approaches to Thin-tile Vaulting

Figure 85 Classes of Vaulting Geometries

Figure 86 Building the small vaults
In both theory and practice sessions, the space of the trainers and the space of the trainees was one, both working on finishing the pavilion structures (Figure 87). A high level of freedom was granted to participants to choose their tasks without any pacing or sequencing measures other than keeping the construction’s progress. Likewise, no strong evaluations were conducted at the beginning of the construction other than the direct comments and feedback of trainers.

**Framing after Workshop**

The workshop’s conclusion showed a shift towards a strong framing; participants were asked to prepare, fix, and finish their final arches mock-up. A new work pattern emerged where pacing started to become an essential factor; participants were given one day to finish the arches. What started as a try and see activity is now a particular task with the expected output. Spatially, the workshop divided between trainers finishing the pavilion, and trainees finishing their small arches (Figure 87). Some participants gave positive feedback about this change in the rhythm of the construction, stating that they have to gain more trust in what they are doing.

**Training Context**

The workshop in Santa Pola was short and only a part of long vocational training, it was hard to see an apparent emergence of thin-tile training practice and its relationship to the overall community of students in the program. However, observing how participants responded to the workshop shows a shift from tasks completion in the beginning to a clear interest in learning. Sessions of classes also had an impact on the language between the trainees, it brought all of us into a zone of the established language of engineering and made communication more accessible, I note:

> This is the second class; students are moving from talking about strong and weak vaults to talk about lines of thrusts and masses of vaults. Words and terms like these are sparing us a lot of time and, when used in the right place, makes communication much easier between the trainees and me.

The presence of a goal in training, represented by building a pavilion, motivated the participants. Sessions of design and calculation of vaults were vibrant with many questions and projections from thin-tile vaulting to concrete shells.

Unexpectedly, sustainability as an aspect of thin-tile vaulting was very central in the discussions. Being a construction that is rooted in the region, all the materials needed to build a thin-tile vault is available. However, the trainees were interested in alternatives that ‘more sustainable’, such as replacing cement with lime and each for mortar used in the second layers.

> The participant had a conversation today with me and Salvador about possible ways to make thin-tile vault more sustainable. One suggestion was the use of earth and lime instead of Portland cement for adding the layers, they had previous knowledge about natural mortars, and we used lime and earth for the vault.

While the workshop’s work progressed, small groups started to take shape for specific tasks and experiments. Most of these groups were self-organized, and the organisation was associated with thin-tile vaulting as a prerequisite to building a vault

> Builder 04: Perhaps the most important thing in building vaults is cooperation and teamwork
When the workshop was concluded, the work on smaller arches showed a fast forming, responsive and decision-taking groups of two. Although the results of the arches were not of a high craft, the process learned from the construction of the pavilion was organically followed. The discussions on the vaults' design helped the trainees make their structures without intensive help from trainers. This has raised confidence in the participants' work and ideas.

Builder 03: What I liked in the workshop is the experience, both in exploring ideas and in realising them.

Figure 87 Spaces and Organisation of Training and Construction of the Pavilion in Santa Pola
### Santa Pola Pavilion: Summary of Training Analysis

#### Content in Training

**Classification**
- **Theory/ Practice**
  - Theory and construction were given together in the training.
- **Activities/ Tasks**
  - Activities and tasks were not twinned, participants could work on the technique without the need to finish a structure or draw a structure without the need to build it.
- **Specialisation**
  - No specialisation was given any priority to participate in the training.

**Framing**
- **Trainer / Trainee Relationship**
  - The work with the trainer was very close and intertwined with the participants.
- **Sequencing / Pacing / Evaluation**
  - Very loose pacing in training with time opened for reflections and comments.
- **Inside/outside Knowledge**
  - Outside knowledge was allowed to take place in the training; trainees could experiment with stone or wood to use in the construction of their vaults.

#### Content in Full-scale Construction

**Classification**
- **Theory/ Practice**
  - The work on the project was only focusing on the techniques.
- **Activities/ Tasks**
  - The project tasks were clear and the margin to practice until completing to vaults was not possible.
- **Specialisation**
  - Those who were trained but had no previous building activities were replaced with concrete builders to speed up the construction of the project.

**Framing**
- **Trainer / Trainee Relationship**
  - The trainer left the site after the training without participating in the construction of the vault.
- **Sequencing / Pacing / Evaluation**
  - During the project, strong sequencing was made, and time was very important for builders to meet targets. An evaluation was made with explicit rules.
- **Inside/outside Knowledge**
  - Outside knowledge was not incorporated in the construction of the project.

#### Context in Training

**Practice (Work relief vs Profession)**
- **Market / Employment**
  - The training was done through an extended program of building and construction vocational training.
- **Development / Adaptation to local mat**
  - Thin-tile vaulting was only one technique among others that the trainees were exploring.
- **Goal/usability of the technique self-building**
  - Building, in general, was the focus of the training without looking for any possible job.

**Community (Cultivated vs Self-structured)**
- **Organisation**
  - Participants are students in a vocational school.
- **Decision making**
  - Decision making was solely done by the instructor.
- **Boundaries**
  - Students were also organised in groups of friends, but on-site work was completely individual or instructed.
Domain (Technique vs Design)

- Tile placing / speed / precision
  Working with small steps in placing tiles without exploring any precision

- Curvature formwork / no formwork
  Training started with limiting the work on following the catenary curve traced on a hanging chain

+ Geometry / typologies / tile patterns
  Vaults geometries and typologies were introduced at the beginning of the workshop as part of the theoretical study

Context in Full-scale Construction

Practice (Work relief vs Profession)

+ Market / Employment
  The project opened questions about further long and specialised thin-tile vaulting

- Development / Adaptation to local mat
  Thin-tile vaulting was only one technique among others that the trainees were exploring

+ Goal / usability of the technique self-building
  Many participants expressed their interests in applying the vaulting in their houses

Community (Cultivated vs Self-structured)

- Organisation External / Internal
  Participants are students in a vocational school

+ Decision making Extended- limited
  A space of experimenting was made for student

+ Boundaries On-site- off-site
  Groups of students started to form their own spaces to build and finish their specific tasks

Domain (Technique vs Design)

+ Tile placing / speed / precision
  Project-related issues have arisen during the workshop to result in significant inquiries about the design and construction of tile vaults in general

+ Curvature formwork / no formwork
  No guidework or formwork was used to follow the curves

+ Geometry / typologies / tile patterns
  Several vault geometries were examined during construction with attention to the catenary section curves in all of them

Figure 88 The positive development of training in Santa Pola from ‘task’ training to ‘value’ training be developing a weak framing into a stronger one. The training starts with reflections and explorations and ends with applications of skills.
Discussion:

Unlike regular craft training, the thin-tile vaulting workshop in Santa Pola starts from the general to the specific and principled to the tacit. The result was delivering a comprehensive examination of how vaults work, which proved beneficial when training concluded with building more vaulted structures with the same technique (Figure 88).

The shift from the general to the specific relinquished any divisions between learning, theory and application, trainers and trainees. The work's evaluation and pacing were not essential during the workshop except for the last day when participants were asked to build vaults in one day. This training model offered an extended sense of 'personal authorship' and a 'zone for trial and error', which elevated the engagement of the trainees in the construction. It also offered a 'reference of comparison' represented by the central vault that the trainer is building, "a live performance of art" as one participant phrased it. The combination between the two showed that this vaulting has potential as a sculpture and a ceiling alike. However, the weak framing at the beginning of the training allowed some to withdraw from activities; two participants preferred to only prepare materials and did not engage in any design practice. A training with week classification and framing was possible in this project because of its small scale, and the active role the trainer played to build the pavilion. This left a space for intensive work on the design. The design sessions and presentation were similar to an introductory level to structure for graduate architecture students, with design principles, graphic statics calculations, and material specifications.

The result of these workshops was reflected in the final drawing exercise, where participants were asked to give three vaulting solutions for a room. Students were able not only to give examples from the workshop but also to extrapolate them in new expressive designs of vaults. The builders in the vocational school in Santa Pola will be able to recognize a thin-tile vaulting construction, understand its architecture and participate actively in it. Some will be able to build small scale vaults or domes. However, intensive training on the technique of placing the tiles will be inevitable for a fast and well-executed structure. This can be achieved by either doing many small projects to practice or being an apprentice for a thin-tile vault maker. Some already expressed their wish to work for the trainer, Salvador Gomis.

Builder 05: the workshop is great, but I think if I want to be a specialist, I will have to spend a year with Salvador and Jesus learning from them.

Unlike the other examined training, this possibility is high in Spain, where there can found several thin-tiling workshops for vaults and stairs. In such training, the compressive knowledge on vaults is achieved, but the follow-up activities and interest are crucial in shaping a specialised thin-tile vaulting builder.
3.4 Conclusions: Building and Training of Thin-tile Vaulting

3.4.1 Impact of the project’s geometry

To study the impact of the training on trainees’ approach to vault design, the research focused on co-drawing with the builders a solution of vaulting for the 4 by 4 meter room. The impact of the geometry of the projects was very evident in the imagination of the trainees. In Rwanda, the sail vault’s geometry was used in almost all solution, which is understandable because it is the only thin-tile vault that they saw and built. Furthermore, many trained builders faced difficulties in adopting expressive sail geometry to room, especially with the substructure of walls, beams, and plinths. This impact was not as explicit in the sketches in Santa Pola, given that the training in Spain introduces vaulted geometries in the course. The process of the construction of the vault was equally impacting. The formwork in the cricket stadium construction in Rwanda resulted in drawing them in the soliton; many builders instructed and sketched the formwork and described their solution with diagonal and perpendicular sections. In contrast, the builders in Jordan were very sensitive to the substructure, represented in the steel beams in the projects, and most of their incorporated beams and vaults together (Figure 89). This sketching activity also showed that some solutions were shared in all three cases, namely barrel vaults and rib vaults; the two vaults are easy to be described geometrically.

3.4.2 Practised and Principled Training

In this chapter, I extrapolated the relationship between craft training and design in relation to the context of three training programs in Rwanda, Jordan, and Spain. The examination illustrates two models in training: practised training and expanded training.

In practised training, the focus is on applications and techniques; it relies on the skill gaining for efficient, fast, and capable builders (Figure 90). Practised training introduces thin-tile vaulting as a technique without expanding on its geometrical and design aspects. It is conditioned and contained within strictly dictated tasks, especially at the beginning of the training; it starts with strong classification and framing, similar to what the training in Rwanda did and the training in Jordan missed. In Jordan, the absence of structured steps of learning caused underestimating the technique, which resulted in adverse effects in the construction of the project ramified through the community of builders and losing trust in the material. Most of the builders in practised training will not replicate what they learned about vaulting outside the projects site, and less likely in an informal and vernacular construction. This is due to the little knowledge in geometry and design of vaults, shown in many requests from builders in Rwanda to learn design and making formwork. When this training develops, it is conditioned with opening a flexible area for reflections and development; this can be achieved by loosening both framing and classification towards the end of the training.

In the expanded training, the focus is on designing the vaults, the substructure and selecting appropriate materials. It is more explorative and opens channels for a dialogue between the knowledge that is being transferred and the existing knowledge in the context of learning. This model starts with weak classification and weak framing; it engenders flexibility between teaching subjects, activities, tasks, allowing for observations, reflections and experimentation (Figure 90). This training constructs a community of practice by preparing key-persons assigned to overview the project when the trainers are not on-site. Finding of the key-persons is attributed to what James Bellamy described as “confident on the site”. This key-person on the site might not be the fastest or most accurate builder but can show an agile comprehensive understanding of the process and an eye for imaging and estimating the vaults’ curvatures.
Figure 89 Drawing vaults with participants in thin-tile vaulting workshops
In expanded training, more training activities that are paced and evaluated are introduced while the programme is developing to acquire a ‘practical familiarity’ as one trainee in Spain phrased it. This training is suitable for small-scale projects without an extensive construction schedule. Like practised training, it is also conditioned with the presence of the trainer in the building. What this training offer is a comprehensive understanding of different geometries and methods to build vaults. The building activity itself will require attention and practice. Most builders in this kind of training can identify and design a vault, but they will need more focused practice (which can be done without extensive supervision of a trainer) to improve the building’s detailing and speed.

It can be noted that the two training strategies are complementary, expanded training can serve as an introductory activity to practised training, or it can also be a follow-up activity (Figure 90). In Rwanda, after the project’s construction, it took only one day to discuss geometries of vaults and build them. The opposite happened in Spain, where integrated curriculum become strict towards the end of the construction (Figure 90). Choosing and constructing the two models is related to the reading of the project’s context. One of the crucial roles of training context is the ‘institution’ in which the training is taking place as it represents the dynamics of power and control affecting aspirations and realities. In Spain and Rwanda, vaulting workshops took place in an established structure of school or construction company, in contrast to the School project, which relied on cash-for-work labour in the locale. The training in Jordan suggests that establishing a community of training is a precondition for successful and sustained participation of builders in the construction within the lack of a regulative institution. A community of training requires a guarantee of work during the whole project, not on a cash-for-work basis, and the trainer’s support in the initial period of the project and during construction, both were not the case in the school project in Jordan. Recalling the project in Mapungubwe, with a very similar context of the school on Jordan, James Bellamy mentions that he had to negotiate with the contractor to support the builders on site. Another crucial element is phasing the training within the scale and complexity of the vaults. In Rwanda, the edge arches’ construction, which was built with full formwork, proved very useful.

Finally, introducing thin-tile vaulting in new regions must consider the diverse “component” to the technique: materials or material alternatives, systems of production, and the informal and formal market of construction. While essential to procurement and resourcing, these considerations give an idea of what a builder can (or cannot) do with this skill after constructing the project. From discussion with trainees in the examined workshop, three industries were mapped and considered essential to the Building trades in general. Therefore, craft training should be situated at the intersection between three industries: artisanal work, construction, and restorations (Figure 91).

However, learning a craft within these sector needs time, and traditional forms of training represented by the master-apprentice exchange are no longer the norm. This is due to two reasons. First, thin-tile vaulting is usually introduced in new locations with limited time and availability of masters to train local builders. Second, training programs today are usually shaped in a format of short workshops within vocational training centres. Between the traditional too-long training and the emergent too-short training is the critical question in today’s adequate form of craft teaching and learning. The two training models (practised and principles) concluded from examining the training programs help answer the question.

Instead of approaching training by its length, it can be described by its nature. Short workshops are intensive learning activities, while long training is the knowledge infrastructure from which learners understand and reflect on design and construction aspects in craft (Figure 92). Community as an ‘expanded training’ can be observed in the pavilion construction in Santa Pola.
Chapter 03

Figure 90 Designbuild pedagogy with practised and expanded training.

Figure 91 Training Model within Existing Business Models

Figure 92 Training model in Construction Craft
Activities in ‘practised learning’ strict steps to learn is seen evidently in Rwanda, can serve to magnify the role and impacts of small tasks within the overall project. In other words, the goals of practised training can be achieved by activities, and the goals in principled training can be achieved through a community of artisans, apprentices and architects. Training of craft is the ability to move between activities and communities of this craft.

3.4.3 Training Model in Architectural Education

Although the examined programmes of thin-tile training show explicit cases of vocational training. The extracted models and study of the context impact from these training are relevant to education in architecture, specifically design-build activities. On a conceptual level, the expanded and practised training can provide a framework of where and how learning-by-making can be considered in architectural education. On a social level, the models show engaging by co-making can produce communities of practices and a dialogue between the local conditions and design aspiration.

The “making” dimension is not new in architecture education. In 1874 John Ruskin worked with students at Balliol College on making for a community service project, repairing swampy roads between North and South Hinksey, Oxford (Canizaro 2012). One of Bauhaus’s central points in education is the comprehensive approach to design, phrased in Walter Groupies’ words, “let’s become builders again” (Kraus 2017, 3). In the US, Buckminster Fuller and students built geodesic domes in the 1950s, and Yale’s building project was established in the 1960s. Since the late 1980s, there was an increasing and influential number of design-build studios. Today, almost every school of architecture has a design-build program. However, design-build programs are still facing challenges within cohorts of pedagogy in architecture, usually critiqued for being too vocational and marginal without a thoughtful link to critical thinking in design and research and limiting the space for self-expression and personal development of students (Canizaro 2012). Analysing craft training programs can project some lessons on the meaning and goals of learning to build and learning while building. The proposed training model shows that a holistic and general approach to learning a construction craft can be through expanded learning, leading to a specific tacit knowledge conditioned with reflective practice. This model is very popular in design-build education. However, the study also shows activities in ‘practised learning, (with strict steps to learn, master and apply) can also lead general design approach related to the craft in hand. This model, seen evidently in Rwanda, can magnify the role and impacts of small tasks within the overall project, where no task is a small task. This approach should pay attention to reporting, reflecting and reiterating what seems very vocational in a design studio, such as wood carving, cutting, concrete casting. The dialogue between tasks and the project can be projected on a whole design curriculum.

This leads to the second contribution of the proposed craft learning model to design learning. Building for the community is central in design-build education, but building with the community is less tackled: the analysis and engagement of local building methods. If the design-build pedagogy in architecture strives to replace the forever lost master-apprentice models in reindustrialised society, looking at modern teaching of traditional craft is a must. The design-build project should capitalise on introducing a new way of making to the site and learning a new way of making from the site—the two are usually interconnected. Under the current environmental emergency, one of the most pressing skills to learn is establishing a dialogue with culture as a site. Thin-tile vaulting, as a craft, was a medium for this dialogue. Similar mediums should be investigated and employed for broader research on teaching craft in the era of fast-fabrication methods and specialised education strategies.
Chapter 4
Design Approaches in Thin-tile Vaulting

Material, Time, and Tools

As an architectural element, thin-tile vaulting interlaces many building aspects. As seen in the last chapter, it has a strong connection with tacit knowledge inherited from it being a craft before anything else. However, thin-tile vaulting also engenders design aspects governed by gravity and material properties. In construction, the abundance or lack of material, time, and tools can be a limitation that hinders or develops to use thin-tile vaulting in construction today.

This chapter will examine how design, equipped with analysis tools, can engage with thin-tile vaulting in contemporary construction through three case studies. The first case examines material; it illustrates a strategy to find an alternative building material to the traditional terracotta tiles, projecting the strategy on the case of destroyed areas in cities in Syria. The second case concerns time; it transforms thin-tile vaults into building components that can be manufactured, transported, and assembled. The third case studies geometry; it examines how formwork and guidework, an essential element in thin-tile vaulting, can be generative, not only descriptive of shell forms to facilitate their construction for unskilled labour.

In all three cases, the primary purpose is to push the design thinking to include making vaults accessible through material alternatives, prefabrication strategies, and generative tools. To achieve such a goal, I avoid the use of on-site fabrication tools and advanced machinery. The three projects rely partially on computation but as analysis and simulation tools and not as tools of fabrication. This approach produces solutions based on geometry, rendered in patterns, rules of thumb, and strategies easy to use by artisans of thin-tile vaults with their habitual tools.
4.1 Material: Vaults from Buildings, thin-tile Vaulting from Stabilised Rubble Tiles

Thin-tile vaulting traditionally uses terracotta tiles and plaster of Paris to achieve minimum-formwork construction. While plaster of Paris is abundant in many countries, terracotta tiles are not. So far, alternatives to fired clay tiles include earth blocks and aircrete or lightweight stone. Tiles from these materials were made for specific project construction; another approach can be system-oriented, incorporating the technique within local construction methods. In the context of many developing countries, the prevailing material is concrete blocks. They are usually produced in small enterprises and factories with semi-mechanized systems of vibration–compactor moulding machines. Reintroducing the fabrication of tiles within these systems provides an opportunity for thin-tile vaults to replace concrete slabs.

This section investigates the applicability of thin-tile vaulting in the context of post-war reconstruction in Syria. It proposes using stabilised rubble tiles for vaults to reduce concrete consumption and eliminate steel in slabs altogether where seismically possible. Current concrete blocks in the region have a standard cement to an aggregate ratio of 1:6 to 1:8; we are working on lowering the cement to a ratio of 1:10 and rely on the geometry of compression-only shells to achieve the required strength in low-rise housing construction. For low and mid-rise housing, the study capitalises on thin-tile vaulting for its advantages in using available materials, simple construction that can be reduced to rules of thumb. The research also shows that the proposed vaulted system reduces the carbon footprint to almost 50% of the typical solid reinforced concrete slab. The research includes a geometrical study, material fabrication, prototype construction, and structural testing under a line load.

The proposed system is shown to have a lower embodied carbon than common alternatives. Because the proposed system is built on an existing production method, the proposed thin-tile vaulted unit’s application and use are envisaged to be intertwined with prevailing everyday informal building methods. Similarly, the research speculates on the positive environmental impact of recycling destroyed buildings into vaults without complicated processing.

4.1.1 Introduction: Traditional Thin-tile Floor System

Thin-tile vaulting has been widely used in Spain (Figure 93). Midrise housing blocks in Catalonia, Valencia, and Extremadura abound with thin-tile vaults of different geometries: barrel vaults, sail vaults, and rib vaults (Collins 1968). Because it exists as a vernacular construction, the technique inspired many architects, including Francisco de Asís Cabrero, Luis Moya, and Rafael Aburto (Mosteiro 1996) vaults for houses in the difficult post-civil war period in Spain between 1939-1960. The technique offered a low-cost and locally resourced construction, especially at the beginning of the reconstruction, when wood and steel were scarce in Europe during the Second World War.

In more recent projects, thin-tile vaulting for sustainable and low-cost construction has been directed towards developing countries’ contexts. Because it is labour-intensive, the technique is advocated to provide jobs for manual work where needed. Several thin-tile vault projects were built in Africa, including Mapungubwe Interpretation Centre and Rwanda Cricket Stadium (M. H. Ramage, Ochsendorf, and Rich 2010; M. Ramage et al. 2019) (Davis and Block 2012b). Almost all projects in these contexts produce the tiles from the soil on-site, resulting in efficient earth shells for halls and pavilions. The soils are made into stabilized earth tiles using the same steps of producing compressed earth blocks (CEB). CEB fabrication is abundant in East and South African countries, producing air-dried thin tiles with cement stabilization ranging from 5 to 10% by weight.
Thin-tile vaulting systems have also been influential on the advanced design and fabrication of floor structures. Sail vaults with stiffening ribs were abundantly used in Catalan and Valencian multi-storey buildings during the 18th and 19th century (Collins 1968, Huerta 2003; Truño i Rusiñol et al. 2004). This solution has inspired lightweight concrete vaults designed and developed by the BLOCK Research Group research at ETH Zurich, reducing the weight of conventional concrete floor slabs by 70% (M. Rippmann et al. 2018; Liew et al. 2017). Thin-tile barrel vaults sitting on beams were also explored as floor systems, either prefabricated in forms of steel mesh and tiles rolls to be deployed on-site, by Bes Casariego (Bes and Casariego 2016). Recently, thin-tile vaulting is used as formwork for reinforced concrete has been explored historically and structurally by López López (López López, Van Mele, and Block 2018; López López et al. 2019).

The system proposed in this research engages with vernacular methods, labour, and materials for making thin-tile vaulting in a context of extreme restriction on fabrication technology. While focusing on the Syrian context, which will be explored in the following sections, the investigation explores the possibility of using rubble as an alternative to traditional terracotta of thin-tile vaulting. The recyclability of the material and the construction of the vaults is examined and tested. The proposed system of thin-tile vaulting is compared with typical existing floor structures in Syria in terms of mass, materials, codes, and construction. The research promotes the use of structural geometry to elevate material performance in vaulted structures. While recycled rubble may reduce the strength of the tiles, the use of compression-only vaults with ribs can make slabs that comply with the regulations fulfilled by conventional concrete slabs. A model of the thin-tile vaulted system is designed, built, and tested to verify this proposal to the Syrian Building Codes (SBC) standards.
4.1.2 Context

Material- Aggregate from Rubble

Most of Syria’s housing and infrastructure has been affected by the war. In 2017, it was estimated that 50% of the infrastructure is non-operational (Overton and Dathan 2019). In 2019, reports from the World Bank indicated that a third of Syria’s housing stock had been destroyed (“The Toll of War: The Economic and Social Consequences of the Conflict in Syria” 2017, 19). Millions of cubic meters of rubble occupy Syrian cities. Only Aleppo and Homs were subjects of estimation studies: 15 million tons in Aleppo and 5.3 million tons in Homs. The amount of destruction in Aleppo is similar to that in Ghouta near Damascus, with 36,000 damaged buildings. In Raqqa, Hama and Homs, the number of damaged buildings in each city is around 13,000 buildings (REACH Reports 2019, 5). We can estimate that rubble in these five cities, the ones most affected by the war, sums to over 45 million tons.

Housing is the most destroyed sector, followed by energy, health and education (REACH Reports 2019). However, roads are the earliest sector to improve, given the fact that the removal of rubbles can make the roads usable again. The urge for immediate clearance of rubble and fast recovery of housing forms the main drive behind this research’s recyclability consideration. The materials needed for the vaulting can be processed and prepared in small manufacturing units dispersed within the affected zones.

Studies and reports on recycling rubble in war-affected zones provide a guideline and specifications for when and how rubble can be useable as a recycled material (Bjerregaard 2010, “Guidance Note Debris Management” 2013). Only clean debris is associated with applications of recycling into so-called “structural uses”. Clean debris refers to those with no material other than aggregates and crushed concrete (“Guidance Note Debris Management” 2013). Clean debris from war-torn zones is usually associated with manual sorting of materials, a considerable expense and a waste of a workforce that might be better invested in fixing water systems, for example (Bjerregaard 2010, 13). However, sorting and recycling rubble into usable materials are noted as good practice when it is a source to support small manufacturers and factories’ livelihood once the debris is tested for hazardous substances (“Guidance Note Debris Management” 2013, 8, 12).

Aleppo in Syria is one of the early cases that shows a governmental plan for debris management. The 2017 early response to the debris in Aleppo included only clearance of debris into landfills in the city’s outskirts. However, a new law was issued in February 2018 (law number 3) whose legal and administrative framework of the debris clearance regulated assessment reports about each affected zone (“Enabbaladi” 2019; Ferrier 2020, 6). International development organisations such as UNDP, OCHA and ONGRescate worked with the Syrian authorities to establish a factory for producing concrete masonry units (CMU) in Ramouseh (“ONG Rescate” 2019). In another governmental initiative, Aleppo City Council has embarked on a similar Karem Al Jabal project (Ferrier 2020, 6). In 2016, extensive recycling was made by inhabitants in northern Homs when it was an opposition-held area. Under siege, and with simple machines, small factories and workshops recycled rubble from partially destroyed buildings to make CMUs, stating that each 2 m³ of rubble can make 1 m³ of useable aggregates, which cost only a quarter of aggregate from quarries (“Radio Alkul” 2016).

However, it is observable from the previous initiatives and studies that recycling rubble into cement-stabilized blocks must comply with three conditions. First, rubble must be confirmed as being clean and hazard-free (Bjerregaard 2010, 7). Second, recycling is only effective when distributed in small enterprises recycling from partially damaged areas. Third, the characteristics of the elements produced by these enterprises are usually
expected to be used for non-structural elements (Fund n.d.). The proposed system of thin-tile vaults from rubble fits within these considerations as it capitalises on local and non-centralised recycling and relies on the geometry to elevate a non-structural material into structural uses.

**Unit- CMU blocks**

Concrete blocks, also known as breeze blocks, are among the most prevalent construction materials in Syria. While used for walls and ceilings, the blocks are locally produced in factories scattered in cities and villages. Although large and fully mechanised CMU production can be found in Syria’s industrial regions, the industry relies predominantly on small factories. A typical small factory comprises a vibrating press machine, a cement mixer, two workers, and a space for airdrying the blocks (Figure 94). Our preliminary study of CMU materials and types of machinery in Syria noted that many half-mechanised presses are locally fabricated; they are cheap and easy to find. Many local factories also make moulds. While the fully mechanised press costs around £23,000, the cost of a vibrator press is around £400 and the cost of the moulds between £100 and £140.

Introducing thin cement tiles is achievable within these already established supply chain. The standard length and height of the CMU blocks in Syria are 400 by 200 mm. The blocks' thickness ranges between 60 to 250 mm, and the most common thickness is 150 mm (Figure 94). Modifying these dimensions is achievable by changing the press mould and production process, making the basic building unit (the tile) available for the construction of shells. The blocks are usually voided with cylindrical voids, and the thickness of the walls is no less than 15 mm. The average weight of the 150 mm thick block is 1.6 kg. To make a thin CMU, modifications of the moulds should be introduced; the 150 mm block moulds can make five blocks of 25 mm thickness. Another method of fabrication can be through stacking the tiles horizontally with dividing plates between them, as used in Rwanda Cricket Stadium’s construction (M. Ramage et al. 2019).

The Syrian construction code set specific requirements for CMU blocks. The cement used per m$^3$ is 200-250 kg, which gives 12.5-15.6% of cement. Aggregate should be under 10 mm diameter and have a ratio of 6:4 for sand to gravel. The required compressive strength of the CMU after 28 days is 60 kg/cm$^2$ (5.88 MPa) for solid CMU and 50 kg/cm$^2$ (4.9 MPa) for voided CMU (Syrian Engineers Syndicate 1998, 1:28). Another set of regulations consider CMU blocks as common unreinforced concrete of C8 (15% cement ratio) and compressive strength of 8 MPa (Syrian Engineers Syndicate 2004, 37). Concrete blocks are considered non-structural elements for exterior and interior walls. For floor structures, a specific type of CMU, called Hourdi blocks, are used for hollow-core slabs. The standard blocks are tapered with a width that ranges between 320 and 400 mm and a height of 200 or 250 mm. The ceiling blocks are placed along reinforced concrete ribs cast in-situ. The Syrian code specifies that a Hourdy block should have the same compressive strength as a normal CMU, but it also should withstand a 200kg line load applied on its upper surface (Syrian Engineers Syndicate 1998, 128).

**System- Slabs**

While most of the cement in Syria is produced locally, steel is still mostly imported either as rebar or as raw material that is made into rebar in factories inside Syria. Steel is five times the price of cement. In 2020, the average cost of reinforced concrete housing construction fluctuated around £150/m$^2$, most of which is spent on the construction of floors. During the crisis that followed the 2011 uprise in Syria, construction and material costs in Syria have increased tenfold from 2010 levels due to the destruction of cement factories, restrictions on imported materials, and increased local transport prices (Manar 2017). Despite the skyrocketing prices of reinforced concrete construction, it is still the only available technique in Syria. The Syrian code covers only reinforced concrete floor systems, including flat slabs, hollowed slabs, and ribbed slabs. The first two are the
most common in housing and small to mid-scale buildings (Figure 95). Expanded Polystyrene Sheets (EPS) were recently introduced as an alternative to hollow blocks. In all cases, the Syrian construction code prescribes a minimum compressive strength of 7.8 MPa with 300 kg of cement per cubic meter of reinforced concrete (14-16% by weight).

Informal construction in Syria also offers solutions in constructing houses, applying rules of thumb in place of rigorous calculations. Solid and hollow concrete slabs are abundant in informal construction, but more techniques were introduced through adaptations to site and material limitations, especially during the war. One of these limitations is time. Authorities can demolish a building while it is under construction only if the ceiling is not built yet. Once the ceiling is made, the structure is considered a house that cannot be demolished (Asali and Shahin 2019). Informal builders take advantage of this legal margin and aim to finish the ceiling’s construction as soon as possible to avoid demolition. Building traditional wooden scaffold, casting concrete and waiting for it to set is usually avoided. Instead, alternative systems are used that are only found in informal construction in Syria. The first is placing CMU blocks directly on I or T section steel beams welded to a ring beam. The spacing between the beams is about 400 mm (the length of a CMU). The second covers a grid of small sectioned steel beams with corrugated metal sheets, or terracotta, or PVC roofing tile and casting a 50 mm concrete layer on the top, usually used for the roof of the building. One infrequent system uses wire-nets, rebars, and plaster to form a mould on which reinforced concrete is cast (Figure 95). In these systems, the builder makes fast floor systems that are instantly considered ceilings, but they are formwork for later concrete casting. This is similar to how thin-tile vaulting works.

4.1.3 Architectural and Structural Design

This section proposes thin-tile vaulting as a solution for ceilings in low to mid-rise housing. The vaulting systems and materials are examined and finally compared to existing solutions. By studying the current construction sector in Syria, one of the significant challenges is the availability of materials imported from outside the country and transported between national regions. This drives a need to invest in the recycling of the available materials, including rubble. Because the current systems of producing CMU blocks are based on light infrastructures, small factories can be deployed to areas where rubble is recyclable. This is already taking place in Aleppo. Another challenge is the cost and scarcity of steel for reinforced concrete; minimizing the amount of steel can be achieved by introducing vaulting where steel is only used in ring beam and column reinforcement. This extreme scarcity encourages the use of local materials and construction labour.
Design Approaches to Thin-tile Vaulting

Figure 94 Tools and Machines for Cement Block production in Syria
To convert rubble into tiles for construction, thin CMU tiles’ fabrication out of stabilised gravel and sand with 8% cement is explored. These are proposed for a thin-tile vault construction with stiffening ribs that also support the floor itself. By doing this, the system minimises the mass of both concrete and steel for cost and environmental reasons and maximises small local enterprises’ involvement in material production and construction. The limitations of skilled labour in Syria are mitigated by incorporating design parameters of vaults requiring simple formwork that can be learned quickly. The last characteristic will be developed through observing the vernacular construction of thin-tile vaulting in Spain and a collaboration with a master vault builder.

Figure 95 Existing formal and informal flooring systems in Syria. Top: Solid and hollow blocks slab that are common in formal and informal construction. Down: Steel frames with corrugated metal or CMU systems found in informal construction for fast construction of ceilings.
Sail and cross thin-tile vaults are very common in multi-storey housing in the vernacular construction in Spain. Sail vaults’ main advantage is that the builder starts in one corner and ascends spirally to the apex without cutting tiles while building. However, a sail vault is formed by two perpendicular arching directions making a vault whose span to rise ratio is 1:5 for edge arches with a span to rise ratio of 1:10, for example (Figure 96). Cross vaults retain a shallow geometry as they extrude the edge arches towards the centre, but the construction of a cross vault is laborious because it requires cutting the tiles at the diagonal intersections and inside the webs.

The proposed vault blends sail vault and cross vault geometry, the rise of the edge arches are higher than a usual sail vault, so the top of the vault is flattened. This blend results in a shallow vault built in a spiral fashion without the need for tile cutting. Edge arches were introduced to accommodate horizontal thrust. Formwork for arches is commonly used for sail thin-tile vaults springing from piers or ring beams. The resulting geometry is a surface of a sail vault that reduces the arches height in the centre. The key geometric parameters are edge arches with 1:10 rise to span ratio and an apex of 1:6 ratio. Edge arches are located at the vault large span with width of 0.1 times that of the vault. Edge arches catenary profiles can be found by a hanging chain on site (Figure 96). The thickness of each tile is 25 mm and the thickness of each mortar layer is 10mm. Traditional thin-tile vaults for spans of 3 to 4 meters have three of four layers of tiles. In the proposed geometry, various thicknesses can be considered, where the edge arches can have more layers than the web of the vault.
4.1.4 Structural analysis and design

The proposed geometry was verified and the required thickness calculated using a structural design methodology conforming to Syrian codes (Syrian Engineers Syndicate 2004). The vault must resist dead loads, including the vault’s self-weight and superimposed loads (including finishing), plus live loads. For multi-storey residential buildings, the Syrian code (Syrian Engineers Syndicate 2004, 46) determines a superimposed dead load of 2 kN/m² with a safety factor of 1.5. For live loads, the code sets 3kN/m², factored by 1.8.

Unfactored Dead load (minimum total load)

To calculate the dead load, a calculation of the self-weight is needed. The vault’s self-weight is based on the typical volumetric weight of CMU blocks, which is 17.5 kN/m³. For a three-layer tile vault, the thickness is 80mm. The corresponding self-weight is 1.5 kN/m². The sum of the self-weight (1.5 kN/m²) and the superimposed dead load (2 kN/m²) gives a total unfactored deadload of 3.5 kN/m². This is the minimum total load.

Factored dead and live load (the maximum total load)

The factored dead load is 5.25 kN/m² and the factored live load is 5.4 kN/m², giving a maximum total load of 10.65 kN/m².

<table>
<thead>
<tr>
<th>Description</th>
<th>Load</th>
<th>Factor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load 1 (self-weight)</td>
<td>1.5 kN/m²</td>
<td>1.5</td>
<td>2.25 kN/m²</td>
</tr>
<tr>
<td>Vault 80mm thick made with CMU blocks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dead load 2 (Superimposed)</td>
<td>2 kN/m²</td>
<td>1.5</td>
<td>3 kN/m²</td>
</tr>
<tr>
<td>Syrian building code</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Minimal loads</td>
<td>3.5 kN/m²</td>
<td>1.5</td>
<td>3.5 kN/m²</td>
</tr>
<tr>
<td>Live load (Residential buildings)</td>
<td>3 kN/m²</td>
<td>1.8</td>
<td>5.4 kN/m²</td>
</tr>
<tr>
<td>Syrian building code</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Maximum loads</td>
<td></td>
<td></td>
<td>10.65 kN/m²</td>
</tr>
</tbody>
</table>

Table 6 Minimum and Maximum loads for the vaulted floor system

The structural analysis considers two loading conditions. Firstly, the maximum load applied uniformly, which gives the largest compression and thrust, and secondly, the maximum load applied to one half only, with the minimum on the other, which gives a maximum asymmetric load and displacement of the line of thrust.

An example of a typical mid to large room area of 4.2 by 3.3 m is adopted based on our observation of Syrian houses where a room with this dimension is considered a typical living room. The vault structural analysis is carried out using graphic statics. First, loads were calculated by section in the web of the vault. The resulting horizontal and vertical thrusts are then accommodated in the edge arch. The method has previously been used in thin-tile vaults calculations using compressed-earth tiles (M. H. Ramage, Ochsendorf, and Rich 2010). The maximum load in the edge arches is, in this case, 250 kN (Figure 97). For CMU blocks of 5 MPa compressive strength, the arches’ thickness at the springing point will be 126 mm, this is five layers of tiles (140 mm).

Under asymmetric loading, the vertical thrust line’s maximum displacement is 50 mm at the third points of the arches. The final arch section, therefore, descends from 5 layers (140 mm) at the corner to 3 layers (80 mm) at the centre; the final web section can be reduced from three layers as assumed from traditional application to two layers of tiles 60 mm as the maximum load in the web does not exceed 25 kN. The final design, showing all tile thicknesses, is in Figure 98.
4.1.5 Fabrication and Construction

Two 1/3 scale prototypes of the previous design were constructed, with the aims of verifying and observing the material behaviour of the stabilised rubble in comparison to traditional masonry structures and examining the hand-making of the tiles, the transport of the material and how it is used in construction in comparison with the traditional terracotta tiles.

Tiles

The testing and fabrication of tiles used gravel as a substitute for rubble. The gravel stabilised tiles started with several iterations of manually moulded tiles, using a wooden frame (Figure 99). Several mixes and ratios were tested in relation to gravel, sand and cement ratios and the water added to the mix. The final tile mix with acceptable consistency was 6.5:1 by weight of sand, gravel, and cement respectively (giving a cement ratio of 8%). The maximum diameter of the aggregate was 8mm. Sieving, mixing, casting were all carried out manually. The tile dimensions were the same as traditional terracotta tiles in Spain, which are 120mm by 240mm with a thickness of 15-20mm; the resulting tiles weighed between 1050 and 1150g resulting in an average density of 1910 kg/m³. The resulting tile weight is acceptable in relation to construction, as the solid traditional terracotta tiles of 30 mm thicknesses have a weight range between 1100 and 1200g. The making of the tiles took two weeks within a month, with one person only doing all the sieving, mixing, casting and storing with a production of up to 25 tiles per hour. During the last week tile making two persons worked on the production, and the number of maximum tiles per hour jumped to 70. The tiles were cast on wooden racks and stacked for drying in a climate with relative humidity between 70-95% and temperature between 10 and 16 °C. After three days of initial curing, the tiles were taken from the wooden racks and stacked. Water spraying took place every five days; the tiles were not covered but stored in an enclosed area protecting the tiles from direct wind (Figure 99) to prevent drying out. The minimum curing time before vault construction was ten days, and the maximum was three weeks—the production of the tiles provided around 250 for testing and the construction of the vaults. Samples for testing the tiles were prepared. However, the tile’s scheduled material test was cancelled due to the pandemic and the closure of labs and facilities. We, therefore, assumed a compressive strength of 5 MPa of the tiles following previous study on recycled rubble CMU by Matar and Dalati (2011). The assumed value also aligns with the Syrian Building Code’s minimum compressive strength for CMU (Syrian Engineers Syndicate 2004, 1:24).

Vaults

To be able to move the specimens, the vaults were constructed on 24mm plywood sheets with wooden brackets at the corners. Each prototype was 1.4 m long by 1.1 m wide with a rise of 140mm at the edge arches and 210mm at the centre of the vault. The edge arches were built over plywood formwork, followed by forming the web by placing tiles with plaster in a spiral fashion without formwork. The second layer was added using cement mortar. Once the vaults were complete, the edge arches’ formworks were decentred, and the vaults were left for three weeks to cure before structural testing (Figure 100). Both vaults were constructed similarly. The handling and placing of the tiles did not pose any problems. Unlike traditional terracotta tiles, the gravel tiles were not immersed in water before adding the plaster, given its inherent high porosity that allows a better plaster bond without damping the tile. However, extra caution was needed in placing as extensive knocking on the edge of the tile with a trowel, a typical move in thin-tile construction would lead to breakages of the tiles. Similarly, cutting the tiles with hits from the trowel was not possible, given their behaviour when broken. Instead, the builders did multiple scores on the cut with the edge of the trowel until splitting them into two pieces. Aside from the cutting and knocking on the tiles, the vaults’ construction took the same steps as any terracotta vault would (Figure 100).
Figure 97 Graphic Statics, calculations of the vault’s web and edge arches. The values shown are forces in kN.
4.1.6 Testing

Test design and set up

As previously mentioned, the two shell specimens are 1/3-scaled models of the shells design in Section 3.2. Following the worst-case asymmetrical point load scenario for arches, the shells were tested under line load at the quarter of the large span (Heyman 1997, 19). The line load was represented by four loading patches of 120 by 120 mm. The corners were supported with steel brackets fixed rigidly to a strong floor; plaster filling was added to the corner at the intrados forming a bearing pad of 80 by 80 mm.

Two sets of measurements were added to the shell to map the displacement behaviour. The first system was a set of LEDs for the three-dimensional displacement measurement. 36 LEDs were added as a grid on the vault with 200 mm spacing. Another 18 LEDs were placed at the centres of the arches and on the sides of the vault. The main set of LEDs was supplemented by a secondary system of linear displacement transducers. The transducers’ role was to verify the LED and measure the displacement in the areas hidden by the camera or blocked by the hydraulic arm’s fixtures.

Predicted failure load

Using the same method in the design calculations, graphic statics was used to predict the failure loads in the specimens. Unlike the full-scale vault’s designed vault, the thickness of the specimen was uniform with two layers of tiles, giving an overall thickness of 50 mm. Each vault’s weight is around 140 kg. The maximum thrust of the specimens under their self-weight is 2.2 kN, with lateral loads of 2.0 kN in the direction of the large span (Figure 102).
Chapter 04

Figure 99 Tile’s testing and fabrication

Figure 100 Vault’s construction

154
Design Approaches to Thin-tile Vaulting

Figure 101 Physical test set-up and equipment.

1. Hydraulic press
2. Loading patch
3. LED sensor
4. Transducer
5. Corner support
6. Corner pad

Figure 102 Test prediction calculations with graphic statics. The load cd is found from the angle between a, transferred from the thrust line diagram to the force diagram. Loads units are in kN.
The predicted line load at failure was deduced by finding the maximum thrust line when a line load the quarter of the vault is applied (Figure 102). The form of the maximum thrust line was taken from Heyman’s study of the voussoir arch under point load, forming cracks at four hinges until collapse (Heyman 1997, 18–20). The thrust line was divided into two at the point of the line load; each had a curve through the three-point of the hinges. The maximum predicted line load is determined by the angle between these two segments, specifically between C and D in Figure 102. When the angle is transferred to the force diagram, the applied force (cd) in hinge 2 will be the maximum load before the vault’s section can no longer accommodate the thrust line. The predicted failure load at one edge arch (half of the vault) is 1.15 kN which result in a total failure load of 2.3 kN.

By studying the displacement of the thrust line, graphic statics can indicate the location of cracks, assuming that the specimen acts as a typical masonry structure. However, this analysis only predicts cracks in one direction. Therefore, a diagrammatical study was also made to displace the vaults using the physics simulations engine Kangaroo2 for Grasshopper (“Kangaroo Physics” 2010). The vault surface was modelled as a hanging chain model. A catenary mesh was created first with uniform loads, representing self-weight, then a line load was applied in the same location as in the vault load test (Figure 103). The line load was 12 times more than the distributed loads—following the predicted failure load ratio to the vault’s self-weight loads. The comparison between the two meshes, one with line load and one under self-weight, shows the heights displacement of the thrust lines (represented by the mesh) will be at the centre of the two middle hinges along the vault hinge 2 and 3 in Figure 102. However, the comparison also shows hinges’ possibility to be formed perpendicularly on the line load, specifically at the centre of the short span of the vault (Figure 103).

As-built geometry

3D scanning was used to compare the as-built geometry with the design. A limitation to the scanning process was the inaccessibility of capturing the vaults’ underside due to the limited space of managing and manoeuvring the 3D scanning device. However, the upper surface and the edges were scanned. The vault’s average thickness was 50 mm, as expected for two layers of tiles and one of mortar. The comparison between the built geometries and the designed surface shows that Vault 2 was built flatter in the short span direction than the design, in contrast to Vault 1 whose curvature was more acute than the idealised surface. In other words, the short edge arches in vault 1 were higher than those of the designed geometry and in vault 2. This makes vault 1 more sensitive to cracking patterns perpendicular to the line load direction, as shown in Figure 103, unlike vault 2 that is closer to a flat arch geometry.

Testing

The test started by using the hydraulic jack and spreader beams to apply the loads on the patches. Both vaults withstood the predicted failure load of 2.3 kN with no visible cracking. The load was increased, and the shell started to crack. Crack patterns and locations were registered in association with the loads until the collapse of the vaults and are shown in Figure 12. The maximum load of Vault 1 and Vault 2 were 18.5 kN and 20.5 kN, respectively (Figure 105, Figure 106). Both vaults showed a cracking pattern that is close to the four-hinge collapse mechanism of an arch but with variations in the cracks in the extrados. Vault 2 had almost all cracks parallel to the line load except the one in the ¼ of the vault (H4) where the cracks were diagonal: connecting the long and short span edge arches. Vault 1 showed a more complex crack pattern than Vault 2. In addition to the four-hinge cracks, another major crack happened in the ¾ part of Vault 1 perpendicularly to the line load (Ha). The crack, which appeared simultaneously with the hinge parallel to the line load (H2), was also accompanied by a three-dimensional rotation of the corners of the vaults (H1) (Figure 105). The appearance of the perpendicular
crack corresponds with the variation of the geometry between the two vaults (Figure 105). The high curvature of Vault 1 in the short-span direction made it more prone to longitudinal cracking, as was predicted in the schematic study of the displacement in Figure 103. In both tests, the first cracks were the ones at the ¼ part of the vaults (H4) at the top of the vault. These appeared at 9.4 kN in Vault 1 and 14 kN in Vault 2, followed directly by the intrados crack at the line load location. The crack patterns and locations show that the vaults made from stabilised rubble behave like a masonry structure (Figure 107).

Figure 103 Diagrammatical displacement study using Kangaroo 2. A hanging surface model with line load applied to the mesh in addition to its self-weight. The diagram helps in estimating possible hinges along the short span (perpendicular on the line load).

Figure 104 As-built top-surface geometry comparisons from three-dimensional scans.
Figure 105 Cracks patterns and the corresponding line load

Figure 106 plot of displacement against load showing the loading curve pre and post cracking.
4.1.7 Discussion

Analysis methodology
The physical testing of the stabilised rubble tiles vaults shows a factor of 8 between the predicted strength and the measured maximum loads. The method of designing and calculating the structure using graphic statics and the edge arches as the datum is therefore highly conservative. This is not unexpected since it is a lower-bound approach. Using a conservative design approach aligns with typical construction practice in Syria, where many of the structures are produced informally and sometimes without any direct interaction with engineers. This approach advocates a possible improvement to be made on material efficiency even within the context of self-built housing. This can be achieved by the simplification of construction tools and the application of rules of thumbs. Two hanging chains govern the design of this system on the edge arches. The construction process was intended and shown to be easy and formwork-free. The study assumed the lowest compressive strength of CMU at 5MPa, producing CMU with larger compressive strengths will reduce the mass of the vaulting system, but the same methodology will be valid for designing the geometry and thickness of the vault.

Comparison with typical floor systems
This section compares the proposed system with current flooring systems in Syria, shown in Figure 95, in terms of material consumption, labour, and self-weight. Table 7 summarises the comparison between these systems and the stabilised rubble vault for a room of 4.2m by 3.3m. The key outcomes of the comparison are highlighted in Figure 108. It should be noted that the vault system includes reinforced concrete tie-beams which are calculated according to SBC and have section decisions of 110 by 200 mm for the short span and 110 by 250 for the large span. The calculations of the beams' materials are included in the table.
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### Table 7 Floor system Comparison

<table>
<thead>
<tr>
<th></th>
<th>Stabilised Rubble Vault</th>
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<th>Hollow Slab HS</th>
<th>Steel Beams slab SBS</th>
<th>Corrugated Metal CMS</th>
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<td><strong>1. Main dimensions (m)</strong></td>
<td></td>
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</tr>
<tr>
<td>Thickness</td>
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<td>0.16</td>
<td>0.18</td>
<td>0.15</td>
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<tr>
<td>Volume m³</td>
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<td>2.16</td>
<td>2.43</td>
<td>2.08</td>
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<table>
<thead>
<tr>
<th><strong>2. Materials Volumes (m³)</strong></th>
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<tbody>
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<td>Reinforced Concrete</td>
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<tr>
<td></td>
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<tr>
<td>Volumes</td>
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<tr>
<td>Steel</td>
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<tr>
<td>CMU</td>
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<td>Concrete</td>
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<tr>
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<tbody>
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<td>Reinforced Concrete</td>
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<td></td>
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<tr>
<td>Volumes</td>
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<td>Concrete</td>
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<th><strong>4. Cement used kg</strong></th>
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<td>Flexural Strength (MPa)</td>
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<td>Cement</td>
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<td>CMU Units</td>
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<tr>
<th><strong>8. Embodied Carbon [kgCO₂e/m²]</strong></th>
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<tr>
<td>Steel rebars, modules A1-A3 (1.99)</td>
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<td>Steel I sections, modules A1-A3 (1.55)</td>
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<td>Galvanised steel sheet (2.76)</td>
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<tr>
<td>Total</td>
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<td>34.02</td>
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</tbody>
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a. Thicknesses: Thin-tile vault (3 layers) and ribs | Solid slab (Syrian Building Code SBC): l/t ratio 30 | Hollow slab (SBC): l/t ratio 25 | Informal slabs from observations and fieldwork studies
b. Volumes: thin-tile materials are three layers of CMU and two of cement mortar | Solid slab: 1% steel 99% concrete | Hollow slabs 1% steel, 33% concrete, 66% CMU | Informal slabs from observations and fieldwork studies
c. Volumetric weights: CMU 14 kN/m³, Mortar 23 kN/m³, Concrete (reinforced) 25 kN/m³, Steel 80 kN/m³, Concrete (unreinforced) 23 kN/m³
d. Cement weight in 1 cubic meter (kg): Tiles 100, CMU 150, Concert 250, Reinforced Concrete 350
e. Compressive strengths: Thin-tile vaults: assumed | Solid Slab (Syrian Building Code SBC) | Hollow slab (SBC) | f. Cement and aggregate are calculated from both reinforced concrete and the CMU
g. Cost per ton: Cement: 110USD, Aggregate: 20USD, Steel: 1100 USD | Costs per unit: Thin-tile CMU 0.05 USD, Normal CMU: 0.05 USD
h. Embodied Carbon is calculated based on ICE database, using modules A1-3.
**Figure 108: Thin-tile vaulting in comparison with other floor-systems.** CMS: Corrugated metal sheets, SBS: Steel beam slab, HS: Hollow slab, SS: Solid slab.
The first possible achievement of the slab system in construction is a reduction of cement used by between 50-80% compared to formal flat slabs, as cement is used only for stabilisation of the tiles and for the mortar and tie beams. It is also noted that informal slab systems use less cement than those defined by the Syrian Building Code (SBC). However, their use of steel is high, whereas the vaulted system uses steel only in the beam-ties, saving not only expenses but also carbon as the mass of steel is also reduced. This leads to another achievement noted in relation to the carbon footprint (Figure 108). The reduction of cement and steel correspondingly reduces embodied carbon in the vaulted system by 75-85% in comparison to reinforced concrete slabs and 60% in comparison to informal corrugated metal ceilings in informal construction.

The second note from the comparison is related to cost. Prices for construction materials in Syria are very difficult to map and predict. However, in January 2020, the official prices from the Ministry of Economy stated that the cost of 1 ton of cement is between £75-90, while it is between £650-850 for steel (Manar 2017; Codingest n.d.). The CMU unit block’s cost is £0.08, with building labour cost of £0.15-0.25 for placing each CMU block (B2B-SY 2018). The overall labour price of building 1 square meter in housing building without finishing in Damascus reached £25 in 2016, ceilings are the most expensive elements in the construction, reaching to £17 per square meter (around 70% of the overall price) (B2B-SY 2018). In the vaulted system, the cost comes from the labour and not the materials. The sum of the two is still 20% less than solid and hollow slabs systems. However, the labour factor is conditioned with the existence of skilled builders who can build the vault—a challenge that can be overcome with training prior to the construction. The extensive use of labour in construction aligns with the proposition of the study that capitalises on building as a mean to support livelihoods, the same way the fabrication of the stabilised rubble tiles is proposed to be noncentralized and reliant on small factories of workshops of CMU.

It can be noted in the comparison that the use of rubble for tile making does not have a significant impact on the cost of the roof systems. While aggregate forms the larger mass in the slab systems, ranging from 72% in the corrugated metal systems to 92% in the vaulted systems, the cost is very low and does not extend beyond 15% of the overall cost. The economic factor might not be very effective on a scale of one slab. However, the specificity of the post-war Syrian case makes this margin essential both economically and environmentally, given the massive amount of rubble. If 20% of rubble from Aleppo only (which reaches 15 million tons (“Enabbaladi” 2019)) can be recycled into tiles, it can vault up to one million apartments of a size of 100 m$^2$. A different study must be conducted to reiterate and generalise the concept of rubble recycling for different cases where rubble is produced from regular demolishing of old structures and not from natural or human-made disaster.

Finally, while this study operates within the SBC, more research is needed to accentuate the proposed systems to other requirements of the SBC, specifically those of the seismic and fire considerations. Nevertheless, the study’s inclusion to informal slab systems, which does not officially comply with many SBC requirements, is an invitation to acknowledge and understand other forms of building outside the regular route of codes and regulations. Informal and self-construction needs to be addressed concerning building policies. It is also an invitation to architects and engineers to reconsider building codes to become more vibrant and dynamic, maximising their opportunity to develop a built environment beyond sets of rules.
4.2 Time: Craft and Manufacture of Thin-tile Vaulting

Time and location have an implicit influence on the form, construction, and structure of load-bearing shells. Manufacturing building components is usually imagined as being accompanied by heavy machinery and advanced tools. However, in the case of tile vaults, craft can be central to their manufacture. In this investigation, the typical construction of tile vaulting was challenged by constraints of skill and time. I examine thin-tile vaulted projects in which the craft of the artisan is pushed to the edge of mechanisation. The examination started with a commissioned project of three vaults as a temporary walk-through pavilion (Fabricarte) at the Ceramic Expo 2018 in Valencia, Spain. The project investigated off-site construction of the vaults, transport and reassembly. The project influenced another iteration of research (Fabricarte II) to design and build concrete-ribs and thin-tile vaulting modular floor system.

4.2.1 Introduction: Ancient and Recent Prefabrications of Vaults

Designing and making tile vaults is a process with many cases of reciprocity: form and force, skill and formwork, material and manufacturing, and labour and design. This section examines the effect of time and location on labour by presenting manufacturing methods to either speed on-site construction or mitigate on-site lack of skill. Placing handicraft alongside modern construction is central to these methods. Current research on tile vaulting explores material alternatives, forms and design, and history (M. H. Ramage, Ochsendorf, and Rich 2010; Davis and Block 2012b; Ochsendorf 2010). However, the manufacturing of a thin-tile vault as a ‘building component’ is yet to be fully explored. Vaulting, in general, is rarely approached as off-site construction. In history, one of the early mentions of pre-building vaults is William Eton’s description of vaulting in Bosra, Iraq in 1799 (Eton 1798, 228–29). Eton mentions that

“At Bassora, where they have no timber... The mason, with a nail and a bit of string, describes a semicircle on the ground, lays his bricks, fastened together with a gypsum mortar, on the lines thus traced, and, having thus formed his arch except the crown brick, it is carefully raised and in two parts placed upon the walls. They proceed thus till the whole arch is finished. This part is only half a brick thick, but it serves them to turn a stronger arch over it.”

Although no other mentions have been found about this construction, it explicitly represents two elements. The first is the fast fabrication of half-arches on the ground, and the second is the lightweight of the parts to be easily lifted to serve as formwork for a thicker and bulkier vault. Therefore, such a proposition of vault making is not new, but it is not developed. It is majorly in Latin America during the mid-twentieth century that vaults were imagined as a possibility for the emergence of new construction methods, including off-site fabrication. The works of Eduardo Sacriste (Argentina), Mario Kalemkerian (Uruguay), Rodrigo Levere (Brazil), and Carlos González Lobo (Mexico) are based partially or entirely on tile vaulting to manufacture shells, mainly for housing (Muñoz and Fernández 2014). Most of their work relied on the repetition of simple geometry of a barrel vault or dome. With today’s tools and technologies, the projects presented in this section investigate manufacturing methods that overcome the limitations of geometric simplification. Such a focus is vital for finding building solutions with less material consumption and waste production. It pushes the shell structures outside the boundary of being elements, proposing them as systems with freedom in construction and adaptation to site-specific conditions.
4.2.2 FR2: The manufacture of 200 identical Vaults

In contemporary construction of thin-tile vaulting, FR2 interior design project by Light Earth Designs exemplifies vault prefabrication and design-thinking. The project is briefly studied in a review paper by Light Earth Designs about their approach in construction (M. H. Ramage, Hall, and Rich 2014). The project is an office space for Joe Ritchie’s FR2 office, a financial services firm in Chicago, IL, USA. The office is composed of a system of suspended ceilings of 200 units of conic vaults, an entrance pavilion, and a set of wooden elements for furniture and interior sculptures (Figure 109). The project emphasises the use of natural materials and celebrates it in all interior elements. The office spaces were designed to be lofty and open but also to allow for discreet working areas that were formed by beetle-damaged pine aedicules (interpreted in the project as cubical workspaces) of different shapes and heights. The two vaulting systems are the 2 meters height vault at the entrance of the office and the earth tiled suspended ceiling soffit formed of 200 triangular vaults. The design proposed an earth tiled soffit formed or triangular vaults that span between the steel structure. The tiles for the vaults were made from the soil found in the client’s farm near the construction site. A master mason made the entrance vault with the help of a comprehensive plywood system that supported and guided the construction, but local bricklayers made the 200 vaults.

Two constraints drove the design and construction of the offices in Chicago. There was a lack of skilled labour able to build thin-tile vaults, and the need for 200 identical elements meant that only mass production of the same element was a viable solution in a high-wage context. The solution included a process that transferred the mason’s skill of a carved physical prototype into a three-dimensional CAD model. Based on a physical prototype of 1:3 model made by a stonemason in the UK, the CAD model allowed a CNC machine to reproduce a full-scale model in wood in the US. Finally, a negative model was then made by casting silicon on the wooden master and served as a mould for labourers to follow the designed vault’s overall coursing (Figure 110).

The early phase of the project proposed a conventional approach to building the 200 vaults with a training program for workers in coordination with the bricklayers’ union. Instructions with details of construction were sent to the bricklayers to follow. However, the bricklayer’s work was not successful in producing vaults with a highly crafted look of the interior where tolerance in the details is usually minimal due to the close distance between an observer and a built element. Furthermore, it was evident that training and construction would take a much longer time than programmed. A move to a more specified guidework was a must. The design challenges conventional vault construction and manufacturing because the vaults are small and numerous, and the wages of the workers, who have no previous experience in tile vaulting, are still costly. A method of knowledge transfer through digital models that were later translated into physical moulds kept the construction in the builders’ hands but accelerated it and reduced the cost (Figure 111).

The 1:3 prototype and digital model were developed in the UK with mason Sarah Pennal. The models allowed for close attention to the detail before the vaults’ actual building, saving the time of approvals and supervisions in the early stages. The CNC-carved negative mould facilitated the production of several silicon casts, hence maximising the workers’ productivity and lessening the time for construction. The casts defined the coursing and the placement of the tiles in the vault. The work of the master mason on the carved 1:3 prototype presented a nonconventional coursing approach that articulates the overall shape and accentuates a dynamic visual effect of the ceiling vaults. This coursing was achieved with three sizes of tiles. Because the tiles were produced for this specific project, the tiles were all cast from soil-cement slurry in the three sizes beforehand, saving time and wasted material from cutting standard tiles. After an individual vault was made, it was lifted by an
automotive transmission jack to the right height and then slid into the triangular-shaped steel frame, which was pre-hung from the slab above. The FR2 project shows how labour’s relationship with time can be a challenge due to the production type and the number of identical vaults. Producing two hundred vaults of the same shape is different from the case of an individual structure. Production time, material waste by cutting tiles were all minimised by crafting a digital model that was transferable and reproducible on-site.

Figure 109. FR2 Interior.

Figure 110. Left: digital model, centre: positive computer numerical control (CNC) mould, right: silicon mould and built vault.

Figure 111 FR2 Process of construction
4.2.3 FabricArte: Time in Tile Vault Construction

During the annual Expo of Spanish Ceramics (Cevisama), a central space the Expo building, called Transhitos, is usually dedicated to new experiments of material, construction, and fabrications of ceramics to celebrate the Spanish ceramic industry. In 2018, I was invited to design a pavilion in a project that was coordinated by the Instituto de Tecnología Cerámica (ITC) and curated by the Asociación Española de Fabricantes de Azulejos y Pavimentos Cerámicos (ASCER). I proposed to make a walk-through pavilion that celebrates the craft of tile vaulting in Spain, a one that converts ceramic work from decorative cladding to structural compression-only shells. However, expo regulations in Cevisama have strict rules on times and types of machinery allowed in the Expo building. The design was asked to consider the limitations of the site in the design and makes them into design solutions in the traditionally labour intense construction of thin-tile shells. A manufacturing vault method should serve to install the structure in the Expo within the allowed construction time.

Design concept

Inspired by late-gothic vaulting in Valencia 13-15th century, FabricArte's design is based on a groin vault composition (Figure 112). However, the vaults are one of two integrated systems: a compression shell and linear tension elements (Figure 113). The integration of the two systems was kept as visible as possible, resulting in a shell that changes from flat systems of shallow slabs to a full height expressive vault. The transition allowed for the exploration of the manufacturing of three vault typologies. I tested a shallow vault resting on columns, a full vault, and a vault that springs from two different levels, similar to vaulted stairs. Furthermore, the shells' overall design also highlights how compression-only vaults would behave under different corners conditions, expressing a vault that is grown from flat to full height.
Construction Design

Expo regulations permit two weeks for transportation of materials, on-site construction, and preparation for the exhibition. This period did not allow for the designed 7.5 m walk-through structure to be built traditionally. Construction needed to be rethought and designed. The challenge prompted a new experiment in tile vaulting, in which the vaults were built in a workshop, sliced, transferred to the site, and re-assembled for the exhibition. Tile vaulting is rooted in Valencia and was part of the late Valencian Gothic architecture, where modular units mirror, repeat, and array to compose the main structure (Catalán 2009). Repetition and modularity were central to the design and formed a guideline for the smaller manufactured pieces of the vault. The modularity of the cross vaults and the Gothic pattern helped in building quarters of vaults and then slicing them into smaller sections. The slices were made to avoid linear horizontal cuts in the structure. The cuts in the side arches were higher than those in the infill. The calculations of the cuts were digitally studied based on the height and weight of each piece. The decision was to keep the manufacturing process manageable without using heavy machinery, such as cranes and lifts, by downsizing the 3,800 kg vault surfaces into smaller components (Figure 114). The vaults had three layers, but only one layer was built off-site and sliced, making the transportable pieces lighter. The height was another factor that influenced the cutting pattern. Each piece was calculated to be held by two workers on the ground (maximum of 120 kg) or one person on a scaffold (maximum of 50 kg).

Structural Analysis

The vault’s structural analysis was made using graphic statics with a particle-spring system for form-finding, verification, and maximum loads. The vault shell was made of three layers of tiles with a maximum thickness of 100 mm. The maximum force of 8.2 kN was the intersection between the full height vault and the transitional vault, resulting in maximum stresses of 0.82 MPa (Figure 115). Because the transitional vault springs from two different levels, like a stair flight, the line of thrust of the stair would result in a deviation of the apex of the vault towards the flat vault (similar to what a hanging chain will do). This was counter-intuitive to the aim of using the potential of modularity in construction. The structural design solution suggested that the mass of the steel column between the full height vault and transitional vault would need a little help of earth and lime filling to accommodate the transitional vault’s thrust line without changing the geometry. While the other two symmetrical vaults were calculated by graphic statics for parallel sections, the forces in the transitional vault were studied in both directions (Figure 115). In addition to form-finding the efficient geometry, graphic statics provided the direction and intensity of loads, which influenced the selection and design of the steel frame structure and joints (Figure 113). Square steel tubes of 64mm steel and 4mm wall thickness were used with customised fixture for the crowns where the flat vault is placed.

Construction of Fabricarte

The team worked closely with one of thin-tile vault master builders, Salvador Gomis Aviño. The collaboration facilitated iterations between design and craft and between industrialisation and handmaking, where each discipline influenced and improved the other. Moulds were designed for modular quarters of the vaults to support the construction, transport, and assembly. Building vaults in quarters impeded the visualisation of the shell’s overall geometry and made it hard to imagine the tile angles, joints, coursing, and cuts. This has resulted in difficulty applying conventional carpentry without the extensive use of drawings. Instead, the medium-density fiberboard (MDF) sheets were cut using computer numerical control (CNC) and were made for screw-less easy assembly and disassembly without plans or models. The geometry of the moulds defined the curvature and the cutting patterns (Figure 116).
Chapter 04

Figure 113 Steel frame system

Figure 114 Construction and manufacturing strategy
Design Approaches to Thin-tile Vaulting

Figure 115 Structural design and analysis

Figure 116 Mould design and assembly
Chapter 04

Figure 117 Construction of Fabricarte

Figure 118 Fabricarte exterior views
In a workshop, the moulds were assembled, and one layer of tile vaults with plaster was built over the mould (Figure 117). Only side arches had a second layer to add stability to the pieces during on-site assembly; the remaining parts of the vaults were only one layer thick. After completing a quarter, it was sliced by radial saws using the suggestive pattern as a guide. At areas where the edge was the intersection with other quarters, the saw helped cut and refining the edge after construction. While the original design has many small cuts in the composition of the vault, the workshop's construction resulted in difficulties in the cutting of the small triangles, and they were joined in larger bits. As a result, each quarter had between 3 to 5 cuts, depending on its size.

The pieces were transported on a mid-sized truck, and the moulds were used to support the shells. All loading and unloading were carried out by the building team (Figure 117). During the unloading, a few minor breakages happened at the edges of the pieces. In the Expo, the installation of the mould/formwork took one day, and the assembly of the vault took five days. The assembly of the shell was made with plaster glueing the parts again (Figure 117). The tiles were hollow, and the plaster at the cut edge did not need to be thick, making only minimal changes in the original geometry. After the completion of the whole shell, two additional layers were made in three days. Strips of fibreglass textile with plaster were added under the primary diagonal edge connections. Once the pieces were joined in the three vaults, two layers of artisan 20 mm were added at the vault's top and bottom (Figure 117). The lower layer was made with plaster, and the joints between the tiles were filled with cement mortar. Whereas the added bottom layer of tiles hid the Gothic patterns of cuts, the pavilion's flooring reflected the lines as a diagram of the process of manufacturing.

Fabricarte examined the possibility of tile-vault manufacturing. It showed a prefabrication system that does not rely on the high-precision fabrication of building components for rapid on-site construction. Instead, the precision is inherent from the cutting of the shells. Thin-tile vaulting remained the primary technique used in the building (Figure 118Figure 119Figure 120).

4.2.4 Discussion: Time Factor

While the core inquiry in this experiment was about time, every construction and design decision influenced the time consumed on-site and in the workshop. One of the leading recording tasks was to keep track of construction steps and decisions and how they influenced construction speed. The tracking influenced the second iteration of Fabricarte. An iteration that maximises the construction of tile vaults by reducing the cuts of the tiles. A tile-vaulted stair whose surface area is about 7.5 square meter takes an average of between two to three days for completion. If Fabricarte's 28 m² surface is 3.7 stairs, the construction would have taken 9.25 working days. However, this estimation was out of reality.

Fabricarte's workshop construction took around 15 days to be built. Because it is a groin vault with edge arches, many were cut at an angle for the intersections between the vault's surfaces. Cutting requires measuring, marking, cutting with a wet saw, and placing. The procedure magnifies the time of construction up to five times more than a regular tile placement. Pre-cutting the tiles beforehand based on measurement was tested to speed up the construction, but the tile vaulting changes by many variables and the dimensions of the tiles at each corner were never predictable. One solution was to station a worker on the wet-saw only for cutting tiles when needed without the need for builders to move away from the vault. During the construction, it was noticed that there are two central features with a significant effect on tile cutting. Those are the coursing and edge condition. Both features had an impact on the size and the shape of the tiles that needed to cut. Modifications on coursing and edges' conditions were made to eliminate using the wet-saw as much as possible (Figure 121 A).
Figure 119 Fabricarte interior view 1
Design Approaches to Thin-tile Vaulting

Figure 120 Fabricarte interior view 2
**Changing the coursing**

The initial horizontal coursing for the cross vaults was time-consuming because 86% of the tiles needed to be cut. We changed the coursing to a vertical one that used fewer tiles in general and reduced the percentage of cut tile to 62%. Horizontal coursing is associated with stone masonry where masons sculpture each stone to its exact position. In thin-tile groin vault, vertical coursing is used more than the horizontal one; it converts the web of the vaults to a series of arches while only the tile at the intersections will be cut (Figure 121 B). It seems that a similar story about tile coursing and its impact on time had happened before we did this project. When looking back to Cuban thin-shell experiments in 1961, explained in Chapter 02, the largest sail vault built in the ministry of construction courtyard shows that the corners of the vaults had horizontal coursing that changed to vertical coursing.

**Cutting the edges with a radial saw**

In the edge condition, placing full tiles along the edge and then cutting everything with the radial saw helped reduce the percentage of cut tiles from 62% to 47%. The tiles from the cut part could be rescued, cleaned from plaster, and reused as tiles cut in the construction (Figure 121 C). However, what remained challenging in the edge intersections was the inevitable and laborious intersections between the side arches and the infill, where tiles needed to be tilted and sliced simultaneously, resulting in a three-dimensional cut in the tile.

**A vault without cuts**

The work in Cevisama had an impact on the artisan’s perception of pricing. Salvador now includes estimating the tile cutting in the vault in his pricing and quotations for architects and construction companies. The exploration of tile cutting and vault construction prompted further research on the groin and other doubly-curved vaults that can be built with no or minimum cutting during construction.

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Figure 121: Design impact on cutting tiles: A) original horizontal coursing design with many tiles to be cut. B) Vertical coursing minimises the number of tiles and the number of cuts. C) Cutting edge with a radial saw after building full tiles also minimises the number of individual cuts.
4.2.5 Fabricarte II

The second iteration of Fabricarte reconsiders the tile cuts at the groin intersections to reduce the time of construction. Instead of high-precession cutting by robotic arms or other digitally controlled tools, a material-based approach was adopted by casting material in the irregular shape. This approach presents two possibilities: cast concrete in the void during the construction on the mould (high precision construction) or cast it on-site after placing the vaults parts with the help of formwork (low precision construction). This phase of this project focuses on the surface subdivision of shallow vaults for mid-span floor systems in housing and office buildings. Singly curved vaults like barrel vaults are studied for prefabrication, especially within construction studies in South America. However, doubly curved vaults perform better as shell structures than barrel vaults, but strategies for their prefabrication in studies about thin-tile vaulting are not yet explored. Proceeding from Fabricate's shell typologies, I examine two vault geometries, a sail and a groin vault. While both are abundant in the vernacular construction of houses in Spain, the segmentation of the vaults pushes them into industrialisation. As a case study, a room of 4.2 by 3.3 meter is subjected as an example with a span to rise ratio of 0.1, similar to the one examined in section (4.1) about materials and rubble-stabilised tiles. For the sail vault, the rise to span ratio of 0.1 will be at the apex of the vault, the arches at the edges will have a 0.05 rise to span ratio. The resulting vaults have a surface area of 14 m$^2$. Each shell is considered one layer only during manufacturing with a total weight of the manufactured elements of 490 kg (each square meter weights 35kg).

Considerations for Shell Subdivision

The digital modelling of subdividing the shell structure was based on specific goals for the modules’ size, the tools and mediums needed during both off-site and on-site making, and the structural approach within the segmentation process.

Weight of elements
All pieces of the system should be manageable by two workers during the installation. Based on the experience in Fabricarte, the maximum weight of each piece should not exceed 70 kg. This makes the maximum area of each piece below 2 square meters. For a room with areas below 8 square meters, for example, four pieces would suffice. Systems with large pieces that exceed 70kg can be installed but with light cranes and lifting systems that incorporate more on-site machinery.

Number of Moulds
In subdividing the vault surfaces, the number of identical elements is crucial. A minimum amount of moulds for off-site fabrication is preferred as it optimises materials for production. Minimising the number of moulds requires either minimum subdivisions with accepting heavy pieces or a more robust modular design approach and analysis to approximate similar pieces without jeopardising the vault’s structural integrity.

Number of props
For the installation of the pieces, temporary support will be required when the pieces meet. Construction props can be used for this purpose. Design for fewer points of intersection reduces not only the number of props but also the effort needed for on-site calibrations between the different pieces of the vault.

Internal forces
Forces within shell structures are vastly studied using finite elements (Ramm, Maute, and Schwarz 1998) and thrust network analysis based on graphic statics (P. (Philippe C. V. Block 2009, P. Block and Ochsendorf 2008). Specific patterns of optimising strain energies or three-dimensional thrust networks influence design decisions.
for optimum material distributions within the structure. Assuming that the cuts will have a concrete’s compressive strength is higher than 20 MPa (C20-C25), it will be higher than that of hollow ceramic tiles that ranges between 15 to 18 MPa (Brown and Borchelt 1990), the edges between the pieces can be treated as nerves of the shells and oriented to conform with the thrust networks of the shell, Figure 122. This also gives a possibility for reinforcement of the concrete along the ribs. However, subdividing the surface for internal forces would generate nonmodular elements that would necessitate many moulds for manufacturing.

4.2.6 Panelling and subdividing

As seen from the previous section, the correlation between the panelling considerations is not always positive. Favouring lightweight elements, for example, might result in many moulds and props, but can also enhance the structural efficiency of the vault. No one solution can be adopted for all construction contexts, but different possibilities can be selected based on the limitations and possibilities found in the site. Those possibilities will be explored. All proposed subdividing options are shown in Figure 123. In the first raw (A1, B1) the inevitable diagonal sections were made to avoid tile cutting, but the resulting pieces were almost two times heavier than the maximum weight of 70 kg. Another possible approach was by making perpendicular cuts in the vaults (C1), which could reduce the weight to 100 kg.

Another iteration of panelling (A2, B2, C2) combined vertical and diagonal sections that could reduce the element’s weight, but 50% of the vault still needs to have moulds for production. This was overcome with another iteration (3) where a mix between the sail vault and the groin vault was introduced, pieces started to be modular, and moulds number was lessened. In Iteration 4, maximum modularity was introduced by enlarging the central area from phase three and isosceles triangles (A4, B4). For mid-span shallow sail vaults, three isosceles triangles can be fitted along the large span, generating another two isosceles at the short span. However, this modularity implies a change in the groin vault’s geometry; it maximises the extrusion of the vault in one direction, making it closer to a barrel vault. The second implication concerns the limitation of these subdivisions concerning the vault’s rise to span ratio. While the pieces are very similar, they are not identical due to a catenary section’s curved surface. A digital analysis was made to understand this limitation by panelling A4 and B4 options under different span to rise ratios. The analysis was conducted by parametric modelling of the segments based on the design exploration shown in Figure 123.

For a groin vault, a rise to span ratio of 0.05 implies a negligible deviation of only 2 mm; this is still the case for ratios of 0.1, 0.15, and 0.20, where the deviation becomes 8, 11, and 17 mm, respectively (Figure 124). If the shell thickness is 30 mm, the lines of thrust will still be maintained in the mass of the shell. Rise to span ratios superior to 0.20 will result in differences between the triangulated pieces, and specific joining strategies will be needed.

For a sail vault whose surface is doubly curved, the changes between the modules are much more pronounced than in the case of the groin vault. A ratio of 0.05 implies a difference of 10 mm between the triangular pieces (Figure 124). The difference escalates rapidly for ratios of 0.1 and 0.15 and becomes 40 and 60 mm respectively. However, it is also noticeable that the difference is limited to the boundary of the triangle and not the piece’s overall geometry—the curvature remains unchanged. This can be solved in joining the pieces and on-site construction, which will be examined in the following section.

The exploration of the subdividing sail and groin shallow vaults shows three main approaches (Figure 125). The first is production-oriented. It favours big few moulds and advanced heavy machinery for an on-site assembly where cranes can manage the fabricated pieces. This method is similar to the conventional systems of
manufacturing large modular elements. The second is structure-oriented. It relies on off-site novel precision and additive manufacturing such as 3D printing and robotic cutting. While these tools easily make different shapes, manufacturing uses fewer materials and maximises structural efficiency. Finally, the third approach is construction-oriented. It favours approximation and craft-skill. It maximises the modularity of the pieces by accepting and calculating the margins of their differences. This approach uses digital analysis and relies on geometrical exploration to favour and develop conventional construction of thin-tile vaulting that does not need cranes or 3D printers. The tools of the builders remain the same, but the order and pattern of construction are changed.

Construction

The proposed manufacturing system can be broken down into two elements, the concrete ribs and the terracotta tile web. The order building each element give several options grouped into three approaches:

On-site rib tiling

This approach does not require a departure from traditional thin-tile vaulting construction. Full span arches are first built on-site, then the web between the vaults is filled. Luis Moya’s work in Spain during the second half of the 20th century is exemplary of this construction. In many of his monumental and religious buildings, such as Iglesia de San Agustín (Madrid) and Gijón University’s chapel, both have the same approach illustrated in Figure 126. Reinforced brick ribs are built over formwork left to set and then covered with thin-tile vaulting (Moya Blanco 1947). Like Moya’s rib vault, this approach reads the rib and the web as separated elements where the thickness of the ribs will be visible in the vault’s interior.

On-site casting

In this approach, the manufactured pieces are built on the moulds but without the concrete cast edge. Instead, the tiles make a stepping edge. After placing the pieces in the site, concrete is cast in the void between them. Although this method requires a system of sheets to fill the gaps between the cast pieces, it offers a significant advantage by overcoming challenges of precision and adaptation to site variables. For example, filling concrete in irregular joints is used in Conzett and Bronzini’s Glenner Bridge, where the nodes of the wood intersections were made of concrete cast on site instead of making customised nodes for each intersection. The on-site concrete cast uses the same approach for joining the vaults’ parts.

Engineered Joints

The art of structural carpentry in Spain, known as Carpentaria de lo Blanco, interlaces wooden pattern for ceilings. The 15th century technique is visually sophisticated as it uses ornamental rules in the making of the panels. However, recent studies of the craft revealed that the construction is not as complicated as the appearance (Nuere 2001, “Albanécar – Bitácora sobre la carpintería de lo blanco” n.d.). The whole system can be deduced to a trihedral resulting from the angle of the common rafter at the two directions and the hip rafter. By adopting the angles in this trihedral, joinery work produces both the pattern and the ceilings’ structure. Lo Blanco is nothing but a prefabrication system of wooden elements made by novice carpenters, left to location and then joined by a master-carpenter. A similar system can be applied in the joints system of the thin-tile vault’s panels by embedding a precise joining system in the manufacturing with projections and recesses in the concrete edge.
Figure 122 Left: E. Ramm et al. Typology optimisation by nonlinear finite element methods. Right: Block and Ochsendorf thrust network analysis for lower-bound analysis of masonry.

Design Approaches to Thin-tile Vaulting

Figure 124 Approximation of isosceles triangulation in relation to the rise to span ratio. Left: groin vault. Right: Sail vault.

Figure 125 Three approaches to shallow thin-tile vaulting panelling. A. production approach: with the use of cranes and lifting systems. B. structural approach using digital fabrication methods. C. Constructional approach using panelling analysis to approximate identical and small panels assembled without cranes.
Figure 126 Construction and manufacturing methods that mix precision and imprecision techniques.
The three construction methods are summarised in Table 8. Selecting the suitable method is subject to the limitations and possibilities of manufacturing and construction. It can be noticed that these methods can be aligned with the subdivision strategies highlighted in Figure 125. Off-site engineered joints are associated with advanced fabrication tools, for example.

<table>
<thead>
<tr>
<th>Construction Method</th>
<th>On-site Tools</th>
<th>Off-site Tools</th>
<th>Tolerance</th>
<th>Speed</th>
<th>Labour skill</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site ribs tiling</td>
<td>Formwork for arches</td>
<td>Moulds</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>On-site casting</td>
<td>Wood for casting in gaps</td>
<td>None</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Off-site Engineered Joints</td>
<td>None</td>
<td>Precise Moulds for joints</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 8 Construction methods of thin-tile vault panels

4.2.7 Prototype

A 1/3 scale working prototype was made to test the method and application of the manufacturing. The moulds for the prototype were similar to the ones in Fabricarte for being sheets of MDF put together without the needs for screws. Thin plywood sheets ran along the edges to give a space for the concrete edge casting. A drawing on the plywood gave an approximation of the tiles’ location to give the overall coursing of the web.

Because the moulds were small, I used brick slips of 215 by 55 by 18 mm instead of tiles. To make the edges, I placed the tiles on the plywood following the suggestive drawing of the coursing and cast the concrete in the void between the tiles and the edges (Figure 127). The concrete edges were left two days to set. Afterwards, using plaster of Paris, the web was filled with arches spanning between the edges. On another try, I used plaster of Paris of the edges instead of the concrete to avoid waiting for the concrete to set. In both cases, when the edge arches are set, another layer of the tiles was added only at the edges to stiffen the piece for moving and transport. The second layer was made using standard cement mortar that needs another day or two to set.

When the piece is ready, it was de-moulded by disassembling the mould’s edges and then stored. The four quarters were made the same way, and the saving of the time was significant. The work was done by me only and each piece working time was not more than two hours. The whole vault working hour does not one working day. The prototype vault is a 1/2 scaled model of Fabricarte. The equivalent flat vault in Fabricarte took around three days with three workers involved (Figure 128).

The assembly of the vaults was made on a wooden ring beam of 1.2 by 1.2 meter. Each quarter weighed around 15kg, which was manageable by one person. The pieces were for a precise assembly where the edges must align with each other. However, the ring beam making was not as accurate, and the MDF sheets of the mould curved 8mm outward when the wet concrete was cast. This has resulted in a deviation of 15mm between the four pieces filled by cement mortar. The assembly took around two hours. The result was a demonstration of the concrete ribs and thin-tile vaults system.
Figure 127 Prototype vault model and mould.

Prototype
Total area: 140
Total tiles: 60
Full tiles: 60
Cute tiles: 00

Figure 128 Prototype of Fabricarte II. Top: Mould arrangement, tiles and produced elements. Bottom: the assembled system.
4.2.8 Discussion

Prefabrication of vaults in modern construction is not a new subject, but Fabricarte I and II are examples that propose a modus operandi driven by craft without compromising design or construction. The manufacturing of building components is usually imagined accompanied by heavy machinery, cranes, and advanced tools. The projects presented challenges to this image by constraining all manufacturing phases to a hand-built scale, which pushes the construction industry towards a more inclusive approach to craft where complex geometries can still be achieved without the extensive use of heavy machinery.

In FabricArte I, vault manufacturing is optimised for rapid in-situ construction. In Fabricarte II, the approach was enhanced by avoiding cutting individual tiles and providing calculations and analysis for approximation between slightly different pieces to be identical without jeopardising the shell’s structural performance. In this approach, concrete, a material that takes the shape of its mould, will be used for the groin, whereas the tiles, material that can arch without formwork, forms the vault’s infill. This underdevelopment system is advantageous because the concrete groins can also be areas for reinforcement or friction-only joints between the parts. The concrete frame can be built without the tiles and installed to then be vaulted. However, the most crucial feature is that it saves time. In a test of a 1.2 m span vault built by one of the authors, each quarter took two hours. The waiting time was the mortar’s time to set, which was three days for acceptable results.

This section’s key conclusions are that thin-tile vaulting can be examined as a manufacturing system for the fast and efficient floor system. Second, there is a variety of solutions for prefabrication methods of thin-tile shells. This chapter proposes three categories: Machine-oriented, advanced manufacturing-oriented, and craft-oriented. Choosing the manufacturing method depends on the site and context of building, such as skilled labour, cranes, and concrete 3D printers. For shallow thin-tile vaults, an isosceles triangular panelling along the large span direction gives almost identical pieces. The differences between them can be negligible, and one mould can be used to make them all.

Finally, thin-tile vaulting is a building practice with high tolerance, accommodating a margin of the tolerance in the manufacturing system is needed. Building thin-tile pieces off-site but casting concrete between them on-site is one example of tolerance accommodation. Therefore, prefabrication methods in thin-tile vaulting can still be craft-inclusive, where the role of the builder is essential.
4.3 Tools: Bending-active Systems for Thin-tile Vaulting Guidework

In both traditional and contemporary architecture, making compression-only shells usually requires a set of temporary structures that either support or guide the construction. Shells and the formwork with which they are built have critical reciprocity. The selection of materials and techniques has immediate implications for the formwork’s type and intensity: some structures require complete shuttering while others, such as thin-tile vaulting, mitigate the need for formwork. A relationship can be observed between the use of formwork and the availability of materials, especially wood. The abundance of wood and labour in the Roman Empire’s western areas resulted in concrete vaults with full shuttering (Lancaster 2015). The lack of timber in Mesopotamia and Egypt produced an architecture of mud blocks that forgoes formwork altogether; it cheats gravity by changing the successive bedding paths so that a brick is always leaning on a previous brick (Ramírez Ponce and Ramírez Melendez 2004; Wendland 2007). In the current application of this construction, builders often resort to a hanging rope or chain fixed on both ends of a vault to help them visualise the perfect arch, even in a reversed fashion. In thin-tile vault construction, heavy formwork is avoided using fast-setting plaster of Paris and light tiles to build a first layer that serves as the formwork for further layers (Truño i Rusiñol et al. 2004; Ochsendorf 2014).

4.3.1 Introduction

Today, we aim for construction that is conscious of material and energy consumption as well as minimal waste production; hence, reducing or recycling the materials used for formwork becomes critical. Many approaches to “rethinking formwork” have been suggested since the beginnings of mechanised construction. Geometry-oriented solutions offered ruled surfaces that reach complex structures by repeating a linear element. Examples of this approach can be found in the architecture of Antoni Gaudí, who used a hyper-parabola for thin-tile vaulting guidework, and Felix Candela, who used similar systems for the shuttering of concrete shells (Huerta 2006). Another approach is to recycle and re-employ formwork materials for furniture or other building components or for a stay-in-place part of the shell (M. H. Ramage, Ochsendorf, and Rich 2010; López, Mele, and Block 2016). There are many recent technology-oriented solutions, including the use of three-dimensional printing for making shells over curved surfaces composed of piles of gravel or soil, robotic arms that temporarily carry vault bricks, and cable-net systems with fabric that are made for concrete shells (Zivkovic and Battaglia 2018; Van Mele and Block 2011). Rethinking materials for new systems of guidework and formwork can result in new construction methods, especially when linked to geometry. When structures are understood as the materialisation of their inherent material properties, bending for compression-only structures produces not only buildable vaults but also makes possible geometries that result from, and are described by, simple in-situ applications. In this section, I return to the raw status quo of the formwork problem: How can the perfect form of structural arches be captured? In other words, since the perfect form for compression-only structures is shaped, in Robert Hooke’s words, “as hangs the flexible line”, this study’s main objective is to flip Hooke’s flexible line to serve as formwork for many geometries with the same line’s length. For this purpose, I investigate using the elastic curves of a buckled strut as a method for a flexible formwork for compression-only shells. This section is an extension of previous research (Al Asali 2016).

4.3.2 Approximation of Elastic and Parabolic Curves

If we could flip a hanging chain and keep it solid, this would be a perfect guide or formwork system for masonry or cast vaults. However, we usually engineer such temporary structures using wood, steel, or other materials. One such system is based on elasticity: strips or surfaces are bent for vaults. Bending to create guidework in
construction is not a new technique. In fact, thin-tile vaults’ construction incorporates bent elements: traditionally, reed and, recently, steel reinforcing bars (rebar). Diagonally oriented rebar is wedged between the vault’s corners to mark the curvatures for sail or cross vaults. Bending follows an elastic curve, whereas the line of thrust in compression-only structures follows a catenary or a parabolic curve, depending on the loading. At moments of minimum bending, the two curves are very similar. Thus, a slightly bent steel bar aids the thin-tile vault builder, as it is close to the parabolic section.

However, when bending with more acute angles, the two curves begin to diverge significantly, and the bent steel bar is no longer valid as a reference for vaulting. Figure 129 shows the different behaviours between bending steel bars and hanging a chain where the deviation between the two is shown in relation to different bending angles. From mapping the two curves’ behaviour, the divergence becomes noticeable when the height of the elastic curve is more than half of its span. Traditional builders recognize this problem and solve it by anchoring two sides of the steel rebar with strings bringing the elastica back to a parabola. For more recent advanced fabrication techniques, the controlled active bending of wood is being explored through kerf bending or using bi-layer structures in which joints have two parts, one of which can move while the other restrains movement (Capone and Lanzara 2019; Baseta and Bollinger 2018). In both approaches, the freedom provided by the joints or cuts is what drives the movement, however, they are usually predesigned for a specific “target curve” and require intensive advanced fabrication work. My approach to control bending is to change the stiffness of the material along the strut, which leads to an approximation of the bending curvature to a parabola. This can be achieved by adding and subtracting material at a given location along the strut, which modifies the bending stiffness, and thus the curvature at that location. The stiffness profile alters the shape of the curve, and with the appropriate profile, it is physically possible to form a parabola. To find the stiffness variation, two main equations were used to describe the buckling equation (elastic curve) and the parabola equation. When the two are equals at a given span to height ratio, the material variation can be solved. For the resultant strip, the overall shape is the graph of the stiffness (Figure 129).

The tool in hand, now called the bending parabola, can be used to devise an elastic guidework for a parabolic arch as it closes and opens (Figure 130). The bending parabola can be used as a generative tool for many shapes. Structural and design properties vaults become inherent in the tool, and they can be made without designing a geometry specific structural analysis. Giving the rule of thumb of how the change of thickness, the length of the strip and the footprint of the vault will suffice for a builder to make the vault. This approach outlines the power of geometry to replace advanced on-site fabrication tools with advanced off-site design rules.

4.3.3 Bending Linear Strips: Vaults by Extruding Sections

Sweeping, revolving, and shifting create sections of the bending parabola and generate multiple geometries of vaults. This strip then offers the possibility for an autonomous in-situ form-finding of structures, using simple materials such as rebar, wood, and bamboo. The method of extrusion of sections is to design the rail on which the linear strip will run; the resulted geometry will always be a load-bearing shell, some of these typologies were illustrated in my MPhil study (Al Asali, Reynolds, and Ramage 2020).

Based on the bending parabola tool, three vaults were built using engineered bamboo strips with multiple sections achieved through the number of laminas of the bamboo. The method successfully described the geometry and served as a learning tool for the builder to understand how to control the geometry of the vault while building (Figure 131). The only wasted material of the guidework system was the tape that joined the laminas of the strip.
Figure 129 Up: Elastica and Parabola behaviours, the divergence starts after the rise to span of the curve is more than 0.5. Down: Results from approximation by changing stiffness in relation to the height of the parabolic arch.

The Changing Section (Stiffness) of the Curve

The Shape of the Curve

Figure 130 Physical modelling of the bending parabola. Top left: Using the cutting along the strip. Down left: Adding laminas to a rectangular strip. Right: the cut strip tested to different heights.
Figure 131 In-situ, vaults prototype by bamboo strips as guidework. 2016. Up: Building the vault by using engineered bamboo with changing thicknesses by adding laminas of bamboo. Down: The built structure.
4.3.4 Bending Curved Strips: Vaults by Unrolling Boundaries

The previous research focused on a movement of linear strips, or the sequence sections, to generate geometries of compression-only shells. The current investigation is to design sets of elements that work together as a network system to describe load-bearing surfaces. This development’s primary purpose is to find a flatpack-deployable bending active element that can describe a vault without the need repositioning the guidework for each arch and with the possibility to realise vaults whose sections form not always a parabola of the same length. Like the previous examinations in this chapter, the work will focus on a variation of sail vaults.

For an active bending system, a sail vault can be described by the edge arches and the central sections, whether perpendicular or diagonal. To visualise a sail vault by bending strips, it is possible to make individual unconnected linear strips for each of the vault’s section, as Figure 132’s left figure shows. However, another possible solution is using one system of connected curved segments that, when pushed from corners, will bend as sail vault (Figure 132, right).

The main target in this approach is to unroll the edge arches into a plane. Unrolling the surface of vaults is explored in studies by using bending active sections (Bruetting et al. 2017), tensegrational tessellation (Hemmerling, de Falco, and Angeli 2019), and the integration of multiple singly curved surfaces (Zhang 2019). However, this section’s bending approach capitalised on the simplicity of employing curves (not surfaces) represented by the squashed curves from the shell. Although they visualise a surface, the curves in hand rely on the vault’s spline boundary and not the surface properties themselves. The exploration of this section constrains the study to a vault covering a square so that all spans are the same (Figure 132).

Unrolling boundary arches

First, a parameterised model was made for unrolling the arches of the sail vault’s edges. For a given arch, there is an unrolled curve whose apex has the same XY position. Therefore, the unrolled arch is constrained by having 1) the same length as the final arch, 2) the middle point (apex) at the middle of the span, 3) and the endpoints located on the movement curves rail 1 and rail 2 (the diagonal curve extending outwards at 45°) (Figure 132).

The arch and the unrolled curve have a reciprocal relationship. This relationship’s governing factor can be extrapolated from the relationship between their heights (the hatched area in Figure 132). The same model was used to find the unrolled curves for a sequence of arches with changing rise to span ratios (Figure 133). Figure 134 shows how the two curves relate to different positions. For arches with a low rise to span ratios, the unrolled curve has a height of 0.15 of the vault’s arches. This ratio increases as the arches become higher and reaches a range between 0.4 to 0.5 when the arch height is half its span (Figure 133, Figure 134). The collected data from the parametric model suggested the following nominal equation that can be used to draw the unrolled curve of an edge arch of a sail vault:

\[ y = 0.07x^2 + 0.4x - 0.3 \]

Where \( y \) is the height of the unrolling arch, and \( x \) is the height of the boundary arch. The two curves are parabolic.
Design Approaches to Thin-tile Vaulting

Figure 132 Two ways for a sail vault guidework. Left: individual elements, right: boundary

Figure 133 Exploring the resulted unrolled curve for a changing rise to span arches

Figure 134 The relationship between the arch and the unrolled curve of the arch. Above: heights variation for a vault’s arch with 10-meter span. Below: the relationship between the two heights in the same vault.
Changing stiffness along section

To verify the proposed methods, several iterations of the bending tool were cut using transparent acetate sheets (projector's sheets), bent, and measured (Figure 135). For shallow and medium height arches of ratios between 0.1 and 0.4, the bent structure gave an exact height as predicted by the equation is shown in Figure 134. However, when bending progresses, the resulted arch start to become lower than the ideal curve, and the strip starts to bulge out, making a closer shape to an elastica. Giving more contrast in the thicknesses along the individual strip can solve this deviation. That is, making the fusiform strip thicker at the quarters can give a parapolice curve for arches with a rise to span ratios superior to 0.6 Figure 138, Figure 137).

Figure 135 Physical verification of the unrolling method. For the tested thickness, the correlation between the arch and the unrolled curve starts to be affected after a rise to span ratio of 0.5 as the strips starts to become an elastica

\[ y = 0.075e^{0.4x} \]

Figure 136 Relationship between the thickness variation and the rise to span ratio of a parabolic curve
The exact change of the thickness can be solved from the two equations of the parabola and elastica curve, as shown in a previous study (Al Asali, Reynolds, and Ramage 2020). However, a numerical method was also used for mapping the change of the arch’s rise to span ratio arch. The input was used from multiple ratios (Figure 129). The exponential relationship between the height of the arch and the thickness is mapped and can be predicted using the following equation:

\[ y = 0.075 e^{0.4x} \]

Where \( y \) is the variation of the thickness and \( x \) is the ratio of the arch.

In Figure 137, Selected variations of the strips were selected and mapped for quick selection of the appropriate thickness for a range of rise to span ratios. For arches with ratios between 0.3 and 0.5 the strip with a variation of 0.25 can be used: a strip whose thicker part is four times larger than its thinner part. As a result, it is now possible to design a guidework for a given vault or predict the shape of the vault’s boundaries from a given guidework. The two parameters for designing the system are: 1) the unrolling equation and 2) the thickness variation of the individual edge (Figure 137).
Guidework for the web

Like the edge arches, the guidework for the vault’s internal fill will be integrated into the same system of unrolled curves. Three approaches can be made to control the web’s guidework inside the vault (Figure 139).

Perpendicular sections

For perpendicular sections: the bending of the system will have minimal effect as their springing points are only moving in the Z direction but the span between the points is the same. The perpendicular sections are useful when the vault at the centre does not get much height than the edge arches or remain at the same height. One option can be to maintain the perpendicular sections at the centre of the vault. Although these sections must stay straight in the digital model, the physical testing shows that they get slightly bent. The bent of these two sections is not because their springing points are moving but because of the change in the bezier direction of these points. When the curved strip is pushed to the bending location, torsion can be noticed at its apexes, the side toward the vault’s interior gets higher than the one located at the exterior edges. This torsion makes very limited bending in the perpendicular strips as the strips themselves resist the rotation because of their fixed length.

Diagonal sections

For diagonal strips, there will be major bending when the flat sheet is bent. More iterations of simulating variable arches gave the resulted diagonal sections when the system is completely bent. In Figure 140, the mapped heights of the diagonal arches are drawn in relation to the vault’s boundary. When the vault is rise to span ratio is less than 0.12, the diagonal section has almost the same height as the edge arch. It gets higher than the edge arch to eventually stay around 1.2-1.4 when the edge arch’s height is half of its span (Figure 141). Therefore, when the edge arch rise to span ratio is more than 0.1, the diagonal section’s height can be described by a linear relationship with the edge arches by the following equation

\[ y = 1.15x + 0.42 \]

Where \( x \) is the height of the edge arch.

The diagonal sections' use can give a useful visualisation guide for builders at the web of the vault. In case the height of the section needs to be changed, the use of the thickness variation can be used but with attention to the global curvature of the diagonal arch not to get closer to an elastic curve, as shown previously in Figure 137.

Curved connection

A different method of making the web guidework can be explored by maximising the effect of the rotation of the apexes and getting a higher guidework at the central area of the web than what the perpendicular sections provide. One can break the perpendicular sections into curved connections between the adjutant peaks of the edge arches with curves (Figure 142, Figure 143). More layers of the secondary curves can be added between the curved segments. The curves can be drawn by connecting the middle points of the previous set of curves and with their tangents are aligned to the main perpendicular sections (Figure 142, Figure 143). A physical model was made to test the curved connections (Figure 143). It is noticed that the rotation of the apex of the edge arches helps the curved connections to visualise the web of the vault. The curved connection provides an additional height to the centre of the shell that ranges between 1.05 and 1.15 of the edge arches, making it a middle solution between the previous two options. By implementing this method of guidework, a modular arrangement of vaults is imagined to be made from one single bending system, as shown in Figure 144.
Figure 139 Guidework options for the web of the vault

Figure 140 Diagonal section and unrolled arch variations.

Figure 141 The relationship between the arch and the diagonal curve height. Above: heights variation for a vault’s arch with 10-meter span. Below: the relationship between the two ratios.
Figure 142 curved connection guidework

Figure 143 Curved connection physical modelling and testing

Figure 144 Modular vaults guidework
4.3.5 Recipe for bending-active guidework for sail vaults

A step by step ‘recipe’ can be summarised from the previous digital and physical testing. For a target sail vault whose footprint is a square, a guidework system can be carved out of a single flat sheet by doing the following:

1- Edge Arch: First, the unrolled curve and shape of the edge arch should be determined:

a. Unrolled Curve: to find out the curve of the unrolled arch, we can use this nominal equation

\[ y = 0.017x^2 + 0.4x - 0.3 \]

Where \( y \) is the height of the unrolled arch, \( x \) is the height of the edge arch. The height determines the two endpoints of the curve on the diagonal bending tracks.

b. Thickness Variation: To draw the variation of the mass in the individual strip, another equation is used:

\[ y = 0.075e^{0.4x} \]

Where \( x \) is the rise to span ratio, and \( y \) is the upper thickness.

2- Guidework for the web: After unwrapping the vault’s boundary, other strips can be added for describing the geometry of the vault between the boundary:

a. Sections strategies: depending on the vault’s geometry, the initial set of the guide work can be selected. For vaults whose centre is as high as their edge arches, cross-sections can be used as they stay flat when the system is bent. For higher centre by 1.05 to 1.15 than the edge arches, a system of curved connection is useful. For yet a higher centre that reaches 1.3, diagonal sections can be used. The diagonal section’s height can be described by a linear relationship with the edge arches by the following equation:

\[ y = 11.5x + 0.42 \]

Where \( x \) is the height of the edge arch.

b. Changing thicknesses of the strip is made as in step 1A.

Note 1: Shallow Vault: In the case of shallow vaults, the three options give very similar results, and the use of the inner guidework system can be densified with more elements.

Note 2: Non-square footprint vaults: There are two points to consider when developing this work for vaults with a non-square plan. The first is that the method can be followed but by changing the angle of the bending axis. In this section, it was always assumed to be 45. This can be changed so that the bending axis is heading towards the centre of the vaults plan. The second point is that because there will be different lengths, the height to span ratios of the edge arches will be different; larger spans will have shallower arches (or different thicknesses change to become higher).
4.3.6 Applications

Guidework of thin-tile vaulting

The application of this method opens the possibilities for more iterations and geometrical design inside the vault shell itself. More secondary links can be added between the strips to enhance the overall visualisation of the surface. Some of these possibilities are summarised in Figure 145. In the top row of the figure, a starting point of a plain solid plate is bent to serve as a reference to compare all iterations. Slicing the surface along one direction or by radial arrangement improves instantly the shell's curvature and approximate it to a funicular structure. In the second row, diagonal strips drive the overall bending with thin connections between them, while the final raw eliminate redundant materials from the diagonal ribs by voiding them. The study of bending active guidework design for thin-tile vaults presents a geometrical approach to convert flat systems into three-dimensional surfaces. The instant application of the study is to device the system for thin-tile vaulting construction. However, the work on the guidework as a tool and a device for on-site form-finding has developed to considering the tool itself as a structure. The guidework themselves became bending-active structures approximated to a funicular surface.

Grid shells

While this is not the focus of this research, it can be noted that further application of the changing stiffnesses of strips can also be explored in relation to other shell systems such as grid shells and similar bending structures made from natural material such as wood, the compression friendly sections in these structures helps in dealing with the creeping of the material. Maximising the thickness of the linear elements in a grid shell can be considered as a form-driven approach to approximate the overall geometry of the shell to a funicular shape (Figure 146). Small models were made for this proposes with wooden elements joint with screws and bolts. The approach used in the physical prototyping is based on adding laminas to the shell's segments in the same locations where the strips should be thicker in the guidework.

Hybrid bending-flexible formwork moulds for shell floors

The move into bending plates offers a divergence from thin-tile vaulting (where the bent structure is a guidework) into considering using bending-active systems as flexible formwork for concrete slabs or as lightweight flat-packed structures. What prompted this direction was the last row of strips exploration in Figure 145, where voiding the diagonal ribs were reimagined as stiffening ribs of the shell structure. Adding or subtracting material to the plate does not only drive the bending but also allow for a sagging effect of flexible formwork to make the stiffening ribs (Figure 147). Following the pattern of the internal forces inside the shell, which was explored in the vault manufacturing section, the voids were reconfigured to align to the force's direction, enhanced with changing the number of layers of textile to control the sagging depth. Two 1/100 prototypes were made with wood plate and spandex. After cutting the plate, a layer of spandex was added to the bent plate, another layer was added in places where reduced sagging is preferred. The scaled prototyped showed a possibility for developing this approach towards making concrete floor system from flatpack formwork (Figure 148). Because it is a pattern, the system can be translated into an object by various techniques, ranging from advance computer-aided fabrication to a saw in the hands of a skilled carpenter; It can be reused or left as a stay-in-place formwork, be an off-site manufacturing industry or made on the move. It is nothing but a geometrical play, and, unlike materials, geometry is cost-free (Figure 149).
4.3.7 Discussion

Bend-and-build has been explored as a possible guidework for shells given the ubiquity of linear elements in nature—bamboo and reed canes—and in the engineering and construction industries. This section focuses on bent linear elements and their movements to produce thin-tile shells with parabolic sections, but an entirely new possibility has opened in the study of unrolling vault surfaces with curved strips. In some vault’s typologies, such as sail and cross vaults, the making of the formwork is more challenging than making the vault itself, mostly when made for unskilled labour. The same can also be said about formwork, where the temporary structure works as shuttering and not only as a visual guide. The focus in this study on guide- and formwork aims to simplify the making of these temporary systems and to store the structural geometry of vaults in their behaviour when bend.

While the core of the research in this section was about thin-tile vaulting, the technique itself was secondary, and the focus is shifted to a numerical study on describing the load-bearing shell by bending structures. Hence, what was examined was the tool to build and not the building. In the conventional construction of shells, the formwork is usually ‘descriptive’, it describes the shell and supports it. Formwork becomes a parallel project that is usually built using drawings and models prepared only for the targeted shell. In this section, the aim was to make a ‘generative’ guidework whose inherent properties can find many shells. Although some limitations were encountered in the curved bending strips, such as the limited range of parabolic curves a strip can make, they expand the possibility of a formwork beyond solving one shell only. In many forms of making, jigs are essential. To cut a piece of wood at 45 angle using a table saw, for example, a jig is made to support the rotated wood board while sliding and cutting. Jigs resemble a rule that modifies or implements a temporary mode of making for a specific target. However, jigs rely on principles and simple on-site applications and have a considerable potential to play an essential role in reconsidering construction. Today’s advanced fabrication methods favour universal manufacturing, exampled in additive or subtractive manufacturing, making almost everything. While highly relevant when these technologies are available, an alternative and more contextualised approach is to rely on principles that push everyday tools into jigs. The geometry-oriented examined method advocates this approach. To bend a plate for a vault, a pattern of cutting will suffice. To build guidework from linear elements, a role of how many laminas on the strip will also suffice.
Figure 145 Exploration of bending-active plates for shell structures
Figure 146 Bending active grid shell with variations of sections through adding laminae along the individual members
Figure 147 Flexible formwork over bending active plate for concrete casting. Making the mould.
Figure 148 Floor system from flatpack sheets from drawing to casting

Figure 149 Floor-system from flatpack sheet, a possible application in self-built areas in Damascus
The main key findings from this section are: first, bending-active elements can serve as systems for guidework and formwork for thin-tile vaulting. Second, by changing the stiffness of a bent strip, we can drive the bending geometry to approximate it to the shape of the parabolic sections; this became an unrolling technique based on spline exploitation of the boundary of the vault. Using sail vaults as an example, unbending the shells' boundary presents a mode to flatten unruled surfaces of vaults. More internal sections can also be unrolled by following the guidework shell's movement from flat to bent. Finally, while initially was considered research for guidework for thin-tile vaulting, the bending technique converted the tool (guidework) into a structure itself. Bending plates can serve as moulds for casting concrete for loadbearing shells as floor systems.

4.4 Conclusion: Design strategies in thin-tile vaulting

In this chapter, I worked on three different aspects of thin-tile vaulting prompted by different limitations of resources (Figure 150). In studying thin-tile vaulting in Syria, the challenge was the material. The absence of the terracotta tiles, and fired brick in general, prompts a study on sourcing local alternatives. The focus was on the structural capacity of the alternative material (the stabilised rubble tile) when placed in the shell. The geometry of the vaults, the construction process, and the tools were all kept unchanged as they exist traditionally in the craft. However, what was needed is a simplification of the process of building vaults, which was achieved by introducing a simple rule of thumb in the rise to span relationship. In the study and design of Fabricarte, the critical element was time. The narrow on-site construction window introduces off-site construction. The initial work in Fabricarte was not about systemised and modular manufacturing of thin-tile vaults but was a trick to cheat on time. Vaults were cut and transformed into a puzzle where each piece is useful only when placed back in its original location. This manufacturing necessitates the use of formwork or probing systems to assemble the heavy pieces on the site. In the second iteration of Fabricarte, the focus shifts to reduce the time in both off and on-site construction. This leads to making concrete and tiles panels for modular triangular pieces, mainly for shallow domical and cross vaults. The study uses digital analysis to understand and outline the geometrical limitations of the proposed systems. As a result, the study systemises the traditional process of thin-tile construction towards industrialisation. In the study of guidework in thin-tile vaulting, the need is to reconsider the use and reuse of the guidework. However, what is more important in this approach is to recompense the lack of on-site knowledge of forms with on-site form-finding by allocating the form to the material behaviour. The use of the bending system can be used anywhere, and it will always describe a loadbearing shell. Digital analysis and simulation were used to map and generate bending behaviour to generate a medium that helps the builders understand construction. As a result, the study changed the order of design in thin-tile vaulting by setting up autonomous devices that generate vaults without the need for structural analysis, but the construction of thin-tile vaulting is kept the same. Moreover, the device itself becomes a vehicle for applications in different forms of shells, such as grid shells and a concrete cast of vaulted floors.

Table 9 has a summary of the research elements in each approach. The Table shows how each design methodology corresponded to policy, analysis, fabrication, and construction constraints. Policy concerns the legal and procedural infrastructure of the proposed system. The examination of the stabilised rubble is focused on how introducing the material in the vaulting system can be aligned with the existing building code in Syria. On the other hand, Fabricarte tapped on the manufacturing systems, and the bending strips are proposed as devices to assist and train builders to vault. The design in Fabricarte concerns how to cut a shell into smaller pieces and build them without compromising the craft aspect of the technique. Finally, the design approach in the bending formwork is a mix of geometrical and material behaviour analysis.
Figure 150 Three vaulting aspects. Top: Rubble-stabilised tiles. Middle: Concrete ribs vault. Bottom: Bending active-flexible formwork
<table>
<thead>
<tr>
<th>Design</th>
<th>Verification of the material and the geometry</th>
<th>Conventional analysis for pavilion construction</th>
<th>Approximate Elastica to Parabola</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Traditional Vaulting Typologies</td>
<td>Approximation of shells geometry for modularity</td>
<td>Unrolling Vault edges</td>
</tr>
<tr>
<td>Material</td>
<td>Physical testing</td>
<td>Breakages during transport and manufacturing</td>
<td>Bending with changing thicknesses</td>
</tr>
<tr>
<td>Policy</td>
<td>Limitation to comply using structural and physical analysis</td>
<td>Extending construction of thin-tile to workshops</td>
<td></td>
</tr>
<tr>
<td>Manufacturing process</td>
<td>Using the debris that already exists in many Syrian cities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply chain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training</td>
<td>Unskilled builder can make the assembly</td>
<td>A device can help builders to build better</td>
<td></td>
</tr>
<tr>
<td>Fabrication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building component</td>
<td>Time and size of construction can be systemised</td>
<td>Different shells can use the method</td>
<td></td>
</tr>
<tr>
<td>Off-site tools</td>
<td>Moulds and medium for off-site construction are inevitable</td>
<td>Unconventional tools will need to be made</td>
<td></td>
</tr>
<tr>
<td>On-site tools</td>
<td>Use of heavy formwork</td>
<td>Geometry is embedded in the system</td>
<td></td>
</tr>
<tr>
<td>Building Material</td>
<td>Altering the current fabrication method to make tiles</td>
<td>Saving in materials for guidework of different vaults’ geometries</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machines on-site</td>
<td>On-site use of crane might be needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machines off-site</td>
<td>Cutting and casting machines for vaults parts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed techniques</td>
<td>Ribs are advantageous for structural and constructional proposes</td>
<td>New skills need to be introduced to make the tools</td>
<td></td>
</tr>
<tr>
<td>Rules of thump</td>
<td>Rules of thumb can be useful in the prevalent Informal building</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9 Overall comparison of the design approach in the three projects in this chapter
While each method is trying to solve a specific limitation, it can also be noted that it somehow generates new challenges. For example, the urge to design building components for fast on-site construction has resulted in more materials and fabrication methods for moulds and the assembly of the vaults. This highlights that any approach to include a construction strategy imposes its limitations, which challenges the notion of optimisation altogether.

The examination and reflection on the three case studies show a methodology of how to incorporate the use of technology in construction craft such as thin-tile vaulting. Another concept of optimisation can illustrate the answer. That is the optimisation of “site” technology by using “analysis” technology. A clear example of this optimisation is the bending guidework. A pattern to cut a sheet of wood will provide guidework for a vault. The pattern encapsulates a long process of using technology for gematrical and material analysis, but it will be cut by a saw on-site. Another example is the subdivision pattern of shallow vaults, which can be reduced to simple rule to be communicated with the builder.
Chapter 5
Conclusion

Towards a Craft-Inclusive Construction
5.1 Approaches in Thin-tile Vaulting

During the construction of the pavilion in Santa Pola (Figure 82), the head of the local school of vocational training in Alicante called to pause all activities for ten minutes. He improvised a speech about how an architect and craftsmen, referring to Salvador and me, are working side by side, and both are making mutual decisions about how design and construction should progress during the project. The activities in a doctoral thesis can sometimes be extensive enough to impede a vivid expression of its focus. But the director of the school rightly put it as “rebuilding tacit trust between builders and designers”. By tacit trust I understand two strands, the first is a trust in the tacit knowledge itself, the second is to constitute and validate mediums of exchange between builders and architects that do not necessarily follow conventional routes of codes, building specifications, and drawings.

In rebuilding this trust, this research focuses on one specific technique, thin-tile vaulting. There are two reasons for the adoption of this technique; the first is that it produces structural and decorative building components which are essential in architecture and construction, the second is that thin-tile vaulting exists in different locations and manifests in different cultures and contexts, thus it offers an examination of how a local building technique, traditionally practised in the eastern Mediterranean region, can become global. The research hypothesises that building design and digital analysis represent a fertile space in which vernacular ‘wisdom’ can act in dialogue with construction methods. My PhD dissertation examines this through a historical analysis of buildings and purpose-designed case studies. It demonstrates how thin-tile vaulting responds to the limitations of materials and resources in different contexts and periods.

The research’s central question is about accommodating localised building techniques (also called traditional, vernacular, artisanal and indigenous) in contemporary construction, focusing on contexts of scarcity in materials and resources. From exploring secondary resources, the research overviews the rise and fall of thin-tile vaulting in history, with attention to the period after the industrial revolution (table 01). The reviews study shows how contexts of scarcity, especially restriction on using steel and wood, forced designers to resort to formwork-free terracotta vaulting. However, the study also shows that the reasons contributing to the abandonment of the technique are not only limited to the return of steel and wood but also ingrained in the emergence of new architectural styles, codes, and opportunity for industrialised construction. The relationship between materials and resources and the use of thin-tile vaulting is not linear. The examination of this vibrant and nonlinear correlation through design can give a practical framework for the architectural practice to deal systematically with vernacular construction.

Proceeding from the overview, the research proposes a framework summarised by three approaches to thin-tile vaulting: policy and state-led initiatives, knowledge transfer and training, and design. The study adopts the three approaches in three chapters to examine, observe, and design a series of historical and contemporary projects summarised in Table 10.
<table>
<thead>
<tr>
<th>Project</th>
<th>Research Type</th>
<th>Data</th>
<th>Methodology</th>
<th>Key Research contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICONs research 1959-1965 (Cuba)</td>
<td>History of building</td>
<td>Archives (Restaura) Site Visits Interviews</td>
<td>Content Analysis Drawing/Modelling</td>
<td>Map of vaulted buildings in Cuba Examination of vaults manufacturing in Cuba Mapping state policies concerning thin-tile vaulting</td>
</tr>
<tr>
<td>AlSharqyat 1980-1990 (Syria)</td>
<td>History of building</td>
<td>Archives (Milihouse) Interviews</td>
<td>Content Analysis Drawing/Modelling</td>
<td>History of vaulted projects in modern Syrian construction Mapping state policies in vaulted housing</td>
</tr>
<tr>
<td>Rwanda Cricket Stadium (Rwanda)</td>
<td>Ethnography Education</td>
<td>Observation Interviews/questionnaires</td>
<td>Content Analysis Drawing/Modelling</td>
<td>Models of project-specific Training in thin-tile vaulting Examining the aftermath of training</td>
</tr>
<tr>
<td>Refugee School in Azraq (Jordan)</td>
<td>Ethnography Education</td>
<td>Observation Interviews/questionnaires</td>
<td>Content Analysis Drawing/Modelling</td>
<td>Models of project-specific Training in thin-tile vaulting Examining the aftermath of training</td>
</tr>
<tr>
<td>Santa Pola Pavilion (Spain)</td>
<td>Ethnography Education Design</td>
<td>Observation Interviews/questionnaires</td>
<td>Content Analysis Drawing/Modelling</td>
<td>Models of project-specific Training in thin-tile vaulting Examining the aftermath of training</td>
</tr>
<tr>
<td>Stabilised rubble Vaults (Syria)</td>
<td>Design</td>
<td>Fabrication Load-tests Codes</td>
<td>Prototyping Drawing/Modelling</td>
<td>Floor systems of thin-tile vaults Comparison between existing concrete slabs in Syria in terms of cost and use of cement</td>
</tr>
<tr>
<td>Fabricarte (Spain)</td>
<td>Design</td>
<td>Commission Full-scale construction</td>
<td>Prototyping Interview with builders</td>
<td>The craft-based Manufacturing process of vaulting Slicing pattern for approximated modular pieces of shallow sail vaults</td>
</tr>
<tr>
<td>Bending parabolas</td>
<td>Design</td>
<td>Fabrication Design assignment</td>
<td>Prototyping Digital analysis</td>
<td>Active bending systems for on-site form-finding Hybrid active bending flexible from work for vaulted concrete slabs</td>
</tr>
</tbody>
</table>

Table 10 Summary of Examined vaulted projects
5.1.1 Policy Approach to thin-tile vaulting

Both in Cuba after the 1959 Revolution and in Syria during the sanctions (1980s-1990s), materials were hard to import, and architects looked at vaulting techniques to build houses and other buildings. In each case, vaults were produced at a mass scale. While in Cuba the vaulting technique included both thin-tile vaulting and full-brick vaults with shuttering, thin-tile vaults were not part of the Syrian vaulted houses. However, the comparison between the two cases is useful in determining the successes and failures of state-led vaulting construction.

From finding and examining primary resources in the two cases, new narratives of construction history in the two countries were constructed. In Cuba, it has been believed that the only thin-tile vaulting example is the famous and controversial project of National Art Schools by Ricardo Porro, Vittorio Garatti, and Ricardo Gottardi. This thesis revealed that there are many other vaulted buildings (perhaps more utilitarian) dotting the country. Those buildings were the fruits of an investigation team at the Ministry of Construction (MICONS), led by the architect Juan Campos Almanza, with engineers, architects and master builders of thin-tile vaulting. In Syria, the case of the village project called Al Sharqyat (Orientals), has always been associated with luxurious and expensive housing. This research revealed that the original proposal of Al Sharqyat was to build low- and medium-cost housing, and vaults were used for this specific purpose. However, the project’s scope was changed after 1985 to become a village for Syrian expats outside Syria and vaults were then emphasised not as a solution for low-cost construction but, somewhat superficially, as a symbol of Syrian rural architecture.

The study and comparison of the two cases revealed that successful vaulting strategies in construction policy rely on two crucial elements. The first is to establish a direct connection between centralised experiments and applications of these experiments in pilot projects. The second is to allow, within the development of building components, for on-site modifications engendered in vernacular construction which is conditioned by the mutual work between master builders and architects. The Cuban team successfully produced well-executed vaulted structures through this dialogue whose absence in the Syrian case resulted in poor architecture and low-quality housing where vaults are considered more as a problem than a solution.

Through design, architectural practice can contribute to these two conditions. The use of graphic tools, models, and illustrations are essential in explaining and demystifying how vaults, and vernacular construction in general, work. This specific role is called ‘the dialogue zone’. The other crucial and complementary role of design in connecting construction policies and thin-tile vaulting is to set codes to allow for variations and on-site testing. On-site testing in the conventional construction industry is about verifying compliance to regulations and specification; it becomes a zone of modification and development in vernacular building and design keeps being central in the process. This role is called the ‘verification zone’. The combination of the two will inevitably require an architectural practice that negotiates craft in explaining and developing them at the same time. This notion of negotiation is evident in the case of the investigation on vaults in Cuba that, while being a shorter period, resulted in more diverse and vast applications of vaults than in Syria.

5.1.2 Training Approach to thin-tile vaulting

Like many other construction crafts, traditional training of thin-tile vaulting entails models of master-apprentice that usually happened within families of builders or artisans’ schools. However, this model is becoming less prevalent. Short-term training is now the dominant model of knowledge transfer, with experimental and project-specific training programmes that introduce the techniques to new regions and cultures. Challenges of time, site conditions, and the adaptation of the method to local construction become intrinsic to the process of
learning, imposing questions about the aftermath of the training and the applicability at a local level and beyond the completion of the intended project.

The research examines three training programs through three projects: The Cricket Stadium in Kigali, Rwanda; the Azraq Schools of Refugees, Jordan; and the exterior pavilion of Santa Pola Cultural Centre, Spain. Training in the three projects showed two complementary models, practised training and expanded training. In practised training, the focus is on applications, which include the control of the setting time of the plaster, the position of the tiles, and speed. In the expanded training, the focus is on the design of the vaults, the substructure, and the selection of appropriate materials. The intensity and order of these two models in the three projects reveal that practised training can be conducted to prepare builders to build a vault quickly. However, it is conditioned with continuous supervision, and it is unlikely the builders will use vaults after the project. In contrast, when expanded training is introduced, it offers a comprehensive understanding of how to approach vault. Still, it is conditioned with self-training and the existence of vaulting in the tradition of where the training is taking place; hence this model proved useful in thin-tile vaulting native Spain.

Architectural design and practice can have an impact on accommodating vaulting, where appropriate, in vocational training. The direct route can be the use of vaulted projects in contexts where labour is not expensive and training programmes are possible. In contexts where labour is costly, training programmes can be established as part of vocational education and within construction companies. In both cases, and because thin-tile vaulting is connected to different components and disciplines in the field of design and construction, its training cannot happen without it being linked to the already established industry of architecture, construction, and conservation. Craft training should be situated at the intersection between three sectors: artisanal work, construction, and restoration.

5.1.3 Design Approach to thin-tile vaulting

Learning from the historical and current cases of thin-tile vaulting in the last two approaches, the research situates design-build experiments in thin-tile vaults to respond to limitations. Specifically, three limitations were examined: materials of tiles, time for construction, and skill of labour.

Materials as alternative to terracotta tiles: The project proposes the use of gravel-stabilised tiles, which can also be made from rubble, for the construction of vaults. To suggest the alternative materials, the project needed to respond to two conditions: construction codes (as per the Syrian building code), and the simplification of geometrical properties of a sail vault. The project includes the fabrication of rubble tiles with 5-8% of cement, building the vaults and testing them under line-loads. The material used, and the rules of thumbs to describe the vault geometry can make a ceiling system that uses 80% less cement than typical solid concrete slab systems and can be 30% cheaper.

Time reduction in thin-tile vaulting: The experiments were directed towards systemising vaults as a building component. The initial exploration built a pavilion in a reduced on-site time by building it in a workshop, slice, transport, and reassemble it. The experiment shows how slicing tiles can be time-consuming and proposes the use of concrete only where vaults are sliced at the groins. Shallow sail vaults for ceilings show a promising domain of geometrical approximation when cut into almost-identical triangles. The use of the concrete proved beneficial as the concrete edge can tolerate the imprecision of craft-produced pieces. As a result, a craft-produced sailing vault can be manufactured for mass-scale rapid on-site construction.
The absence of skilled labour: The research focuses on the tools and mediums that can teach how to build vaults. In specific, the study proposes a mechanism for on-site form-finding. The research shows that the use of bending-active systems can be useful when bending behaviour is controlled to produce a catenary-like curve. The control of the behaviour is made by changing the section of the bent element. The first use of this "jig" is made with straight elements that can generate a vault's geometry at varied bending angles. The research then shows that sets of curved strips, when they bend together, can describe a geometry of sail or groin vaults. As a bent set of strips, the tool starts to become an independent vaulted structure that serves as the formwork for steel-free vaulted concrete slabs.

5.2 Contributions

5.2.1 Towards a Craft-inclusive Architectural Practice

During my postgraduate research, I have positioned my work at the of between the "technical" and the "social" domains in architecture. At this intersection also lies a perpetual tension between the two realms. The first is represented by the 'optimism' of engineering and design systems proposed to solve problems associated with the built environment. The second springs from the 'pessimism' of urban and theoretical studies in which architecture is pictured entangled in contested conditions. Being mainly framed as an inquiry of architectural practice, this research operates within this tension, illustrated in the discrepancy between construction as systems and construction as cultures.

Therefore, while examining how the design of vaults can mitigate or deal with scarcity, terms such as optimisation and rationalisation of resources were not claimed as definitive solutions. Instead, they are tools for working with limitations in the space of diversity and creativity, a space of manoeuvring between interconnected parameters—a system. An elaborate description of what this manoeuvring system will look like in practice is offered by James C. Scott’s in his book “Seeing Like a State”. Scott contrasts plans of controlling and processing natural resources to the organic forms of interacting with these resources by indigenous inhabitants and frames the latter as a skill, using the term ‘Metis’. Descending from Aristotelian philosophy, Metis, translated to English as ‘cunning knowledge’, is defined as “a wide array of practical skills and acquired intelligence in responding to a constantly changing natural and human environment.” (Scott 1999, 313). The keyword in this definition is “changing” as it implies that rules may exist, but there is no universal solution for similar problems. Metis is placed as the opposite of Techne, which he defines as a “settled knowledge” that is “organized analytically into small, explicit, logical steps and it is both demonstrable and verifiable” (Scott 1999, 320).

This critique of Techne as a scientific universalism approaches modernity from a broader perspective, one that calls for diversity and inclusion and opposes thin simplification of systems. Although very powerful conceptualisation, Scott’s embracement of Metis lacks the suggestion of practical applications, and, as phrased in Ulf Zimmermann’s review of the book, needs to be linked with “phronesis and praxis, or, in more ordinary terms, to produce theories more profoundly grounded in actual practice so that the state may see better in implementing policies.” (Zimmermann 1998). What are the key-elements for diverse and inclusive systems of design? In switching between craft and construction, the research continually deals with this question. It proposes design tools as a methodology that contributes to the knowledge on how to establish a roadmap of a dynamic and culturally aware production of the built environment. In other words, the research links the social and technical by showing, in practical examples, how a metis-friendly policy can work in the case of thin-tile vaulting in construction—a needed connection between Metis and Techne.
My PhD finds that construction for environmental resilience operates within the same limitations as vernacular construction. While local building crafts are useful for sustainable construction, they are usually excluded from policies and formal building regulations as they are inherently difficult to be abstracted into codes. Architectural design can play a decisive role in bridging this gap. Architects can contribute to demystifying vernacular building at a policy level by using digital modelling and analysis to understand how they work. At a training level, architects can not only design buildings, but also design how their buildings can be built. This is intrinsically associated with the engagement with local building cultures and training programs. At a design level, they can develop construction tools in conversation with craftspersons to help the latter to find new possibilities of their craft, build faster, or build more efficiently.

The map of these approaches is shown in Figure 24. The map evolves from the theoretical framework that structured the research (Figure 24). The figure shows how aspects of thin-tile vaulting are interconnected and positioned with the three approaches. For example, on the continua between design and labour lays tools and skill in the construction of thin-tile vaulting. This case represented the case study of the active-bending guidework study in Chapter 04. Likewise, the examination of building codes concerning thin-tile vaulting design will have to address systems of construction and experiment to verify or expand these systems.

The map of these approaches can be a helpful tool for engaging with thin-tile vaulting by knowing how intervening with one aspect of the technique will affect the other aspects. The diagram also suggests the type of “methodologies” needed in examining the different approaches. In testing and systemising the technique, prototyping becomes inevitable while the method “explain” is associated with making codes accessible to labour. Finally, the method “analyse” refers to the use of digital and geometrical analysis to create a productive relationship between labour skill and design skill.

In projecting all projects in Table 10 on the diagram, the different approaches in these projects can be compared (Figure 152). One can first notice that in cases in which vaulting was less successful, such as the case in Al Shraqyat in Syria and the Refugee school in Jordan, the scope of intervening was narrower than in other cases. Expanding the work to include the nearby aspects would usually lead to a comprehensive approach to vaulting, which, in turn, root the technique in both practice and policies. This finding reiterates the needed diversity of design approaches in relation to craft.
Figure 151 Diagram of approaches to thin-tile vaulting: Policy, Labour, and Design. The Nonagon shows the range of aspects related to each approach. The internal space of the diagram shows the methods associated with each zone of exploration.

Figure 152 Approaches of thin-tile vaults across all case studies in the research
5.2.2 Building Craft Training Models

Learning from the training programs of thin-tile vaulting in Chapter 03, it can be said that the notion of the period of training, being long or short, is becoming irrelevant to the gaining of skills. Today’s communication tools and ways of knowledge exchange are increasingly developing. It can be proposed that what used to be called short training is aimed to accelerate practising, which can be considered an ‘activity’. Similarly, conventional long training, aimed to gain a general and specific experience of problem-solving by interacting with skilled masters, can be considered a ‘community’. Therefore, it is possible that short vaulting training programmes can have an impact in changing building habits at a grassroots level, but only when it is accompanied by growing a community that would sustain and develop vaulting locally. The combination of the two provides a knowledge infrastructure to cover both practised and expanded learning. However, it also offers a model for a school of building craft.

This concept has developed into a venture in Valencia, Spain. The enterprise offers a partnership between architects and master builders to create a space for training and collaboration to realise innovative building solutions through local, traditional, sustainable construction techniques. It functions as a social-good enterprise and community of practice where members are all part of the centre’s network and have access to the tools, space, and regulated sessions with artisans.

The construction industry is one of the main employers of low-skilled workers in Spain ("OECD Skills Strategy Diagnostic Report Spain 2015" 2015). There are 1.7 million employees in construction sectors, of which 1 million are labourers involved directly in building activities. Only 30% of construction workers in Spain had received appropriate training in comparison to the average of 60% across other sectors (‘Tras la crisis, el sector de la construcción envejece’ n.d.). In vernacular construction, craft centres and construction schools in Spain offer workshops. The workshops are short and usually serve as only an introduction to the technique at hand. They run workshops only during summers. Most workshops are generic and oriented as an outreach activity rather than the preparation of professional builders. Construction companies are not included, and it targets only individuals.

There is a need for training that specialises in specific construction crafts. The model offers diversity and the scalability of training from public events to personalised training for companies. Based on findings from this research, a training model is proposed to mix ‘online’ and ‘on-site’ flexible learning for more extended periods of practice with iterations of a short in-person course with online follow-up. This allows for a tangible and trackable process. All training programmes will be committed to having an exact result: builders with the capacity to build with vernacular techniques.

5.2.3 Digital Analysis for Vernacular Construction

While the research is focused on thin-tile vaulting, more can be said about the role of geometrical analysis in building crafts in general, specifically those with a strong geometrical drive in their realisation, such as traditional carpentry reed and bamboo weaving. The research expands the understanding of digital analysis to avoid advanced building manufacturing and keep the on-site construction limited to builders’ everyday tools. A prominent example of this is Gaudí’s ruled-surface vaults’ construction, where he combined ruled-surface logic with traditional string guidework. Gaudí’s alteration of fabrication was minimal; the tools were still everyday strings. However, he transformed them into an unprecedented mechanism for producing complex geometrical compositions. In this particular context, architecture’s role is to mediate between materials, craftsmanship, and physics.
In maintaining off-site technological tools to minimise the use of on-site advanced fabrication, the research shows that what can be altered to develop a traditional construction technique is not 'what' but 'how' the construction is practised. In rethinking the traditional structural carpentry in Spain, for example, geometrical interrogation can be addressed in the joint system to include torsion or bending of the wood for structural or aesthetic reasons. Finding these solutions for traditional craft and structures can become a seed of local grassroots construction that supplement the construction industry with situated knowledge from vernacular practices.

### 5.2.4 Making as a Methodology

The contribution of this research is also methodological. The research uses conventional methods but combines them with built case studies and digital modelling. This methodological interface between the social and the technical has been simultaneously challenging and rewarding; it offers and demands a breadth of activities that stretch from the history of buildings and ethnographic studies to design and construction. This range has enabled me to construct historical narratives regarding thin-tile construction in Cuba; devise tools of training and examine programs for the training of novice builders in Jordan and Spain; develop systems of vault manufacturing in two experimental design-built projects; and explore recycling war-torn buildings in Syria into vaults.

What could bring all this method under one field is "making". Making, which includes digital and physical modelling, drawing, and mapping, has been central to the study. In the examination of vaulted projects in Syria and Cuba, using drawing and modelling have been indispensable in reinforcing the archival work. But it was more than that too. The work has uncovered new elements and relationships between seemingly separated projects and experiments. The formal and procedural relationship was found thanks to modelling and drawing every vault located in the archives and positioning it in its temporal, geographical and geometrical conditions. Drawing and modelling become tools to understand and communicate simultaneously.

Similarly, modelling was part of the ethnographic studies and, naturally, in the design-build experiment. However, while being enthusiastic about making as a methodology, the research recognises that it needs a theoretical scaffold on which it can be constructed and can be beneficial only when used with conventional qualitative or quantitative methods. Making can be a supplementing methodology that offers perspectives that are otherwise hard to notice.

### 5.2.5 Future research

This research is a contribution to the growing body of research on thin-tile vaulting. Several cases that are worth studying were found during the research outside the scope of this PhD but will be a continuation of it. In specific, the thin-tile vaulting exchange between North Africa and Europe is a promising and under research topic. Current studies are mainly associated with finding the origins of thin-tile vaulting, but the exchange during European (mainly French and Spanish) colonialism of North Africa is still to study. George Collins mentioned the work of Marcel Lathuilliere in Algeria, but more can be explored in relation to the work of Roland Simounet, P. A. Emery and L. Miquel (Collins 1968).

Furthermore, a close examination of the thin-tiled projects in post-war Spain can be conducted through a series of a state-produced journal *Reconstrucción*, published by the governmental *Servicio Nacional de Regiones Devastadas y Reparaciones*. The journal was Francoist propaganda, and its political aspect is evident in its structure, selection of cases, and language. Tile vaulting might have been heroised as a Spanish local building.
technique. However, the journal provides an excellent overview of the reconstruction work in Spain between 1940 and 1953, a period that covers several changing economic conditions.

Finally, the work in Cuba can also be expanded to examine other publications on the theme of vaulting, specifically the one about reinforced ceramics called Ceramica Armada (Cerámica Armada 1962). Because reinforced brick vaults are not part of the research, the examination of this theme was not included. However, when linked to the presented work on thin-tile vaulting, working reinforced brick vaults will expand the studies on vaults and shells and Cuban construction history.

From a broader perspective, the research opens the field for future research in the relationship between design and the inclusion of construction crafts found in the site. This approach proves important in the current debates about construction in the era of environmental emergency and the emergence of digital fabrication. Acknowledgement of the fact that construction is one of the most environmentally extractive activities in society has fuelled increasing questioning of the way ‘we build’. Two strands of critique have emerged. The first seeks to introduce digital tools, smart applications and data-driven planning into design and construction to optimise, recycle, reuse, or redistribute materials and resources. The second emphasises the role of situated knowledge in the protection and development of ecology and the built environment. However, relatively little has been said about the relationship between the two and how to use situated knowledge in contemporary construction.

A future route can further develop this research by examining one vernacular technique, thin-tile vaulting, in different geographies to examine different construction techniques in one specific socio-geographic space. By examining more than one vernacular technique, we can understand how architectural practice can use digital analysis and fabrication tools to facilitate a peer-to-peer process between designers and builders’ communities. Another possibility for future research is a comparative study between thin-tile vaulting and other vaulting techniques, such as the pitched brick vaults or corbeled dome construction. The comparison will add another layer of complexity to how vernacular construction techniques are manifested in different cultures.
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