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Developmental route to functional and adaptive integration

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This article seeks to address the question as to how architectural systems can be better developed to support locally specific design. The biological concepts of 'developmental plasticity' and 'structural hierarchy' are introduced as key concepts for the development of material-based structural systems with multi-functional and adaptive properties that can be adapted to locally specific conditions. This discussion emphasizes: the integral relations of material, structure, space and environment; flexibility in proportioning with emphasis on reduced dependency on mass; and the heterogeneous treatment of space, based on the notion of a spatially and environmentally conditioned and conditioning 'matrix of interconnected spaces'. While the lack of integrative capacity delimits architectural design in general, this paper focuses on masonry systems as an example, highlighting some of the developmental pathways available to masonry design. This effort includes analysis of selected historical cases and a contemporary case study entitled 'Nested Catenaries'.

Keywords*: developmental plasticity, structural hierarchy, indeterminacy, local-specificity, Nested Catenaries*

1 Introduction

The overemphasis on developmental constraints has obscured the attention to developmental plasticity in architectural design in general and masonry systems in particular. However, it is the latter, which is critical for enhancing innovation and variability, and thereby design's capacity for functional and adaptive integration that allows for locally specific design solutions. What follows is an attempt to displace this common emphasis and to rethink the developmental role of structural hierarchy from the view of plasticity. This exercise is advanced on the basis of masonry design challenges and potentials that arise from the integration of material–structure–space–environment, through selected historical and contemporary case studies.

Two sorts of information can greatly contribute to the development of material-based structural systems with multi-functional and adaptive properties, which can be adapted for locally specific architectural applications. The first can be obtained from the analysis of the use and evolution of materials in architecture by mapping structure according to property (historical information). The second can be obtained from the models of structural hierarchy that map the effects of material and environment on property across levels of complexity, covering a range of size scales (developmental information). In creating access to both, design tools such as Michael Ashby's *material-property charts* [5] and *Material-Ontology* [41], which are respectively enabled on database and ontology-driven information systems, can deliver key methodological approaches. *Material-property charts* allow extensive mapping of materials (material may stand for: depending on size: e.g. cellulose; micro-fibril; cell wall; wood; plywood; laminated beam; timber grid-shell; and based on classification: e.g. monolithic, hybrid or engineering, biological material) into structure-property space. Material properties (e.g. cost, shape, energy use, tolerance) are correlated in pairs (e.g. stiffness–density) or more (e.g. specific strength–specific modulus) at a time to graphically register the distribution and abundance of materials, which populate the graph according to their property values, displayed in logarithmic scales within upper and lower range limits. The charts show current usage and property with design criteria plotted on them. New materials and structures fill the “holes” while the remaining empty space indicates “vectors for development”. With its ability to give directions to unexplored developmental pathways by effectively matching principles and effects with property conflicts inherent in the development of trends and processes that operate across scales, *MatOnt* can help fill these gaps by resolution of conflicts without compromise (thus eliminating detrimental trade-offs). One line of research in which these are considered as complementary sources of information is the ceramic-based design and construction system entitled *Nested Catenaries*.

In this case, the implication of 'nesting' is two-fold. The first one refers to the structural and spatial principle used for developing an unreinforced thin masonry shell with uniform thickness of a single layer of bricks, laid on face. And second, to a specific process of designing with arches and vaults, which gives rise to spheriodality (curvilinear form or curved space) and possible structural hierarchy. The *Nested Catenaries* masonry system is based on this principle and process of nesting. A combination of principles including nesting, curvature, branching, and local shape control was found to be critical for creating properties that are useful for loadbearing functions. This achieves maintaining light-weight-ness, while at the same time preventing critical stress concentrations that could initiate fracture due to the low tensile strength of unreinforced masonry under combined uniform (e.g. self-weight) and non-uniform (e.g. wind, snow, seismic) loads [42]. Another advantage is derived from the process that expands the set of conditions within which structure and space can be formed across scales according to usage and relative to changes in the environment. *Nested Catenaries* shows structural and spatial organisation across several length scales. This results in multi-functional and adaptive properties relative to scale and environment, and makes it possible to use locally specific conditions as design drivers. So far, seven levels of hierarchy have been considered: the cellular structure of ceramics as solid–space composite that make up; the building element bricks; combined into arches; and vaults; forming first-level nesting that articulates an undulating wall; second-level nesting that articulates a cavity wall; and third-level nesting that articulates a spatial shell structure.

Structural hierarchy, which can be observed both in nature and culture, has been a subject of much discussion and research. Among those who have contributed to this field is Roderick Lakes, who discussed this concept not only in descriptive terms based on the recognition that “structural features occur on different size scales”, but also with respect to its importance for determining useful physical properties and behaviour (improved strength and fracture toughness, negative Poisson’s ratio, super-plasticity), suggesting the potential applicability of this idea to the analysis and design of materials and structures [31]. In support of this view, he compared the third-order hierarchical framework of the Eiffel Tower – one of the earliest examples – where the struts are organized across three size scales, with the first-order of the Centre Pompidou, highlighting the structural and material advantages of the former. Lakes also gave examples from natural hierarchical cellular solids such as rock, wood and bone, considered as solid–space composites. In architecture, the idea of structural hierarchy has remained marginal. Yet, structural hierarchy can offer improved hyperstatism (Hyperstatic or statically indeterminate) or topological toughening [4] – a response to the static indeterminacy of masonry structures that provides safety in case of local failure. One way to approach this is to facilitate multiple load paths for distribution of loads that enable: effective use of material properties; reduced dependency on formwork and ease of construction due to small size modules; the formation of cellular spatial complex; and functional and adaptive integration. The latter brings attention to a far less explored area, namely the developmental role of structural hierarchy.

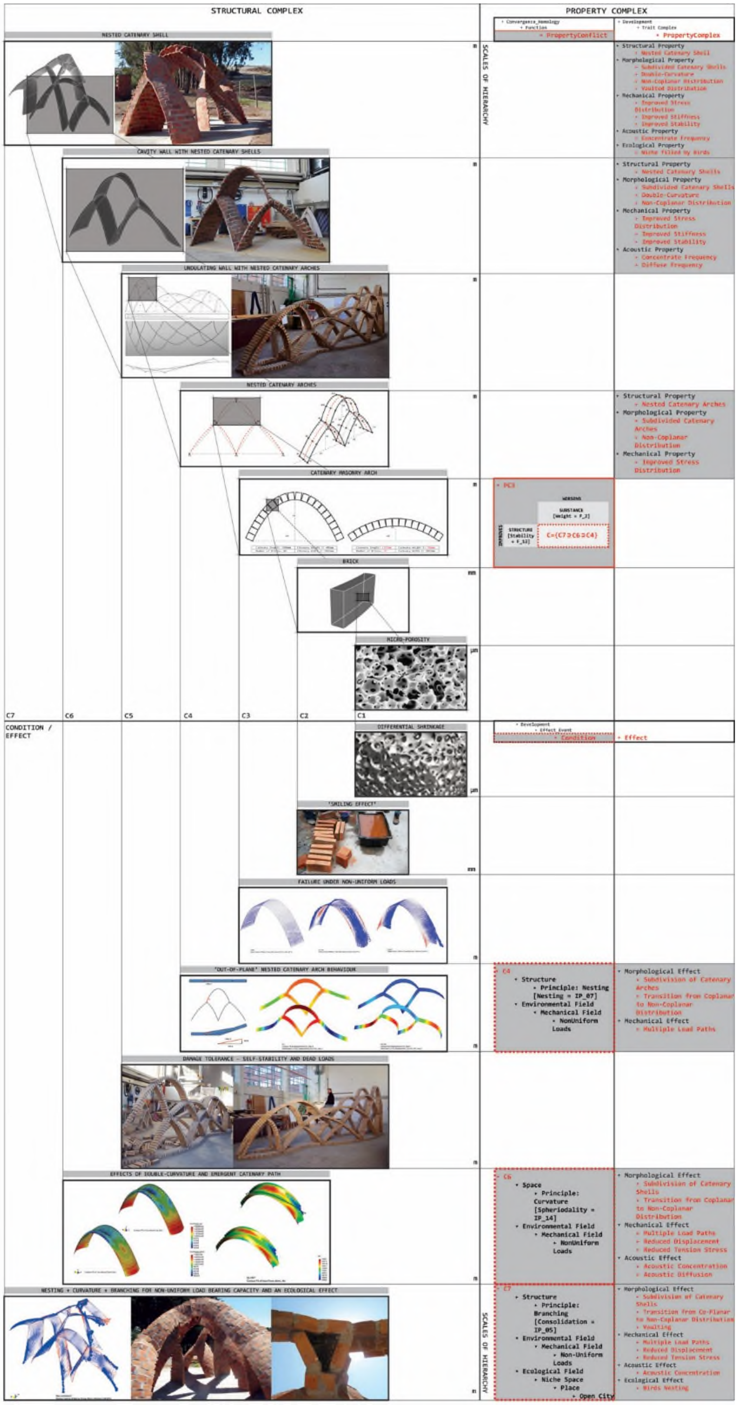

Figure 1 Nested Catenaries general Condition–Effect–Property Chart, mapping conditions (including material and environment), effects and properties registered across scales of hierarchy.

The advancement of structural masonry in architecture and engineering follows a long lineage with the true arch, which can be traced back to 4000 BC Mesopotamia. Its development can be mapped according to the design capabilities concerning functional integration and adaptability of properties to local environment. Function entails the process of carrying out work (supporting loads, keeping warm, delaying circulation) that arises out of the interactions between material, environment and individual(s). Properties such as stiffness, curvature, porosity, self-shading, self-similarity, symmetry and asymmetry can in this context be informed by, and formed as a response to, local circumstances and conditions. Changes in context, use, incompatible requirements or not well-understood, unanticipated interrelations and interactions between variables may generate conflicts between properties, which in design often result in improving one property while compromising another (e.g. stiffness–weight). The evolutionary history of masonry architecture reveals a number of inventive solutions that successfully circumvent these conflicts, especially in cases where the strategy of variation does not provide an answer. The ongoing *Nested Catenaries* research is built upon this historical background, and specific examples that have contributed to the potentials of masonry shells for locally specific architectural applications through innovation and variability. Structural hierarchy underlies developmental plasticity (a biological concept invoked in the explanations of inventive change and epigenetics, also known as phenotypic plasticity), which implies that there is more than one pathway to a design solution, thus drawing attention to the developmental basis of innovation and variability [43]. This is key for moving from general *Nested Catenaries* properties towards particularized ones that are informed by specific requirements and local conditions. This approach can foreground: the integral relations not only between material and structure but also space and environment; properties of flexibility in proportioning: reduced dependency on mass; structural independence from symmetry; freedom from uniform repetition; geometric unconstrained from compression-only forms; and heterogeneous treatment of space. Furthermore, it entails a shift from a universal prototype to a system that can be specific to the conditions of each setting in which it is to be implemented in an architectural design; in other words, a shift from a general Condition–Effect–Property chart to project specific ones.

2 A cultural continuum in practice and theory

One of the challenges for architectural development today is how to design and build according to the heterogeneity and variability of materials, local environmental conditions, as well as taking historical and contemporary scientific advances into consideration that concerns the cultural evolution of masonry over millennia. The reasons for how come that such an integrative logic is strongly present in traditional masonry architecture with ancient roots, is not immediately obvious when considering that the static indeterminacy of masonry structures is a good enough reason for contemporary engineering and architecture to favour distance from the use of masonry. But what seems evident is that masonry's high compressive strength, low tensile tolerance and the criticality of proportion and mass for stability were evident to early practice. Material constraints, challenges behind the integration of material understanding in the solution of structural problems and spatial, environmental consequences have majorly influenced the evolution of masonry design.

2.1 Material integration in structural understanding

Galileo was the first to attest the determining role of scale for structural behaviour, which he explained with the "square-cube law" as early as 1638. He demonstrated this by comparing the bone of the bird and dinosaur relative to the corresponding differences in dimension and proportion, although exaggerating the bulkiness of the latter. The implications are that structure–scale relations are not as simple as geometric ones: although stability scales in a linear way, strength for instance is not directly proportional to volume. But the rule of geometric proportion suits well a design process that is concerned with stability. As Addis wrote “compression structures progressed to such a remarkable degree, both in Roman and medieval times precisely *because* their stability is independent of scale and hence *because* building (i.e. testing) a scale model is a reliable way of predicting the behaviour of a full-size structure” [1]. Rules of linear proportion measured according to a single key module governed both the ancient classical and Renaissance architectures. Yet, there is a shape aspect to this that requires attention. Robert Hooke’s idea was to use the hanging chain model to find the form of thrust, which would correspond to a catenary arch, working in pure axial compression when inverted. Hooke (1675) posited this as “The true Mathematical and Mechanical form of all manner of Arches for Building, with the true abutment necessary to each of them. A Problem, which no architectural writer has ever yet attempted, much less performed …” Hooke continued to state: “…As hangs the flexible line, so but inverted will stand the rigid arch” [24]. In order to understand the great diversity of masonry forms the idea of catenary needs to be viewed in the context of its elaboration by the mathematician David Gregory (1697): “None but the catenary is the figure of a true legitimate arch, or fornix. Moreover, when an arch of any other figure is supported, it is because in its thickness some catenaries are included” [19, 25]. Hence, it is not only shape but also the thickness (cross-sectional dimension) that is important for securing stability. A building form configured by small format components, have brought a great deal of attention to the practical implications of the arch and shell geometry on formwork and stone, brick or tile patterns.

The invention of the arch and its derivative, the vault (i.e. barrel, rounded vault or dome) predates the origination of masonry theory. Possibly the earliest example is a barrel vault with a span of 1m which dates back to about 5000 BC Mesopotamia. The cultural anthropologist Alfred L. Kroeber wrote that the earliest vaulting technique of corbelling was a result of independent evolution while the self-supporting true or *voussoir* arch and vault evolved from a single Sumerian origin in Mesopotamia which was introduced into Europe, Africa, America and throughout the rest of the world before closing the loop after several thousands of years of improvement and transformation [27]. Yet, this cultural evolution may not have been quite so linear.

The masonry arch theory that originated in the late 17th century was rediscovered three centuries after its replacement by another idea: the elastic theory, and was introduced into the modern framework of ultimate load theory through the significant contributions of Jacques Heyman (1966). The competing ideas of plastic and elastic arch applied to the analysis and design of masonry structures that continue to advance in parallel have material, structural and spatial implications. In relation to this, Karl-Eugen Kurrer pointed to an interesting process of adaptation of meaning to the changing scientific understanding of the vault (Latin volutus = bowed, arched and volvere = to turn or roll) [30]. This change corresponds to the shift from a three-dimensional spatial conception (grounded in the stone Roman camera) to that of two-dimensional thinking (making the vault identical with curved roof/ceiling surface) and in the material approach to structure. The identification of the vault with load-bearing thrust action specific to the heterogeneous material (non-linear–plastic model) as in rigid masonry arch was later expanded to include the homogeneous treatment (linear–elastic model), thus introducing bending to the understanding of masonry structural behaviour.

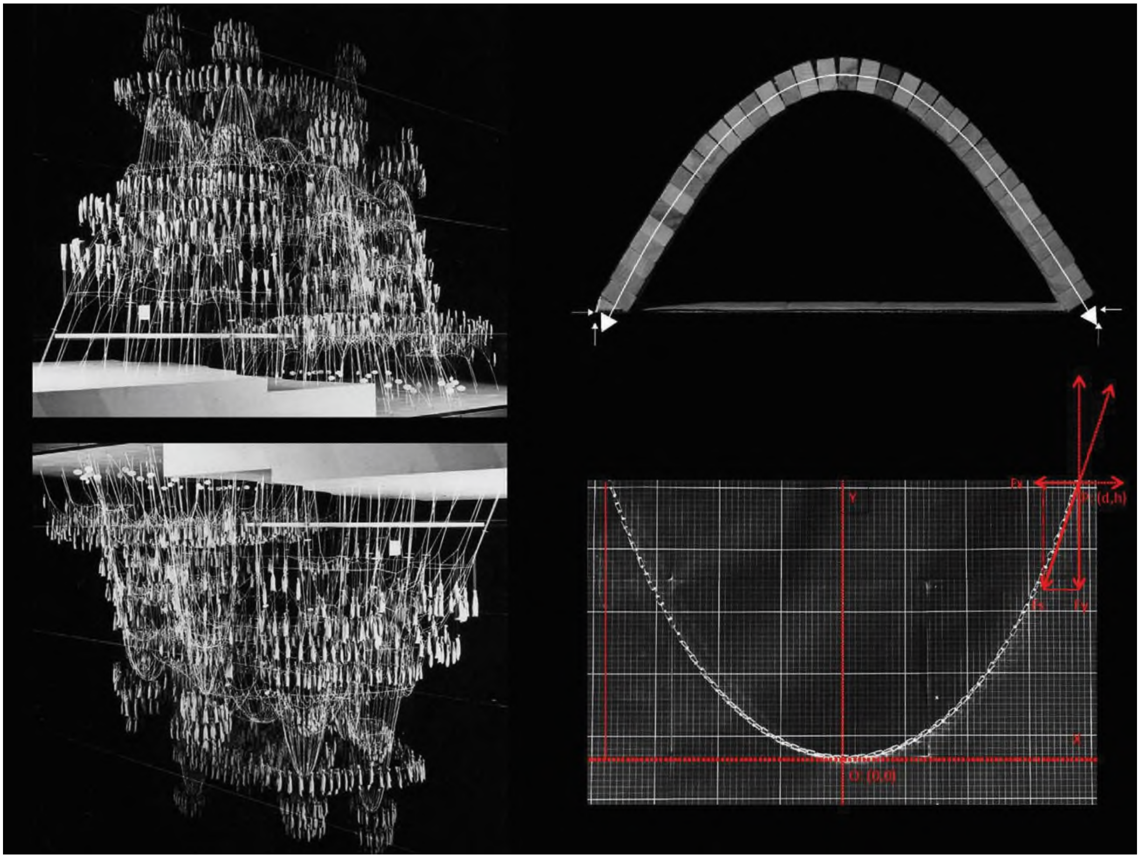

Figure 2 The hanging chain model of the Colonia Guell Chapel (Left) based on the inversion principle and the catenary arch.

Three key approaches opened the way for the application of elasticity and introduction of stress to the analysis of masonry:

- 1660: Hooke’s law of elasticity and consequently the possibility to account for the elastic properties of masonry structures;
- 1817: Thomas Young’s anticipation of the middle-third rule for establishing the geometric factor of safety and the beam theory (including the works of Bernoulli and Euler);
- 1826: combination of the former two by Claude-Louis Navier [34] in the theory of elasticity.

Material improvement in terms of the tensile capacity and the automation of the calculation process made possible by computers and computational methods (i.e. Finite Element Method, FEM) mutually influenced and reinforced the exclusive predominance of the elastic method and the increasing use of reinforced concrete from the beginning of the 20th century. This development and the costs associated with manual labour caused the almost complete disappearance of unreinforced masonry shell structures from contemporary architecture, a condition that begs reconsideration, in particular in light of the more recent developments.

The search for the actual thrust line and simplified, deterministic material and boundary assumptions raised doubts regarding the elastic view as the sole theory, due to its limitation to only provide approximate conclusions that might be safe but not suitable for predicting behaviour especially when applied to unreinforced masonry. Therefore a renewed framework that did not rely on assumptions based on the actual position of the thrust line and would account for the sensitivity to imperfections and environmental effects was needed. For this reason, Heyman (1995) developed the modern limit theory based on three assumptions: masonry has no tensile strength; masonry has unlimited compressive strength; no failure can occur due to sliding between adjacent masonry units. While this theory was initially developed for the analysis of steel frames, Heyman quickly recognized its general applicability to any form with ductile quality, including masonry. With the emphasis back on stability rather than stress, the *plastic model* could be used to analyse masonry arches and shells through a careful combination of the old masonry theory and membrane shell theory combined with experience and observation. Heyman's main conclusions included the formation of four hinges as the minimum necessary condition for static instability and shape as the most important factor of safety: "The key to the understanding of masonry is to be found in the correct understanding of geometry" [23]. The basic postulates behind the plastic and elastic theories render their analytical concurrence apparently impossible. However, this inconsistency nevertheless does not rule out the possibility for their consolidation in design given great care in their application and interpretation of results.

Whichever form the masonry arch takes, the basic principle remains the same: the structure has to accommodate for all possible lines of thrust, the path of which is dynamically modified as a consequence of changes in initial conditions and applied loads. Among masonry forms the catenary is particularly attractive as it is primarily a gravity-influenced form of thrust developed under self-weight and therefore applicable to aboveground conditions. Under uniform vertical loads, the catenary works in uniform axial compression free of bending moments. This geometry allows optimizing thickness according to the line of thrust with the advantage of building a thin arch or surface, while making effective use of its material in compression. However, in reality structures need to respond to more than one load-case. Therefore the catenary can only provide a partial answer. As Barthel pointed out "while a hanging chain represents a minimal construction, an arch which is derived by inverting the chain does not. The stability of the arch is not assured. The arch can buckle if it is too slender, and it can simply fall over sideways. In order to prevent these failures, additional steps must be taken, which cannot be determined using the hanging model" [6]. Masonry is statically indeterminate: from unpredictable initial small displacements can arise large deviations from the actual thrust line [23]. If emergent thrust lines are not sustained within the material thickness, tension concentrations may be generated, leading to fracture and eventual failure as a consequence of the low tensile strength of the masonry. Therefore considerations of multiple load-cases need to include other principles that supplement the catenary action and the safety factor. On the whole, approaches to structural instability in masonry structures favoured as primary parameters: the emphasis on shape independent of scale; adherence to the rules of proportion and symmetry; and strength of material and foundation. Based on these considerations, the typical response to constraints associated with masonry has been: the reduction of unpredictability to a minimum by eliminating the impact of environmental influences; functional decomposition – a one-to-one mapping between structural and functional modules as opposed to integration; and adding more material (hence increase thickness), reinforcement or combining materials.

2.2 A short historical account of key innovations

Structural independence from mass by way of reducing thickness and weight, while maintaining stability and stiffness, hence displacement of mass with space, remains a key driver in the evolutionary development of masonry architecture. The following part maps some of the inventive principles and key traits that supplement the catenary action, found in history.

The resolution of passive and active lateral thrust resulting from dead loads and external forces into multiple load paths through a series of buttresses of linear and radial array is unique to Gothic cathedrals, although structuring arches and/or vaults into tiered or vertical planar organization is a Roman invention. This feature of connected arches/vaults can be seen as spatially integrated (Roman Market of Trajan or Hagia Sophia in Istanbul [2]), or as incorporated into the wall or surface (Roman Pantheon, *scalactic pendentive* of *muqarnas* vault of the Great Mosque of Isfahan and Sayyida ʻĀtiqa, or the Great Mosque of Córdoba, featuring one of the earliest forms of a rib vault, the crossed-arch dome). The structural role of the rib or *mocárabe* (honeycomb or stalactite pattern) seen under arches or vaults, or in the transition from square plan to domical spatial organization has been a subject of study and analysis. With attention to the ribbed dome of Córdoba and in reference to Heyman's analysis of the Gothic rib vaults in particular, Fuertes' and Huerta's conclusive assessment suggests that "depending on the specific situation the rib may or may not carry, the shell may be supported or not, perhaps, a certain indeterminate amount is supported by the ribs and the rest by the shell, and the proportion may vary with time" [16]. This points towards what might be considered conditional functionality and raises the need for condition-specific analysis.

The first scientific structural analysis is credited to Giovanni Poleni, whose assessment of the "double-dome" of St. Peter's showed that in its meridional cracked state the shell worked according to Hooke's theory of thrust and thereby was structurally safe, although hoop stresses needed to be accounted for with further reinforcement (Poleni 1748). In collaboration with Hooke, Christopher Wren used the catenary shape for the design of the "triple-dome" of St. Paul's, where it is applied to the middle conical brick shell supported on walls inclined on the inside to approximate the thrust line. As Melaragno pointed out, these domes belong to multi-layer shell design and construction, which is an old concept and practice, but not all are underlined by a motivation for structural integrity [33]. Each shell layer of St. Paul's dome is assigned a single load-bearing function, if at all. In contrast, St. Peter's multi-layer dome works as a unified shell that can resist multiple loads. Earlier examples to the latter include Santa Maria del Fiore and Gur-e Amir Mausoleum [22].

Unreinforced thin-shell structures based on the traditional Catalan vaulting technique advanced to a great level of sophistication in geometric complexity and was applicable to all building parts. Its success is mainly derived from the effective bonding strength of its plywood-like laminate tile material, as well as the economical formwork and the speed of construction. One of the most astonishing examples are the Catalan wine cathedrals, especially the Pinell de Brai by Cèsar Martinell I Brunet, where a series of tile laminate walls form multiple arches with a large parabolic arch at the centre, supporting the timber roof and creating a three-dimensional connection between the primary and secondary axis in the cross and lateral directions of the bays in between the nave and side galleries. The famous Batlló Factory by Rafael Guastavino and the Vapour Aymerich Textile Factory by Lluis Muncunill i Parellada are other key examples. Guastavino utilized and further developed this traditional method into what he termed "cohesive construction". His contemporary Antoni Gaudí advanced and applied this material and construction technology with ingenuity in projects such as the Colònia Güell Chapel and Sagrada Família School building.

The availability of iron as a substitute for wood (given the tensile strength) for experimenting with hybrid masonry structures greatly influenced architecture during the 19th century. The Reading Room of the Bibliothèque Nationale by Henri Labrouste is one of the early examples made possible by this approach

[32]. Another example is Viollet-le-Duc's highly influential theoretical proposition for a polyhedral vaulted Concert Hall based on the "iron network vaulting" system of iron columns, tie-rods and oblique struts that replace the role of the Gothic buttress through metal-masonry composite construction [8]. However, it was three material inventions of composite masonry that majorly changed the course of developments in reinforced shell design and construction:

- 1890: *ciment armé* by the engineer Paul Cottancin;
- 1907: *béton armé* by François Hennebique;
- 1910: composite reinforced masonry based on Guastavino vaulting by Rafael Guastavino Jr.

Cottancin's composite material is a lightly reinforced double-layered perforated brickwork that acts both as a permanent formwork and an integral part of the material, with metal and cement infill, thus providing combined resistance to compression, tension and bending. Especially notable is the idea of using *ciment armé* as a continuous material throughout the design of a large exhibition space for the Exposition Universelle by Anatole de Baudot, who had previously worked with it on St.-Jean de Montmartre church in Paris [15]. Guastavino Jr. demonstrated the possibilities of his method with the design and construction of one of the largest masonry domes ever built for the St. John the Divine Cathedral.

Still, one of the most remarkable works in reinforced masonry was yet to come. Eladio Dieste developed a reinforced and pre-stressed thin brick shell construction system called *Cerámica Armada* in response to the abundance of brick and lack of cement in Uruguay [37]. His work entails a convergence on the catenary geometry, which is revealed in the cross-sections of the Free-standing and Gaussian vaults. This features majorly in the design of the Church of Jesus Christ the Worker, which is considered one of his most influential works. Another key figure, although mainly known for his achievements in thin reinforced concrete shells, is Eduardo Torroja Miret. Possibly influenced by Dieste's work, Torroja returned to reinforced brick systems in the 1950s. He designed and constructed a series of churches in the Pyrenees mountains, of which the Church of Pont Du Suert (1952) is probably the best-known example. Based on his knowledge of the Catalan vaulting technique and advantages gained from reinforcement, Torroja's initial idea was to use tile laminate shells as the permanent formwork for reinforced concrete that was for the first time applied in the foundations of the Sancti Petri Bridge. In contrast to Dieste, who developed masonry forms subjected to considerable tensile stresses and buckling resisted by using reinforcement and pre-stressing, Torroja limited his designs to compression-only forms based on a lightly reinforced Catalan vaulting strategy [36].

2.3 Coevolution of structure and space

The treatment of spatial organisation and structural articulation as two separate solutions eliminates the possibility to account for the advantages gained from their integration in the design solution. The former is pervasive today while the latter is greatly undermined; therefore attention to the latter is much needed. Introducing openings without compromising structure offers several advantages including improved natural lighting, but which properties are affected when mass is reduced (by way of openings or reduced thickness), and what are the consequences for spatial organisation?

This question indicates the need for functional integration and implies that the adaptive capacity of masonry systems needs to be better integrated with local conditions. Critically, mass is not only a vital structural attribute but also essential for thermal behaviour and for the embedding of spaces of various sizes (cavities, recesses, alcoves or niches) within the thickness of the wall or vault. Structure and space have historically frequently co-evolved in an integrated manner. More specifically structural concepts specific to masonry architecture were correlated with particular spatial ideas. Accordingly, these strategies have produced a set of features that became inseparable from both the conceptualization and production of masonry shells or vaults. A great variety of patterns that occurred, suggests the following spatial concepts including but not limited to:

- Matrixes of interconnected spaces;
- Spatial lattices;
- Interstitial space;
- Variants from central-, nine-square-, "infinite-" grid-plan to free- (stone skeleton) and open-plan facilitated by spatial shell structures.

Existing approaches to these spatial concepts differ greatly. Three-dimensional cavernous natural underground maze patterns of vault complexes are the earliest model for *matrixes of interconnected spaces*. Sigfried Giedion, with reference to Alois Riegl, identified such hollowed-out spaces as the second space conception, which "began in the midst of the Roman period when interior space and with it the vaulting problem started to become the highest aim of architecture" [17]. Its variants can be seen in vernacular structures of cliff-, pit-, cone-form of carved dwellings.

Robin Evans introduced the concept of "matrix of connected rooms" based on an analysis of Raphael's earliest plan of Villa Madame in Rome as a 17th century thoroughfare layout of different rooms all connecting to each other through multiple doors.

This type of spatial organisation evolved according to Evans into the 19th century type of enfiladed terminal rooms with a single entry combined with the idea of corridor. He then went on to elucidate the effects of these types of spatial organisation on the social relations they provided for [12]. This analysis brought to the fore the proximity that arises from patterns of connectivity, distributed circulation and overlapping movement. Most importantly and in general terms, the *matrix of interconnected spaces* highlights the problem of spatial differentiation and integration of spatial difference through connectivity, continuity and conversion, and hence its recognition as a heterogeneous spatial model. The approaches to this model, typically concentrates on mass as the key parameter. However, it could be unnecessarily reductive to assume just that.

Spatial lattices can perhaps be seen to provide an answer to the problem of spatial differentiation and integration of spatial difference. This type of spatial organisation often showcases refined relations between spatial organisation and environmental performance capacities. Once considered a part of a complex set of spatial features with reciprocal functional relations, the *spatial lattice* has now become synonymous with the screen wall. As a result, it has lost its three-dimensional quality in its reduction to quasi-two-dimensional form, similar to the vault. But in order to examine it in relation to the *matrix of interconnected spaces* it is necessary to follow the former conception. As a traditional architectural feature the *spatial lattice* has been adopted in many different parts of the world in response to the external conditions particularly offered by hot arid climate regions and particular eastern traditions of living. Its local adaptations have produced a great diversity of solutions with a number of combined physical and social effects. These include the Egyptian *mashrabīya*, originally a cantilevered space with a lattice screen usually made of wood, the Indian *jali* made of stone or brick, the Middle Eastern *claustra* or Turkish *cumba*, that is extensive both in the direction of exposed and enclosed space and offering multiple orientations as a result of the increase in surface area. The *mashrabīya*, or "drinking place", is considered a favourable room to occupy mainly due to its environmental modulation capacity, in particular the hygroscopic behaviour of the wooden screen in combination with ventilation that engenders evaporative cooling. As a derivative of the *niche* – a small cavity set within thick walls but in contrast formed independent of mass, the *mashrabīya* is a multi-functional element that participates in the production of a number of conditions by way of relating to external influences directly and indirectly as part of a spatial network. The multi-functional properties that arise from it were described by Hassan Fathy, who pointed out its ability to combine five functions: "controlling the passage of light; controlling the air flow; reducing the temperature of the air current; increasing the humidity of the air current; and ensuring privacy" [14]. Depending on the emphasis, the design can respond to different combinations or all of these factors simultaneously through subtle variations in size and shape of the interstices and balusters, the screen pattern and its spatial distribution, as well as through changes in surface area, also considering the material-specific parameters. When a stone-made *jali* for instance is incorporated in load-bearing massive walls, it takes advantage from the thermal inertia provided by structural thickness and porous material make-up. The benefit of the delay effect of thermal mass for maintaining a stable ambient temperature despite the extreme diurnal external temperature changes is an old knowledge. In spite of its lack of involvement in structural action, this feature deserves a great deal of attention in terms of its influence on microclimate and social circumstances. The Brazilian *cobogó*, devised by three Brazilian engineers in the early 20th century, is a modern and standardized interpretation of this feature that configures a porous ceramic screen wall with uniform openings, mainly considered for environmental regulation. Current related fascinations with pattern and ornamentation, which may deliver an equal level of observed geometric complexity or appearance (through customised, nonstandard, differentiated treatment), do not necessarily match the advanced capabilities that their precursors were and are able to deliver. As Michael Hensel and Achim Menges posited: if pattern is recognized both in terms of energy and matter and "even more so if one considers that in natural systems most patterns are generated by the interaction and mutual modulation of both energy and matter", thus if pattern is united with performance (self-organisation, behaviour, response) contemporary architectural design could point further in that direction [20]. From this point of view, there are traits in contemporary architecture that are present but not yet developed: Jean Nouvel's Torre Agbar (especially apparent in one of its intermediate forms during construction that shows the concrete structure undisturbed by the floor slabs), Louvre Abu Dhabi, or Barkow Leibinger's Campus Restaurant.

Another route to spatial differentiation and integration of spatial difference is facilitated by the notion of *interstitial space.* There are at least three conditions that secure its formation:

- Mass as a precondition for space
- Multilayer surfaces
- Spatial provision derived from structure

The former refers to the consolidation of space within the thickness of the wall or vault. In defining it, Peter Eisenman wrote: "Formerly, the interstitial as a formal trope was seen as a solid figuration usually known as *poché*. This was usually an articulated solid between two void conditions, either between an interior and exterior space or else between two interior spaces" [11]. One of the most extreme *poché* type spaces can be seen in medieval castles built on the principles of masonry fortification, with extremely thick structural walls that incorporate rooms surrounding a central courtyard or hall. Louis I. Kahn who had studied these described their power as arising, "strictly from … served-servant planning with great central living halls and auxiliary spaces nested into thick outside walls" [9]. Typically the served-servant planning corresponds to main and secondary zones of programme or use articulated in a one-to-one manner with figure-ground or void-solid configuration. The traditional *poché* wall incorporates a wide range of spaces classified by size and position including cavities, recesses, *alcoves* and *niches* that accommodate for a range of activities, unlimited to secondary space use. *Alcove* is a relatively larger space that expands the room into the wall unlike the *niche*, which is elevated above ground. They are both produced as a form of a nested vault set into the wall. Colin Rowe discussed the effects of the thinning of walls on space determined by mass, by comparing Friedrich Schinkel's Berlin Altes Museum and Le Corbusier's Palace of the Assembly at Chandigarh: "a conventional classical *parti* equipped with traditional *poché* and much the same *parti* distorted and made to present a competitive variety of local gestures–perhaps to be understood as compensations for traditional *poché*" [38]. Another type of *interstitial space* is revealed in between layered surfaces as in the vault-in-a-vault section of multi-layer domes (where distances permit). These have mainly been utilized as access routes for maintenance or service rooms, much akin to its modern technical definition for the gap in between floor levels that accommodate for mechanical installations. The missed potential of the *interstitial* as a social and political space was later to be recognized in contemporary architecture through another concept: *box-within-box* section. Jeffrey Kipnis introduced this concept as a special case of the interstitial or residual space that corresponds to the zones created at the intersections or overlaps in between volumes. Kipnis identified "InFormation" and "DeFormation" as two types of design techniques capable of generating such spaces. The contrast between the two was demonstrated by comparing the *box-within-box* sections found in Bernard Tschumi's Le Fresnoy and Bahram Shirdel's Nara Convention Centre. According to Kipnis the former relied on new technologies, innovative programming of events and the orthogonal geometry of modern architecture for generating *interstitial space* as the "new institutional form", while the latter instrumented new geometries (through topological and geometric operations including folding, morphing and transformation) to create "aesthetic form" for capturing the potentials of the interstitial as a trigger for events [26]. A third option was introduced by Eisenman who recognized the interstitial as a condition of process he termed *spacing*: "The interstitial, then, is the result of a process of extraction which produces a figural as opposed to a formal trope, and it exists as a condition of *spacing* as opposed to forming, as a presence in an absence, that is, between two conditions of figure as opposed to figure and ground" [11]. He emphasized the figure/figure condition as an alternative to figure/ground (as in the traditional *poché* or thickened wall) by comparing Piranesi's Campo Marzio (1762), a hypothetical map of Rome, and the Nolli Plan (1748), an actual depiction of Rome of the 18th century [10]. Again form becomes a central device, like in the DeFormationist approach, yet achieved by overlaid structural grids, lattice frames or interpenetrating volumes that activate space as a background for unfolding chance events. This shows that it is not only through mass that the interstitial can be activated, but also through space and structure, and furthermore it is not limited to a small number of uses.

A critical misconception is the incompatibility of spatial shell structures with heterogeneous models of space due to apparent constraints and contradictory structural and spatial objectives. It is of importance to revisit this common assumption and reconsider whether it can be generalized. A major spatial development that expanded the possibilities of vaulting began with shell structures, which reached its peak of innovation during the mid-20th century. Material constraints, difficulties in analysing and understanding masonry behaviour and challenges of construction had largely limited the vault to Platonic–Euclidean–Cartesian geometry and consequently to a homogeneous space defined by symmetrical form and uniform repetition as can be seen in churches that are central (Greek cross) or longitudinal (Latin cross), as well as axial-field arrays such as the hypostyle halls, like the prayer room of the Great Mosque of Córdoba. Central form indicated by traditional masonry was analysed by Evans, who following an intriguing line of argument discussed the poly-central properties that qualify some of the domical architectures. In so doing, Evans introduced an alternative view on the technique of conveying and realizing multiplicity, which was otherwise achieved by extension of the grid or uniform vault repetition [13].

By contrasting the dominant central form with the diversity of forms offered by shell structures, Giedion referred to the latter as “a new starting point for the spatial imagination” and identified it with the third spatial conception derived from new forms of Gaussian curvature and applied differential geometry [18]. In comparison to the popularity of reinforced concrete, the impact of progress in the field of structural masonry has largely remained modest and confined to explorations in reinforced and pre-stressed masonry shells. In spite of this, the continued influence of masonry innovation on architecture can hardly be ignored. The success of the architectural application of shell structures is often attributed to the properties of lightweight, self-support, spatial flexibility as a result of open-plan, transparency and spatial interpenetration that form a link between architecture and environment. On the other hand, the criticisms generally bring attention to the continued limitations that arise from the homogeneous treatment of form as a continuum of monolithic organisations, which lack spatial differentiation and lead to one single space. As a result, shell structures may be viewed to be incompatible with the heterogeneous spatial model of the *matrix of interconnected spaces*.

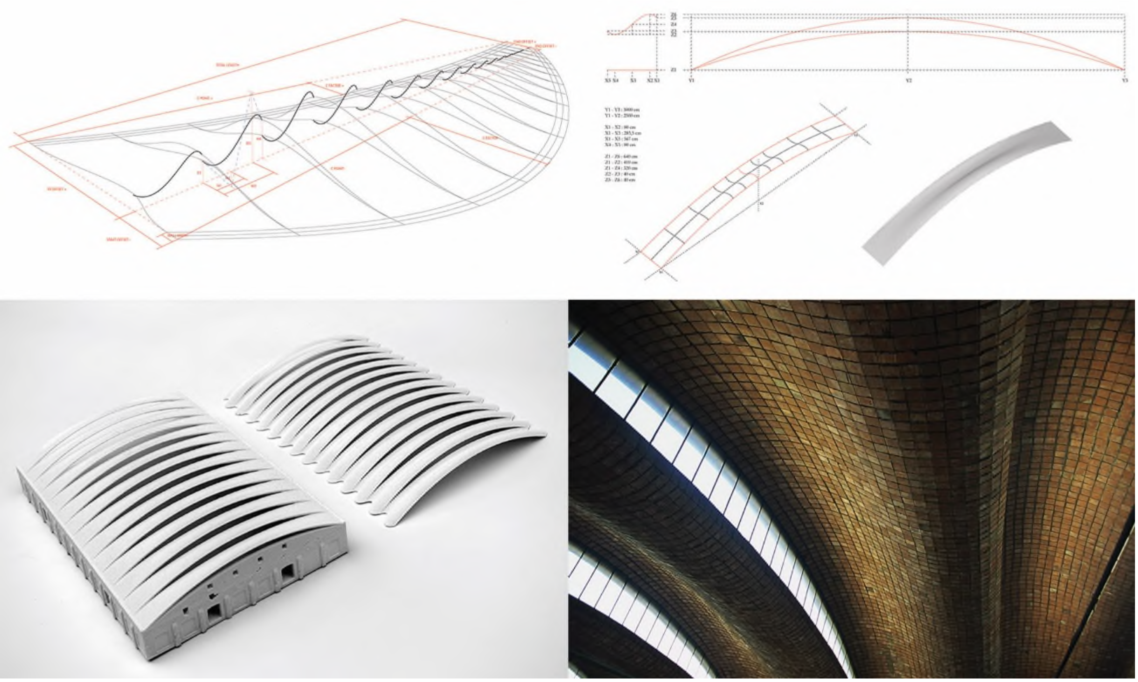

Figure 3 Computing Dieste’s Vaults: Workshop with the Auxiliary Architectures Studio, conducted by Defne Sunguroğlu Hensel, Oslo School of Architecture and Design (AHO), Oslo, 2010. The computational associative model and selected geometric variants of the Port Warehouse, Montevideo, Uruguay, 1979.

One limitation is the constraints on proportioning. One line of work focused on Dieste’s *Gaussian* and *Freestanding* vaults, and the possibility of liberating these from symmetry and uniform axial repetition. This was accomplished through computational associative modelling. The advantage of breaking symmetry comes from the ability for improved orientation of portions of the building volume and the geometrically varied vaults to environmental factors such as sun-path and angle, and prevailing wind directions, as well as the adaptation of the design to irregular terrain and building plots. Dieste's Church of Christ the Worker in Atlántida, Uruguay, consists of vaults and longitudinal perimeter walls that form continuous sinusoidal or undulating surfaces based on ruled surface geometry. Each vault segment displays a two-axial symmetry and a mono-axial directionality, and both properties limit the possibility of proportioning and orienting the building and its parts in a differentiated way. The associative model makes it possible to release form from these constraints, but at the same time needs to comply with the limitations of the structural system and the inherent relation between form, material and structure, in order to expand to a varied and locally specific space, structure and environment relation. It is essential to note that, dependency on formwork and consequently concerns about the economy of construction is a major reason for the uniformity that underlies Dieste's shells.

What other possibilities are open for expanding and enhancing masonry systems' capabilities for functional and adaptive integration?

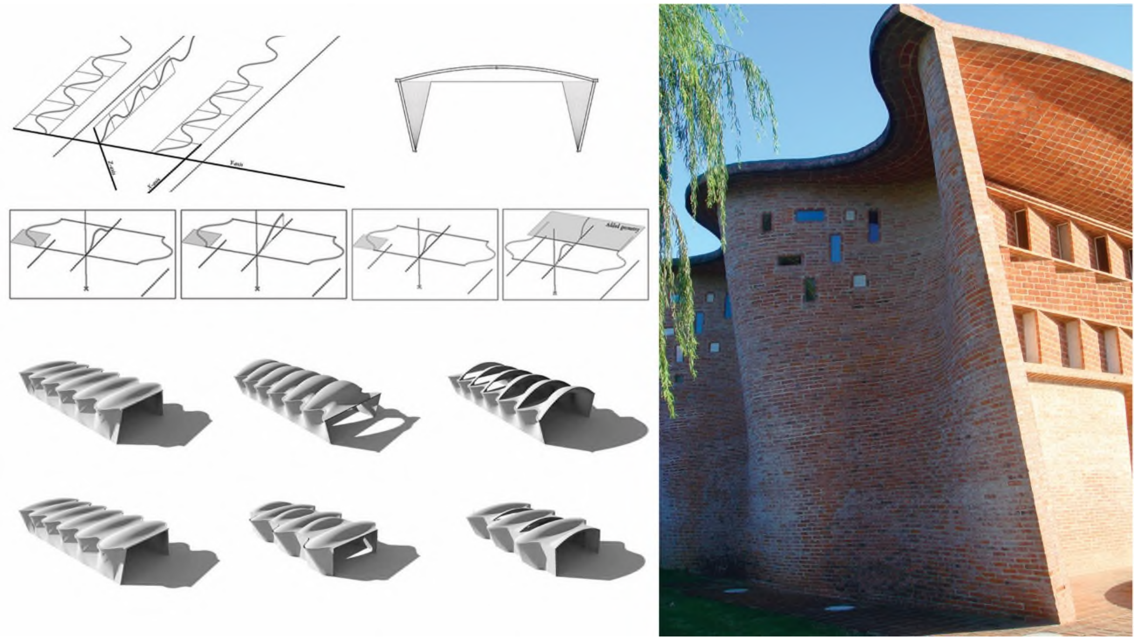

Figure 4 Computing Dieste's Vaults: Workshop with the Auxiliary Architectures Studio, conducted by Defne Sunguroğlu Hensel, Oslo School of Architecture and Design (AHO), Oslo, 2010. The geometric setup and shading analysis of selected geometric variants of the Church of Christ the Worker, Atlántida, Uruguay, 1960.

3 *Nested Catenaries*: a case-based material–structure–space–environment integral

The concentration on developmental constraints has engrained a general dispute over the integrative and adaptive capacity of masonry architecture and conformity over its limitations to homogeneous treatment of space. Here, it is argued that attention to developmental plasticity and the developmental role of structural hierarchy by foregrounding: new pathways derived from the integral relations not only of material and structure, but also of space and environment; flexibility in proportioning: reduced dependency on mass;

structural independence from symmetry; freedom from uniform repetition; geometric unconstrained from compression-only forms; and congruity with the heterogeneous spatial model of the *matrix of interconnected spaces* may lead to a view that suggests otherwise. This approach is demonstrated through various stages of development of the *Nested Catenaries* system. This is key for the continued build-up of the Condition-Effect-Property chart and for moving from a generalised prototype to individually varied locally specific design instances that are particularized at many system scales and spatial organisations, hence for the shift from general to project specific charts. The *Nested Catenaries* system displays structural hierarchy with recognizable structure over several scale levels with the advantage to yield multi-functional and adaptive properties. The initial phase focused on the structural properties of this thin unreinforced masonry shell system. To date *Nested Catenaries* has been taken through three stages of development. These include an undulating arched wall and a cavity wall that were built in a construction hall in Norway, and a *Nested Catenaries* shell located in Chile that is subjected to high seismic impact. The latter has withstood several earthquakes of magnitudes up to seven on the Richter scale. With the emphasis on the integral relations between material, shape and structure, this architectural approach to the complex problem of static indeterminacy specific to masonry facilitates a solution that goes beyond compromising light-weight-ness and allows building a thin unreinforced masonry shell with a uniform thickness of one brick layer that is laid flat. The manifold contribution of structural hierarchy has already been mentioned. The following focuses on its developmental role of functional and adaptive integration by expanding on the integral relations of material, shape and structure to include space and environment.

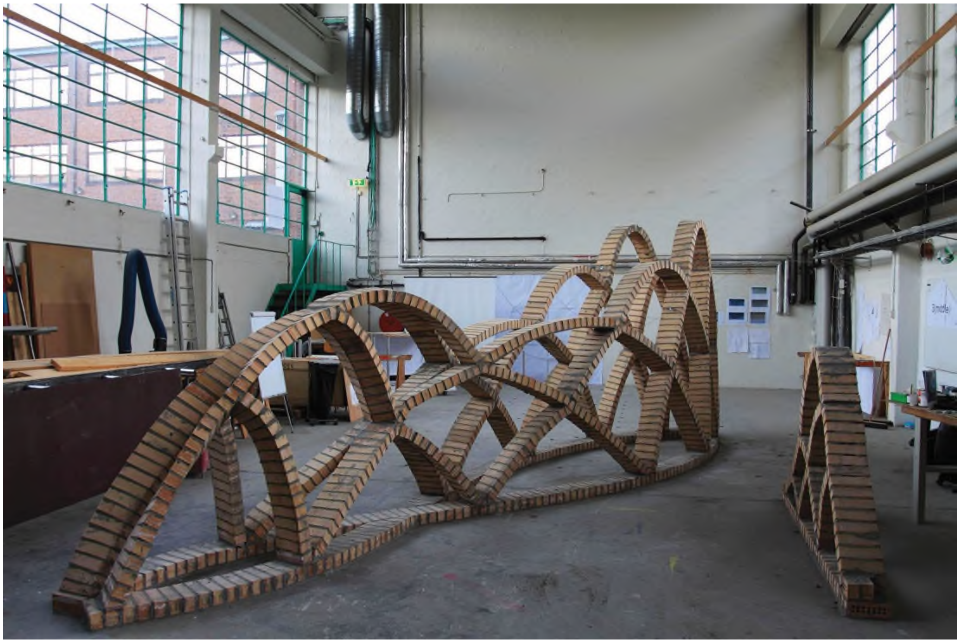

Figure 5 Nested Catenaries Workshop with the Auxiliary Architectures Studio, conducted by Defne Sunguroğlu Hensel and master mason Øyvind Buset, Oslo School of Architecture and Design (AHO), Oslo, 2010 [Phase 1]: An Undulating Arched Wall. The final self-standing structure. A symmetrical wall was built initially to provide mutual support and compensate for the lack of necessary structural calculations at the time. Upon removal of the formworks, used in the overall construction of 30 arches, the support was proved to be unnecessary and therefore removed. Its three-dimensional spatial organisation is contrasted with the smaller structure, on the right, showing a linear arrangement.

Figure 6 Nested Catenaries, conducted by Defne Sunguroğlu Hensel, engineer Guillem Baraut Bover and master mason Øyvind Buset, Oslo, 2012 [Phase 2]: A Cavity Wall. The design involved the use of three shells; two of which could be articulated independently while remaining in relation to the third shell above. These are catenary shells with synclastic and anticlastic surface curvatures connected with the shell above, which displays a transition from a concave to convex transverse section. The reason for two different base-shell solutions was to study their implications on construction and structural behaviour under non-uniform loads.

3.1 New pathways

A critical factor for any masonry structure is the treatment of the foundation and ground datum. As a consequence of the homogeneous treatment of masonry architecture, the irregularities of sites have typically been seen as disadvantages. Instead of being integrated in both the design process and the resulting architectures, they have been eliminated to create a homogeneous ground. In the next stage of the *Nested Catenaries* development, the intention is to move away from reinforced-concrete slab foundations towards a solution developed according to spheriodality or three-dimensional spatial concept of the vault, with a reduced environmental-ecological footprint and an improved locally specific response to the ground. This approach is based on a two-way feedback between the ground and the *Nested Catenaries* system, which expands on the form-finding process that is informed by both the physical properties of the ground and the reaction forces that translate the former into a topographical map. This can be considered either as tension-driven carving or a process of local strengthening, maintaining or adding material wherever necessary and useful, and in so doing creating a particular terrain form.

Formation and multiplication of ground, not only in terms of soil depth but also height, requires expansion of the vault's capacity to include live loads. The principle of 'merging', which implies transforming a single shell into fractal-like composition, can improve structural support due to increased redundancy via added structural hierarchy, but also offer environmental benefits when designing spaces for different climatic needs and conditions. Changes in density, distribution and scale of arches and vaults that increases surface area can serve to improve both structural and environmental behaviour. This can be further improved by the degree and type of enclosure, as well as at the micro-scale by utilising the porosity of bricks for thermal resistance or storage capacity. The latter is a direct product of a given brick's microstructure, porosity, density, moisture content and absolute temperature, as well as its thickness. Interestingly, if changes in thickness were the only variable, this would lead to an opposing relation between structural and environmental properties, but when considering a denser, merged, sponge-like materiality the structure will remain lightweight while acting as a thermal insulator. When considering resistance to heat, synclastic (surface with positive Gaussian curvature) surface curvature might be a better option for providing shade than an anticlastic shell, although surface orientation is one possibility for improvement. Exposed surface curvature is a much-used feature in traditional Islamic architectures with a multitude of domes adorning roof surfaces. Curvature provides self-shading of parts of the exposed surface at almost all times of the day.

Figure 7 Nested Catenaries Workshop at e [ad] Escuela de Arquitectura y Diseno – Pontificia Universidad Catolica de Valparaiso, conducted by Defne Sunguroğlu Hensel, engineer Guillem Baraut Bover and master mason Øyvind Buset, Open City, Ritoque, Chile, 2012 [Phase 3]: A Nested Catenaries Shell. This project was built as an extension to the cemetery of the Open City. The design constitutes 12 sub-shells of varying size, creating a volume of 162m³, each with synclastic surface curvature to retain the complexity of construction according to the allocated time.

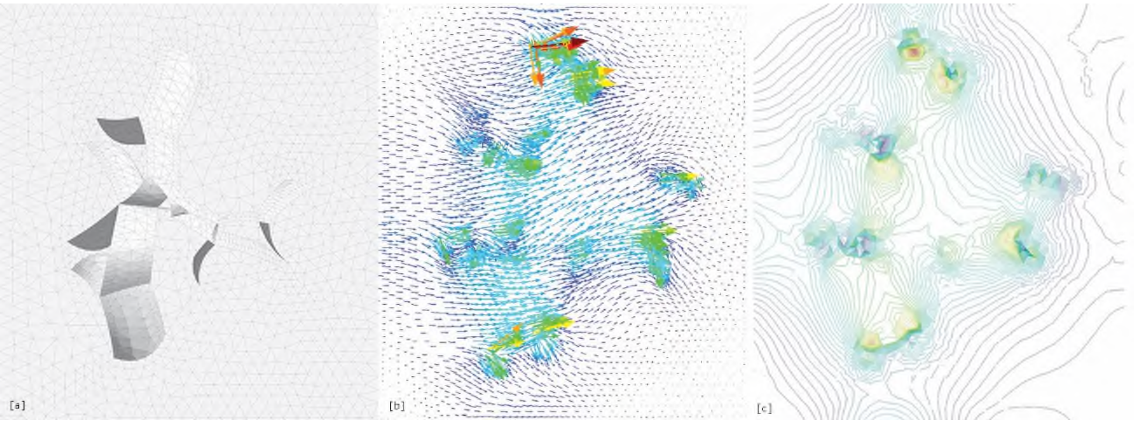

Figure 8 Finite element method can be used in the generation of terrain form with load bearing capacity. [a] the top view of the Nested Catenaries shell digital model, [b] the main axial forces in the ground slab formed during peak seismic loads in the x-direction, [c] these values are simulated with contour lines, representing specific axial forces. Due to the linear relation between the axial tension force and the foundation thickness, this contour map can be directly translated into a new ground form. Defne Sunguroğlu Hensel and engineer Guillem Baraut Bover.

The heated surface area is cooled through the absorption of heat by the cooler areas, thus improving thermal resistance. It is also possible that the same operates in reverse in more moderate climates to maximise heat gain during the cold seasons, where anticlastic form can further enhance this effect. In contrast to unreinforced masonry's limitation to compression-only forms, the possibility to work with anticlastic geometry as part of a wide range of possible shell forms, extend the choices available to design. Critical design parameters include levels of porosity across scales, as well as depth, height, width and orientation of shell curvature. Likewise, porosity on the scale of a single shell can imply creating a *spatial lattice* not unlike the *Mashrabīya* or Mogul *jali*. Arriving at such a level of extended functional integration, including structural capacity is the ambition for the next stages of development.

The slenderness of *Nested Catenaries* vaults can reduce impact on the ground to a necessary minimum. The design of the first *Nested Catenaries* shell focused on a particular three-dimensional spatial organisation of smaller interconnected sub-shells that are nested into two cavity walls. This produced features that evoke chambers, cavities, recesses, *alcoves* or *niches* as spatial potentials for differentiation, organised along the perimeter of larger spaces that arise from the overall arrangement of the system. These can include centric, polycentric, single- or poly-directional arrangements, spatial interconnections, and *interstitial spaces* between independent or interdependent parts of the *Nested Catenaries* system. This approach departs from the traditional *poché* in that it is not dependent on mass, and the more typical symmetrical and repetitive spatial model of arches and vaults organised along a central axis with adjoining secondary vaults to form arcades or chambers in the perimeter, as seen in churches or cathedrals. Instead the intent is high-level flexibility in proportioning and orientations that can facilitate the material and spatial organisation to be informed by local irregularities of the site and according to the particularities of environmental conditions and use requirements.

Unlike the typical limitations of shell structures to the production of homogeneous space, *Nested Catenaries* is built on the heterogeneous spatial model of the *matrix of interconnected spaces*. In this case, the possibility for spatial differentiation and integration of spatial difference through combined strategies of *spatial lattice* and *interstitial space* is enhanced with an additional principle: *spatial undulation*.

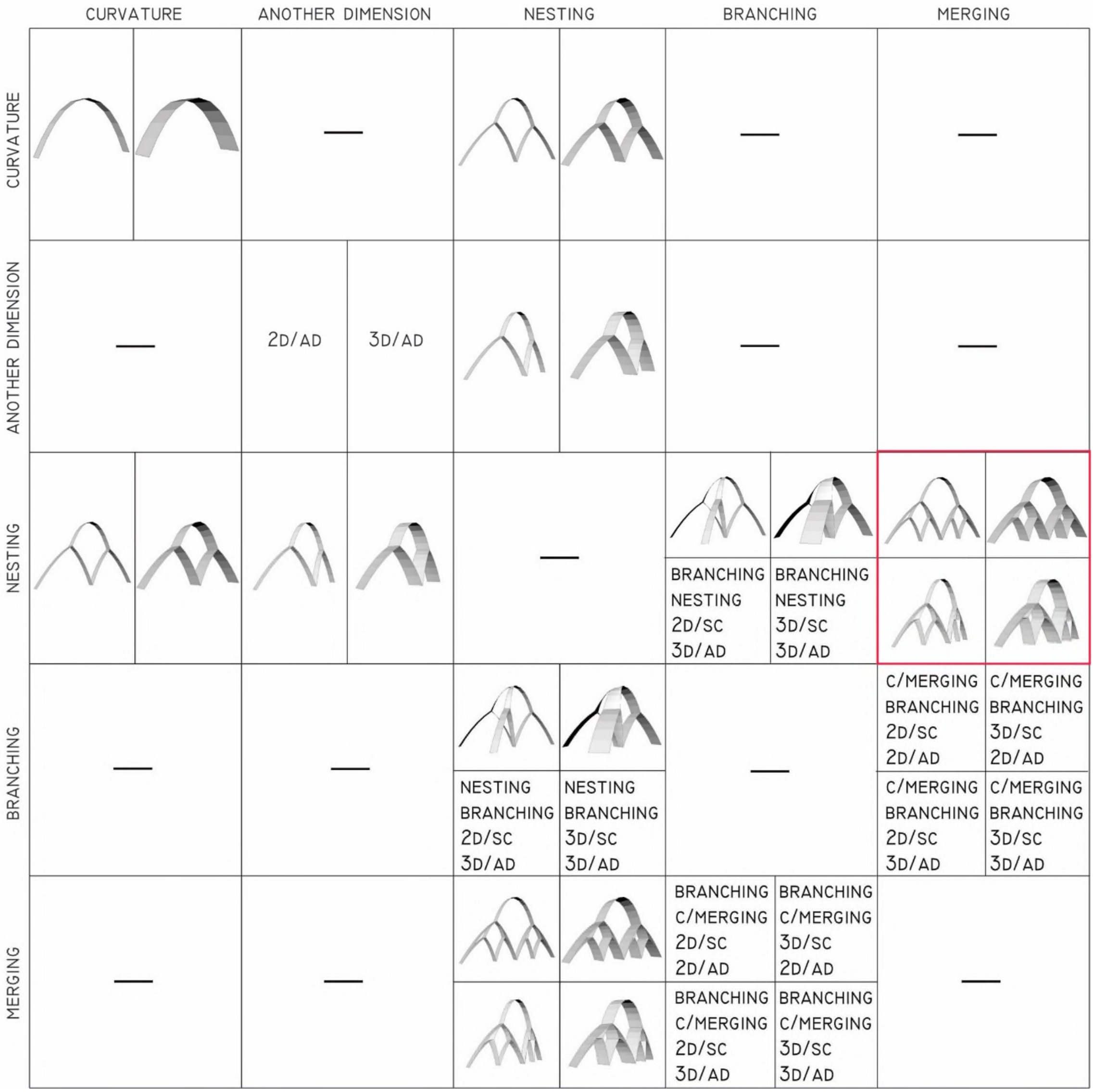

Figure 9 Principles Matrix. This matrix shows the different principles underlying the design system of Nested Catenaries. One of them is Merging, which is highlighted with red. This principle will be explored as a structural and environmental strategy.

Spatial undulation is an architectural innovation with a long history and record of great diversity of applications. Filippo Brunelleschi's Santo Spirito church is an early example for the utilization of this principle in the articulation of the perimeter wall to achieve structural as well as spatial depth and eliminate excessive use of material [2]. A more continuous and complex treatment is seen in Francesco Borromini's

San Carlo alle Quattro Fontane [17]. Later on Dieste implemented it in various projects such as the Church of Christ the Worker and Cadyl Horizontal Silo. The Baghdad Kiosk is one of the important references for the further development of the proposed heterogeneous model of the matrix of interconnected spaces. The Baghdad Kiosk of 1638-9 is part of the Fourth Courtyard of Topkapı Palace and assumed to have been constructed by the royal architect Hasan Ağa under Sultan Murat IV. It served different purposes over time ranging from leisure as summerhouse, to celebratory, library and today it is a museum.

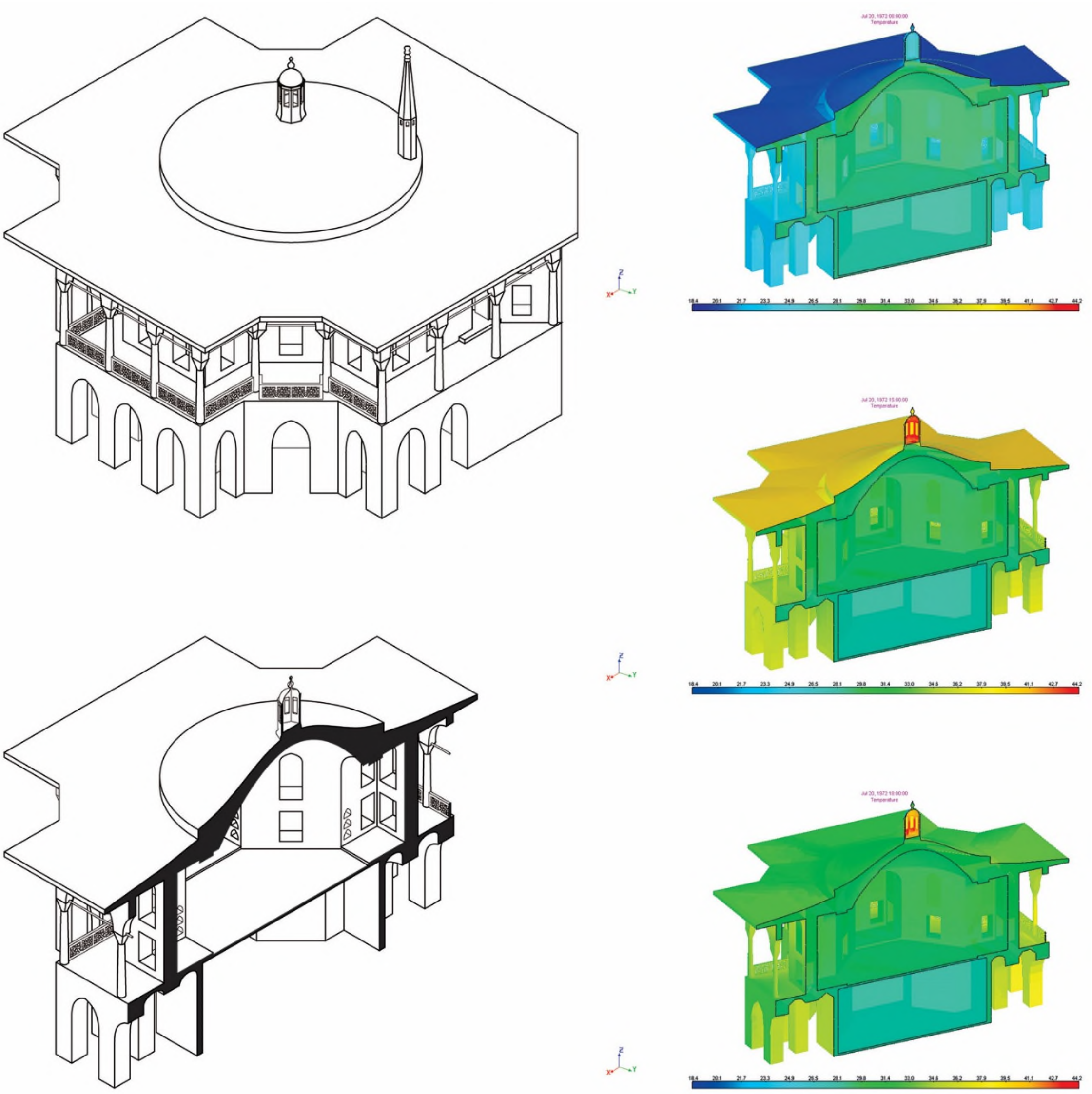

Figure 10 Baghdad Kiosk of the Topkapı Palace, İstanbul. Daily thermal variations in June at three different times. Thermal Analysis Courtesy RadTherm.

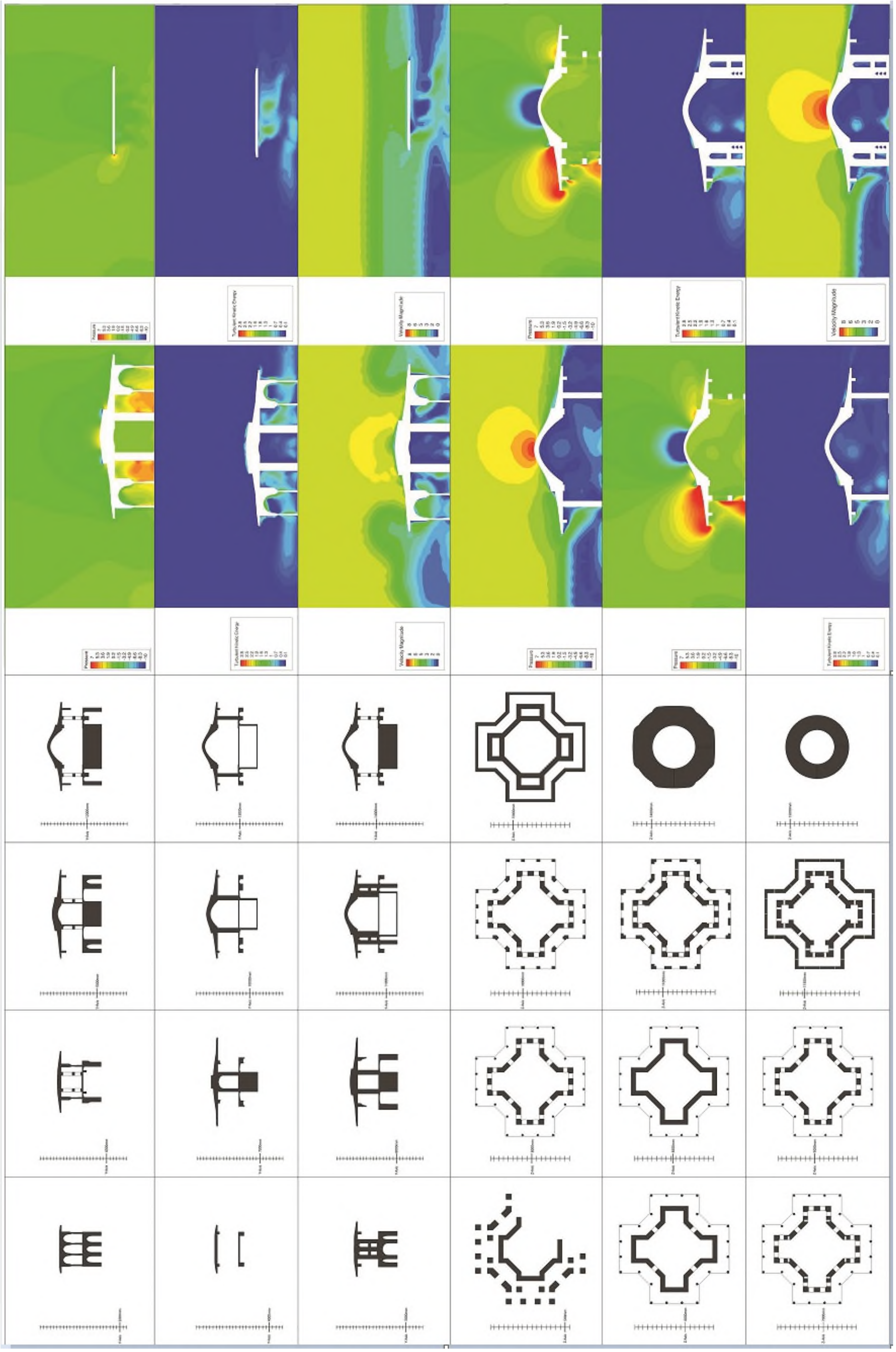

Figure 11 Baghdad Kiosk of the Topkapı Palace, İstanbul. Preliminary CFD analysis. Defne Sunguroğlu Hensel in collaboration with Prof. Dr. Øyvind Andreassen and Emma Wingstedt from Norwegian Defence Research Establishment (FFI).

It is a double-storey building, with the lower floor accessed from the lower-level garden with the upper-level access provided by the raised level of the Fourth Courtyard. The use of the basement has not been established beyond doubt. It is interesting to examine the Baghdad Kiosk as an instance of a unification of the central plan based on an octagonal layout with spatial undulation, and not only as a spatial but also an environmental model. Baghdad Kiosk as a free-running, low- or no-energy architectural solution to climate control through a heterogeneous spatial organisation was previously discussed elsewhere [21]. In its idealized form, this octagonal meander with right angles produces four iwans that protrude into the surrounding arcade creating a spatial continuity while producing local differences that arise from shape combined with orientation, and in the opposite direction consolidating into a centralized enclosed space. In reality, this axial symmetry is broken with an additional room on the south-eastern part of the building. Iwan, a vaulted room which incorporates divans or long - low sofas along the perimeter, can be seen as a derivative of the mashrabīya or jali but formed within the undulating wall rather than projected by way of a cantilever. In this context, a contrast with the “nearly decomposable” model of matrix of connected rooms described by Herbert A. Simon is of use [39]. Simon gives an example of a homogenous treatment, entailing a group of spatial units organised as three sets: defined by outer walls with perfect thermal insulation from the environment that divides into; cubicles through good but not perfect thermal insulators, which are; subdivided by partition walls with poor thermal property to form a further set of rooms. In this scenario an initial condition of thermal disequilibrium and local temperature variations will certainly give way to stable and constant conditions by converging on a single thermal state over time, independent of short-term and seasonal climatic changes. Unlike the thermally determinate model, in the case of the Baghdad Kiosk, environmental indeterminacy is incorporated as a factor of design through a reversed spatial–environmental model base that implements both the conditions of stability and variability in the solution. This gives rise to distinct spatial and temporal patterns of microclimate with prevalence of stability towards the centre of the plan, and variability in and around the iwans, characterized by the sensitivity to external changes. A series of sections taken from the preliminary thermal and air flow analysis shows thermal mass (not insulation/isolation) as the determining factor of stability at mid-range temperatures despite the diurnal fluctuations, and draws attention to the contribution of the roof canopy to mixing of air (from personal discussions with Prof. Dr. Øyvind Andreassen), hence improved air quality of the iwan, which adds to its more obvious roles of shading and keeping dry

The principle of spatial undulation will be reintroduced in the next stages of Nested Catenaries development as part of a larger set of combined principles that address locally specific material, structural, spatial, environmental considerations concurrently in an interrelated manner.

4 Summaries and Discussion

In line with the traditional emphasis on stability, strength, equilibrium and homeostasis, most attention has been placed on developmental constraints that underlie masonry architecture. Another explanation is the typical fall-back on design solutions grounded in functional hierarchical decomposition and decoupling from environment and ecology; reliance on mass; and homogeneous treatment of space due to the neglect of or inadequate, inappropriate response to problems of indeterminacy (static, environmental). This has resulted in the deeply entrenched yet erroneous idea that the integrative and adaptive capacity of masonry design is essentially limited.

The predominance of this approach in general has obscured the integrative and adaptive potentials of developmental innovation and variability, hence the attention on developmental plasticity. The latter leads to a far less explored area: the developmental role of structural hierarchy, which has been introduced initially by foregrounding the integral relations of material, structure, space and environment; reduced dependency on mass; heterogeneous treatment of space; and by considering indeterminacy (static, environmental) as part of the solution. Within this context, the dialectic (conflict resolving) development of masonry systems as a build-up of multi-functional and adaptive properties, adaptable for locally specific architectural applications, has been discussed and demonstrated through key historical examples and the on-going development of the *Nested Catenaries* system.

More recent works and research have their main focus on the application of the ancient material ceramics to standard building systems, contemporary modes of industrial production, computational fabrication and design methods and techniques, including the analytical approaches based on old theory, built with new parametric design tools. The shared vision holds that customized production that is available for most other materials is also available for building with ceramics without the negative labour-related time and cost effects. Moreover this relates to the aim to expand the repertoire of masonry forms and possible variations on both the level of a building element (façade, surface or envelope) and across generations – remember "versioning and patterning". These for instance are evident in the works of SHoP architects (290 Mulberry), Office dA (Witte Arts building and Tongxian Arts Centre), O'Donnell + Tuomey (2014 Stirling Prize winning Saw Swee Hock Student Centre) and in the research carried out by groups such as Gramazio & Kohler with their application of robotics, Ochsendorf and Block with computational graphic statics and more complex funicular forms using the Catalan technique.

Without doubt new technologies allowed for enhanced flexibility in the design space that arise from variation possibilities open to design. With its ability to cover a wide range of modifications with great ease through a long list of available operations, the advantages of modular organisation has strengthened the idea of modular design and construction in engineering and architecture. Modular nature of masonry seems very fitting and has been well recognized. However, explanations biased on the selective advantages of modularity, brings us back to the biased emphasis on constraints and the more restricted concepts and practical applications of structural hierarchy with emphasis on hierarchical decomposition (near-decomposability and ill-structured problems) [40, 3] and structural–functional congruence (Stewart Brand's extension of Francis Duffy's idea of the four-S: building layers based on "longevity of built components" to six with "site, structure, skin, services, space, plan, stuff" and later to seven layers by SLA) [7] as opposed to hierarchical integration and structural–functional incongruence. However, the explanatory power of this approach is limited to optimization where trade-offs are inevitable.

Ulrich Krochs asked: if "a modular design is less flexible than individual design with respect to the adoption of changing requirements as soon as a certain design space covered by the modular systems is left", so why modularity prevails both in technology and biology? He followed up this question with a compelling argument [28].

"In the realized modular artefact, a production module, or an assembly of several such, becomes a structural module. Consequently the structural modules coincide with the functional modules. The only reason for this congruence, however, is that the S-modules are designed as realizations of F-modules. Such a rationale of the design process is missing in the biological case: nobody has designed biological systems to have a 1:1 S-module:F-module map. The modules have evolved by processes of adaptation, response to constraints, self-organization, and so on. Since we are confronted with the empirical findings of distributed functionality and overlapping functional modules anyway, it is unsurprising that F- and S-modules of biological networks are often found not to coincide. To the contrary, cases where F- and S- modules coincide require explanation. In such cases one must identify external causes or internal constraints that “adjust” the system in the direction of such congruence of S- and F-modules” [29].

This brings us back to the realization that discussions about functional and adaptive integration also need to take into account the role of developmental innovation and variability, and therefore developmental plasticity and structural hierarchy with attention to hierarchical integration and structural–functional incongruence (thus to one–to–many relationships [1:n] as opposed to one–to–one [1:1]).

5 Conclusions and Future Research

Historical and developmental information has been introduced as an operative context for the development of material-based structural systems with multi-functional and adaptive properties that can be adapted to locally specific conditions. This subject has been advanced on the basis of the biological concepts of developmental plasticity and structural hierarchy, and by looking at innovation and variability in masonry systems. The intention was to move away from the commonly perceived constraints to integrative potentials of design derived from developmental plasticity. Consequently the need for considering the developmental role of structural hierarchy in view of plasticity was proposed. This was pursued by way of mapping historical and developmental information to identify some of the key principles, effects, processes and models that underlie inventive change and variability derived from the integral relations of material, structure, space and environment. In the evolution of masonry design, one challenge that has shaped these relations in particular ways is the drive towards reduced dependency on mass. It was shown that reduced dependency on mass does not necessarily generate property conflicts and therefore integrative disadvantages or delimitation of space to homogeneous treatment. In contrast to the general design response to developmental constraints, developmental plasticity brings attention to the direct effects of material and environment, hierarchical integration and structural–functional incongruence. *Nested Catenaries* was shown to move in that direction with initial focus on some of the material, structural, spatial and environmental potentials that arise from their integration.

Developmental plasticity is not only implied in the continued build-up of *Nested Catenaries’* multi-functional and adaptive properties but also in the move from a general prototypic system to one, which can be informed in relation to usage and specific local settings by utilising all levels of the structural hierarchy. One of the challenges lies in modelling and mapping complex historical–developmental information to access unexplored developmental pathways, which makes the implementation of *MatOnt* critical. The *MatOnt* capabilities of indicating property conflicts inherent in the development of trends and processes (complex causality) that operate across scales, and potential principles, effects that can be used in the resolution of conflicts without compromise, makes *MatOnt* a powerful design tool. One of the next lines of inquiry is to build *Nested Catenaries* information as well as the historical data into the *MatOnt* environment. Further research will continue on the progress of advancing on the explored and new developmental pathways and the move from the design of a general chart to locally informed Condition–Effect–Property charts. This may contribute to the compatibility of spatial shell structures with sustainable architectural solutions not only in terms of the minimised and diversified use of materials and sensitivity to environment but also through the possibilities that arise from the heterogeneous treatment of space. The latter, for instance, can address the current discussions about how natural variability of the indoor climate in free-running buildings can be considered as advantageous when viewed from the adaptive comfort approach

[35], and in relation to standards such as the ASHRAE Adaptive Standard 55 and European Standard EN 15251.

The improved ability to manipulate material information across the structural hierarchy can have wider significance for sustainable design that is far-reaching without being limited to the world of masonry. This developmental approach implies that in cases where design exhibits plasticity, it also shows signs of integrative and adaptive advantage. The question as to how far design can be analysed, measured, evaluated and advanced in terms of this property and what kinds of statistical techniques may be applicable still stands and requires further detailed inquiry. Next set of research will further expand on the studies of the integral relations of material, structure, space and environment responsible for the generation of adaptive design capacity, also applied to architectural systems based on other material groups such as wood while extending the factors considered. The implications of this developmental approach to local specificity for design and sustainability will be further examined.

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