Digital Vernacular:

An integrated approach to the design and fabrication of unreinforced stone masonry architecture.

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Abstract

This research is an attempt to reawaken the use of stone as a building material from the everyday and the mundane into an architectural language which takes into account the physical properties of the material and respects the cultural significance of stone architecture while imprinting a contemporary zeitgeist with the aid of computational tools and robotic fabrication.

The research evolved from three premises and beliefs: 1) The need of an integrated approach in the design and construction of architecture. 2) The need for a contemporary and exciting language for stone masonry structures. 3)The belief that digital design and fabrication technologies can help in the reinterpretation of local traditional skills and construction techniques such as stereotomy which are becoming redundant due to high labour costs.

In order to manage such propositions, the author chose a material and fabrication design approach; where the material properties and fabrication limitations are of outmost importance in the overall methodology, thus integrated in the early stages of the design.

For the research to be more tangible the study was placed in a strong context of stone masonry architecture, more specifically the southern Mediterranean region. This context also gives an interesting feature when juxtaposing strong local building traditions and vernacular architecture with high-tech open source fabrication technologies.

Keywords:

Stone, Stereotomy, Digital tectonics, material computation, IPD, Robotic Fabrication, Vernacular Architecture, Compression only, thermal mass.

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1.1 Why?

1.1.1. Disassociation between design and construction.

The starting point of my journey goes back to when I graduated and started working in the architecture profession. My personal experience made me realize how much the profession which was once considered to be the mother of all arts, has departed away from craftsmanship and materiality.

Kolarevic argues deeply, about this discontinuity between the act of designing and the act of building. He highlights the turning points from when the medieval “arkhi”-“Tekton” (Master Builder), was once in constant verbal direct dialogue with the material, builders and construction process on site, to the contemporary office designer where the information in the form of abstracted images and documents, is no longer a dialogue but a top down series of orders. One of the main reasons for this disassociation is that since the enlightenment, architects such as Leon Battista Alberti no longer wanted to be linked to the crafts but rather with the artists, which had a higher social status. The 1988 exhibition *Deconstructivism* at the MOMA also emphasized clearly this disassociation. SHoP Architects stated their opinion about the work exhibited there, as narrowing down of the profession to "composers of broken volumes, masters of surfaces (of buildings on paper and of paper itself), amateur philosophers” (Holden 2012, pg33)

1.1.2. The implications of efficiency and standardization

Apart from the abovementioned factors, the post WW2 construction boom and innovations in new materials meant that the architecture office had to find new means how to keep up with such demands. This emphasized on the need for the modernist paradigm of efficiency, standardization and mass production. This method brought a serial approach to architecture design and construction, which lead to a bigger miscommunication between the involved parties. Nowadays, for clarity of liabilities all parties are disassociated form each other by legally binding documents. This setup makes the individual sharing the information liable for any shortcomings done by others; therefore sharing of drawings is not recommended in the profession. The construction drawings are redone for every stage of designing, bidding and constructing, which is excruciatingly inefficient and leads to an architecture of lesser quality. (Kolarevic 2003)

Professional practice suffers a lot from this miscommunication. The opportunity to be creative shrink miserably and in most cases, the only way to keep a project going is to agree with budget cuts which ultimately detracts from the building performance and aesthetic qualities.

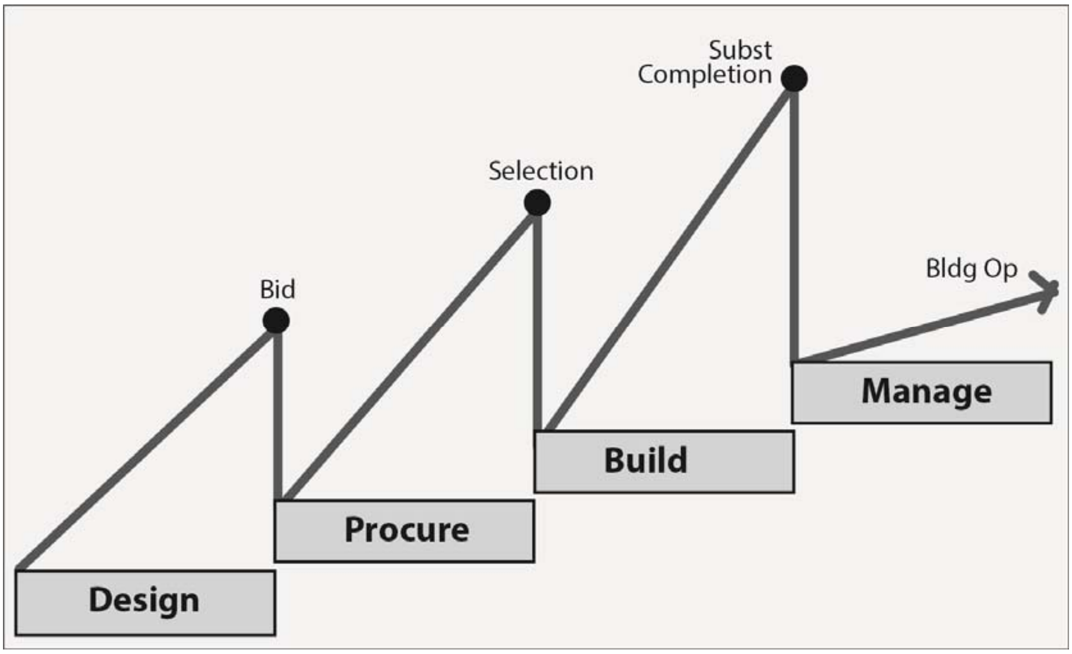


Diagram showing loss of communication between building phases. Information on the vertical axis vs time on the horizontal axis. Image source: (Kolarevic 2003)

Standard contemporary masonry building in the southern Mediterranean region, Malta. Image source: Author

1.1.3. The need to find a contemporary regional architectural language in stone

Due to the fact that stone is natural, durable and a readily available in most parts of the world, it has been chosen by most civilizations as the main building material in architectural history. Until recently, it was much more difficult to transport stone from quarry to building site. For this reason, whole towns and monuments were built with the same type of stone in the vicinity which developed a regional cultural landscape characterized by the material itself, embedding in that particular stone a strong cultural significance. (Siegesmund and Snethlage, 2012)

Grand Harbour Region, Malta. Image source: Author

Sassi di Matera, Basilicata, Italy. Image source: Author

Much of the design efforts in the past two centuries have been mostly focused on expanding knowledge in 'modern' materials such as concrete and steel, pushing stone as a performative building material to the side. With the spreading of a dominant modernist idea throughout the whole globe, this local cultural landscape is recently becoming more and more appreciated. In places where such cultural landscapes are very dominant, there is a common sense of nostalgia for the past where the act of building was deeply rooted in one's own identity and tradition. (Siegesmund and Snethlage, 2012)

From simple observation of historical structures around the world, one could easily notice that the contemporary technique of using stone is much less expressive and exciting then in the pre-industrialised era. There seems to be a longing by society for an architecture that is more sustainable and culturally appropriate. There is a huge discrepancy when comparing what is desired to what the construction industry is offering. Natural stone is mostly used nowadays as either a cladding material or for straight load bearing walls in combination with other materials. I believe that with this standardized masonry unit, a lot of craftsmanship has been sacrificed for the sake of efficiency, which has lead to a system that is very limited in terms of flexibility for architects to be creative and explore new possibilities.

The current modus operandi in construction suggests that stone is too labour intensive, therefore expensive to be manually crafted. The traditional technique of drawing, cutting and assembling custom stone blocks to form complex structures (stereotomy) is getting redundant at a very fast and alarming rate.[1] Due to time constraints and high labour costs, stone nowadays is no longer seen as a moldable material which can be well crafted into a system which takes full advantages of its properties, but as a standard unit to be simply assembled on top of each other.

[1] Projects such as 'Progetto Lithos-Centro Studi Sulla Stereotomia nell Mediterraneo' highly emphasize the issue of this dying craft in our times.

1.2 Premise

1.2.1 Digital fabrication and integral design as a tool to enable the reinterpretation of traditional crafts and construction technique.

"In the future being an architect also means being a builder" Kolarevic 2003, pg57

This paper embraces Kolarevic's idea of 'information Master builder' where the design information is also the building information generated from a combination of bottom-up and top-down approaches depending on what is desired and the construction limitations. It is essential that the material properties and fabrication techniques are integrated at the earliest stages of the design process. As SHoP architects also state, this method could lead in solving the problem of this "self-imposed exile from the essence of the craft." (Holden 2012, pg32). The manipulation of local material with CNC and robotic arms that are not affected by huge amount of data, complexity and fatigue enables mass customisation where the modernist idea of economy of scale and repetition becomes absolute in terms of manufacturing. There is a new possibility to explore innovative free form design while adhering to construction logic at the same time. (Gramazio F, Kohler M, Oesterle S 2010) This offers vast opportunities in relation to aesthetics and building performance, still yet to be discovered.

"The architect as a creator-craftsman finally having the chance to overcome the fifteenth and sixteenth century schism between intellectual and manual labour, as well as the nineteenth-century gulf between automatic mechanization and poetic creation" (Spiller 2008 pg192)

2.1 How?

The study will formulate from the limits and opportunities in the choice of material and fabrication technique. More specifically, robotic fabrication techniques and the physical and mechanical properties of limestone will be researched and used in combination to investigate an approach for a renewed tectonic expression in stone.

As stone is a very well known building material, history and vernacular architecture will be considered as the main teachers in this matter. The task here will not be to emulate what is already known but mostly to understand the way stone was used and reinterpret and enhance it with the wide range of state-of-the-art computational and fabrication tools. The main material characteristics studied are; Compressive and tensile strength, Thermal absorption, Permeability, Porosity and workability. In order to present concrete findings, the study will be placed in a southern Mediterranean context. While particular material characteristics might vary slightly, the methodology is still relevant in other regions with similar climate conditions and material characteristics. The structural strategy researched will revolve around the assumption that stone has no tensile strength. For this reason, the theories on compression-only structural systems in equilibrium (funicular structures) will be investigated with special focus on thrust network analysis and Spring-Particle systems. This section will be a combination of literary research and hands on experiments in setting up computational models, which would simulate material behavior.

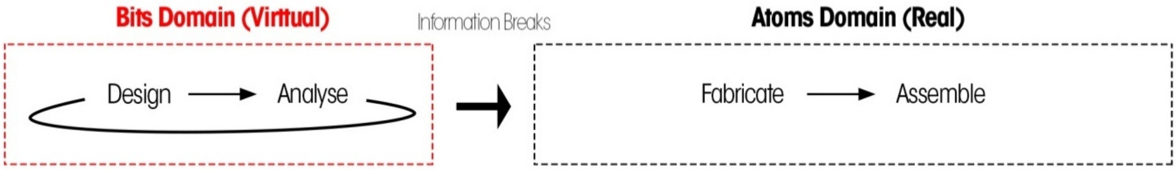
The second part of the research will be focused on the fabrication limitations and other on-site processes that could enhance the performance of the architecture in question. The research will benefit from open source information regarding recent innovations in digital tools and new ways in using the full potential of robotic fabrication. (scanning the stones, cutting stones from the quarry, nesting, assembly of parts, cutting size, tessellation of surface, geometry limitations,) The Robotics Lab in Rotterdam, managed by Jelle Feringa will also be used to run physical experiments in parallel with the digital to validate the whole research and show that the stone components can be fabricated.

The literature review and hands-on experimentations will give the information needed for the development of a computational setup, were site parameters, structure, programmatic needs and fabrication limitations will be integrated. The two parts of the study will eventually combine to show how these findings could be used in a hypothetical design project.

3.1 Materialism through the digital tools.

Digital fabrication processes should not be seen only as a tool to fabricate artifacts from a digital file. For architects to exploit the full possibilities of digital fabrication, it should be seen as a bidirectional link between the realm of bits and the realm of atoms.

Existing model



Material and fabrication Integration model

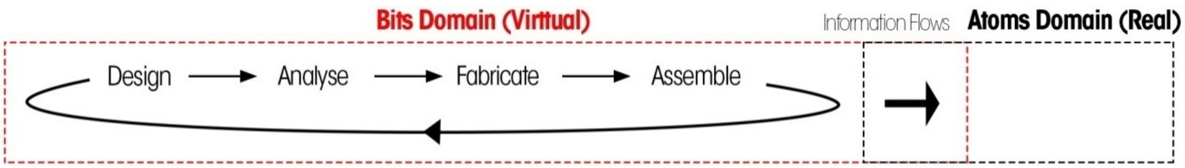


Image Source: Author

In parallel to these innovations in technology, the work of contemporary philosophers such as Deleuze, Guattari and DeLanda brought the idea of material morphogenesis in which by 'teasing' a particular material a form emerges out from the properties of the material rather than being imposed on it. (DeLanda 1998)

This combination of technical and philosophical works brought the idea of digital tectonics and material computation in architecture, where the act of making and material characteristics are transliterated and embedded in a digital model. This makes it much faster and cheaper to simulate and iterate such analog processes, thus enables a bottom up morphogenetic design approach where the material is 'teased' through a series of iterations and feedback loops.

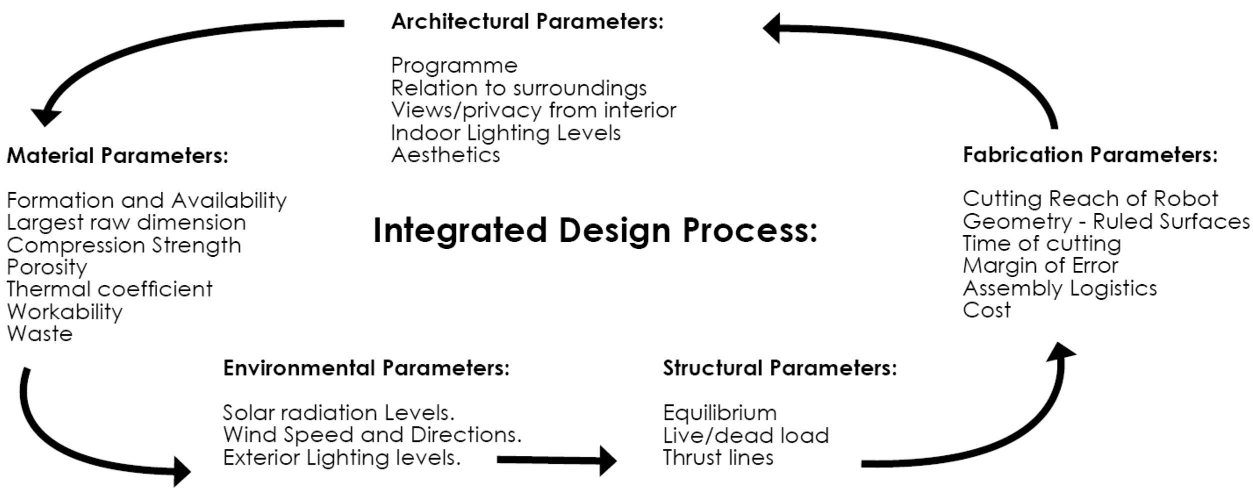
> “We are beginning to recover a certain philosophical respect for the inherent morphogenetic potential of all materials. And we may now be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create.”
> (Menges,A 2012) Quoting DeLanda[2]

[2] ‘Material Complexity’, in Neil Leach, David Turnbull and Chris Williams (eds), Digital Tectonics, John Wiley & Sons (Chichester), 2004, p 21.

In order for this methodology to work on an architecture scale, all the partners involved need to be integrated into one singular digital environment which enables new synergies. This same bidirectionality can be seen in the Sagrada Familia, Barcelona. In an interview, Mark Burry states how the craftsmen and builders' ability affect the design rather than the designers asking for the builders to do the impossible. This technology made them closer to how Gaudi would have worked with his craftsmen and builders on site. (Burry , 20012) .[3]

"In a strangely paradoxical way, the world of the analogue can be brought closer to the hand of the designer by a mastery of the digital. This current art, may be viewed as a highly iterative and synthetic process that oscillates between the words of the digital and the physical on a linear trajectory towards a built outcome" (Phil Ayres 2008)

This new thought on digital morphogenesis, share the same iterative process of vernacular architecture, which is a series of improvements and adaptations throughout generations to get the best result (structural, cultural and environmental) within local conditions. Rivka Oxman states, "Vernacular architecture represents the essence of material technologies in being a pure and, generally, a direct expression of the structural and constructional potential of the material." It is in how the material is being processed and manipulated with traditional crafts which "elevates the material to the technologies of material systems" (Oxman 2009). In a way, these performance iterations in vernacular architecture which would otherwise take generations to modify, can happen through simulation in a fast digital environment.



Conceptual diagram of an Integrated design methodology setup.

Image source: Author

[3] https://www.youtube.com/watch?v=pPdCIunpoH4

4.1 Formation

Building stones can be classified under three categories; igneous, sedimentary and metamorphic. In the case of the Maltese limestone, the stone is of a sedimentary nature; meaning that it has been formed from a deposition of naturally weathered pre-existing material. These particles come into contact with calcium carbonate which originated from shells and skeletons of once living sea organisms. Sand grains and pieces of shells acted as a nucleus and concentric layers of calcium carbonate forming ooliths.[4] The carbon dioxide in the sea reacted and slightly dissolved the calcium carbonate from the ooliths which when redeposited on the sea bed created a binding effect which cemented the ooliths together in one layer. This process repeated over and over again for millennia under the pressure of the sea and weight of further sedimentation above. One of the main features to consider when building in stone is that as a material it is heterogeneous and its properties vary along the different strata and within the stone bed itself due to faults occurring at a later stage. Compressive and tensile strength, Porosity, Density, Colour, Surface finish and workability are all heterogeneous characteristics in stone. (Cachia J, 1985)

From the main geologic formations in Malta, three main strata are used in the building industry; The Upper Coralline Limestone, The Globigerina Limestone and the Lower Globigerina Limestone. The soft yellowish Globigerina limestone (known locally as ''Franka'') is the most favorable from the three strata due to its fine ooliths which gives it a durable and relatively homogeneous properties and a highly workable structure; which makes it easy to extract and process into any shape. (Cachia J, 1985)

4.2 The implications of Material properties.

4.2.1 Structural properties - Compression and Tension Strength.

Like any other stone, the tensile strength of globigerina limestone is negligible when compared to its compression strength. Due to the stone's heterogeneity, the assumptions made in modern conventional structural design and analysis does not hold. For the material to be used effectively, rather than focusing on the flexural strength of stone, the structural has to be in equilibrium and in compression only. As Heyman and Huerta explain, this equilibrium is solely derived from the geometrical shape of the

[4] Name derived from the greek oion- egg and lithos - stone clearly depicting the nucleus inside a concentric layer.

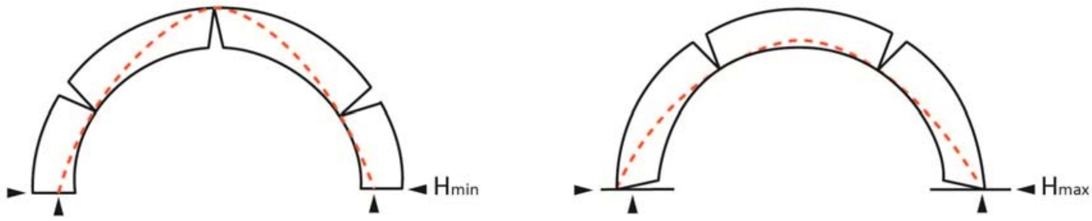
building. (Huerta, 2001) This reminds us of Deleuze and Guattari's theories on material morphogenesis that a material is teased for a form to emerge rather than imposing a form on a material. There is a huge number of historic examples of such structural systems were by means of corbelling or arching, the stones seem to float in mid air.

"The most subtle and exquisite part of Architecture... is the formation of every sort of Arches and vaults, cutting their stones, and adjusting them with surface artifice, that the same gravity and weight which should have precipitated them to the earth, maintain them constant in the air, supporting one another in virtue of the mutual complication which links them" (Vincente, 1707)[5]

Lady Gordon Chapel at Ta Braxia Cemetery designed by Gothicists Messers Pearson and executed by the illustrious Emanuele L Galizia in 1893, Image Source: Edward Said

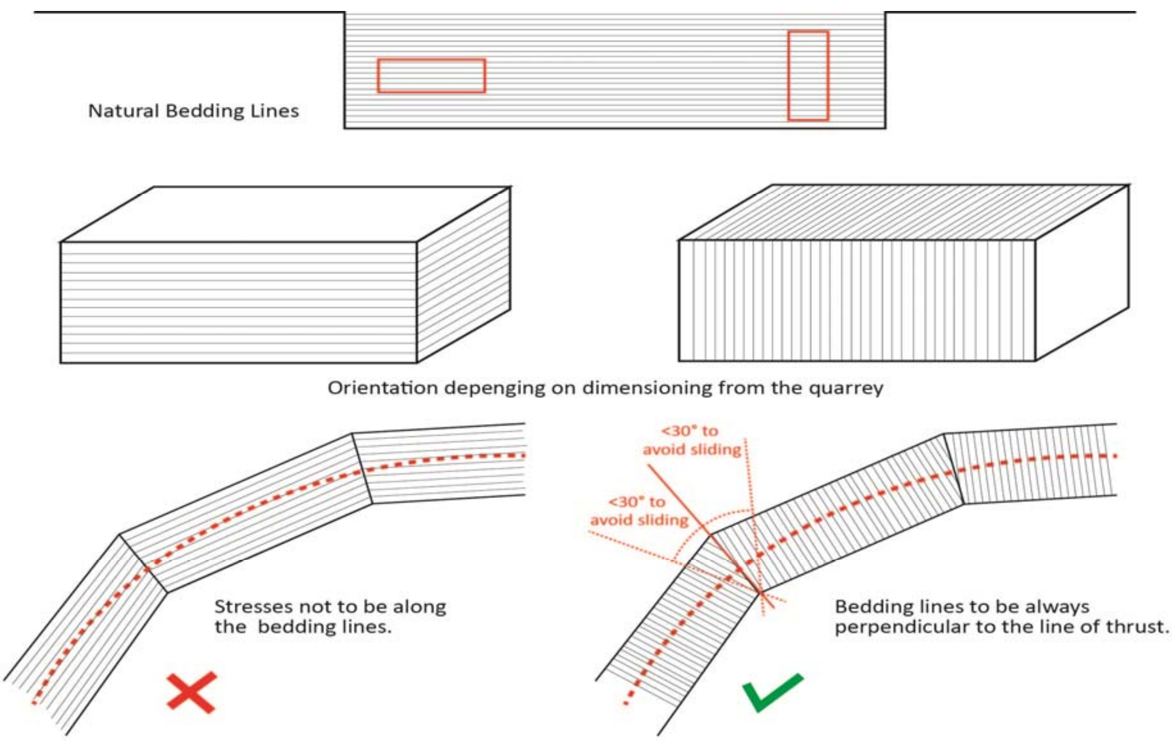
[5] Quoted in the paper; Huerta,S Mechanics of masonry vaults: The equilibrium approach, Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães, 2001

As Heymen further explains, for a system to be in equilibrium, the arch/vault section should hold the thrust line (lines of force) between its boundaries. If the line of thrust exceeds the material section, hinges are created in the system to find a new equilibrium. If more than three hinges are formed, the structure transforms in a mechanism and will collapse. The design will achieve the maximum safety for a specific load case when the central line of the structure and the line of thrust coincide. To increase the safety and stability from point loads and movement of the abutments, the arch/vault has to be thickened to include the thrust lines of other particular loading scenario. (Heyman, 1995)

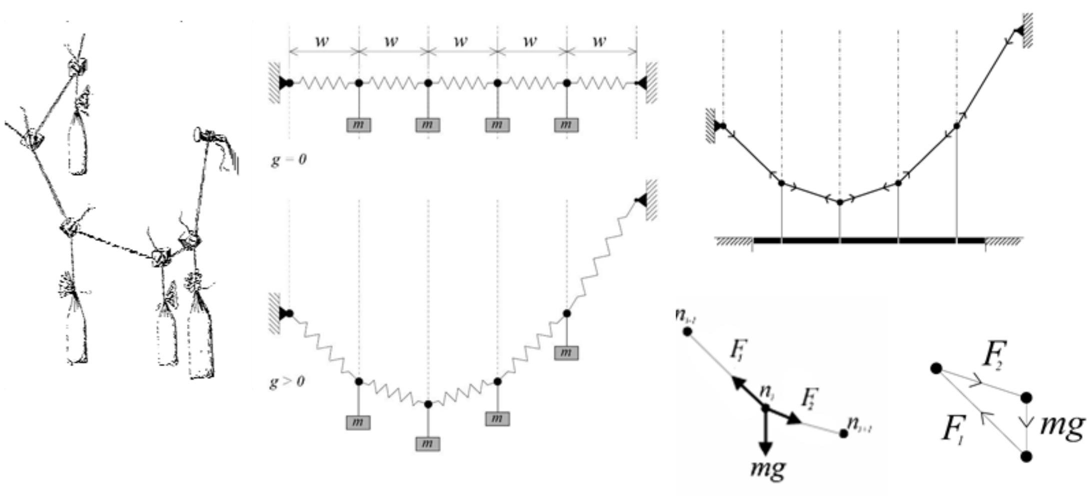


Semicircular arch under its own weight. a) Minimum thrust; b) maximum thrust (Heyman, 1995)

With regards to material, the Equilibrium approach make two assumptions; that failure by crushing is negligible and that friction between stone elements is high enough to avoid sliding. (Huerta, 2001) Apart from these assumptions, when building in stone, it should be placed so as the compression forces in the stone is perpendicular to the direction of the sedimentation of the bed it was extracted from. Therefore, in an arch the bedding lines should be at right angle to the thrust line to reduce the risk of delaminating and failing due to the different layers of sedimentation.



"As hangs the flexible line, so but inverted will stand the rigid arch" (Huerta 2001)



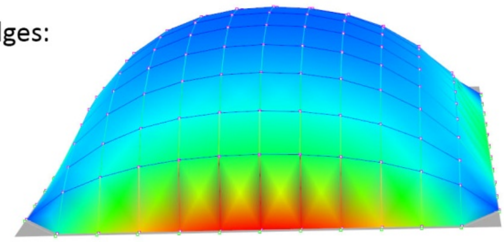
Left) the idea of using string and loads to create funicular systems (www.gaudiclub.com)
Centre) Springs used to simulate funicular systems in computation.
Right) Graphic Statics method. Image source: Harding and Shepherd (2012)

Calculating the thrust line seamed complex until 1670, when Hooke discovered that it can be found by inverting a hanging chain. This knowledge brought the idea of formfinding with the help of hanging chain models. By manipulating the anchor points, length of the chain and the imposed loads; the form could be varied to satisfy architectural spatial desires. After 1879, Graphic Statics[6] was also used for the precise calculation of thrust lines with the use of force vectors. These methods were vastly used by structural artists such as Antonio Gaudi, Eladio Dieste and Heinz Eisler. (Pedreschi R, 2008) One of the main drawbacks in finding the thrust line in this method is that it can become very tedious process for 3d networks. Furthermore, iterations and improvements of the structure meant that the analogue process had to be done all over again. (Block, Rippmann, Lachauer, Van Mele, 2013)

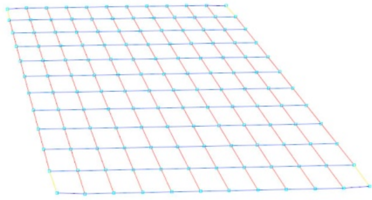
The BLOCK research group at ETH has developed a computational tool which overcomes these intricacies and opens up possibilities for asymmetric funicular structures, which are more flexible in respect to site and architectural needs. Apart from the above benefits, RhinoVault also enables interactivity between form and force diagrams which gives an overall flexibility to the final outcome. This tool was used to explore and develop a series of structural typologies that are possible in a compression only system. (Block, Rippmann, Lachauer, Van Mele, 2013)

[6] Graphic Statics as the name implies, is a method of calculating statics with the help of vectors. In concept, the resultant force vector has to form a closed polygon, which results in a structure in equilibrium.

Shell with fixed outer edges:

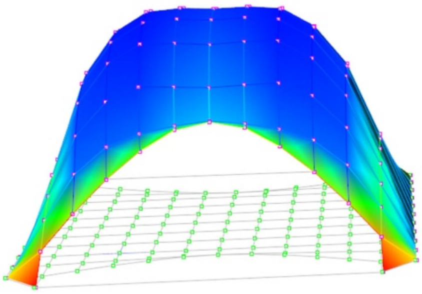


Form Diagram



Force Diagram

Shell with two open edges:



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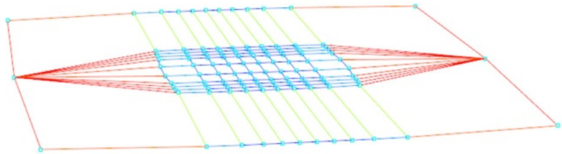
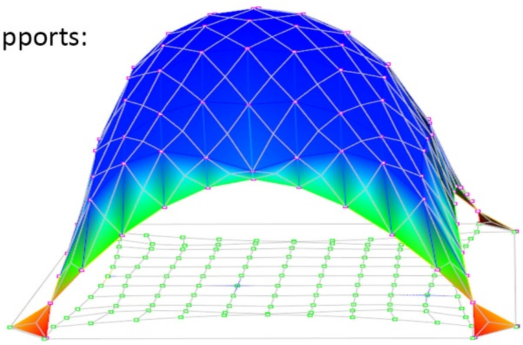


Force Diagram

Shell resting on four supports:



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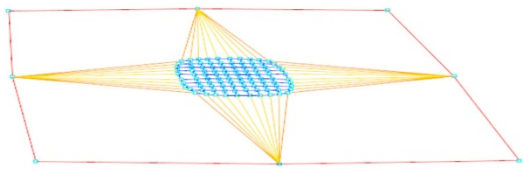
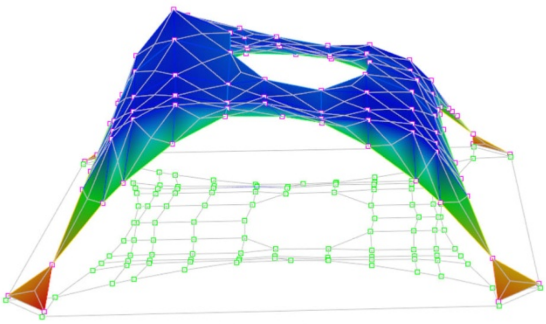


Force Diagram

Shell with aperture:



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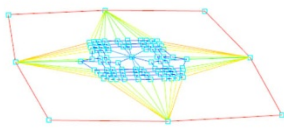
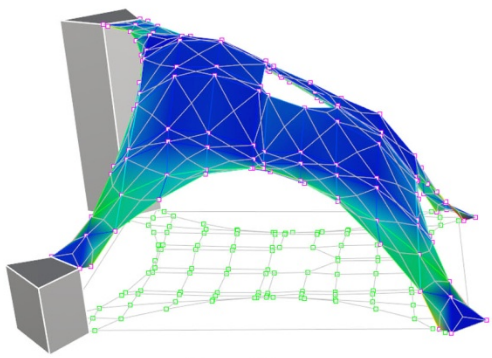


Force Diagram

Shell with aperture and
assymetric supports:



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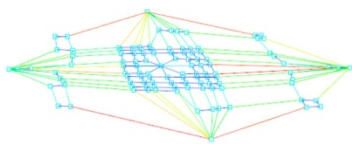
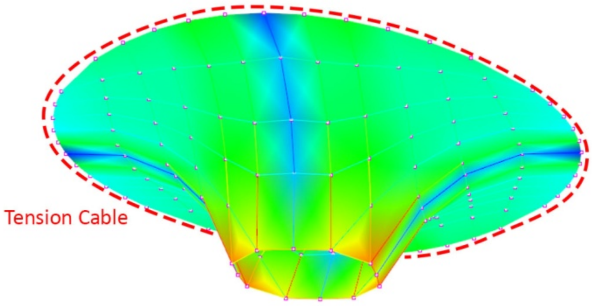


Force Diagram

Shell with two fixed outer edges:



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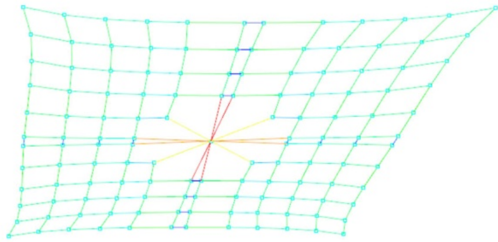

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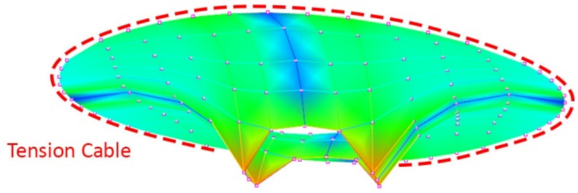

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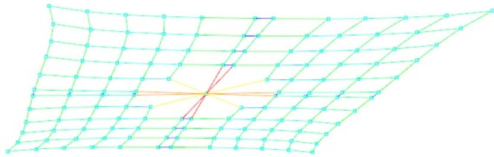

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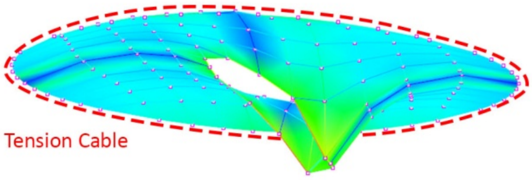

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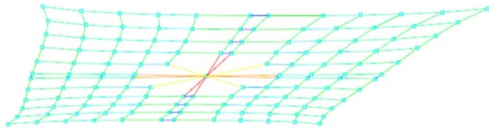
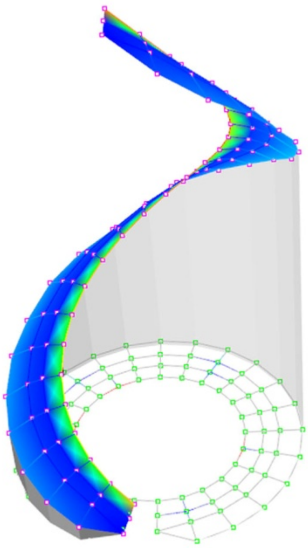


Force Diagram

Guastavino Stairs:



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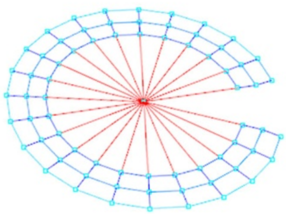
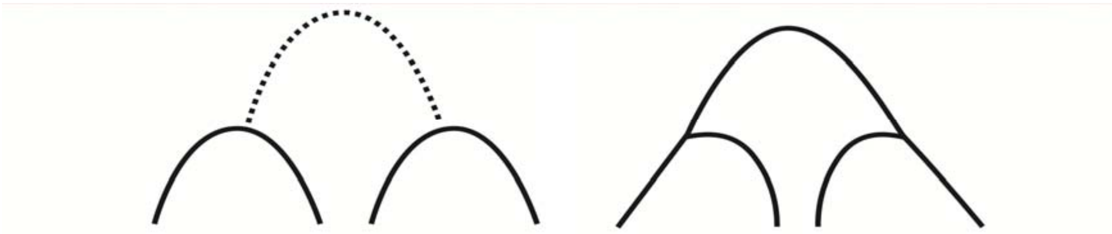


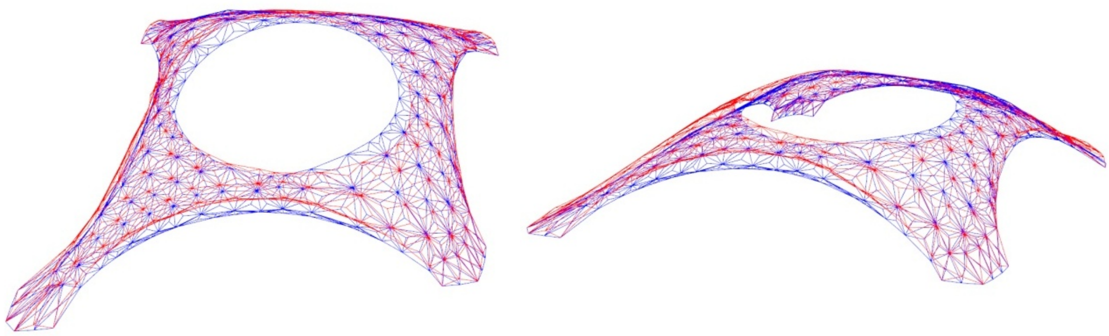
Force Diagram

Although RhinoVault resulted being very precise, it only allows the calculation of one shell at a time, which makes it impractical for the calculation of multistory structures. An attempt has been made to stack multiple shells on top of each other by transferring the loads imposed by the top shell to the shells below. Further research into the way RhinoVault was setup showed that this translation of forces was only possible for vertical loads. The horizontal component of the reaction forces at the supports has to be zero which is a condition that never happens in compression-only shells. (Block, Rippmann, Lachauer, Van Mele, 2013)



Left) Shows the possibility of RhinoVault to compute singular shells independent from each-other.
Right) Shows the need for a system to be able to compute two or more shells influencing each other.
Image source: Author

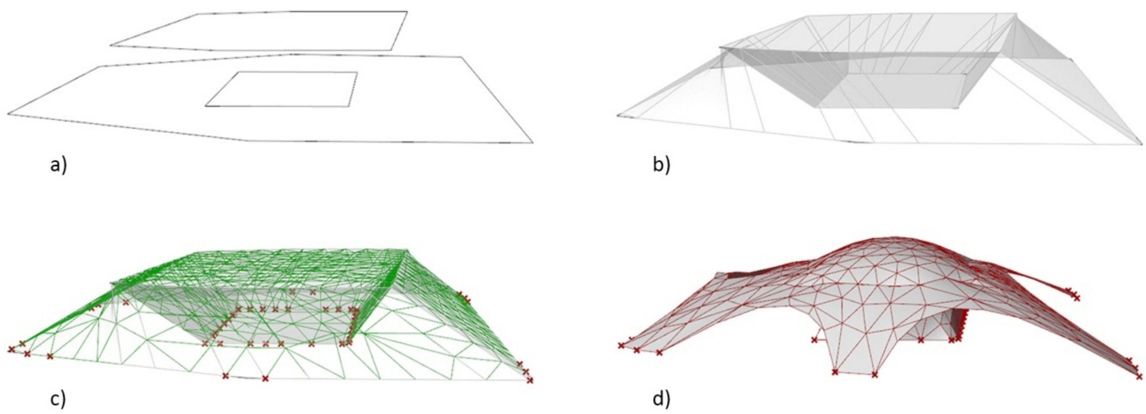
For the purpose of this research, a system had to be developed in order to connect two or more shells to interact and influence each other depending on the loads imposed. The most logical and intuitive step to solve this issue was to setup a digital simulation of a hanging chain model and apply it to a multitude of chain networks attached together. A Particle-Spring system was used in a Live Physics engine[7] fully embedded within Rhino3D Grasshopper. This choice enabled the possibility of an interactive simulation, where parameters such as spring lengths (lengths of chain segments), loads and anchor points could be varied and results simulated in real time. This approach brings the designer closer to Gaudi's method while sparing the time consuming process of physically building the chain models. (Attar, Aish, Stam, Brinsmead, Tessier, Glueck & Khan, 2009)



Diagrams showing a comparison of results between Kangaroo in red and RhinoVault in blue.
Image source: Author

[7] Kangaroo is a free Live Physics engine developed by Daniel Piker for the Rhino, Grasshopper.

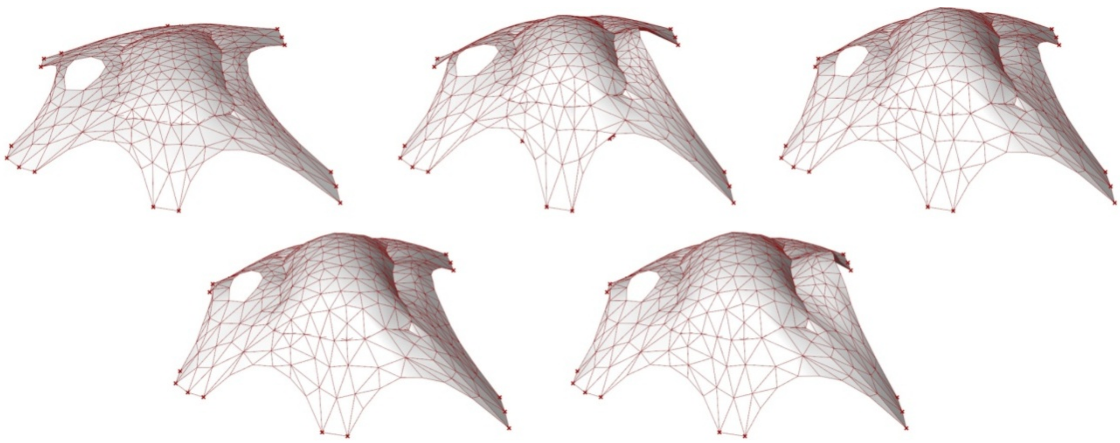
As for most digital simulation processes, the Particle Spring system works by subdividing a continuous curve or surface into a number of discrete elements. These discrete elements can be seen as the stone voussoir elements in a masonry shell. For the setup to work, a predefined flawless mesh has to be drawn and later translated into springs with specific rest lengths and loading for simulation. The main challenges to set up this multiple shell interaction arise from the edges where the shells meet. This branching creates a non-manifold situation[8] which is not recommended in 3D Modeling. (www.rhino3d.com) This situation makes it difficult for mesh vertices to match, resulting in punctures in the shells if not fixed manually. To enable an iterative process, a parametric model had to be setup to resolve these issues. The diagrams below give a explanation of the system.



a) Input Curves controlling exterior and connection edges b) Creation of a simple B-Rep geometry
c) braking down the surface into a closed and welded mesh. Mesh edges in green and structural supports marked in red d) Mesh edges transformed into springs (red) and simulated under a uniform distributed load with a negative gravity (flipped). The two connected shells influence each other.
Image source: Author

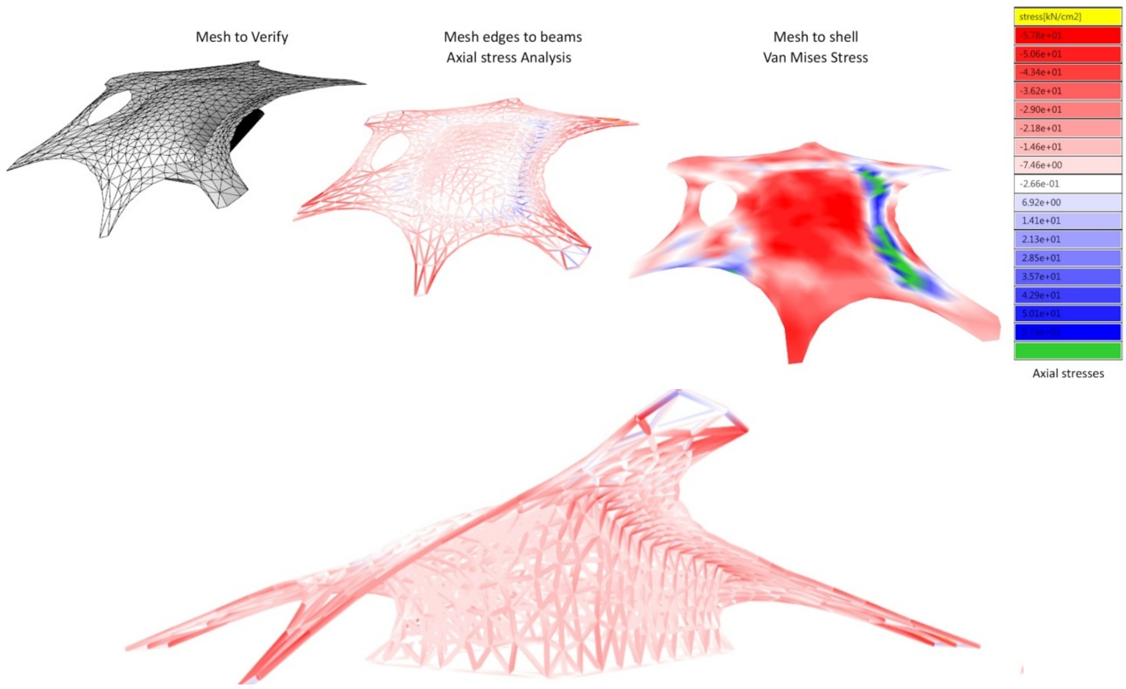
This setup automatically redraws the mesh when the other and the non-manifold edges are moved around. This gives the ability for the designer to move the support conditions freely and explore new possibilities that fit better to the design intent. This system also allows for the creation of perforations in the shell that would be beneficial for lighting and ventilation purposes. Further parameterization was done in order to freely influence the form by changing the rest lengths of the springs and the applied loads. This was done in order to give the designer a stronger say in this bottom-up process and be able to implement architectonic and spatial decisions in the form finding.

[8] A non-manifold edges arises when more than two faces share the same common edge. In reality situations like these never happen because of the fact that no plane has a thickness of zero.



Five different options with varying spring lengths and load cases. Source: Author

Due to the combined bottom-up generation and top-down decisions, the resulting thrust network has to be validated in order to find out if it is still a compression only system. The generated geometry underwent a finite element analysis in the same digital environment. In this section, the designer could understand what the implications of their decisions on the structure were. Where analysis shows signs of tension forces, it means that the actual thrust network has deviated from the generated one that would require a thicker section, hence more material. Here a conscious decision by the designer has to be done in order to find balance between material efficiency and architecture intent. If the shell is desired to be maintained as thin as possible, post tensioning cables could also be integrated by embedding them in the joints between the elements. (Betchthold, 2009)



Screen captures from FEM Analysis showing compression in red and white; tension in blue and green. Load Case: UDL of 5KN/m^2. The Extensive blue and green area coincides with the area where most tweaking has been done to address architectural intents.

Main structural parameters recapitulate:

Material to work in compression only.

The thrust network should always pass through the section of the material

(preferably the central 1/3 of the section)

Compression stresses right angle to the sedimentation

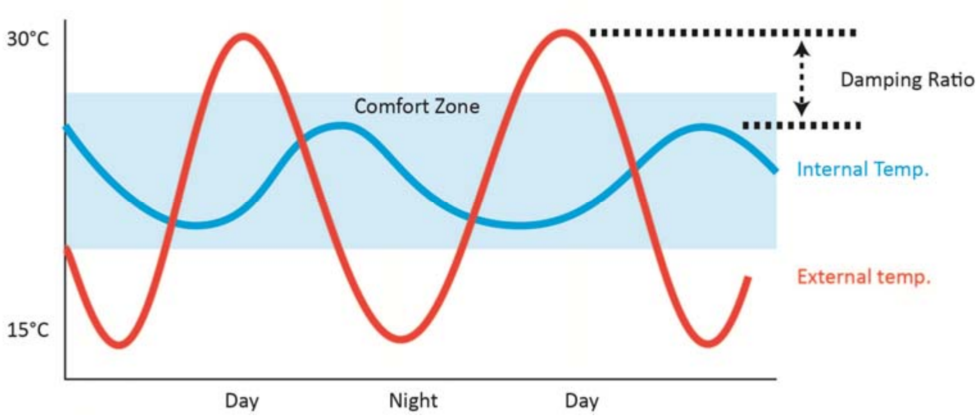
Proportion of weight applied on springs should be equal to the proportion of design (and analysis) load.

4.2.2 Environmental properties of Stone

4.2.2.1 Thermal Mass

As a building material, one of the main advantages of stone is its high thermal mass. Stone's rate of heat release and absorption (thermal conductivity W/m.K) is also relatively in phase with a building's daily heating and cooling cycle. These characteristics made stone ideal for it to be used to keep indoor temperatures steady from fluctuating in extreme temperatures. This has been discovered and used throughout the ages as a passive heating and cooling strategy in masonry vernacular architecture. All across the southern Mediterranean region, one can easily notice the thick masonry walls used in order to keep indoor climate as close to comfortable temperatures as possible. The south and west facing walls are particularly thicker than the rest as they receive more solar radiation, hence more material is required to store the energy.

The settlement of Sassi, in Matera, Italy showing the intensive use of thermal mass to reach comfort level throughout the hot and cold seasons. Source: Author



Thermal mass benefits in relation to indoor/outdoor climate. Source: www.greenspec.co.uk

The amount of energy stored in a particular material can be found with the simple formula;

$$Q=MC\theta\Delta$$

where Q is the amount of heat energy absorbed or released in Joules (J)

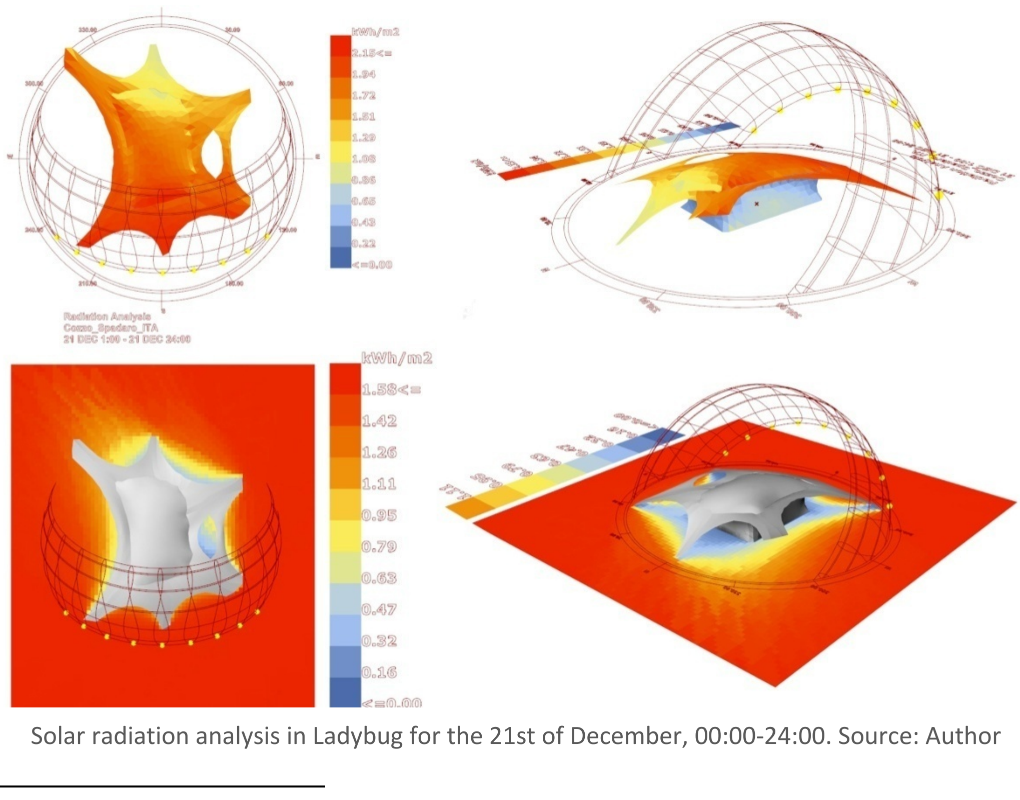
M is the mass of the material in Kg

C is a constant number referring to the specific heat capacity of a material J/Kg.

and $\theta\Delta$ is the change in temperature of that particular mass of material with that specific amount of energy change Q. (www.greenspec.co.uk)

In the context of this research Q is derived from solar radiation hitting the outer surface of the stone elements. Recent advances in computational design tools and other physical computing technologies have made it relatively simple to precisely quantify the total amount of solar radiation for a specific time frame on a specific surface in a specific location. Digital weather files (.wea file format) containing specific geographical and meteorological information about a specific site could be downloaded for free [9] and used as input for solar radiation analysis.

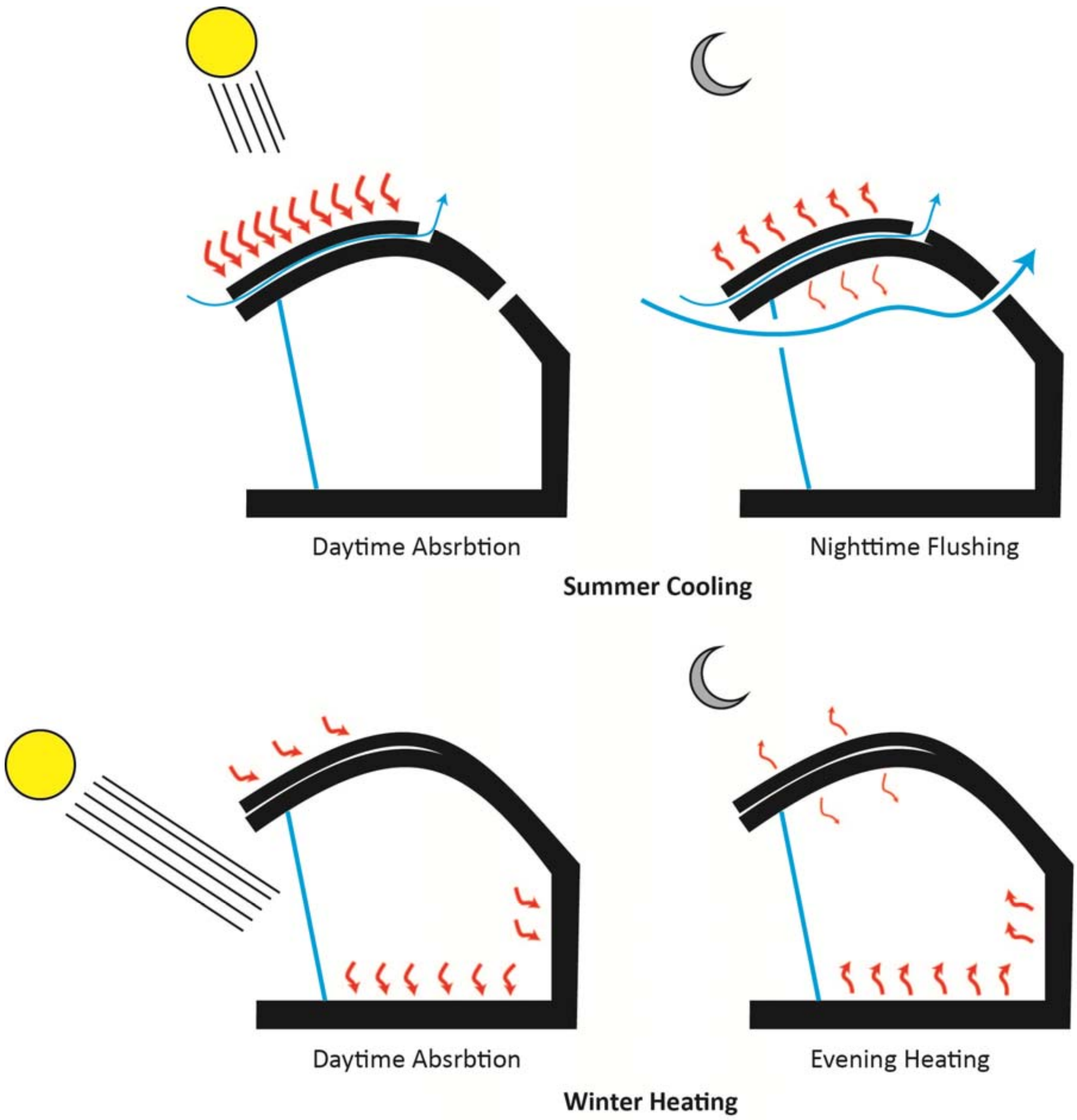
For this research a free and open source climatic plug-in[10] was used to analyze the solar radiation of a given surface in a specific geographical location in the same digital environment. This gives the possibility for the designer to make iterations and improvements to the design based on quantified information. This gives the designer knowledge on what is the best orientation and external surface form.



Solar radiation analysis in Ladybug for the 21st of December, 00:00-24:00. Source: Author

[9] U.S Department of Energy, EnergyPlus Energy Simulation Software.

[10] LadyBug plugin for Rhino Grasshopper, developed by Mostapha Sadeghipour Roudsari.



Thermal mass Strategy. Source: Author

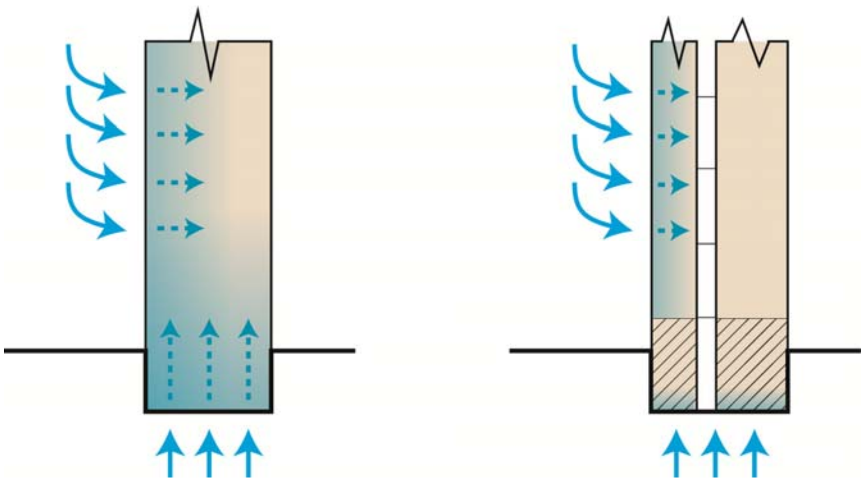
In this case, location and orientation are not the only important factor. The material surface texture and color play an important role in the absorption of the incident rays. A pure black surface will have an absorption coefficient of one whereas white will have a coefficient of zero. The average absorption coefficient of light colored limestone is found to be 0.35 [11].

As most literature and experimentation suggest; for this strategy to perform well, it is of most importance that the mass is well insulated from the external temperature. This will reduce heat absorption in summer and keep heat inside during winter. (Asquith and Vellinga, 2006)

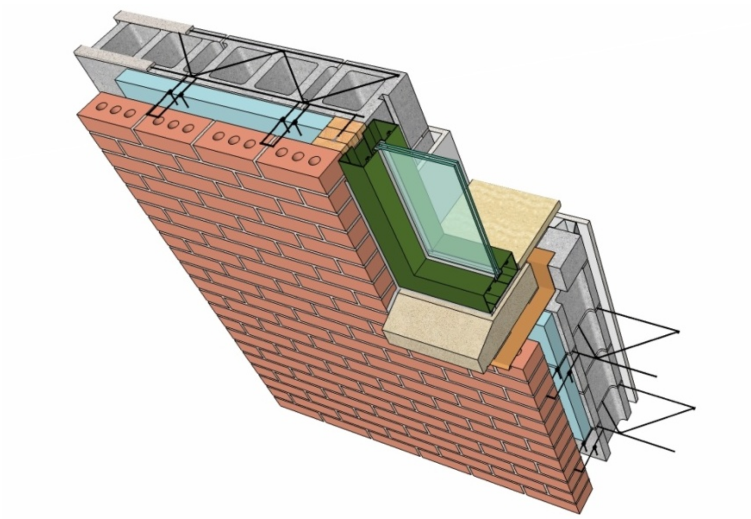
[11] http://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html

4.2.2.2 Permeability, Porosity and Thermal Conductivity

This section will tackle how traditional masonry construction has managed to solve the limitations of the material in a clever and well crafted manner. One of the main drawbacks in stone is its permeability. Most types of limestone are very permeable and result in a lot moisture seeping through its thickness. Moisture does not only travel from the outside to the inside, capillary action also enables the movement of moisture from the ground up. This moisture trapped inside the stone drastically increases thermal conductivity. The most ancient method on how to keep moisture from seeping in was to increase the thickness of the wall as much as possible. Traditional masonry construction evolved by creating an air gap in between two masonry leaves. The first thinner leaf is mostly an environmental barrier, while the second skin serves for structural purposes and further insulation. The air cavity serves a double function, both moisture barrier and thermal insulation.



Left) Permeable Masonry system Right) Impermeable Source: Author



Brick and block cavity wall sill detail

Source: International Masonry Institute - Masonry detailing series.

Main environmental parameters recapitulate:

Thermal Mass :

Radiation levels on surface - Sun paths along the year.

Absorption coefficient, mostly due to color of the surface.

Create a thermal break and moisture barrier.

Dense and impermeable stone or damp proof membrane against capillary action.

Insulation barrier to be on the outer side as much as possible.

4.2.3 Respecting Heterogeneity.

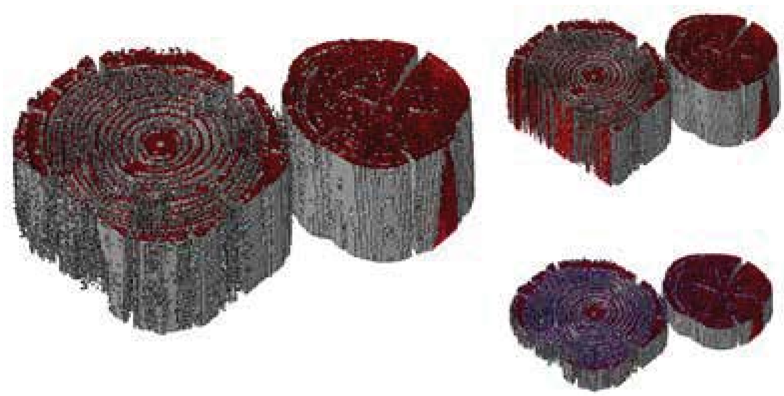
From the very way it is formed; sedimentary rocks imply heterogeneity. In the quarries, a visual quality check by an expert determines weather or not the specific stone bed is fit or not. The different characteristics of the stone are not precisely quantified but rather grouped together depending on their predominant visible qualities. This process reduces the complexity of heterogeneity, but also reduces the possibility of creating something exceptional from unique conditions. In order to ensure the material is of high quality, a margin of error is always taken. Due to this margin of error, certain stone, which is suitable, might be considered as overburden[12]. In the stone extraction industry overburden consists of 51% of the quarried mass. (Waste from cutting consists of 20%) (Siegesmund and Snethlage 2011) The efficiency of stone extraction is solely dependent on the knowledge and experience of the person in charge of the quality control of the material. Unluckily this knowledge for this process is also decreasing rapidly and there is the need to find a way to digitize this knowledge before becoming extinct.

Heterogeneity in stone is not considered as a design aspect in contemporary stone masonry construction. By assuming that all the stone in the same stone bed is the same, a lot of the material opportunities are being missed and misused. Rather than treating stone as a standardized material, these heterogeneous properties should be quantified and exploited. This same idea could be seen in most Maltese vernacular architecture, where, the denser and less permeable stones were placed purposely in the lower courses of the building as a damp proofing. The more dense and durable stone was also used in facades were the material was more susceptible to sea spray and deterioration. The stone industry can take example from the timber industry where the heterogenic properties of the material are considered to be a very important. A paper by Hironori Yoshida at the eCAADe 2013 in Delft discussed about the new possibilities when adhering to the material 'noise' or 'imperfections' and exploits them as a design opportunity. In this paper Yoshida coins the notion of Scan to Production (STP) where the embedded heterogeneous material properties are linked not only to fabrication, but also to the design process. This can create a bi-directional communication between design and the material heterogeneity.

Due to advancements in computation and fabrication technologies this can be done without hindering the efficiency of the production process. Scanning devices such as Kinect cameras and Xray-CT scanners could be used to identify properties such as fissures, porosity, density, visually dominant ooliths and fossils. This bidirectionality can

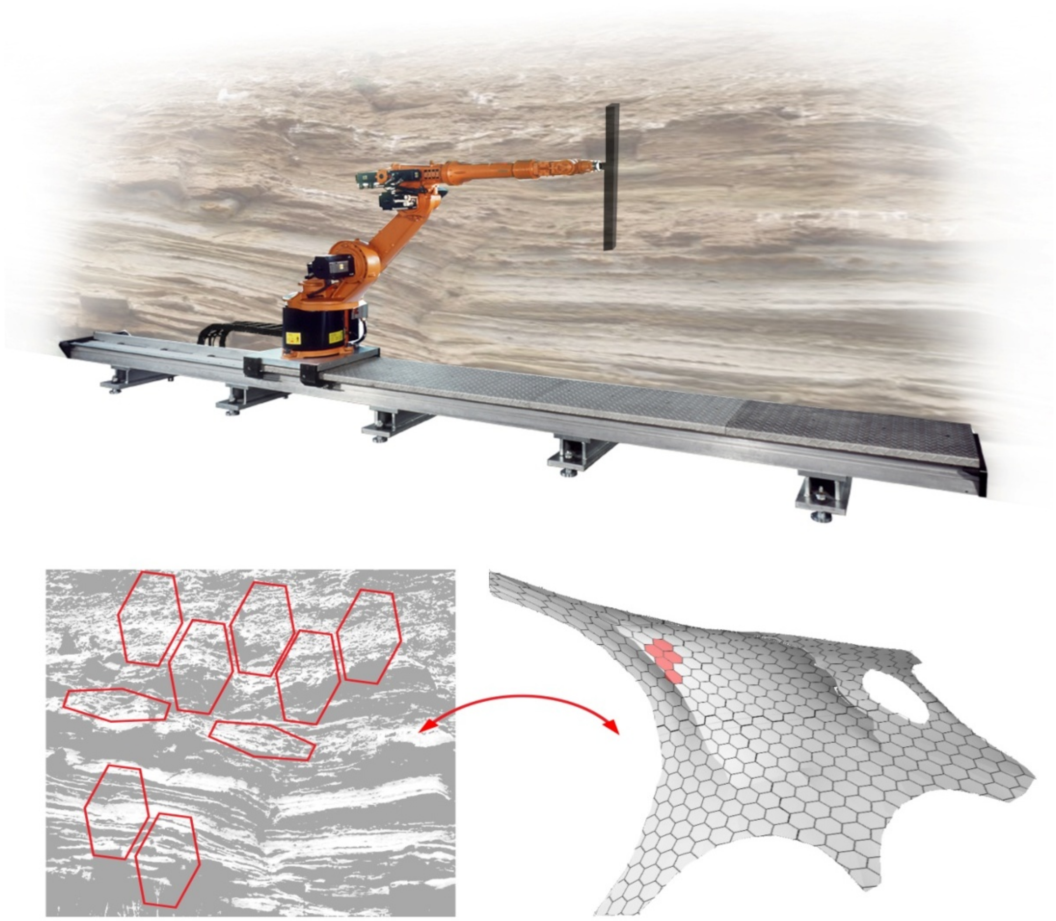
[12] The waste material above the strata of material of interest.

also extend to the extraction of stone and not just the cutting of pre-dimensioned stone, which could result in less waste. With the extensive use of specialized algorithms the masonry elements could be nested in a specific pattern so that the material available is used in the best way possible



3D Image processing of 2D X-ray CT scans Source: Yoshida 2013

Masonry elements with specific performative needs could be tagged with a weighted factor and are more likely to be nested in a stone bedding which fits the characteristics needed. Furthermore if ooliths and fissures are controlled, the possibility rises to be used as decoration features or also avoided from showing in the surface.



Concept diagram of tools and information exhange involved in the scanning, tagging and nesting process. Source: Author

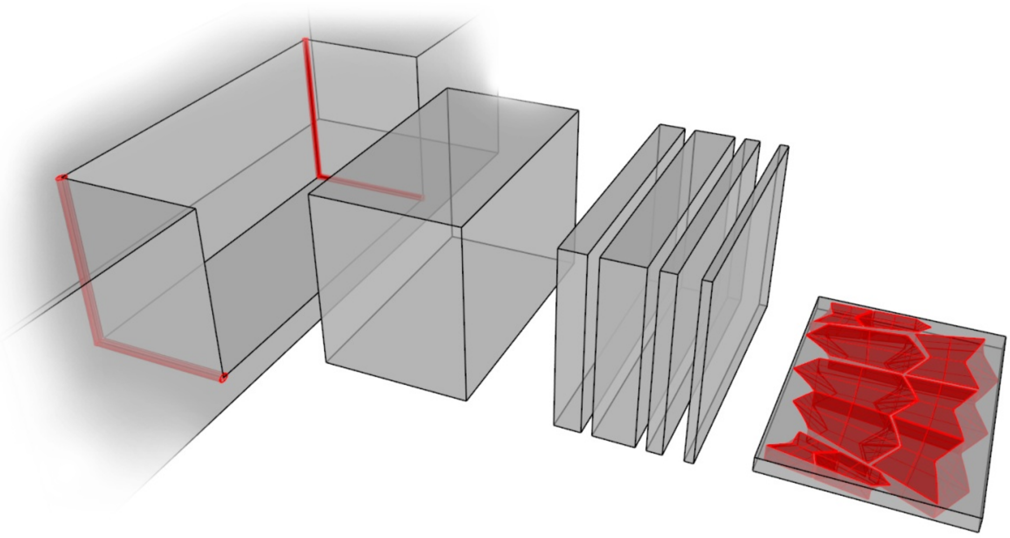
As discussed previously, a particular material alone, could not achieve the status of an architecture tectonic. Craftsmanship and manipulation of the material elevates it to a building technology system.

5.1 Extraction

The first kind of material manipulation starts from extraction. there is a multitude of stone extraction procedures, depending on the stone. The following is one of the main methods of extraction. Holes (100mm diameter) are bored vertically and horizontally to meet at right angles. A diamond wire is fed through the holes and looped around a pulley wheel to separate the material from the main mass. The horizontal cut is made first and then the vertical cuts follow, resulting in an automatic release do to the cantilevering of the block. Rubble material is placed on the bed to soften the impact and the material is tilted from above with hydraulic heavy vehicles. As seen in the image below, it is not the cutting which limits the size of the stone, but mostly handling and transportation issues. Dernie (2003) An approximate of the biggest block which could be handled in the industry is around 3x4x1.8m. (H,Vella 2013)

Stone cut in a quarry in Malta in relationship to the human scale.
Source: www.halmannvella.com

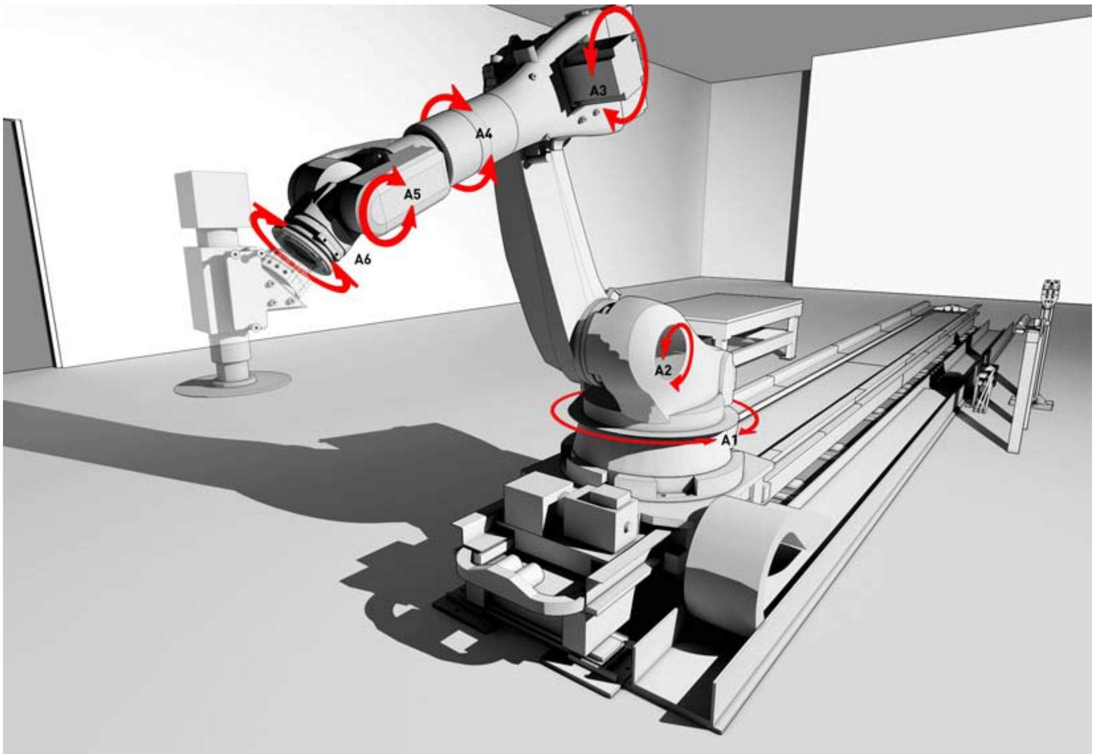
The stone extraction industry usually tries to downsize the block as much as possible before leaving the quarry. Dimensioning and finishing of the stone is also done there. In Malta, the standard stone dimensions are 22.8mm deep x 60.9mm length x 26.5mm height. Due to the fact that the stones used in this research will not be of a standardised dimensions, another option has to be investigated. The optimal option would be having the cutting and finishing machinery located in a protected area very close to the quarry. Cutting from a bigger block of stone, gives a lot more flexibility to the design while also being able to reduce waste and processing time if nesting algorithms area applied in setting out the cutting paths. If stone ashlars are also grouped together depending on thickness before nesting, material waste would continue to reduce.



From left to right: Downsizing stone to desired pieces. Source: Author

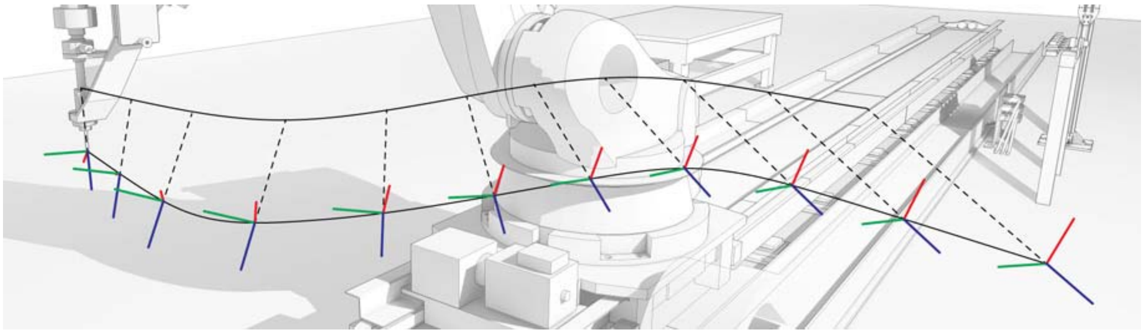
5.2 Cutting

Due to advancements in digital fabrication techniques, certain laborious manual processes could be emulated by a machine. For this research, 6-axis robotic arms were used to test this premise. When using such machinery, it is imperial for the user to understand the limitations and complexity which it entails. The challenge in using such machinery is to be able to communicate between what needs to be done and how the robot should move to achieve this. With 3-axis CNC machinery, it is very straight forward to use as it transliterates digital Cartesian coordinates into machine motion. As the 3rd axis is exceeded, the same position can be achieved with more than one option. With 6 axis, the possibilities are endless and requires an optimization of the kinematics involved. There are different types of codes to communicate with the robot depending on the brand. In this research the robot used is an ABB IRB6400R which requires a RAPID high level language code. This code gives instruction to the robot to more with respect to the tool centre point (TCP)



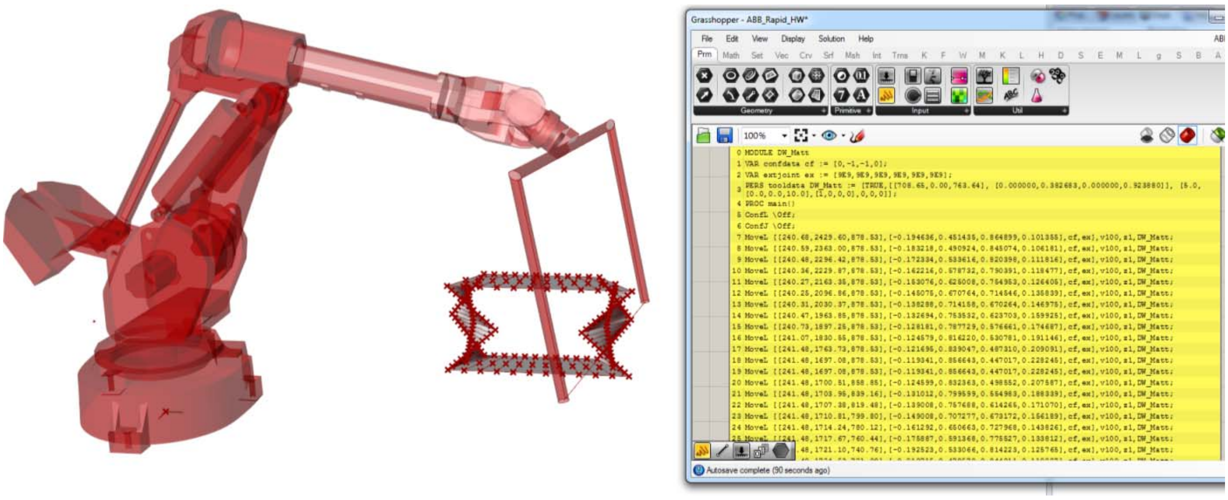
7-Axis Industrial Robot with axes labeled (linear track is the 7th Axis).
Circular cutting saw end affecter in the vicinity of axis 6.
Source: Pigram and McGee 2011

The kinematics involved depend solely on the end affecter attached to the end of the robot. One of the main advantage of using an industrial robotic arm is its versatility. Like a human hand, the robot only manages the motion. It is the detachable tool attached to the arm which ultimately makes the processing. An automated tool changing system gives the possibility for the same arm to use different tools. For this reason, It is not only the position of the TCP which is important, but also the orientation of the tool. (Pigram and McGee, 2011)



Top) Position of the TCP along a given curve. Bottom) Position and orientation of the TCP referenced to another curve. Source: Pigram and McGee 2011

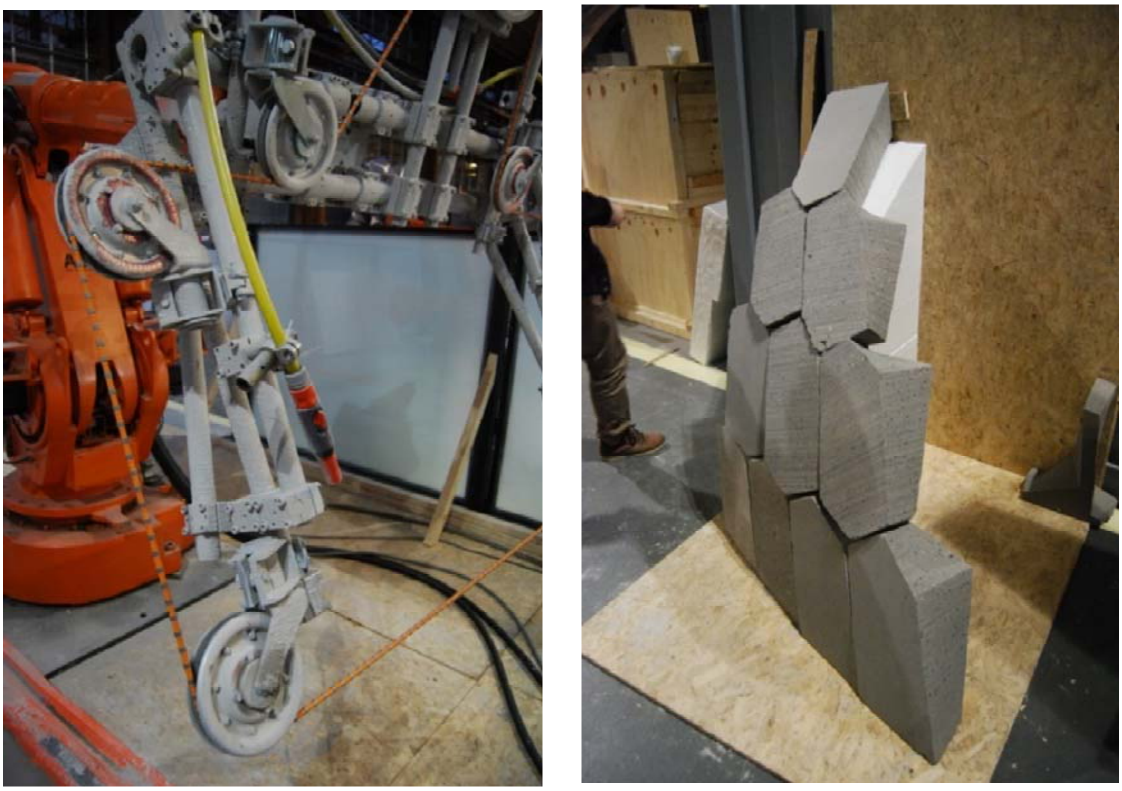
When designing the tool path and orientation, the physical limitations of the machine is very important. This knowledge reduces the risks of exceeding the axial limits of rotation. Due to the complexity of the movements involved a digital model of the robot is also implemented in the design environment[13] and the kinematics of the robot is simulated in order to determine any unexpected behavior or collisions with any object or with itself. This enables rapid testing of pieces which are more challenging to fabricate due to size or complexity of cut. Pieces which are not feasible to cut are easily adjusted and tested for fabrication again.



Graphic visualization and RAPID code generation in the same design environment (Grasshopper, Rhino) source: Author

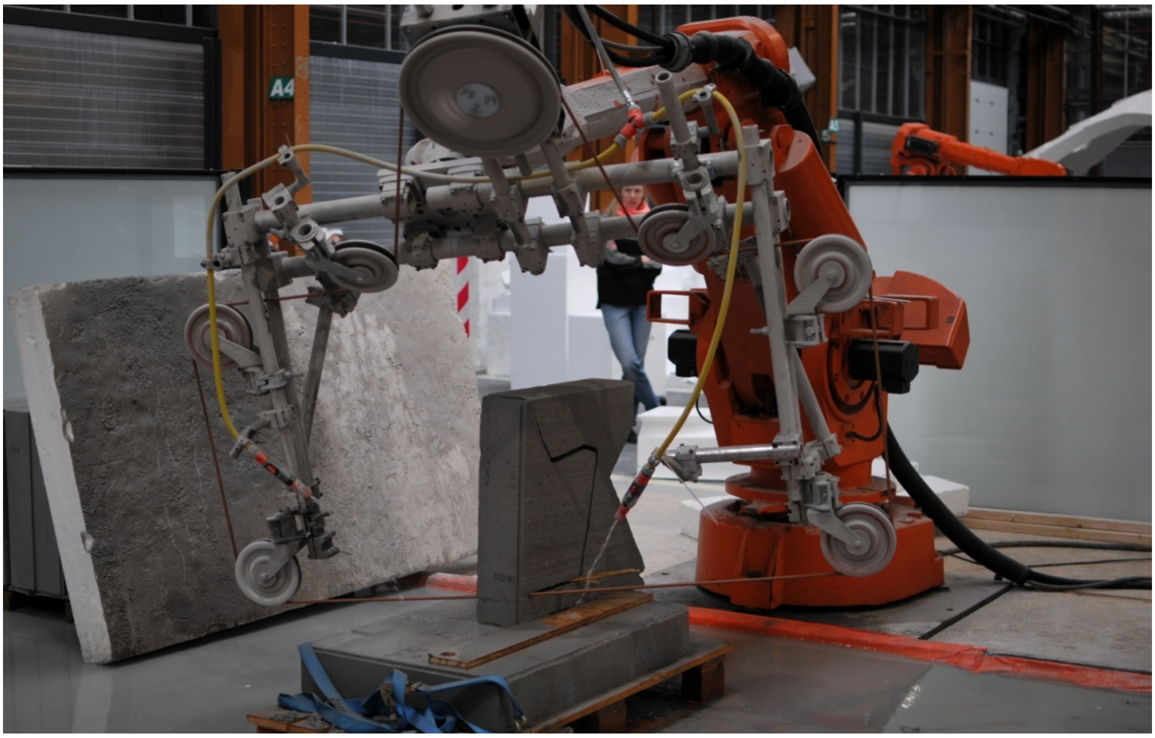
[13] Mussel; An Open Source tool for Grasshopper, Rhino developed by GREYSHED (www.gshed.com) and the Princeton University School of Architecture

The images below show one of the experiments, which the author attended, in RobArch2012, run by Jelle Feringa, Wes Mcgee and Lauren Vasey in Rotterdam. An abrasive rotating diamond wire powered by a 40Kw hydro-motor was connected as an end-effector to a 6-axis robotic arm to custom cut a series of composite limestone ashlars. On average, it took 20 minutes with optimum speed and feeding rate to achieve the best surface finish possible, which makes the whole process viable. Feringa argues how this process of subtracting material is ten folds faster and wastes less material than milling the material away. Feringa and Sondergaard (2013)

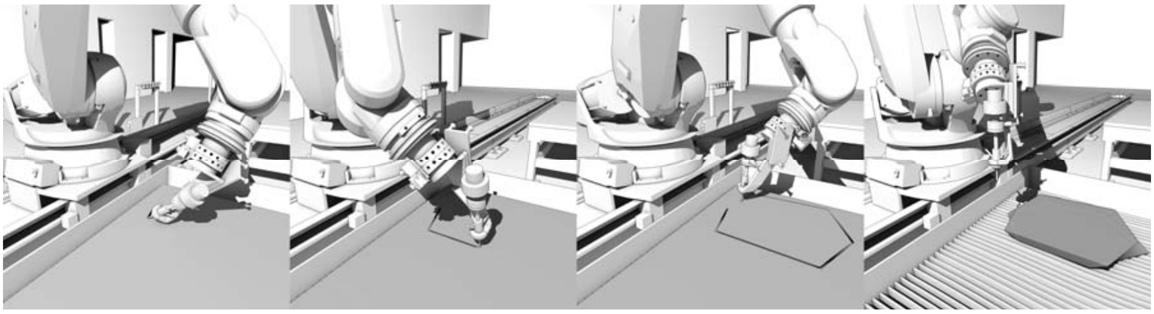


RobArch 12. Left) Abrasive diamond wire cutting end-effector. Right) A section of an asymmetric vault in composite limestone. Source: Author

The main drawback of using a diamond wire is the effects of excessive tensioning of the wire. When speeds are too fast the wire loses its straightness and might tear apart. With the types of cuts produced in this experiment the tool setup was not taken into full advantage. Only a small percentage of the wire was used to cut and the bulkiness of the tool made it difficult at times to avoid self collisions. A better alternative process would be a abrasive water jet cutting. By using a high pressure jet of water (60psi) mixed with garnet abrasive stone can be cut easily. Unlike the diamond wire, there are no friction forces on the robot and the material, which eliminates the need of fixing the material to the cutting bed. (Pigram, McGee and Kaczynski 2011) The kerf of the cutting path is also very thin (1mm) when compared to 15mm produced by the wire. This leads to more precise cuts which reduces the needs for tolerances in the design.



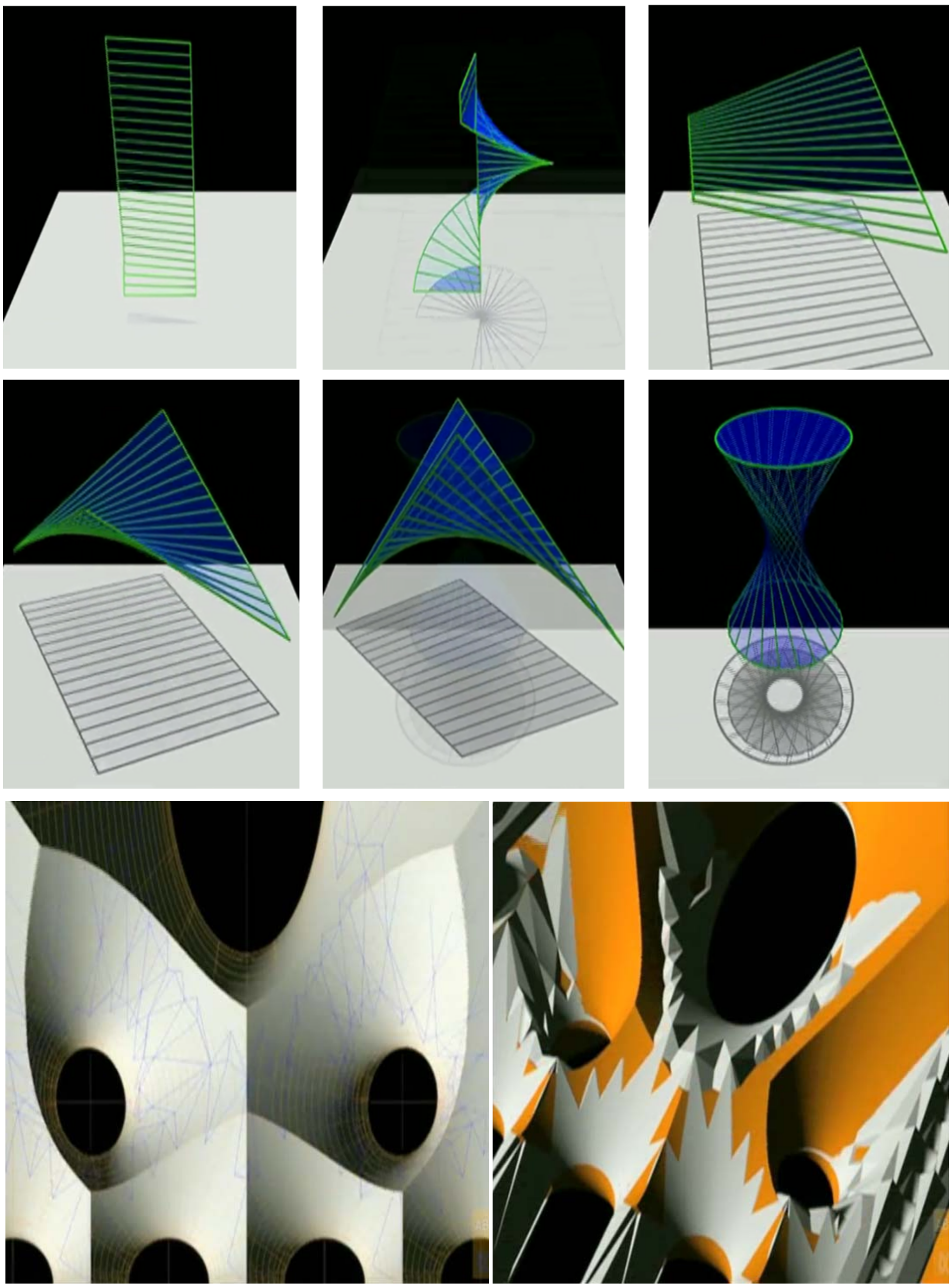
RobArch12: Water outlet still needed to reduce frictional heat and dust particles. Wooden wedges need to be inserted to avoid unwanted splitting. Source: Author



Abrasive water jet cutting processing Berea sandstone.
source: Pigram, McGee and Kaczynski 2011

The water jet cutter has also the advantage of approaching the material from one side and cutting through, rather than having to have a wire which passes through the material and attached at both ends. This means that stone can be cut on a flat bed reducing the need for wooden wedges in the kerf. Also the ability to be able to start and stop the cutting jet at any point raises the possibility to make punctures within the boundary of the desired piece. The water needed for the cutting also functions to reduces dust particles in the air; a preoccupying health and safety issue in stone cutting. (Vella and Camilleri 2005) Regardless all these advantages, a diamond wire is still needed due to the cutting depth limitations of the water jet. The way to make most out of the discussed tools is to use the water jet cutting for cuts which are under 250mm and the abrasive diamond wire when this cutting depth is exceeded.

Irrespective of what from the two end effectors are used, the geometric and size limitations are still the same when designing with such fabrication processes. Due to the fact that both end effectors cut in a straight line, ruled surfaces are utilized as the main geometric grammar. A ruled surface is by definition any surface which could be defined by straight lines. Though this might sound limiting, a vast geometric vocabulary can be achieved with such a system. The material chosen also plays a big role in the geometric limitations during fabrication. One of the main factor one has to keep in mind is the material brittleness, when two cuts in an acute angle, sharp corners are formed. If the angle is less than 30degrees the material will start to fail.



Above: Basic ruled geometry typologies Below) Gaudi's exploiting ruled surfaces and Boolean intersections to create an endless vocabulary of complex geometry. Source: Berry 2009

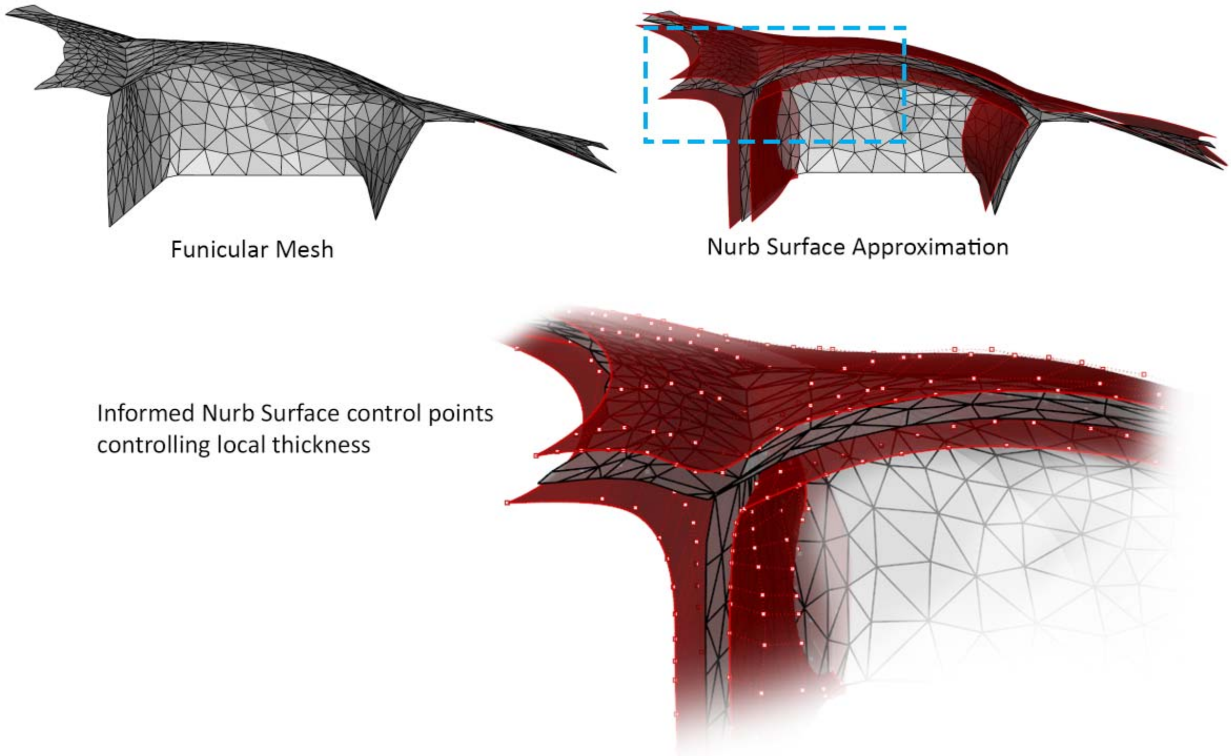
Like every stone masonry structure in history, the way the structure is divided into small elements is very important. This step is one of the most crucial parts as at this moment; structure, material constraints, fabrication constraints, climatic considerations, aesthetics and assembly logistics have to be integrated in one informed system, embodied into one element, the voussoir. The global tessellation of the whole funicular surface and the individual voussoir also need to be worked out in tandem for the system to succeed. Due to the above reasons, the way the structure is descretised in small elements is very important. This stereotomic knowledge can be clearly seen in all masonry structures vaults and domes throughout the ages.

Various Ceiling Details, Hotel de Ville, Philibert de L'Orme, Arles France
Source: Clifford 2013

from left to right: Hotel de Bullioud, Philibert De L'Orme, Lyon France,1536.
Trompe, L'eglise Saint-Sulpice, Paris France, 1635.
Hotel d'Angouleme Lamoignon, Baptiste Androuet du Cerceau, Paris France, 1584.
Trompe, Le Chateau de Lavardens, laverdens France, 1496.
Source: Clifford 2013

This point in the design process shows the strong advantage of using computation in the design of the voussoirs. Back in the pre industrialized era, for every custom voussoir a different set of ''traints'' had to be drawn to describe the 3d geometry.(Evans R 1995) This limited the amount of information and complexity put in the voussoir in order to make it manageable to build. With these new tools we can explore the idea of complexity to embed more performative within the same material, only through crafts. By using parametric logic, a series of voussoir geometries could be tested and analyzed for their performance. The complex task of translating the geometry from 3D to 2D is also bypassed when connected to robotic fabrication.

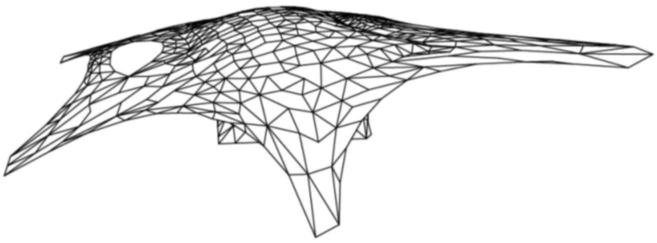
In the context of the design experiment mentioned earlier, the funicular surface will have to be approximated in a way which respects the climatic and structural information acquired earlier. This information defines local thickness throughout the original thrust network. Two surfaces will be produced which define the vaults, 'intrados' and 'extrados'. Technically, the task of approximating a mesh surface with a NURBS surface is very intensive. In the pictures below an attempt was made to approximate the trust network by using lofting tools. This method raised a lot of problems in connecting the surfaces together for tessellating at a later stage.

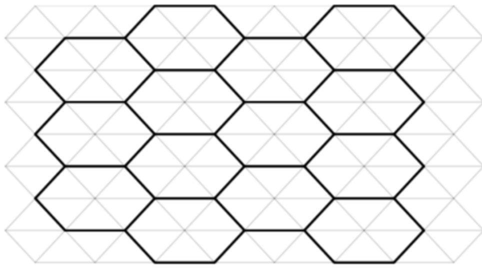


Nurb-Surface approximation and local thickening.

Source: Author

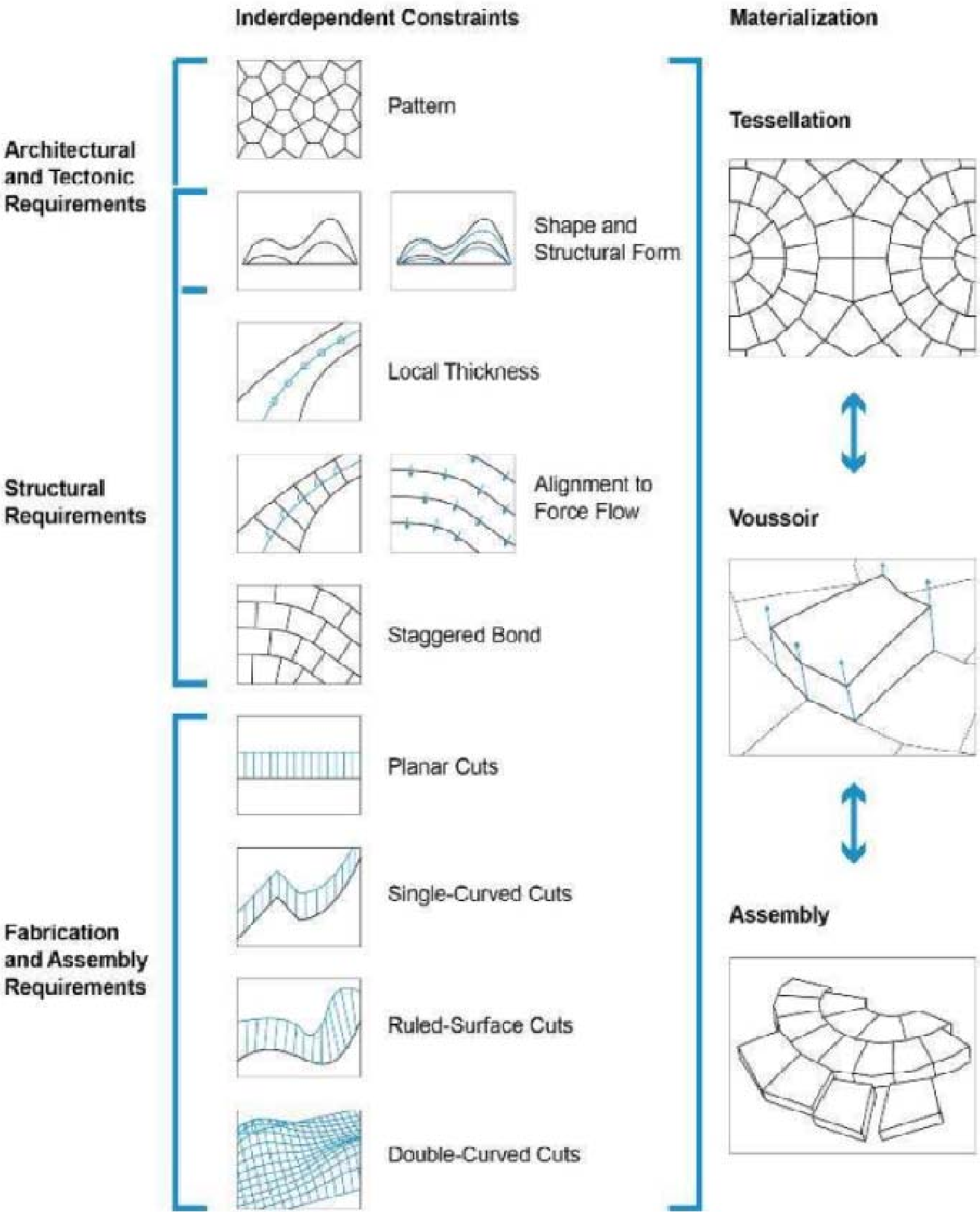
Another unexplored approach could be to rationalize the mesh before or after the dynamic relaxation procedure. This would be the initial geometry for tessellation directly from the mesh which bypasses the problem of having to translate the mesh into a NURBS surface.





Left) Irrational Mesh subdivision. Right) Regular mesh subdivision as base geometry for tessellation.

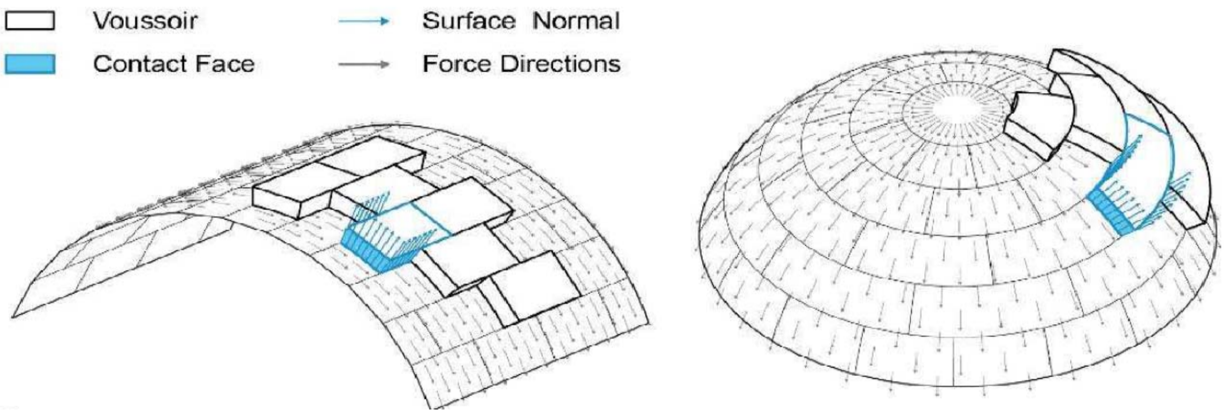
Source: Author



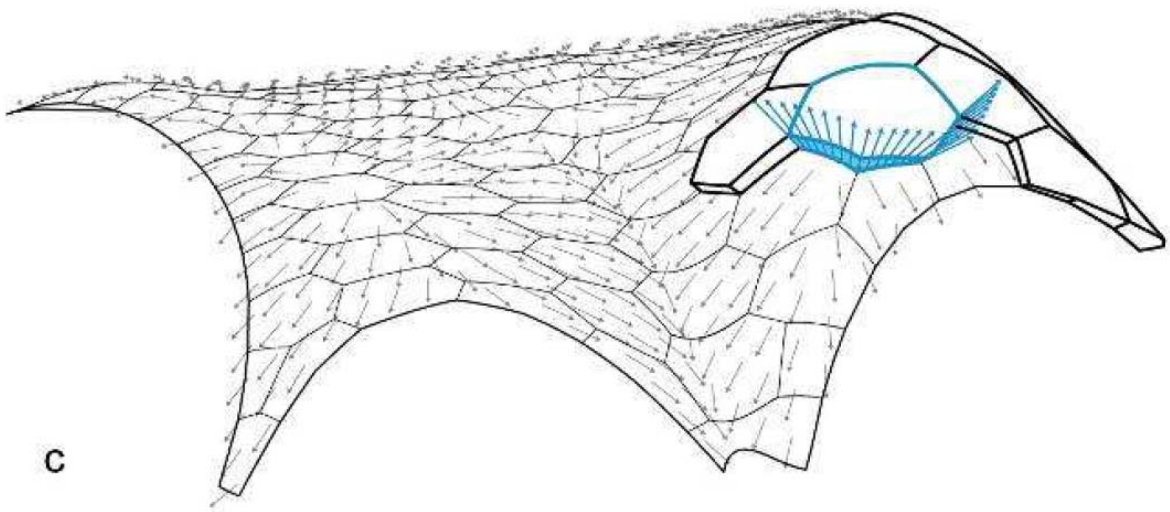
Voussoir Generation Strategy applied by the Block Research Group, ETH.

Source: Block,P, Rippmann,M 2011

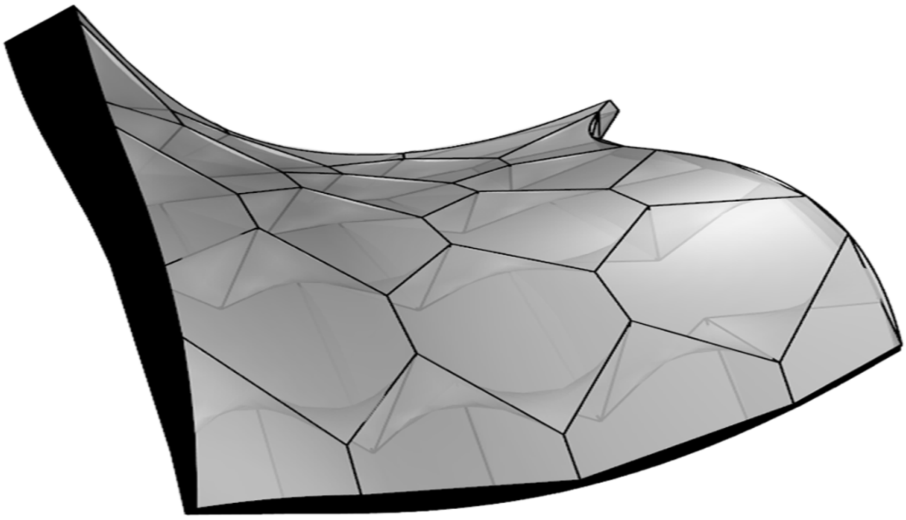
There is more than just thickness that the structure influences in this step. One important factor is the flow of the forces to the ground. It is recommended that to reduce sliding of the ashlars, the contact faces of the voussoirs have to be aligned to the local force flow. The surface should also be divided in such a way that there is no continuous joints going along the stress flow lines. Not respecting this condition would lead to lamination of the ashlars and destabilization of the structure through sliding of the stone elements Ideally the surface normal should be perpendicular to the force distribution but in most cases it is fine not to be unless it exceeds a 30degree angle from being right angle. (Block,P & Rippmann,M 2011)



Contact faces and Force Flow lines
Source: Block,P, Rippmann,M 2011



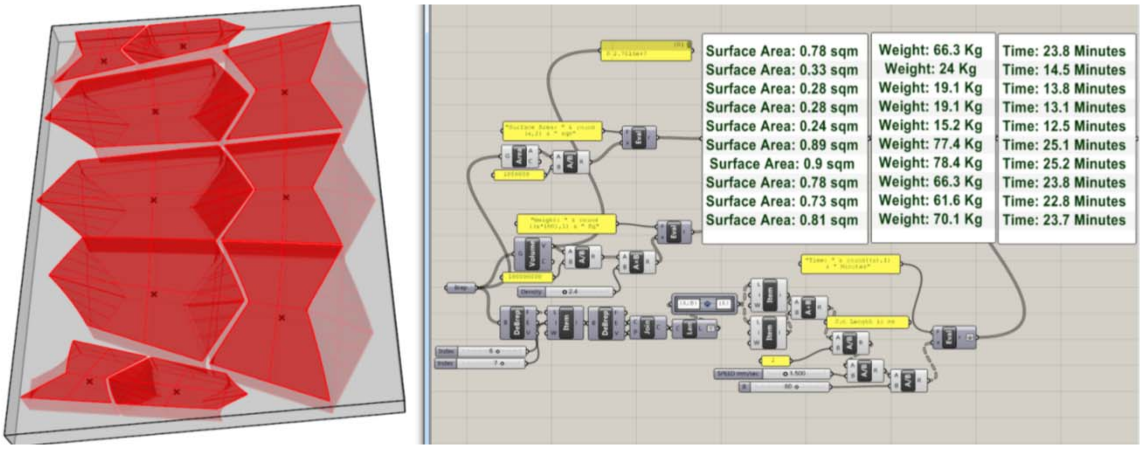
Contact faces and Force Flow lines. Custom Software at the Block Research Group, ETH
Hexagonal tessellation of
Source: Block,P, Rippmann,M 2011



Hexagonal tessellation with differentiated, informed local thicknesses.
Source: Author

The size of the tessellation elements is mostly based on assembly and site logistics. In the case of stone as a material, the main limitation when it comes to dimensioning is weight. Again, in this case it is not the robotic arm which is limiting the dimension, but the complexity of handling and assembly. In this case the assembly process plays an important role in the cutting. EN 771-6 is a standard document operating in European nations in order for the construction industry to adhere to standard specifications in relation to natural stone masonry units. For laborers to be able to assemble the structure easily, a weight limit of 20Kg has to be applied. Where it is not practical to avoid such weight limitations, provisions should be made for it to be handled by more than one person, or steel grips inserted for mechanical handling.[14] With this method of construction, the bigger the elements, the better. Bigger elements will result in less elements which means; less joints, less cutting time and less errors. The bigger the stone pieces are, the easier they are for recycling and reshaping. It is the designer informed by the system which will have to find the right balance between surface area, cutting time and weight. Sharp edges should also be kept to a minimum to reduce the risk of hurting the men on site or damaging the pieces when handling.

[14] More information on: http://www.ibstock.com/pdfs/health-and-safety/blocks-info.pdf



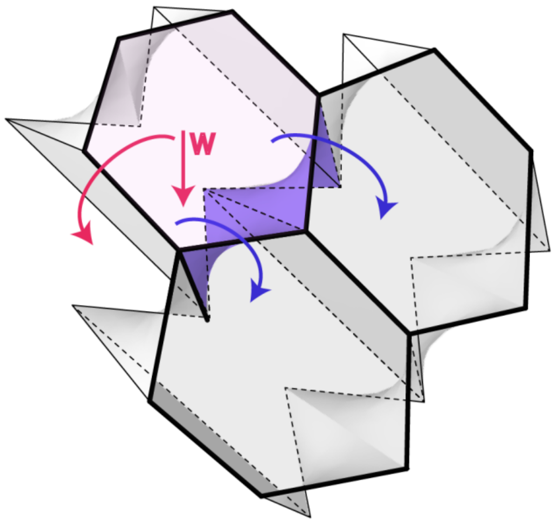
Left) Nested ashlars in custom cut stone slab. Right) Script showing the Surface area, Weight and Cutting Time for every single element. Source: Author

In order to make automation more feasible and reduce waste material as much as possible, it is recommendable that at least one of the intrados or extrados[15] of the voussoirs is a planar surface. This makes it easier for the pieces to be conveyed, transported and stacked for future use. This also makes sure that the intrados of all the ashlars are always matching which makes it less complicated when assembling. To approximate a doubly curve surface with planar surfaces another optimization algorithm is used.

As Scheurer explains In his article *Size Matters*, the other faces could be designed in a way to also help the assembly process. By creating geometry which limits movement, the precise cuts could slide, self align and clip together into place. If all the pieces are numbered properly this system could reduce assembly problems drastically (Scheurer, 2008) Pigram, McGee and Kaczynski explain how by using twisted ruled surfaces (hyperbolic parabaloid) this geometric guide could be achieved. Apart from functioning as a guide, the interlocking nature of the geometry makes the voussoir resist the force to rotate inwards and collapse while assembling. Although the assembly of masonry vault structures is a critical point in the realisation of a project, few literary resources focus on this aspect. The method adopted by Pilgram and Mcgee does not eliminate false work completely but reduces it to a point where such structures could be realistically adopted in contemporary time. This systems employs a similar technique as the Catalan vaulting system, but rather than using mortal as a binder, the voussoir uses its geometric interlocking to support itself. (Stanford A, 2004) The proportion of side faces holding the voussior, the thickness, the weight and the cantilevering length are all aspects which need to be considered when designing the interlocking system. (Pigram, McGee and Kaczynski 2011) The ashlars have to be arranged in such a way that the

[15] Intrados is the inner face in an arch and the extrados is the outer face .

lower course and the upper course share enough similar faces for the frictional forces to exist. In this particular case, two edges of the same top course voussoir, coincide with one face of the two pieces in the bottom course. Hexagonal tessellation was used in this example but more patterns could be used which satisfy this condition (Pigram, McGee and Kaczynski 2011). One other way of reducing formwork is to subdivide a surface in a way to create a conical assembly, rather than working in a concentric arrangement.



Colored voussoir self supporting during assembly. Arrows in red showing the tendency for the voussoir to rotate inwards due to self weight. Arrows in blue show the resisting forces due to friction and interlocking geometry. Source: Author

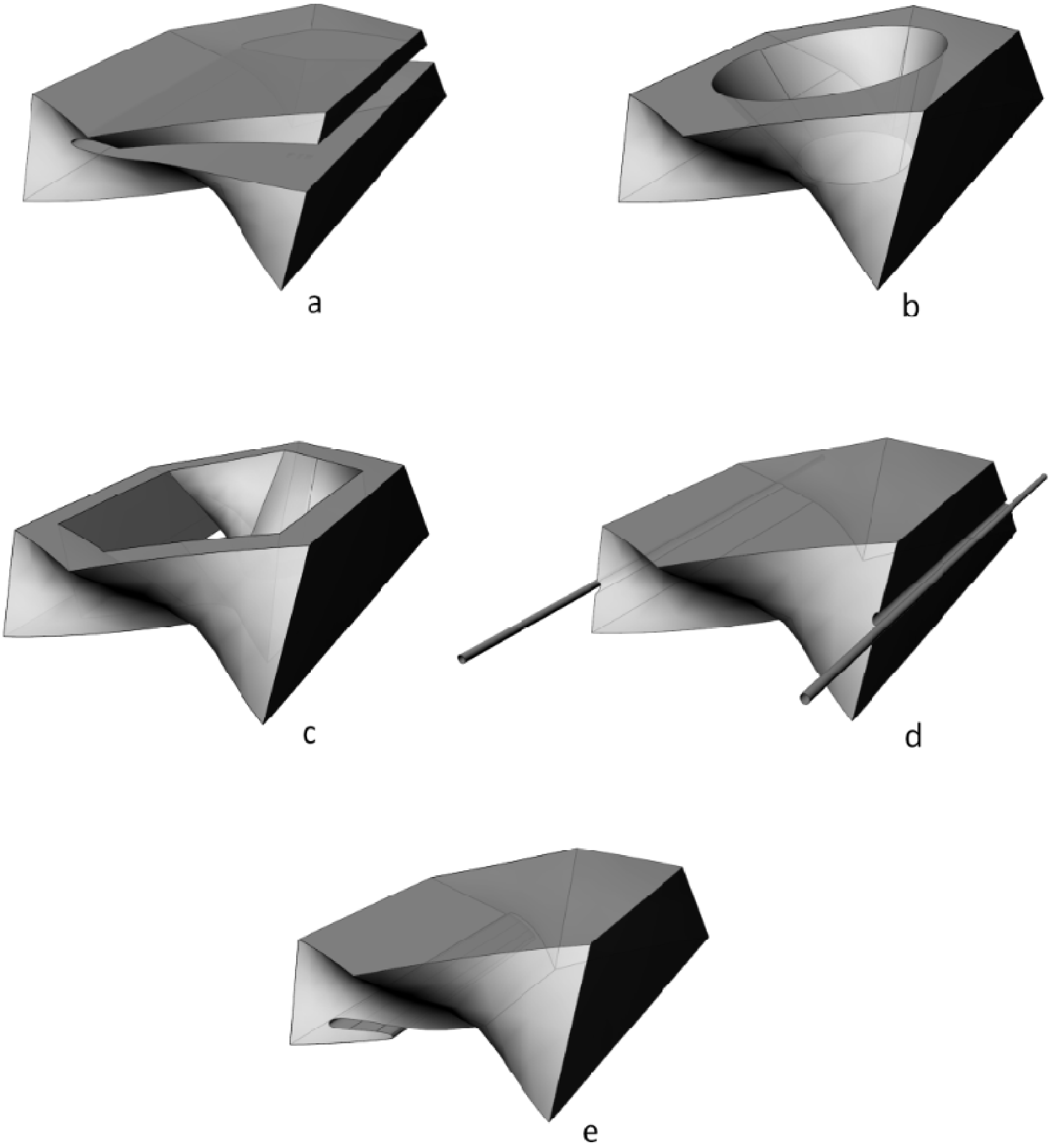
<u>Main voussoir generation parameters recap:</u>

Joints move perpendicular to the force flow. +/- 30 degrees.
The bottom Face should touch at least two ashlars, creating a staggering affect.

Geometry to be limited to ruled surfaces.
Cutting depth limited to 250mm as much as possible
Reduce sharp angles and wedges as much as possible. (>30degrees)
Finding a balance between volume (weight<20Kg) and cutting time.
When weight >20kg, provide adequate fixing for 2+ men or mechanical handling.
Keeping entrado or extrado (at least one) planar to improve production.
Topological interlock to self support during assembly.

Apart from the cutting imposed by the structural and assembly requirements, more information and function can be embodied in the ashlars. Embedding performance through crafts.

Embedded Ventilation functions in the local limestone of Matera, named 'Tufo', Sassi di Matera, Italy
Source: Author



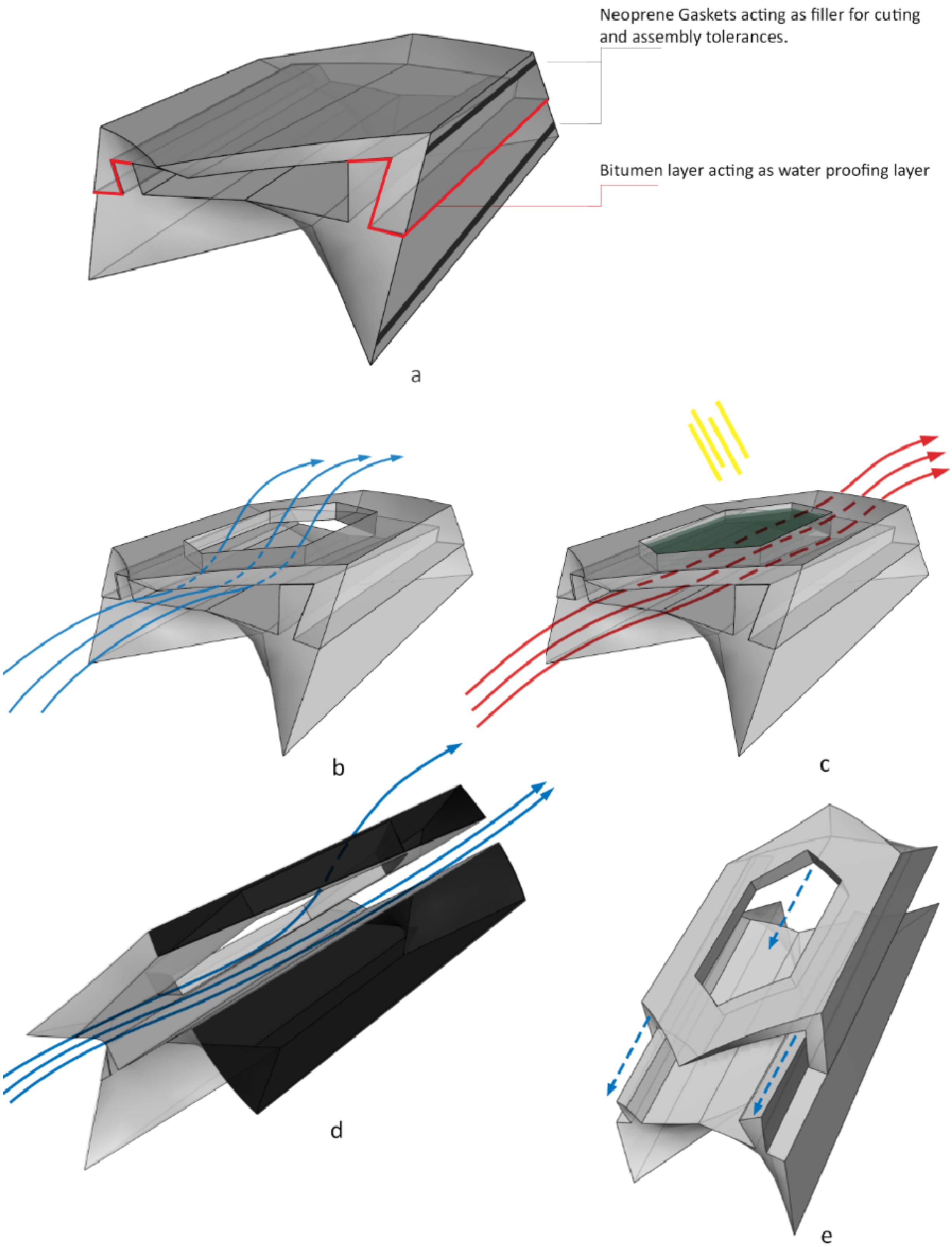
a) Inner cut creating an air gap in the voussoir resulting in a thermal break.

b) Porousity and apertures can be introduced according to architectural and climatic criteria.

c) Ashlars can be seen as frame elements.

d) Tension cables can be introduced either as post tension to stabilize the structure or as temporary supports while assembling.

e)A cut in the entrados and extrados can serve to direct rain water runoff accordingly or host building services.



a) Voussoir tectonics: Mass customized double leaf ashlars including air cavity and water proofing.

b) Opening in the outer leaf used as cool inlet/outlet in summer, keeping air cavity cool in summer.

e)Opening, mechanically closed and exposed to winter sun, radiating of the inner thermal mass and keeping air cavity warm.

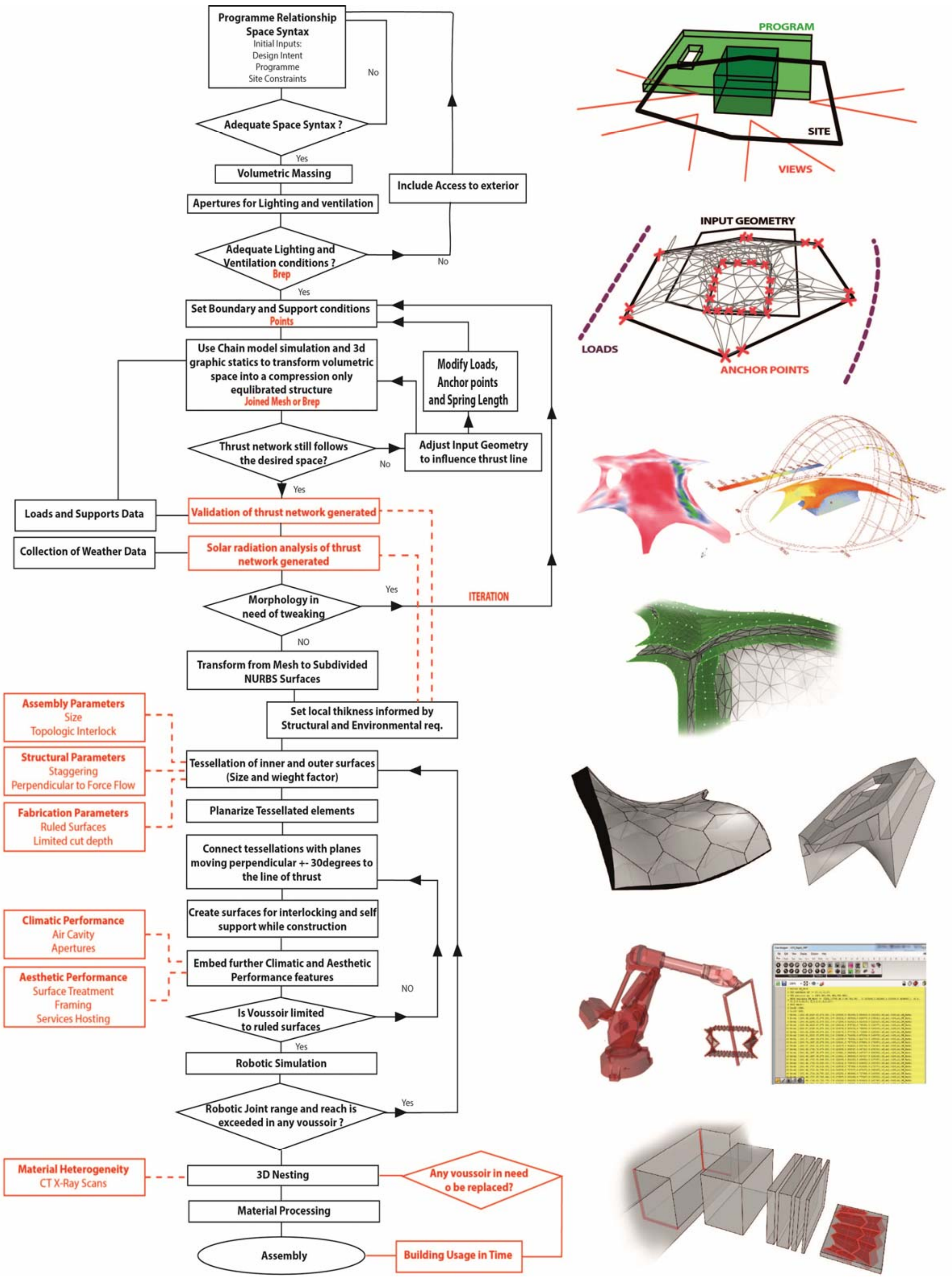
d) Section showing cool air passing through the air cavity in the cooling season.

e) A sliding mechanism is incorporated to ease assembly. Apart from the climatic benefits, by splitting the voussoir in two, the weight per piece is reduced raising the opportunity for larger voussoirs.

Source: Author

Chapter 7
Conclusion

In this section we are going to revisit all the parameters in a hypothetical design exercise. The diagram below shows how the all the parameters mentioned previously are interrelated and how the information should transfer between the different processes.


Programme Relationship
Space Syntax
Initial Inputs:
Design Intent
Programme
Site Constraints
No
Adequate Space Syntax ?
Yes
Volumetric Massing
Include Access to exterior
Apertures for Lighting and ventilation
Adequate Lighting and Ventilation conditions ?
Brep
No
Yes
Set Boundary and Support conditions
Points
Use Chain model simulation and 3d graphic statics to transform volumetric space into a compression only equlibrated structure
Joined Mesh or Brep
Modify Loads, Anchor points and Spring Length
Thrust network still follows the desired space?
Adjust Input Geometry to influence thrust line
No
Yes
Loads and Supports Data
Validation of thrust network generated
Collection of Weather Data
Solar radiation analysis of thrust network generated
Morphology in need of tweaking
Yes
ITERATION
NO
Transform from Mesh to Subdivided NURBS Surfaces
Set local thikness informed by Structural and Environmental req.
Assembly Parameters
Size
Topologic Interlock
Structural Parameters
Staggering
Perpendicular to Force Flow
Fabrication Parameters
Ruled Surfaces
Limited cut depth
Tessellation of inner and outer surfaces (Size and wieght factor)
Planarize Tessellated elements
Connect tessellations with planes moving perpendicular +- 30degrees to the line of thrust
Create surfaces for interlocking and self support while construction
Climatic Performance
Air Cavity
Apertures
Aesthetic Performance
Surface Treatment
Framing
Services Hosting
Embed further Climatic and Aesthetic Performance features
NO
Is Voussoir limited to ruled surfaces
Yes
Robotic Simulation
Robotic Joint range and reach is exceeded in any voussoir ?
Yes
Material Heterogeneity
CT X-Ray Scans
3D Nesting
Any voussoir in need o be replaced?
Material Processing
Assembly
Building Usage in Time
PROGRAM
SITE
VIEWS
INPUT GEOMETRY
LOADS
ANCHOR POINTS

Chapter 8

Further Research

This research only outlines the basic principles of all the steps for the realization of such a project. The main was to setup a framework for all the experts to have one digital environment to share their expertise and for information to flow freely together. This research was not done in order to have one person designing the whole project from start to finish as the parameter involved are too much and too complex. The idea was to find a way to interrelated such parameters together early in the design phase. Experts such as structural engineers, geologists, climatic designers, stone masons and contractors would have to contribute further for the project to be realizable.

Also, for a mass customized block to be realistically incorporated in the building industry, there has to be an update in the codes of practice. This does not eliminate the fact that the new mass customized pieces should adhere to the existing standard as much as possible.

Computational refinement:

Most of the voussoir generation schemes had been done manually to represent the intention of the system. further work on the computational system has to be done in order to make the system fully interactive from start to finish. One of the main challenges is to create a rational tessellation on the thickened funicular surface. Further research has to be done in finding the best way to subdivide the surface into parts before tessellation. Further studies on tessellation strategies in relation to assembly technique is also encouraged for further exploration.

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