Liquid Stereotomy - the Tamandua Vault

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A renewed interest in stereotomy, narrowly entwined with digital technologies, has allowed for the recovery and proposal of new techniques and expressions in this building approach. A new classification scheme for stereotomy research allows for the framing of various aspects related to this discipline, including a newly developed fabrication system specially tailored for the wedge-shaped voussoirs. This fabrication system is based in a reusable mould which may assume an infinite number of geometries, avoiding the wasteful discarding of material found in subtractive strategies. The usage of a mould also allows for more sustainable materials to be employed, catering to current challenges. The strategies subject for demonstration in this project rely on various bottom-up approaches, which involve particle physic simulations such as a hanging model to compute an optimal stereo-funicular shape, or spring mechanisms to find optimal coplanar solutions. The proposed mechanisms work in a parametric algorithmically environment, able to handle dozens of uniquely different voussoirs at the same time. Together with the automatic translation to fabrication data, the proposed shape complexity would hardly be built with classic tools. The Tamandua Vault project has the purpose of exemplifying the possibilities of an updated stereotomy, while its design demonstrates current strategies that may be employed in the resolution of complex geometrical problems and bespoke fabrication of construction components for stereotomy.

Keywords: *stereotomy, digital design, digital fabrication, compression, sustainability*

INTRODUCTION

A great array of the most admired historic buildings found in Europe are built of precisely cut stone. The discipline which allowed for the precision and materialisation of these lithic geometrized blocks is stereotomy, a name which originates in the words, from the greek, στερεο'ς, stereo, solid and τομη', tomia, section (Fallacara 2014). Initially known as Coupe des Pierres, stereotomic knowledge was disseminated in a large number of treatises allowing for architects to gain an important independence from stonemasons, contributing decisively to the creation of the renaissance ideal of the architect role. Stone construction, together with its brick counterpart, dominated the building techniques until the introduction of new materials and processes brought

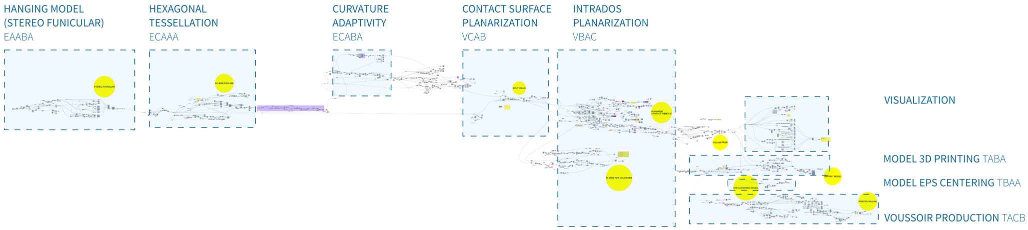

Figure 1
Global view of the algorithm created in Rhino Grasshopper with the various stages labelled in blue.

by the Industrial Revolution. These novelties, epitomised by steel and reinforced concrete, present the possibility of building larger spans with lower rises, allied to the lowered cost factor due to standardisation and mass production. The art of building stone arches and vaults to cover spaces became a rare exception in a world covered in steel, be it in the form of metallic profiles or reinforced concrete.

Despite falling out of favor, qualities inherent to stereotomic construction are still - or even more - valid today, namely: prefabrication; dismantling and rebuilding; usage of local materials; bigger lifespan and acoustic and aesthetic qualities, among others. Recent researches have resurfaced the interest in stereotomy, which has become more interesting due to the possibilities brought by new digital technologies. From the digitalisation of stereotomic techniques (Fallacara 2003), passing on to a reinterpretation of design and fabrication processes (Rippmann et al. 2016), stereotomy is being experimented with a variety design and building approaches, as well as different materials, calling for a reinvention of the discipline, called Stereotomy 2.0 by Fallacara (2018).

The large amount of directions in which experiments and actual constructions are being tested (e.g. materiality of the voussoir, fabrication technique, stability principles, joint geometry, centering technique, among others) is highly disruptive of the great source of knowledge on stereotomy: the classic treatises like those of de l'Orme (1567) or Frézier (1738). In an attempt to bridge this apparent gap, the author has published a draft for an Expanded Semantics of Stereotomy (Azambuja Varela 2019) in which a wide range of concepts related to stereotomic design and construction are classified in an ordered structure with a clear naming convention, which will be used in this article. One of the possibilities of innovation in stereotomy is in the voussoir fabrication field, where masons hand labour is being replaced by automated machinery. The author has researched in a moulding process in which very limited waste is generated with the production of bespoke multiple varied geometry blocks (Azambuja Varela 2017, 2018), reducing machining time and widening the array of possible materials to be employed in a stereotomic construction. This novel materialisation system for voussoir production reached satisfactory results in the form of a variable mould system, which was used to produce a variety of voussoirs for four prototypes whose main purpose was to validate that specific research agenda. This moulding system will be put to test in the following project, whose goal is to validate a complete flow for stereotomic design under the paradigms announced in this work, using digital-based strategies without which its design and construction would be very difficult to the point of not being a feasible endeavor.

DESIGN

The Tamandua Vault project has the purpose of exemplifying the possibilities of an updated stereotomy, while its design demonstrates current strategies that may be employed in the resolution of complex geometrical problems and bespoke fabrication of construction components for stereotomy. The proposed location for the vaulted structure is a garden with a lawn, where its visitors may find a pleasant shelter. This structure is placed in the lawn

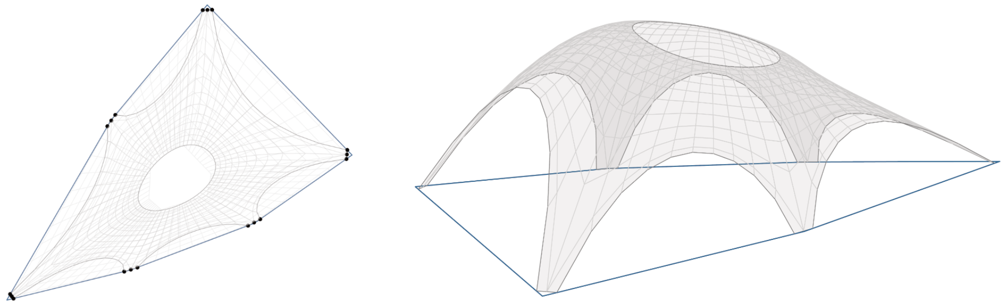

Figure 2
Ground plan of the Tamandua vault, showing the scalene triangle with supports marked. These were offset slightly, rendering an irregular hexagon; b) Perspective view of hanging model of the Tamandua Vault.

as a pavilion-like those found in English gardens. Stereotomic building fosters a construction made of non-perishable materials, with low demands for maintenance, adequate characteristics for an open-air construction.

Design and Macro Shape

The proposed vault base shape is a scalene triangle, whose three sides present a different number of footings each. In the first side, there is only one wide opening with no central supports which may be understood as the main entrance; the second side features one central support resulting in two low arches, and the third side evokes an analogy with a portico for its sequence of four total supports. The interior of the vaulted roof is crowned with an oculus that naturally frames the skydome. The dimensions of the pavilion are subject to human scale, and they are adjusted during the form-finding process with proportion as a goal. As described above, the generating shape of this structure is a triangle which, together with the location of the supports, is the only manually controlled shape in this project, as the whole remainder resorts to algorithmic calculation. The whole algorithm is presented in Figure 1, where the various design and materialisation stages are highlighted. The first design step is to resolve the macro-shape of the structure which, in order to more dramatically express the language of a compressive bound stereotomic dry construction, closely follows an ideal thrust surface for a constant thickness shell; for this, it is devised a hanging model based in particle physics using the Kangaroo library created by Piker (2013). The hanging model takes shape of a zero thickness elastic surface subject to gravity forces and the aforementioned supports - while pre-computer architects were forced to use elaborate string models with weights attached and observe the final result in a mirror or in an inverted photograph, current simulation tools allows using a force opposite to that of gravity, generating the inverted model from the start. Despite the continuous nature of the surface, mathematical simulations are based in the finite element method (FEM), hence the need for a discretised topological network. A polygonal mesh is built using a given width for the supports, where all inner and outer vertices are purposed with weight and every connecting edge simulates elastic strings attached to these vertices in the near neighborhood, thus ensuring topological preservation. The computational model for the hanging surface is run and the result is evaluated, as illustrated in Figure 2. Two constraints are evaluated: vertical free space below the entrance arches, and the general proportion of the building. By adjusting the position of the initial support points and the magnitude of the vertical force, a form similar to the initial sketch is achieved. In the faceted classification (Azambuja Varela 2019) proposed in a previous article, this macro-shape is a Hanging Model whose label is “EAABA” (Equilibrium: Macro-Shape: Generation method: Bottom-up: Hanging model). Regarding its

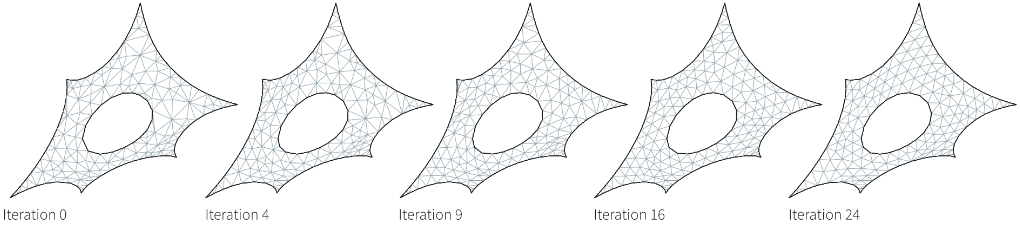

Figure 3
Five evolutive iterations of the process where the subdivision of thrust surface in a triangular mesh whose edges tend to a common length, while having these lengths reduced in parts where the curvature is higher.

continuity, it is a "EABB" (Equilibrium: Macro-Shape: Continuity: Continuous). Still, in the field of Equilibrium, its Structural Functioning is a "EBA" (Equilibrium: Structural Functioning: Compression only).

Surface subdivision strategy

The subdivision of the thrust surface in discrete cells - reminding the meaning of the word discrete as "consisting of distinct or separate parts; not attached to others; unrelated; made up of distinct parts; discontinuous" - is tightly related to the generation of the voussoirs which, in turn, constrain and are constrained by the materialisation process. In order to maximize the usage of the baseboards which are part of the flexible mould which shall be the basis for all voussoirs fabrication, a subdivision that promotes a similar cell perimeter regarding its size and topology is chosen. As such, regular patterns are evaluated as an initial approach. Acute angles in the edges of a stone voussoir leave the tip of material unsupported and dependent in the capacity of material to avoid disaggregation. In the same line of thought, obtuse angles promote a much stronger cohesion between the different parts of the material. Taking this classic stonecutting rule of thumb into account, the tendentially hexagonal tessellation is thus selected as the most suitable. A possible approach to tackle the subdivision of a target complex surface involves its flattening, solving the problem two-dimensionally, and remap the solution to the original target surface (Hormann and Greiner 2000). This strategy creates an uniform tiling - topologically and general dimension wise - in the target surface. However, the cells follow the surface and are curved, a configuration not compatible to the mould system, which presupposes flat intrados. As such, the planarization of these cells detaches them from the thrust surface and some vertices become unaligned, a normal characteristic of convex tessellations of flat cells in anticlastic surfaces. In order to reduce this phenomenon, a valid strategy is to reduce the size of the cells in the highly curved surface areas (Figure 3), so that the difference between the points of the planar cell and its correspondent point in the thrust surface is reduced.

Voussoir geometric definition

This part of the design process is where the shape evolves from its mathematically zero thickness (subdivision cell) abstraction into a volume (voussoir) becoming inextricably associated with stereotomy. The volume of a stereotomic structure comes from the thickness of its voussoirs, which is roughly the distance between intrados and extrados. In an arch, the resultant of compressive forces lies within a line called the line of thrust. Stable structures contain this line within its mass. Similarly, in a three-dimensional system, one can find a thrust surface where forces optimally flow, being wishfully in the innermost position within the section of the vaulted structure. The volume is created towards both sides, intrados and extrados, to maximize the incorporation of the thrust surface inside the structure's mass.

This stereotomic construction does not feature any kind of interlock and ideally no mortar, relying only in the direction of the contact surfaces (and eventually in some friction between voussoirs) to avoid slippage; for this, the contact face should be as normal as possible to the thrust vector. Since every contact face connects each pair of intrados and extrados perimeters - because this project features "VBBBA" (Voussoirs: Intrados and Extrados: Perimeter: Correspondence: Analogous) - it is possible to use these perimeters to model the contact face. By placing a vector normal to the thrust surface in each of the endpoints if a cell edge - see Figure 4 - it is ensured that a ruled surface containing both those skew vectors is normal to the thrust surface in at least those initial points, and tendentially very approximate in the remaining part. These vectors are collinear to the voussoirs contact edges, and the extrados and intrados are parallel to the planar cells, each in half a distance of the full thickness of the voussoir. The intersection of an intrados plane with these vectors produces the vertices of the intrados and its correspondent perimeter in the form of a polygonal curve; the same applies for the extrados. The voussoir geometry is obtained by creating the missing contact ruled surface, either by connecting each pair of intrados and extrados edges, or each pair of consecutive contact edges. For the application of the variable mould described in a previous article (Azambuja Varela 2018), the voussoirs contact faces must be planar to be compatible with the flat aluminium bars which will compose the lateral side of the mould. Following the faceted classification, it is a "VCAB" (Voussoirs: Contact Surface: Geometry: Planar). As seen above, the perpendicularity of the contact edges to the thrust surface usually generates skew lines, hence the ruled surface connecting them. Because of the materialisation planar characteristic, a procedure for the planarisation of these faces must take place (Figure 5), as discussed in other works (Rippmann et al. 2016). A particle physics procedure is once again used to achieve an equilibrium under the conditions needed. In this case, each group of vertices contained in each contact face of the voussoir is assigned a CoPlanar goal, while collinear contact edges are tendentially kept in the original place. This algorithm will deform the contact faces to flat faces, thus altering the proposition of strictly normal geometry to the thrust surface. However, this difference is negligible and, usually, the pair of contact edges self compensate each other creating a planar surface whose normal is the average of the previous no planar iteration.

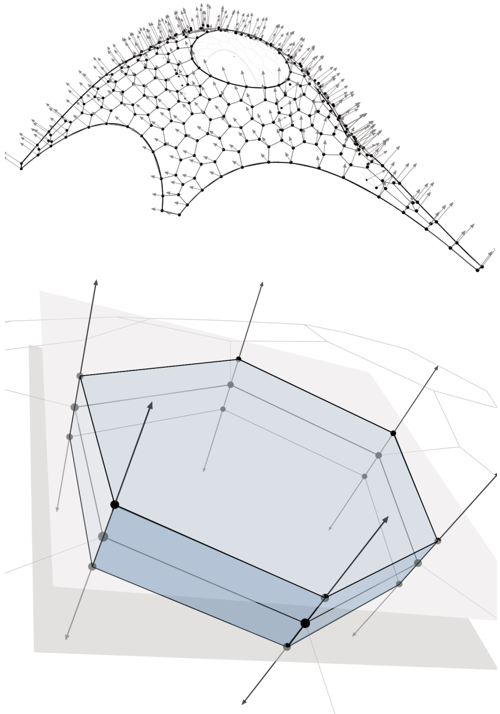

Figure 4
Generating volume: a) Visualisation showing normal vectors to the thrust surface in the vertices of the voussoir cells; b) Generation of a voussoir: the vectors represent lines with the normal direction, which depart from the cell vertices (big dots).

3D printed model

Before any construction endeavors are taken, a functional model is constructed. This model is composed of 177 individually voussoirs at a 1:20 scale, seen in Figure 6. Their production is done in a Makerbot Replicator 2X Experimental 3D printer, which takes sensibly 15 hours in batches of 12 ABS plastic voussoirs, each 60 minutes. The small scale of the blocks is intended for a complete assembly with all participating members of the structural flow of forces at

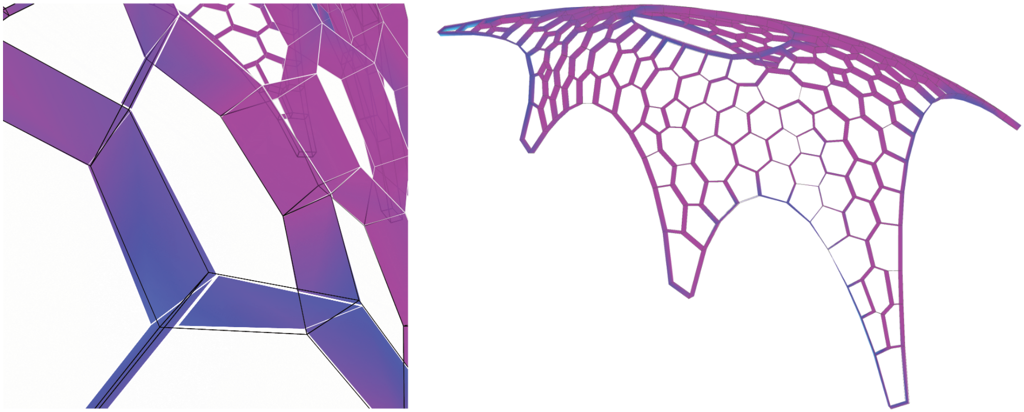

Figure 5
The black outline represents the planarization final result, while the coloured geometry represents the skew contact faces, in which purple is closest to its final position, and blue is farthest.

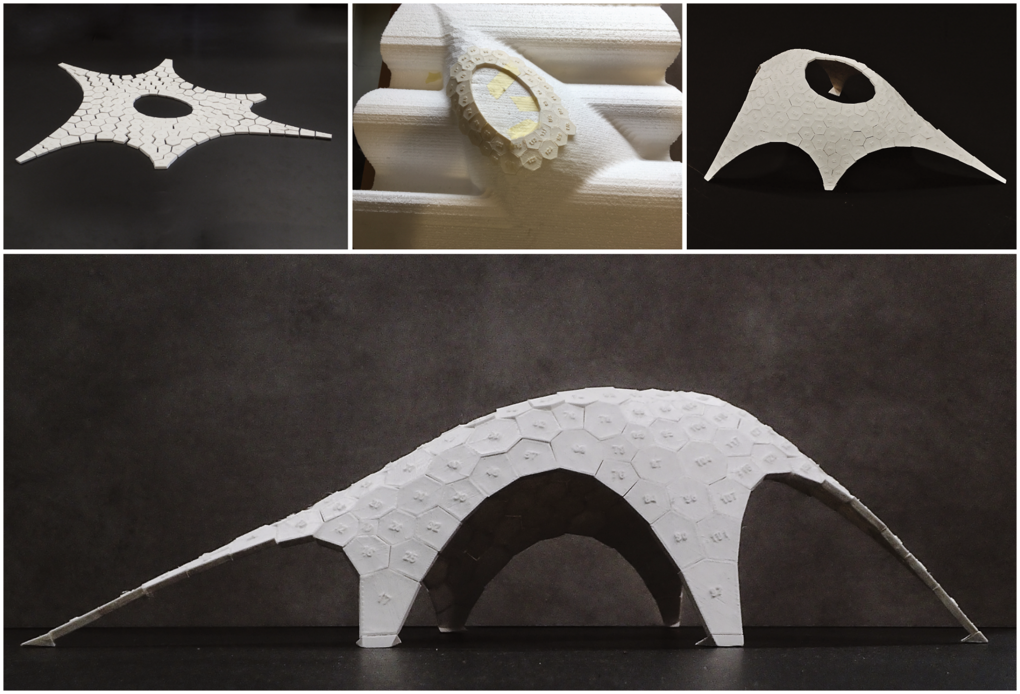

Figure 6
a) All the 177 individually voussoirs at a 1:20 scale laid out in a table; b) Model undergoing assembly; c, d) Assembled model.

play. This is possible because compression-only discrete structures are scalable, allowing for a reliable prediction of the stability of corresponding models and buildings (Heyman 1997). This complex shape is dependent of a centering in order to inform the exact angle and position of each voussoir in adjacency to the next. This centering was milled out of a single block of EPS, leaving imprinted the exact contours of the intrados. The small scale of the voussoirs, the printer's low resolution and the lightness of each piece denies the possibility of a complete mortarless assembly of the model, which is put together with small points of hot melt adhesive. The complexity of the designed shape calls for a more insightful analysis than a regular vault (such as a barrel vault, or fan vault), and the access to rapid prototyping allows for the creation of a model which is able to give this output. This duality between the needed analysis and the possibility of rapid prototyping is part of a symbiotic relationship often found in the osmosis between new technology and novel expressions in architecture. If on one hand rapid prototyping allows for the accessible creation of a model of such a complex shape, on the other hand, this design is also only possible because we have the tools to evaluate it. Besides evaluating structural aspects of the construction, the model is also instrumental in analysing the design, easily observable from various perspectives.

Voussoir prototype

The fabrication of the voussoirs (Figure 7) follows all the same principles used in the reinforced, reusable, reconfigurable molds for cast voussoirs presented in the article of the same name (Azambuja Varela 2019). Recapitulating the main principles, the fabrication used the variable mould system with the large aluminium planar bars as contact face mould parts, and narrow rectangular iron bars as supports. These supports are held in their accurate position and angle by insertion into angled holes milled by a 6 axis robot or 5 axis CNC. This mould's components are reusable, promoting the production of voussoirs without waste and avoiding the need for 3D printing systems precise enough (<1mm) and capable of handling construction final material. For the insertion of the support bars, specially angled holes mimicking the angles of the voussoir contact edges are milled with a robot. Regarding the proper casting of the voussoir, the procedures in the work site mimic those of a previously built tri-arch.

There, special mixes were tried until an optimal mix of cement water and foam is chosen. The process started with the making of a simple cement paste (2,5 kg of cement and 1,0 l of water), to which foam (produced by mixing a foaming agent (AG-1) with high-pressure air through a specialized nozzle) was added (2,0 l). The foam was mixed with the cement, making it a very light mixture that was poured into the mould, previously coated with vaseline, a demoulding agent, to ensure that the less dense concrete mixture would not adhere to the mould surface. The voussoirs were produced one by one, and after each demoulding, the voussoir was carefully removed and left to cure in order to achieve its full strength. A run of trials and errors allows to reach the conclusion that 48 hours is the minimum time for a successful foam concrete demoulding to take place. Due to the large size of this prototype voussoir, it was left to cure for 36 hours before demoulding. The synthesis of the process is documented in figure 7, where the various stages can be evaluated.

CONCLUSION

This article discussed the design and materialisation processes of the Tamandua Vault (Figure 8), a self-proposed demonstrative project whose main feature is the reusability of the molds used to fabricate its building blocks. It documented the various processes essential to control a stereotomic design in a shape with a strong level of complexity. The processes discussed include computer simulation of hanging models, strategies for creating an informed subdivision of a surface, and the geometric control of the angles in the formulation of voussoirs as structurally performative volumes. It was also presented

Figure 7
Various stages of the Tamandua Vault voussoir prototype fabrication: a) Milled baseboard; b,c) Mould filled with concrete; d) Contact face bars removed, exposing contact faces; e) Contact edge bars removed, exposing full block; f) Finalised block.

Figure 8
a) Simulation of the Tamandua Vault as built; b) Inner view with the contact faces in first plane and oculus in the second plane.

a complete 3D printed structural scaled model of the vault, as well as the fabrication of a representative voussoir at full scale and in the final material, foam concrete. The developed processes for the Tamandua Vault were guided by a holistic approach in various design stages and the materialisation processes which illustrate current possibilities for an augmented stereotomy.

REFERENCES

Fallacara, G 2003, *Il Paradigma Stereotomico Nell'arte Del Costruire. Dalla Natura Sincretica Della Modellazione Digitale Alla Progettazione/Costruzione Di Elementi Architettonici in Pietra Da Taglio.*, Ph.D. Thesis, Politecnico di Bari

Fallacara, G and Barberio, M 2018, 'An Unfinished Manifesto for Stereotomy 2.0', *Nexus Network Journal*, 20, p. 519–543

Fallacara, G and Minenna, V 2014, *Stereotomic Design*, Maglie (LE), Edizioni Gioffreda, Verona

Heyman, J 1997, *The Stone Skeleton: Structural Engineering of Masonry Architecture*, Cambridge University Press

Hormann, K and Greiner, G 2000 'Quadrilateral Remeshing.', *Proceedings of Vision, Modeling, and Visualization 2000*, pp. 153-162

Piker, D 2013, 'Kangaroo: Form Finding with Computational Physics', *Architectural Design*, 83(2), pp. 136-137

Rippmann, M, Mele, TV, Popescu, M, Augustynowicz, E, Echenagucia, TM, Barentin, CC, Frick, U and Block, P 2016, 'The Armadillo Vault Computational Design and Digital Fabrication of a Freeform Stone Shell', *Advances in Architectural Geometry*, 2016, pp. 344-363

Azambuja Varela, P and Sousa, JP 2017 'Fabricating Stereotomy - Variable Moulds for Cast Voussoirs', *Fioravanti, A, Cursi, S, Elahmar, S, Gargaro, S, Loffreda, G, Novembri, G, Trento, A (Eds.), ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th eCAADe Conference - Volume 2, Sapienza University of Rome, Rome, Italy, 20-22 September 2017, Pp. 193-200*

Azambuja Varela, P and Sousa, JP 2018 'Reinforced, Reusable, Reconfigurable Molds for Cast Voussoirs', *Kepczynska-Walczak, A, Bialkowski, S (Eds.), Computing for a Better Tomorrow - Proceedings of the 36th eCAADe Conference - Volume 1, Lodz University of Technology, Lodz, Poland, 19-21 September 2018, Pp. 771-780*, Lodz University of Technology

Azambuja Varela, P and Sousa, JP 2019 'Digital Expansion of Stereotomy - A Semantic Classification', *Sousa, JP, Xavier, JP and Castro Henriques, G (Eds.), Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference - Volume 1, University of Porto, Porto, Portugal, 11-13 September 2019, Pp. 387-396*