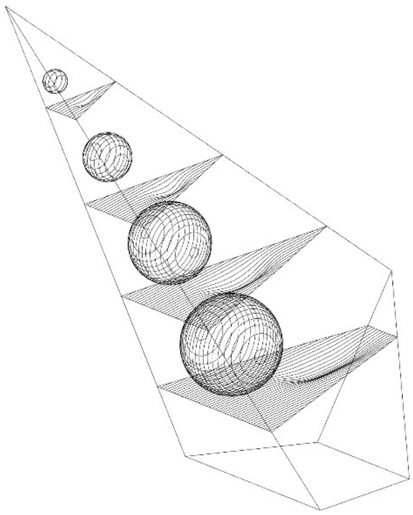

Exploring Equilibrium
with Interlocking Structures:

Stereotomy

Chair of Structural Design

Structural Research

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TUM - SS 2023

1 INTRODUCTION

When building a structure, segmentation into smaller elements can provide various advantages for the building process. Depending on the chosen degree of decomposition, elements can be fabricated off-site, then moved, lifted and set in to position at the construction site in an efficient manner. Assembled, the individual pieces must then form a state of equilibrium. To achieve this, significant attention must be given to the way how individual components connect and their individual load bearing behaviors.

Mortar or glue are fairly simple types of connections, but as they are not reversible actions and hard to adjust, they don't fulfill today's need for buildings to be disassembled again into reusable parts and separated according to their materials. Mechanical joints often lead to intricate design requirements and can incur high costs. Their assembly also requires skilled and experienced workforce.

When seeking simple, but efficient and reversible connections for structures assembled from discrete elements, interlocking form-fitting and force-locking connections emerge as a reasonable solution. These connections involve precisely fitting individual components together without the need for permanent adhesives like mortar or glue. Instead, they rely on interlocking, friction, and other mechanical means to achieve stability, optimal blocking elements from all movement in linear or rotational direction.

In addition, the behavior of assemblies and individual elements can be manipulated through the introduction of intentional voids. Through the removal of mass from solids, the center of gravity can be shifted in order to achieve equilibrium. This subtractive operation would be performed in a digital model first and could be then applied to real world material like stones by carving and milling the material, which is often the case in recent work. However, subtractive manufacturing limits the possibilities of the geometric complexity in order to be efficient. Additive manufacturing could be implemented to further explore possible this topic, as it can produce highly complex elements with complex internal structures that could be even fully enclosed in each element.

This work first introduces basics about the topic of stereotomy, mass shifting through intentional voids and interlocking structures. Next, important recent work and publications about the topic will be presented. In the last part of this work, a method for analyzing and manipulation of the center of gravity of solids and assemblies will be investigated and illustrated with multiple demonstrations. In addition, a method for establishing interlocking behavior at contact faces of discrete elements will be shown. The results will then be evaluated and summarized. Furthermore, the next steps for future research are going to be pointed out and will be discussed.

CONTENT

2 THEREOTICAL FRAMEWORK

2.1 Stereotomy

Stereotomy, derived from the Greek words "stereos" (meaning solid) and "tome" (meaning cutting), is a discipline that represents the seamless union of geometry and construction. At its core, stereotomy involves the art of cutting stones (or solids in general) with precision to create intricate architectural structures when assembled, such as vaulted ceilings and complex facades. This intriguing craft serves as a crucial link between theoretical geometric principles and their practical implementation in the world of construction.

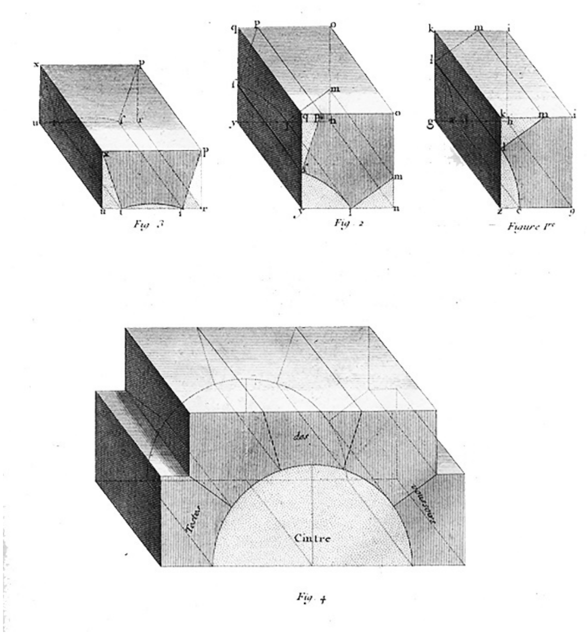


Fig.01. Voussoirs cut from rectangular blocks of stone.

The origins of stereotomy can be traced back to ancient civilizations, where skilled artisans and craftsmen used stone-cutting techniques to construct awe-inspiring monuments and buildings. The practice evolved over centuries, with notable advancements in the Gothic period, especially in France and Spain (FALLACARA 2009: P. 554). Reaching its peak during the sixteenth century until the eighteenth century with daring and intricate vaults and arches made out of stones, the concept of stereotomy as a scientific subject area was developed and was subsequently also introduced at the beginning of the nineteenth century in the schools of the *Ecole des Beaux-Arts* and the *Ecole Polytechnique* in France as an academic field (: P. 553).

One of the key aspects of stereotomy is its focus on the relationship between form and structure, in this case a structure that needs to be decomposed into smaller elements (DEFILIPPIS 2006, P. 951). This understanding is crucial to ensure the stability and longevity of the architectural structures created through stereotomic principles. A variety of reasons can have influence why and how a structure should be segmented into smaller pieces. Structures like the Salginatobel Bridge utilize this in a clever way. Its structural behavior would be in an indeterminate state to the engineer, if it would not be segmented into two elements forming a three-hinged arch (BLOCK ET AL. 2017: P. 108). In general, the decomposition of building parts is of great importance, as elements can then be fabricated easier off-site in sizes that don't exceed the maximum dimensions of a 3D-Printer for example or a milling machine. Another factor for size and weight of elements would be then the transportation options to the building site and the possible options for lifting and positioning of elements.

The exact forms of each of those parts (also called *ashlars* for walls or *voussoirs* for arches and vaults) and their surfaces to adjacent components is a fundamental concept of the stereotomic process. This involves not only determining the optimal shape and dimensions according to named constraints, it also pursues to achieve equilibrium and structural integrity.

The remarkable construction of the Hotel de Ville in Arles, developed and overseen by architect Jules Hardouin-Mansart in the seventeenth century, could be considered as one of the greatest examples for the implementation of stereotomy, utilizing both structural and aesthetic elements. The vestibule features a unique system of intersecting barrel vaults that create a visually stunning and dynamically engaging space. These vaults are carefully crafted using stone construction techniques that were a hallmark of Mansart's era (Jestaz 2008: P. 89). The use of stone allowed for both structural integrity and aesthetic beauty, accentuating the horizontal joints between the complex stonework. What truly sets these vaults apart is their innovative design and composition. Mansart's vision involved merging two different types of barrel vaults: a larger one that spans the rectangular area of the vestibule and a smaller one that forms an apsidal shape on the perpendicular side. This intersection of vaults creates a captivating play of architectural forms and draws the eye upwards, accentuating the again verticality of the space.

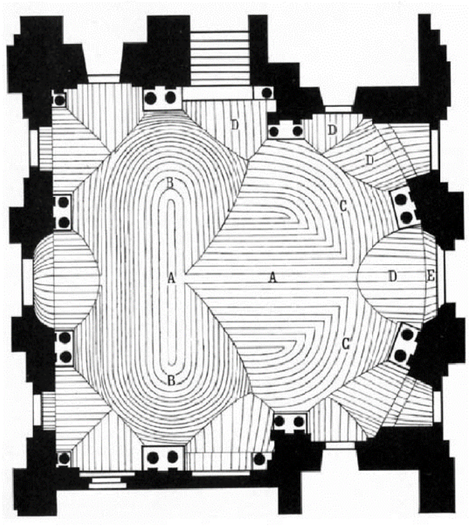


Fig.02. Projection of the ceiling in the Hotel de Ville in Arles, France.

Fig.03. Details of the vaults. The vertical gaps of the stonework were closed with mortar, hence accentuating the horizontality in the structure.

Jules Hardouin-Mansart's mastery of geometric techniques and structural mechanics enabled him to craft architecturally captivating designs, utilizing them for a grand visual and spatial masterpiece.

This delves into the inherent spatial relationship embedded within stereotomy. By viewing stereotomy as a subtractive design instrument, it opens the door to an iterative approach for spatial design (González/D'Acunto 2016: p. 178). This is described by Francesco Cacciatore with his approach for a definition of stereotomy, which further broadens its relationship to architecture*: "the term stereotomic, from the Greek stereos (solid) and tomia (cut), introduces an idea of building, which is not conceived as the assemblage and juxtaposition of elements typical of the tectonic approach, but rather as the gradual removal of matter from an initial shape".* (Cacciatore 2011: p. 27). What is left after generating voids within a solid would be then what is our architectural or structural goal. More on this in Chapter 2.3 – Intentional Voids.

While stereotomy experienced its peak during the Renaissance and Baroque periods, its principles are not practiced in modern architecture and construction. However, this elegant subject returned to universities and is now again discussed in the academic field. In recent years, with the advent of digital technologies and computational tools, stereotomy has experienced a revival. Three-dimensional modeling and parametric design have opened up new possibilities for exploring complex geometries and pushing the boundaries of architectural expression. Today's research aims is to demonstrate that stereotomy's coherence extends beyond being merely educational; it is vital to unlocking new design solutions where geometry, aesthetics, and construction form different facets of the same concept, all developed simultaneously within the project.

Tremendous work with real life applications in this field has been made by architect and professor at the Politecnico di Bari Giuseppe Fallacara, the team of Block Research Group from ETH Zürich and Brandon Clifford, associate professor at the Massachusetts Institute of Technology. This rising interest and the contributions from those and other researches around the world contribute to extend the subject of stereotomy in combination with digital design procedures and fabrication. Most of those projects rely still on the subtractive fabrication process for the ashlars, but possible ways of implementing additive manufacturing has also already caught a lot of interest in the community and first demonstrations of 3D printed discrete element assemblies have been produced, like the Striatus Bridge Project (Block Research Group, 2021).

Fig.04. The Armadillo Vault – A grand piece of modern application of stereotomic principles using CAD and CAM by the Block Research Group.

2.2 Interlocking Behavior

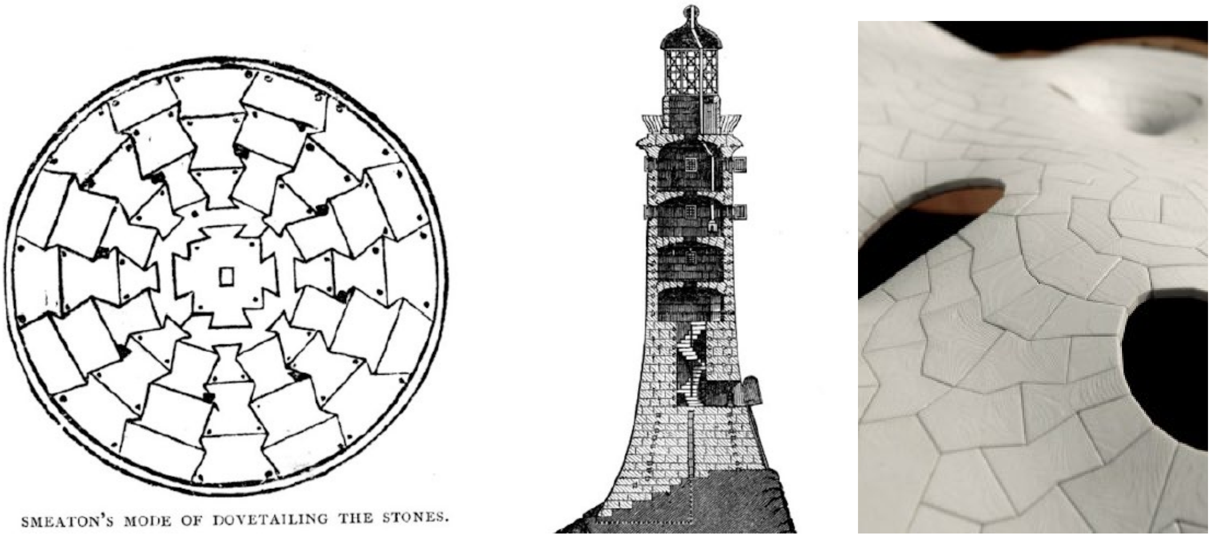


Fig.05. Dovetailing of granite blocks for John Smeatons famous Eddystone lighthouse. In comparison to that, on the right a detail of the "MLK Jr. Park Vault" by Phillipe Block and Matthias Rippmann.

Elements in a compression-only-assembly will stay in place if the contact surfaces of the adjacent voussoirs are orthogonal to thrust. Utilizing the friction of contacting surfaces through a force-locking connection, movement can already be constrained. To improve the connection, instead of flat facets, a three-dimensional interlocking should be favored to create also a form-fitting connection, blocking elements from all movement in linear or rotational direction. This can be achieved for example through dovetailing or a tongue and groove joints, which establish a female and male part of the connection. But even the elements themselves can morph into interlocking geometries, as shown in Fig. 05. Like a puzzle, this introduces also guidance for the assembly, as the joint geometry can give clear hints how discrete elements should be connected and therefore reduces risk of mistakes when developing complicated structures.

Further advantages of glue- and mortarless form-fitting and force-locking connections are numerous. First and foremost, they allow for easy disassembly and reusability of building elements. This feature aligns perfectly with the growing demand for sustainable and environmentally friendly construction practices. By enabling the separation of components based on their materials, these connections facilitate the recycling and reintegration of building parts, reducing waste and conserving resources.

Additionally, mortarless connections promote efficient off-site fabrication. Since the components can be pre-fabricated with precision, construction time on-site is significantly reduced. The assembly process becomes quicker, requiring fewer resources and manpower, ultimately leading to cost savings for the project. Moreover, these connections ensure structural integrity and safety. When correctly designed and executed, form-fit connections provide robust load-bearing capabilities, contributing to the overall stability and durability of the building.

In terms of maintenance, jointed formfitting connections are advantageous as well. Unlike traditional adhesives or mechanical joints that may degrade over time, these connections maintain their strength and reliability for extended periods, reducing the need for frequent repairs or replacements.

Finally, form-fitting connections are fairly easy to assemble, certain examples like the dome of the Tbilisi Sports Palace in Georgia were even build without the use of falsework, assembled out of 480 elements, forming ten concentric rings. While the design of such interlocking components may demand precise detailing, the assembly process does not necessarily require highly specialized workforces, making them accessible for a broader range of construction applications.

In conclusion, adopting dry form-fit connections in building construction presents a host of advantages, including sustainability, cost-efficiency, design flexibility, assembly and maintenance awareness, all while contributing to a more environmentally conscious and forward-looking construction industry.

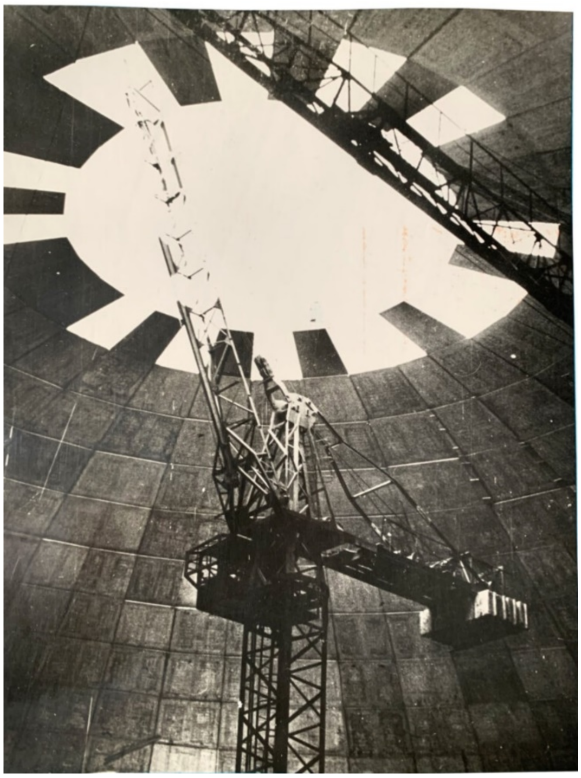


Fig.06. Construction of the Tbilisi Sports Palace. The 480 reinforced concrete slabs were assembled in 32 work days with two cranes.

2.3 Intentional Voids

As stated before, the stereotomic process can bee described as "*the gradual removal of matter from an initial shape*" (Cacciatore 2011). This approach was further explored in the work of Juan José Castellón González and Pierluigi D'Acunto with their proposal in "Stereotomic Models In Architecture - A Generative Design Method to Integrate Spatial and Structural Parameters Through the Application of Subtractive Operations".

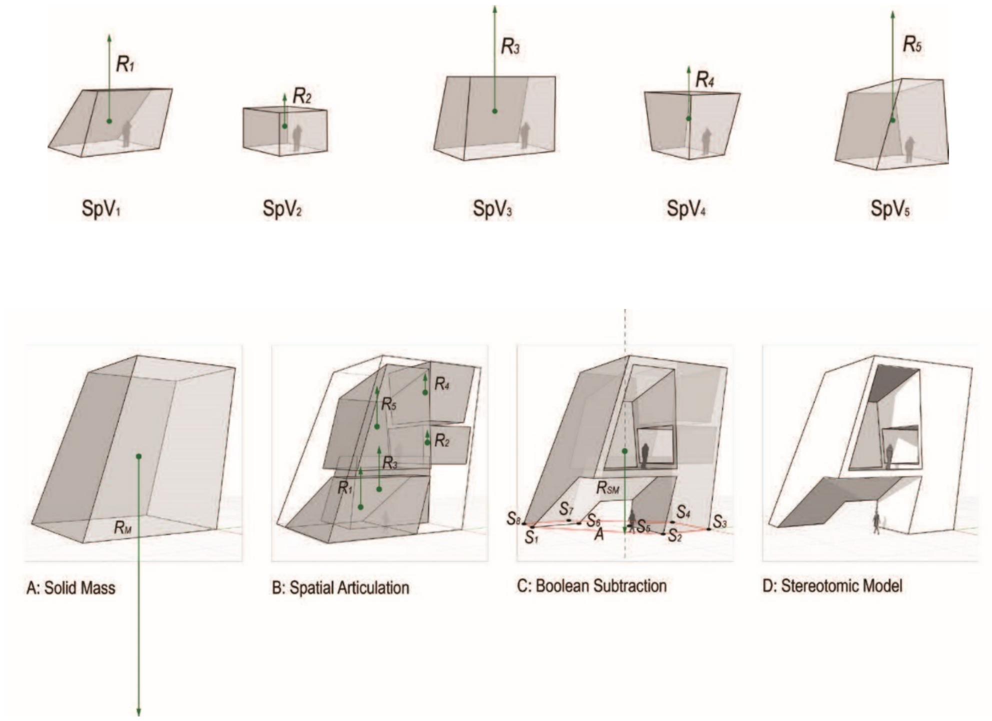


Fig.07. Proposal by González and D'Acunto for integrating spatial and structural parameters in a subtractive operational framework in order to generate "Stereotomic Models"

In order to generate and explore variations of spatial designs in a conceptual phase that already integrates structural parameters, they developed a step-by-step process, that also works in a non-linear way, reiterating over the design:

1. Generation of Stereotomic Model: The authors propose starting with an initial solid mass and then defining and adjusting interior spaces as spatial voids. These voids are subtracted from the solid mass, resulting in a three-dimensional poché – a composition of solid and void spaces.

2. Evaluation of Static Stability: The authors emphasize the importance of ensuring the static stability of the design. They introduce a force-based analysis, considering the weights of the solid mass and spatial voids. The arrangement of voids within the solid mass impacts the distribution of forces, and adjustments are made to ensure equilibrium and prevent overturning.

3. Hierarchical Iteration: The authors advocate for iterative design based on the generated stereotomic model. Additional secondary spatial voids can be introduced within the existing poché to create hierarchical porosity and refine the spatial configuration. The process involves repeated Boolean subtraction operations and evaluations of static stability.

This approach focuses on creating monolithic and compact forms through the gradual removal of matter, resulting in unique spatial qualities and structural stability. Material and fabrication is not considered yet in this process. The method encourages a dynamic interplay between solid and void, offering a framework for generating intricate architectural designs with careful consideration of both spatial and structural parameters. It also seeks to extend the definitions and capabilities of stereotomy, linking it to the work of Louis Kahn, who states: *"In Gothic times, architects built in solid stone. Now we can build with hollow stones (...) The desire to express voids positively in the design of the structure is evidenced by the growing interest and work in the development of spatial frames." (Cacciatore 2011: P. 15).*

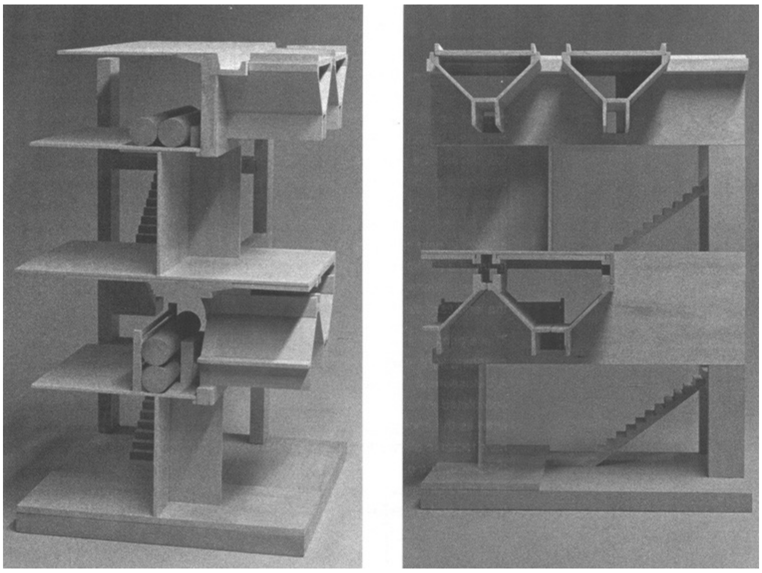


Fig.08. Hollow Structures - Salk Institute Laboratories. La Jolla. 1959-65. Physical Model.

As the authors propose, a hierarchy of the operational framework must be established and spaces are divided in served and serving spaces. Kahn's innovative approach involved treating structural elements as hollow systems, generating secondary spaces within them. This allowed for the incorporation of mechanical systems and functional elements, addressing both spatial and structural aspects in one integral solution. Kahn challenged conventional solid walls, creating inhabitable hollow structures that enabled various programmatic relationships and lighting conditions. His designs, like the Salk Institute Laboratories, showcased the fusion of spatial and structural considerations. By intentionally introducing voids, Kahn redistributed material and internal force-flow, demonstrating a holistic approach to architectural design. This concept of structural porosity offers opportunities for contemporary design methods that integrate space and structure.

3 State of the Art – Current Research

3.1 Quarra Cairn – Mass Shifting and Carving

The project explores the challenges of maintaining stability during the construction of stone structures by shifting their center of mass through material removal, aiming to achieve equilibrium at each stage of assembly. Drawing inspiration from Gaudí's work, as well as advancements by researchers like Frei Otto and The Block Research Group, this investigation utilizes computational techniques to optimize mass distribution while preserving external geometry (CLIFFORD 2017: P. 652). Through methods like shape deformation and mass carving, the project ensures that the center of gravity remains within the base support, ultimately contributing to a deeper understanding of structural equilibrium during construction, with potential applications in enhancing the stability of complex architectural forms. Each element was milled from stone, leading to special constraints that impacted the design process (: P. 652).

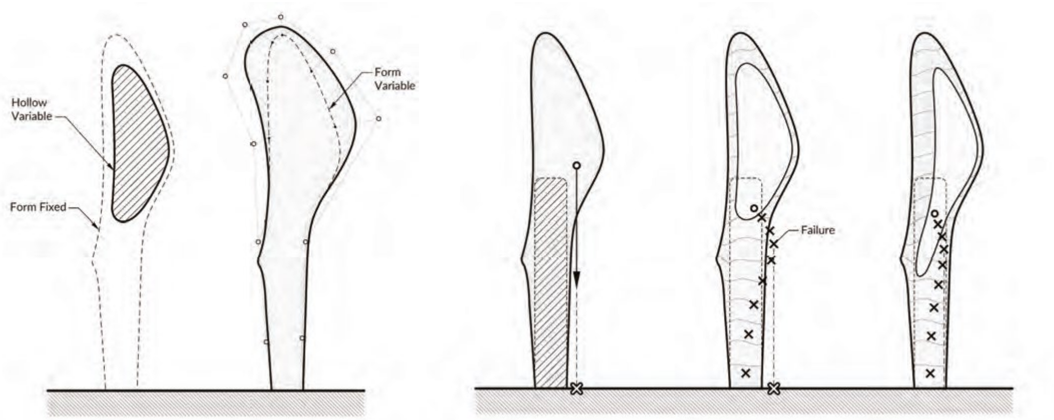


Fig.09. Left: Comparison of the mass-carving and mass-shifting in order to manipulate the balance of an object.
Right: In order to achieve incremental stability throughout the assembly, mass is shifting again.

This innovative approach challenges the notion of stability by showcasing how calculated adjustments to the center of mass through material removal could lead to equilibrium, even in instances where the form seemed inherently unstable. The exploration of stability as an incremental puzzle during assembly, along with the interplay of geometry and forces, presents a fascinating insight and contributes to the discussion about digital applications in the stereotomic approach.

3.2 Decomposing Three-Dimensional Shapes

The research paper titled "Decomposing Three-Dimensional Shapes into Self-supporting, Discrete-Element Assemblies" by Ursula Frick, Tom Van Mele, and Philippe Block, presented at a conference in October 2015, explores a novel computational design approach to generate volumetric decompositions of arbitrary three-dimensional shapes into self-supporting, discrete-element assemblies. These assemblies are structurally stable due to compressive and frictional contact forces between individual elements, eliminating the need for complex mechanical connections, glue or even interlocking geometries. However is only the case when fully assembled, as incremental stability was not a desired outcome of this research (FRICK ET AL. 2016: 194).

The study introduces a prototypical decomposition tool integrated into CAD software, allowing user-controlled design to create such assemblies. The interactive design environment offers real-time visual feedback, enabling exploration and expansion of the design space for self-supporting block assemblies. Surprising and innovative results emerged from these explorations, revealing the potential to achieve equilibrium in unconventional ways.

The relevance of this project lies in its implications for various fields, including the building industry and architectural design. Volumetric decomposition simplifies fabrication, transport, and assembly of complex structures. By focusing on stability through geometry and interactions, the research challenges traditional construction methods and offers insights into more efficient, cost-effective, and sustainable building processes, that could emerge with further exploration and optimization, paving the way for advancements in architectural design and structural engineering.

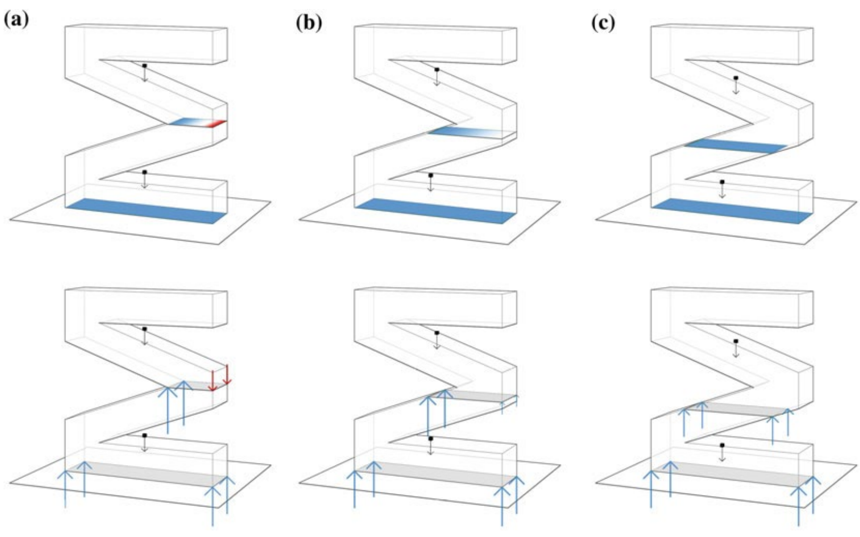


Fig.10. In order to eliminate tension forces and therefore lifting of the part in that area (a), the location of the dissecting interface is shifted (b, c).

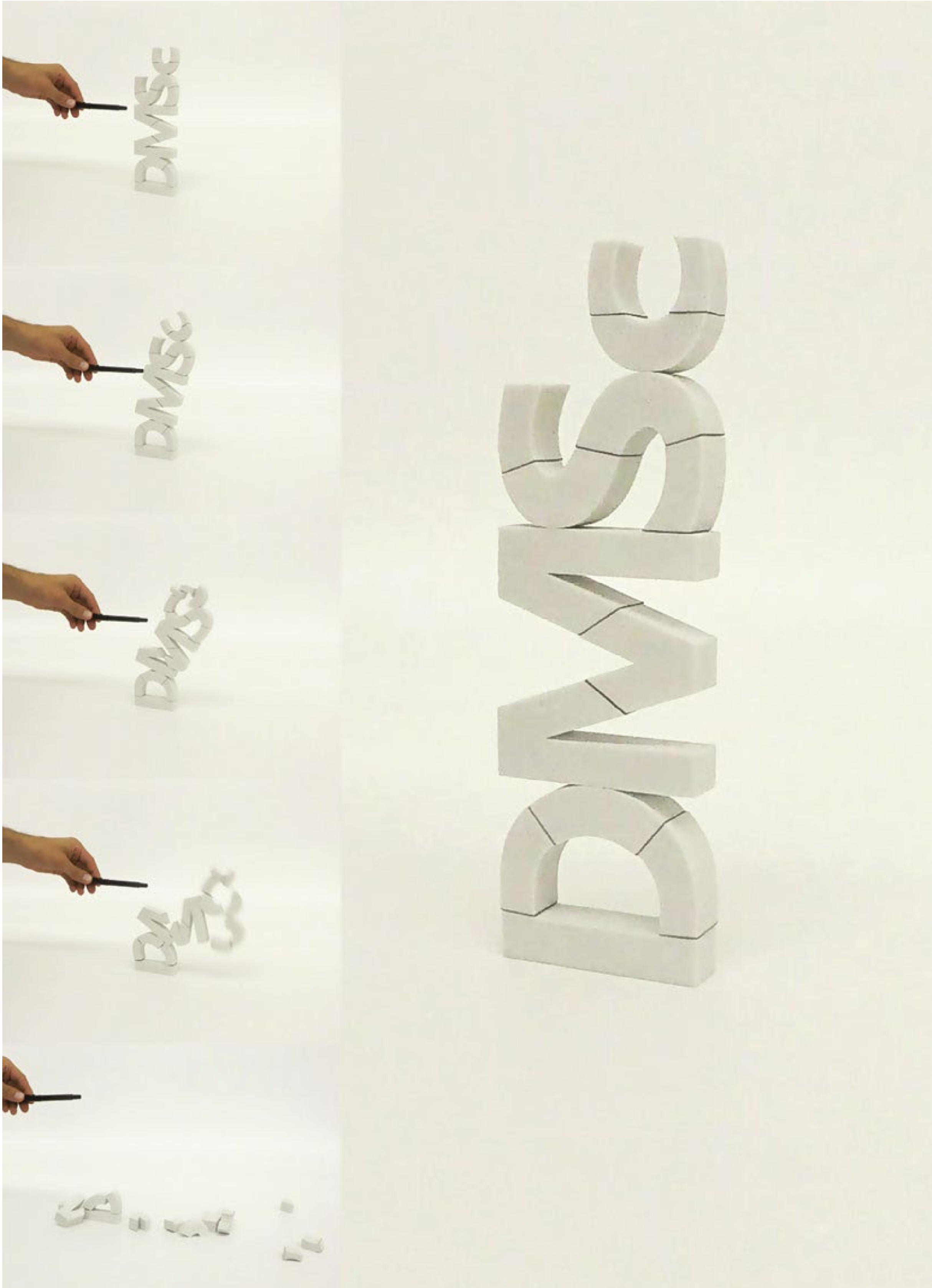


Fig.11. The method relies in friction, balance and arching in order to create (fragile) equilibrium of the assembly.

4 Design Project

4.1 Project Goal

The goal of this project is to generate voids in an otherwise unstable 3-dimensional body that follow a hierarchy, establishing stability of said body (CASTELLON/D'ACUNTO 2016: P. 179). Through shifting the voids in and around the solids, balance should be restored, also during the assembly and stacking of elements. Although not fixated on this topic, the method suggests the use of additive manufacturing to achieve hollow bodies containing voids that are possible fully enclosed. By merging the mentioned techniques of Ursula Frick and Brandon Clifford, a synergistic method is formed, fusing geometric stability principles with basic structural analysis to enhance overall performance.

4.2 Method

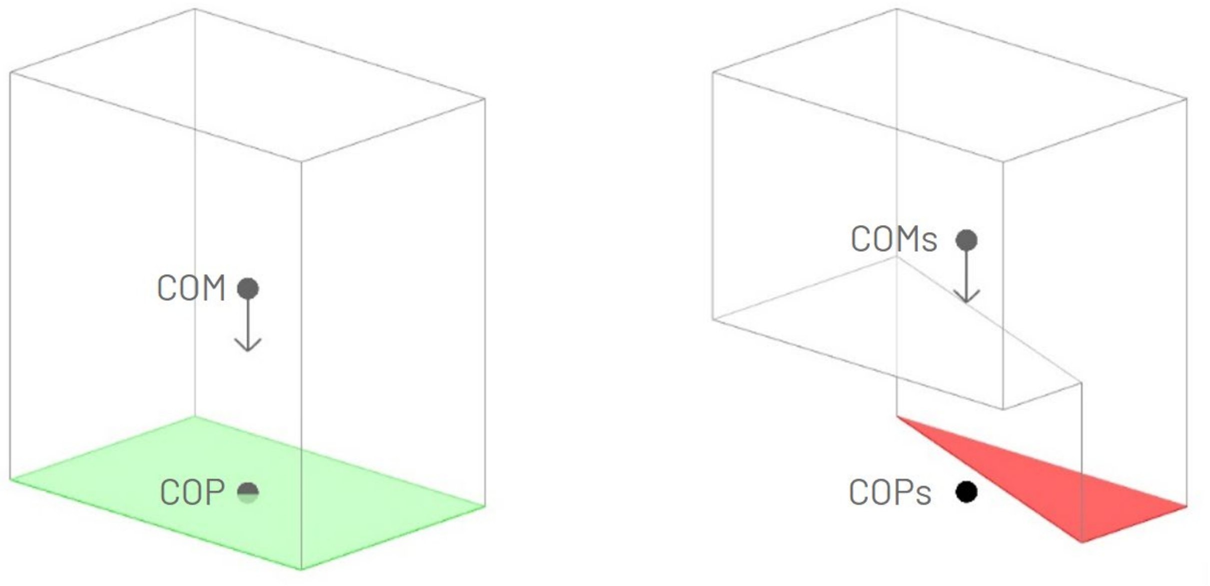


Fig.12. Through the removal of mass, the balance can be shifted, in this case creating an unstable body.

In order to manipulate balance, the center of mass (COM) of a given body must be known. Through the removal of mass, this position of the distribution of weight can be shifted. In order to determine if the body is stable, a line can be imagined that will follow earths gravitational pull downwards, starting at the the COM. A center of pressure (COP) would be the exact point, where this line would intersect a support base, hence the COP is always under the COM of a body. If the COP is within the base support of a body, its contact surface to the ground or inside of the perimeter of multiple contact faces to the ground, the object will be in balance (CLIFFORD 2017: P. 651).

In order to check for this state, using the software Rhino 3D and implementing the Grasshopper Plugin, the COM of a 3D-object can be reliable computed and visualized. At the same time, voids can be generated and the shift in the COM visualized. If the projected COP is within in the support area of the object, the support are will be colored green to indicate equilibrium, otherwise it will be colored red through a check with a python script component.

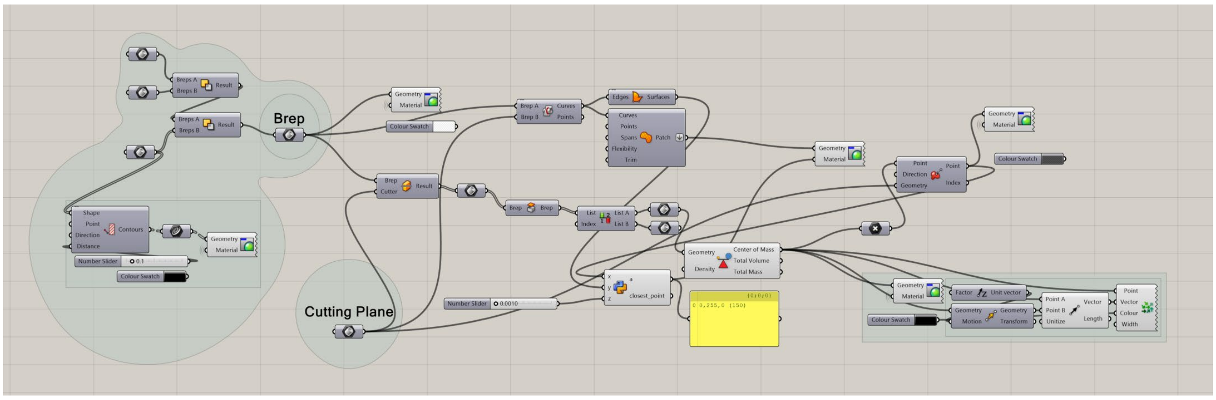


Fig.13. Grasshopper environment for generating the voids in a given object, COM, COP and check of equilibrium.

Through manual placement of planes, segmentation into smaller pieces of the object can be simulated. In order to achieve maximum stability, faces where decomposition of the bodies will occur should also be arranged in a way, that the COP of the elements carried by that contact face is again in that given area. In addition, the cutting plane should be placed in consideration of the (assumed) force flow, optimal orthogonal to the thrust. Furthermore interlocking mechanisms of elements should be established. A series of grasshopper and python components identifies the contact faces and perform multiple actions that will generate undulated surfaces.

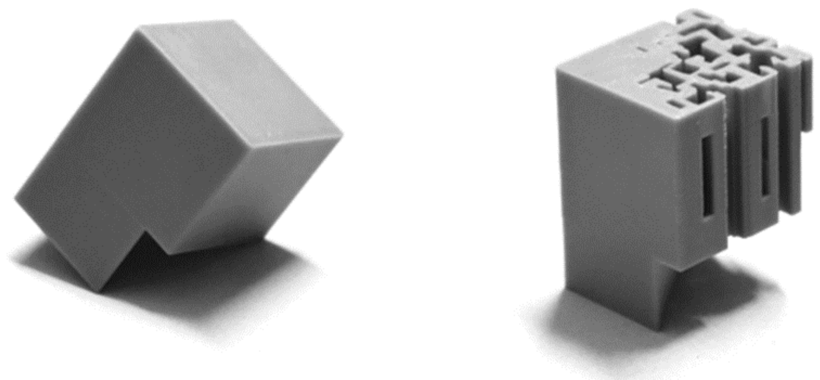


Fig.14. Example 1 – The cantilevering cuboid, that was generated with the method and tested through 3D-Printing.

4.3 Examples

4.3.1 Cantilevering cuboid

Through the removal of a large part oft he supporting material of a cuboid, the center of mass was shifted and the projected center of pressure is located outside of the support area of the geometry. The geometry is nonstable, shifting immediately towards the COP and tilting subsequently. Trough an iterative process of simulated mass removal by adding geometries that will generate the voids through boolean subtractive operations, the COM and hence the COP is shifted again, making the structure stable again. The cubature and appearance of the body was modified purposely by these operations, to illustrate the method.

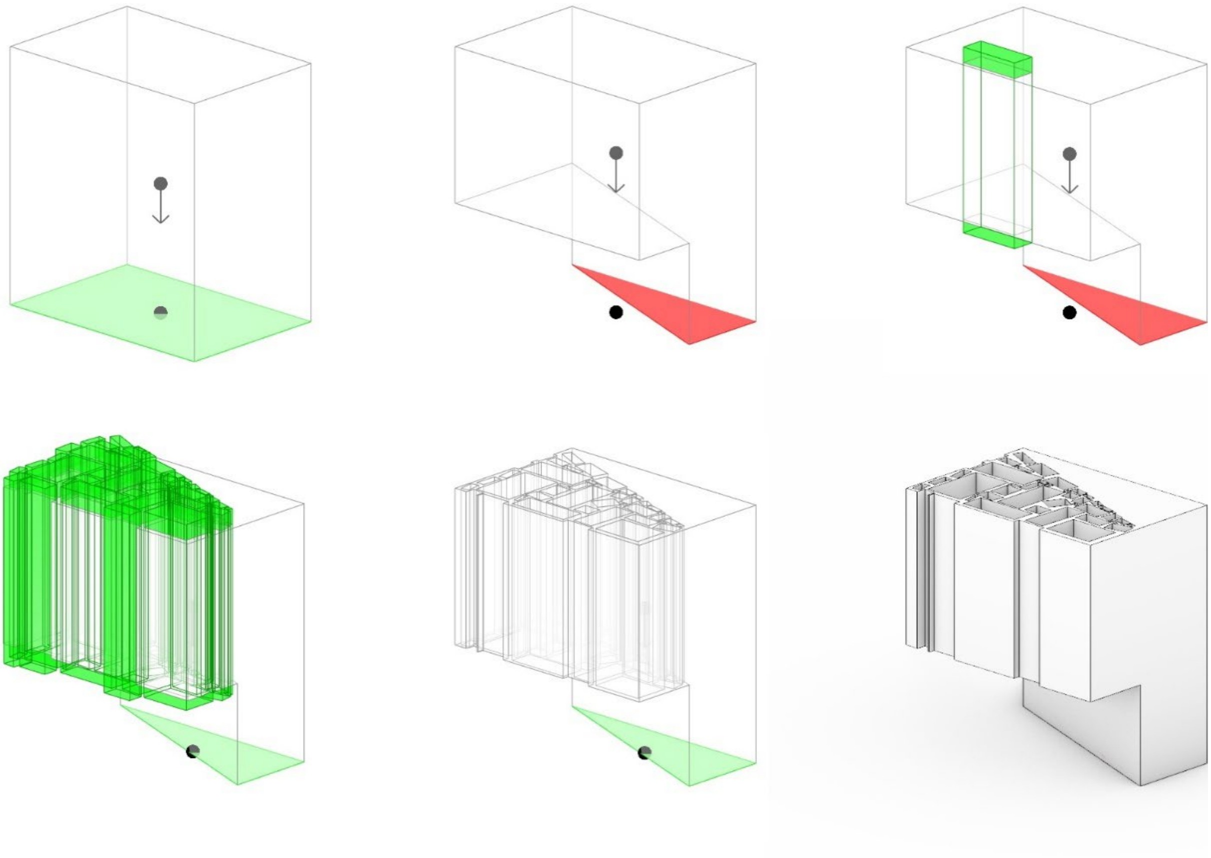


Fig.15. Stepwise the COM and COP will be analyzed and voids will be generated that will shift the balance.

4.3.2 Implementing decomposition

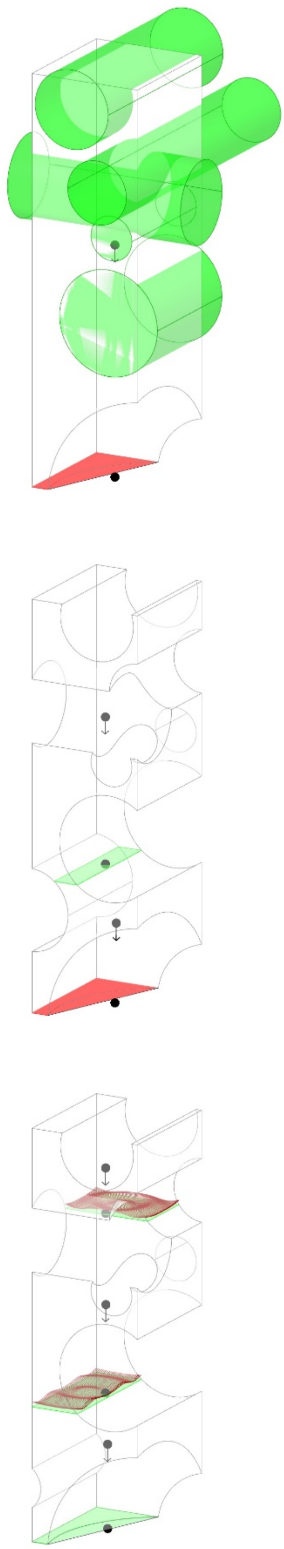


Fig.16. In addition to the shifting of mass, decomposition and interlocking contact areas are introduced.

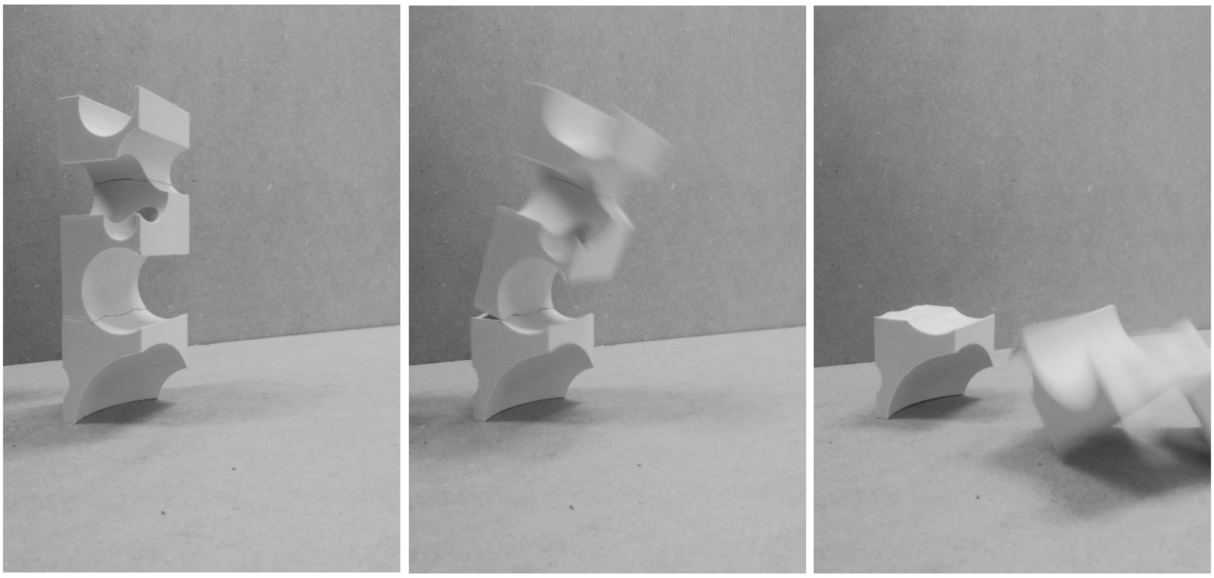


Fig.17. The three stacked elements are stable – until a slight horizontal force is applied.

The next important step was to introduce decomposition into the design process, which would use the exact same method for checking the incremental stability of the assembly. In order to stabilize the shifting cuboid, this time cylinders of various sizes were removed from the object, revealing extreme cantilevers in the structure and thin cross-sections. This time the method was not applied in a linear approach, in order to establish equilibrium of the assembly also the positioning of the voids were carefully reconsidered and changed after the decomposition has already started. The contact faces were then identified and through a parametric input curved and interlocking geometries introduced.

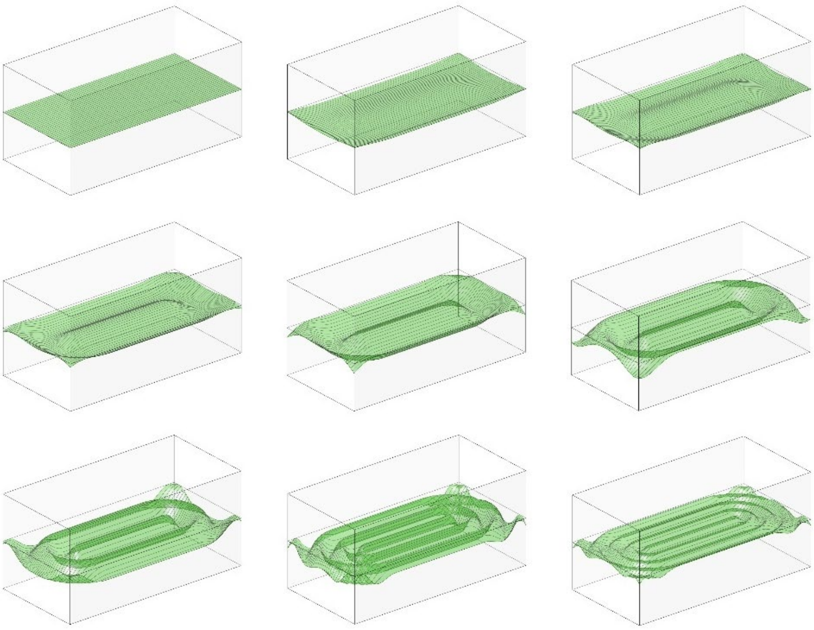


Fig.18. Contact surfaces can be detected and their geometry evaluated. According to that, a parametric workflow is introduced, that will generate rippled three-dimensional surfaces that block movement in linear and rotational directions.

4.3.3 Final Design

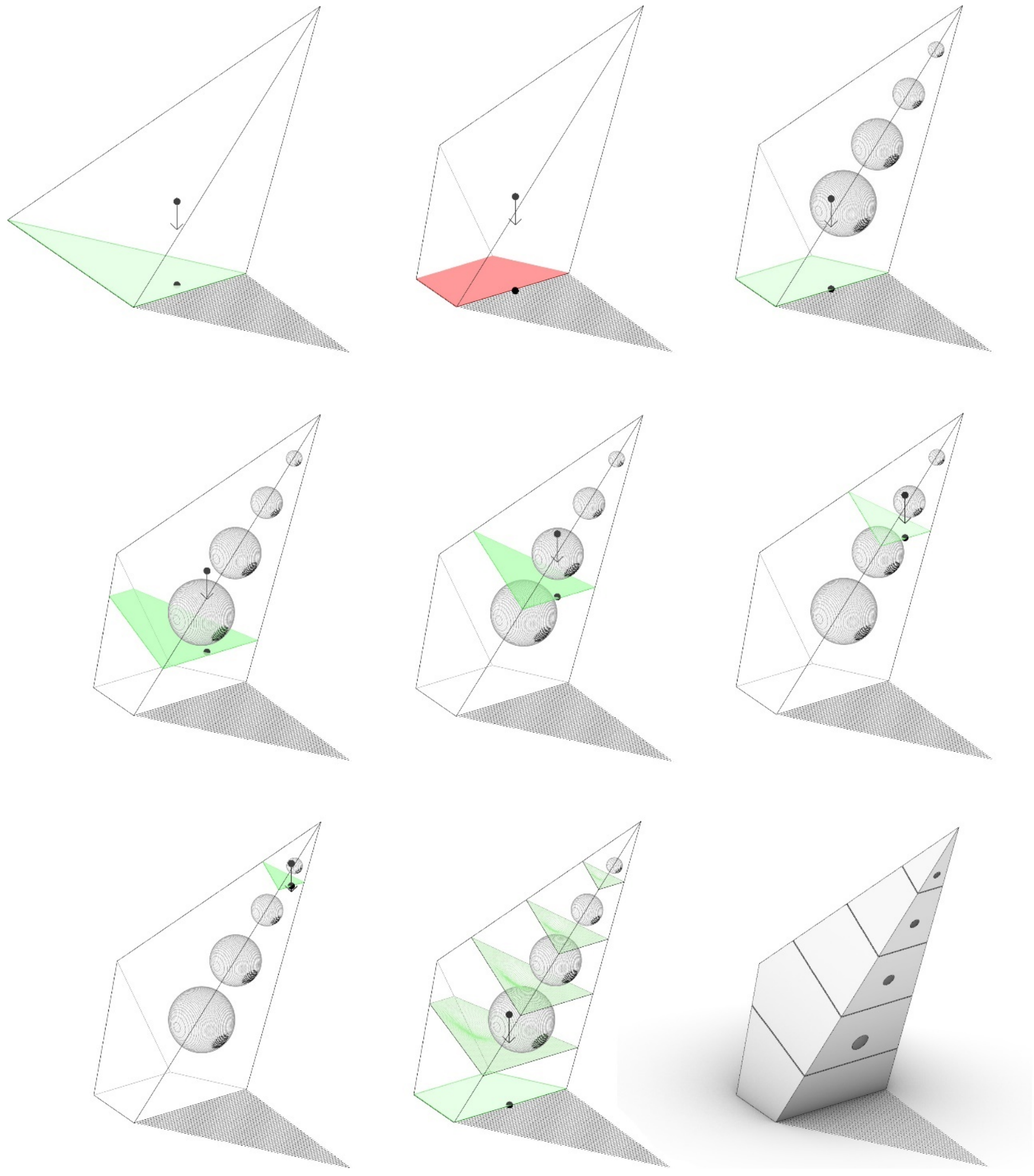


Fig.19. Procedure of the segmentation process, void positioning and generating interlocking contact faces.

In this final example, a leaning structure was generated and the decomposing sequence and sizes of ashlars predetermined. This only left certain spaces for possible voids, differing also in size. After implementing those to the computation, the incremental stability of the process was checked once again and confirmed that equilibrium is achieved at all times. The voids were to be placed completely inside of the geometry. However, for illustration purposes a penetration at the faces was implemented. This traces back to Kahns idea: *Now we can build with hollow stones (…) (CACCIATORE 2011).*

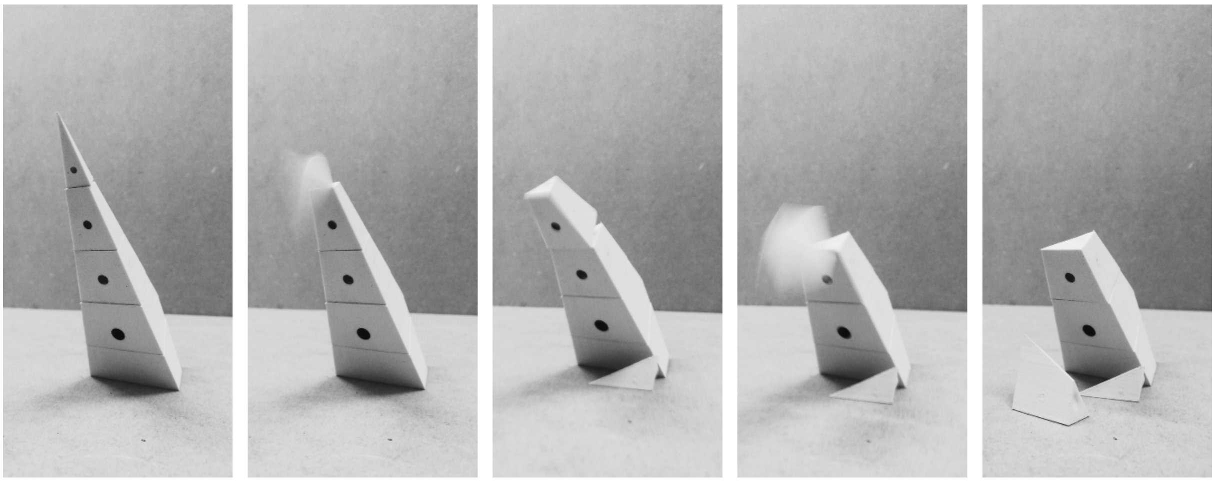


Fig.20. Incremental stability during the assembly is ensured, when horizontal thrust is introduced, the ashlars falls one by one down.

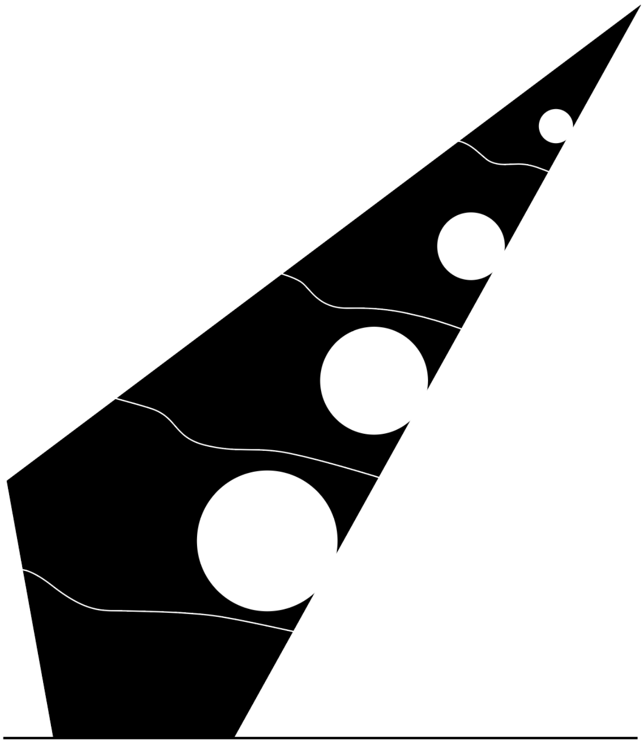


Fig.21. Section of the assembly.

5 Conclusion

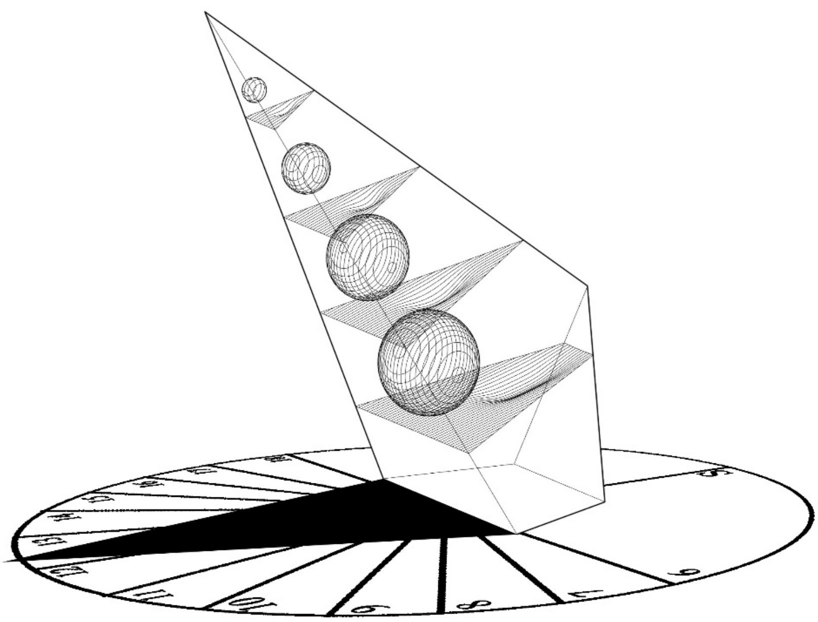
Stereotomy's essence lies in the interplay between form and structure, dictating the strategic decomposition of architectural elements. In this endeavor, intentional voids play a pivotal role, as illustrated by González and D'Acunto's generative design method. By iteratively projecting and shifting voids within solids, equilibrium and stability are achieved, effectively intertwining spatial and structural considerations. This approach aligns with Louis Kahn's concept of integrating structural porosity, forging a dynamic relationship between void and mass. Combining this process with a similar decomposition strategy as in the work of Ursula Frick and other projects of the Block Research Group suggested, a broad set of possibilities for future work is set. By implementing interlocking mechanisms, this can be further advanced. The *Quarra Cairn*, a sculpture created by Brandon Clifford already proves this method in a stunning way. The presented own work of the author endeavors further into that process.

However, the creation of compression only constructions often rely on complicated falsework, this could not be reproduced without that need for now. There is also a high need for detailing and complex forethoughts and structural analysis must be done, leading to a intricate design process. Structures like the Quarra Cairn also demonstrate, that the need for additional support is still the case, as the sculpture in this example is also post-tensioned (CLIFFORD 2017: P. 657).

Modern explorations in stereotomy, spurred by digital technologies and additive manufacturing, can reignite its relevance to the building industry and academia. The marriage of computational tools and age-old craftsmanship not only propels architectural expression to new heights but also champions sustainability, efficiency, and holistic design.

6 Further Steps

Further explorations in the realm of digital stereotomy can encompass a range of avenues that can harness the potential of modern technologies. Advanced digital tools would set the base for these endeavors, making it easier to understand and react to the structural relationship of form-finding. Exploring new materials and fabrication techniques can expand the possibilities of stereotomic construction, especially 3D-Printing. It offers the potential to create intricate and customized stone elements with reduced waste, while also allowing for the integration of complex interlocking mechanisms and encapsulated voids. In addition to this, the implementation of post-tensioning can be beneficial, as it allows for the efficient redistribution of structural forces, enabling the creation of intricate stereotomic forms while ensuring optimal load-bearing capacity and stability and should be a topic of interest for further research.



7 References

7.1 Pictures

Fig.01. De La Rue, Traitè de la Coupe des Pierres [1728], pl. IX, biais par teste par équarissement

Fig.02. Orthogonal Projection of the Ceiling, Hôtel de, Arles France, from: Vocabulaire de l'architecture. Principes d'analyse scientifique, 1972, Chapter IX, 57

Fig.03. ©Mbzt, Wikipedia Commons CC BY 3.0 (https://commons.wikimedia.org/wiki/File:Arles-H%C3%B4tel_de_ville-bjs180820-02.jpg)

Fig.04. Armadillo Vault, Venice, Italy - Block Research Group, 2016

Fig.05. Trinity House Corporation (https://www.trinityhouse.co.uk/lighthouses-and-lightvessels/eddystone-lighthouse)
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Fig.06. González, Juan José Castellón; D'Acunto, Pierluigi (2016): Stereotomic Models In Architecture - A Generative Design Method to Integrate Spatial and Structural Parameters Through the Application of Subtractive Operations. In: Proceedings of the International Conference on Computer Aided Architectural Design, Budapest (Hungary), P. 179-180.

Fig.07. Davit Kajaia – Personal Archive (https://taa.net.ge/en/archive-geo/tbilisi-sports-palace/)

Fig.08. Physical Model of the Salk Institute Laboratories. From: Stereotomic Models in Architecture, DISS. ETH NO. 24793, Juan José Castellón González, 2017.

Fig.09. Clifford, Brandon (2017): "Quarra Cairn: Incremental Stability Through Shifting and Removal of Mass", in: ACADIA 2017 – Disciplines and Disruption, Massachusetts (USA), 650-659.

Fig.10. Frick, U., Van Mele, T., & Block, P. (2015).

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7.2 Literature

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