Reconfigurable architecture for a compression-only structure

LOG BLOCK

Tutors:
Design: Roel van de Pas
Research: Pirouz Nourian
Building technology: Hubert van der Meel

Student:
Leticija Aleksandra Petrova | 5306345

Delft university of Technology, | Explore lab 2021-2022

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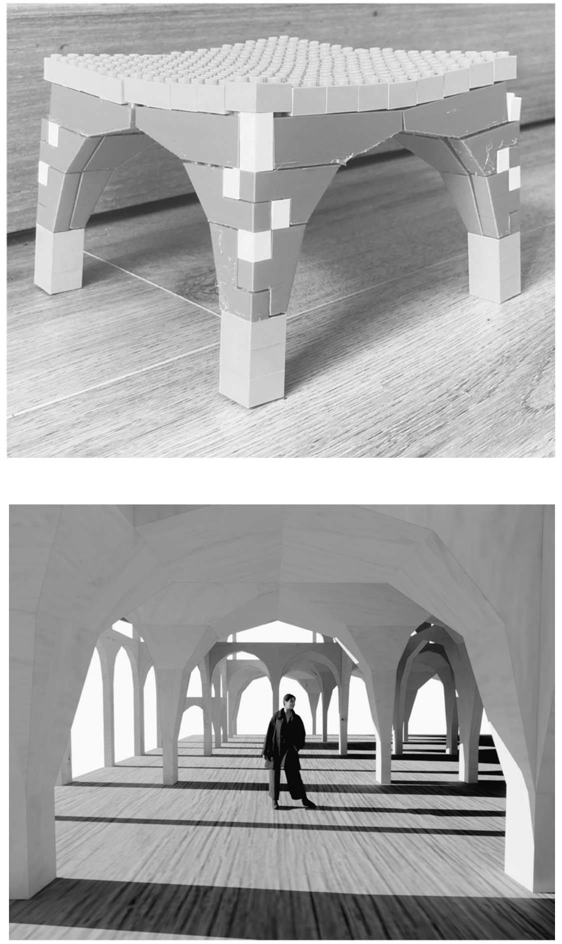


Figure 1: Vault prototype and render images, by Author

1. ABSTRACT

The standard way of building consists on average of 7000 parts and processes which in combination with the decrease in productivity within the construction sector limits the number of actors that can be involved. However, this leads to a housing shortage in many countries. The production of homes should be accessible, affordable and should offer a variety of housing solutions. In order to reach this the production chain of architecture must be rethought by considering design and production throughout the whole process. Modularity of discrete building blocks can be a way to reach efficient production processes as well as diverse housing solutions by means of combinatorial variations. This method has been used in pavilion and furniture designs, but only briefly for housing solutions, mostly the main references can be found in game design – such as Lego. The goal of this research is to devise a methodology to design a small set of stackable timber elements to form both a structure and the inner shells of a building that can be configured into versatile and affordable housing units using combinatorial design and compression-only structures (which is designed based on equilibrium). This leads to an accessible and open-ended building system that strives to be as simple as laying out a Lego structure.

2. BACKGROUND

On average buildings consist of "more than 7000 different parts and processes which need to be assembled together into a functional whole." (Burry et al., 2020) Additionally to the complicated system that a building is, "the construction industry has flat-lined since 1947"(Burry et al., 2020), while manufacturing has increased its productivity with the means of automation (McKinsey, 2017). With labour costs increasing and robot costs decreasing the so-called 'Automation Gap' (Claypool, 2019) decreases the productivity within the construction industry over time. The construction process is slow, expensive and produces a lot of waste (Eurostat, 2018) with only a few actors being able to construct, which evidently limits the supply of housing. Due to the housing shortage, there has been a wider interest in Modularity and Prefabrication. However, for example, the Modernist kit of parts (see figure 2) misses the scalability opportunity due to the variety of forces that are working on the structure as well as it misses variety and flexibility due to the fixed column heights once the building is built.

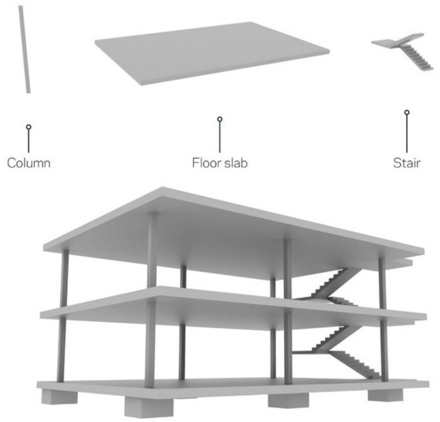


Figure 2: Maison Dom-ino. Image: Ivo Tedbury, Semblr, Unit 19/DCL, 2017.

Overall, with the housing shortage (Groot et al, 2021), the decreasing productivity within construction and the lack of variety within the current modular and prefabricated solutions a new way of thinking about the production chain in architecture is necessary. A method needs to be established to be able to design an affordable, a customizable, and an easily automatable & constructable building system. To find an affordable means to achieve different design solutions with a predefined set of building blocks a modular generative design framework (Azadi & Nourian, 2021) is used, that mathematically formulates the spatial configuration problem. The research is an extension of the Lego (Lego.com,2022) logic and the Belgian "Gablok" (Gablok.be, 2022) that is an architectural lego block for walls, both – the game as well as the building company lack pieces that create full architectural interior spaces with walls, floors, ceilings & roofs, which is the addition that this research provides. Combinatorial design and a grid based on the Lego logic are used to evaluate, inform, and improve the variety and spatial design that the parts offer. Serialized parts have always been more affordable than custom components (Sanchez, J., 2020) due to repetition and possibility to mass-produce. Combinatorial design re-considers serial repetition of parts but under a paradigm of combinatorics. (Sanchez, J., 2020) It explores how through patterns variety can be reached whilst still achieving affordable results which allows to create versatile housing solutions yet keep them at lower costs.

3. RELEVANCE

3.1. SOCIETAL RELEVANCE

Due to a very slow and expensive process of construction the act of building is accessible only to a few actors, therefore the housing supply is limited and leads to a housing shortage. Firstly, housing solutions are necessary, for example, in the Netherlands to take control of the situation, "845,000 homes need to be built by 2030" (Lalor, R. (2021)). Secondly, a home is one of the biggest investments in most people's lives where a considerable amount of time is spent, therefore a sense of identity and variety within the housing supply is necessary for user's to be able to customize their spaces. By redefining the spatial configuration problem through mathematics and using combinatorial design enough repetition and low costs can be reached yet also variation within the housing units can be offered. Through intertwining design, fabrication & automation a more accessible and open-ended built environment can be created.

3.2. SCIENTIFIC RELEVANCE

Research in digital design has moved beyond engaging the field not only through sophisticated forms but also through the

politics and economics of fabrication. (Sanchez, 2021) Current discourse moves beyond modularity and prefabrication and demonstrates a higher degree of variability, versatility through only a limited set of building parts. In addition, it goes a step further using these building parts and exploring the possible patterns that can be created and provide variety and differentiation at a lower cost compared to custom made elements. The combination of a predefined set of elements and thinking in patterns is redefining the way how architectural production chains work, however, there is still a gap between these ideas and physical housing solutions. Most work has been done either on different indoor or urban furniture (Retsin, 2019) (Figures 3) or pavilion designs (Retsin, 2017) (Figure 4), only with a few attempts to create a closed space. (Retsin, 2021) (Figure 5 & 6)

(Left to right, top to bottom))Figure 3: Royal Academy of Arts (Retsin, 2019), Figure 4: Tallinn Architecture Biennale Pavilion (Retsin, 2017), Figure 5: House block & Figure 6: robotically assembled dwelling (AUAR, 2021)

However, there have been a few examples from building structures such as the Belgian "Gablok" (Gablok.be, 2022) for wall systems, but the majority of examples can be found within game design such as the Lego (Lego.com, 2022) blocks. "Gablok" has achieved an architectural "Lego" piece that lays walls as easily as a lego structure. (Figure 7)

Figure 7: The gablok insulated block (Gablok.be, 2022)

The strength of the Lego logic is how simple it is to stack the blocks to create a structure and the grid on what all the elements are based on. The grid is rigid enough for everything to fit and create valid structures yet it is small and open enough to not predetermine the final result. (Figure 8)

Figure 8: Lego architectural models of buildings (Schlaudraff, 2021)

The limitation of Lego is the fact that the structures are made to be viewed from the outside similarly as most sculptures. However, in architecture that would only represent the facade. The most important part is the interior space that is created which people can use for living, working etc. Therefore, the missing elements additionally to the walls are ones that create floors, roofs & ceilings in order to create an interior space. The Gablok system shows potential with the wall creation and the lego logic, therefore, there is room for shaping new elements to create complete architectural spaces. This project, firstly, aims to use the ideas of reconfigurable discrete architecture, combinatorial design and compression-only structures to apply them to a limited set of stackable timber elements to reach a large design space and variety within the configurations that the elements offer. Secondly, the goal is to move beyond furniture and pavilions and to provide complete housing structures - create floor, ceiling, and roof elements in addition to the "Gablok" wall system. Thirdly, to create a set of elements that work as smoothly as Lego blocks within the context of housing. Finally, it also needs to provide variety within the solutions offered for clients to have the possibility to customize their homes.

4. OBJECTIVE

4.1. OBJECTIVE

It is challenging to provide affordable high quality housing solutions at a larger scale. Modularity of discrete building blocks can be a way to reach efficient production processes as well as diverse housing solutions by means of combinatorial variations. The design objective of this research is to devise a methodology to find an affordable means to create many housing variations using only a few stackable timber elements that can be mass-produced. Since customised and affordable solutions always seek a balance between variety and repetition the more specific objective is to reconsider serial repetition of stackable timber elements (that act as a structure and an inner shell) using combinatorial design and a compression-only structure, to explore the ways these parts can be designed and reconfigured in different patterns to create spatially valid and versatile housing solutions.

4.2. RESEARCH QUESTION

How to design a small set of stackable timber elements to form both a structure and the inner shell of a building that can be configured into versatile, scalable and affordable housing units using combinatorial design and a compression-only structure?

4.3. SUB QUESTIONS

• How to design a dimension system of the elements that has a strong relation to people's movement, the used material and its production, and the internal configurational logic of a home based on ergonomics?

• How to ensure that architecturally and ergonomically valid and versatile configurations can be realized by using the proposed limited set of construction blocks?

• How to incorporate the manufacturing costs and limitations in the design of the stackable wooden blocks?

• How to ensure that the predefined set of building blocks allows for a scalable structure?

5. SCOPE

This research lies within the field of design computation and aims to develop a method to create a variety of affordable housing solutions with only a few stackable timber elements that can be mass-produced. The outcome of this research is a method that is showcased in the form of a meta level game (a method which can be followed and another solution can be found) which consists of a few stackable timber elements and a set of rules with which the players can create their desired affordable housing solution with the goal being to be able to create a large variety of solutions by just using a few types of blocks.

This research addresses several areas of study: architecture, structural design, design for manufacturing and assembly and combinatorial design. Since in this research the design process is defined as a decision-making process the tools used in this research are mathematical formalisms and methods from Topology and Combinatorics.

This research lies within the realm of design science research (Peffers, Tuunanen, Rothenburger, Chatterjee, 2007) therefore the process is seen as research and development of a computational model and method to reconsider serial repetition of stackable timber elements (that act as structure and inner & outer shells) using combinatorial design and compression only structure. The topics mentioned below are within the scope of this research:

- Computer aided architectural design
- Geometric Design and Tessellation
- Topological Polygonization & Polyhedralization
- Gamification of Generative Design

The topics mentioned below are related to this research, however, fall outside the scope of this research:

- Computational Shape Optimization
- Computational Topology Optimization
- Participatory design
- Spatial configuration

This research focuses on the serial repetition and pattern making out of stackable timber elements and its relation to housing. It ignores aspects such as technical implementation. The aim of this research is to describe a possible direction for further research and not to provide a final solution.

6. PROBLEM STATEMENT

The production of homes should be accessible, affordable and the housing units should offer a broad range of variety how the spaces can be configured and what spatial qualities they offer. This brings to the fact that the standard way of building our homes needs to be changed, instead of 7000 parts and processes a building needs a simpler production chain where the complexity of the process is decreased, and more actors can participate in constructing. The current solutions of modular and prefabricated parts do not offer variety and broad range of customization. This research aims to create a method which allows to design a limited set of stackable timber elements that can be configured into versatile affordable housing units using combinatorial design and compression only structures.

This problem can be broken down into smaller issues/tasks:

1. Defining an underlying grid for the whole system within the context of housing
2. Defining the aggregation logic and the interface between many elements to create a variety of solutions
3. Defining access and structural constraints within the context of housing
4. Defining the structural approach for the building to be scalable and stable
5. Incorporating the limitations and costs of manufacturing within the design of the elements
6. Choosing an element creation approach
7. Adapting final space desired aesthetics to each building block
8. Defining a Meta level game

7. METHODOLOGY

7.1. RESEARCHMETHODOLOGY

This research project is a Research & Development project since it is within the realm of "Sciences of the Artificial". (Simon, 1996) The methodological approach for the framework of this research is based on design science research which is a way of "structuring research methods as a methodology in the context of developing design or "spatial decision support systems" in the more general context of developing information or decision support systems". (Nourian, 2016) (Peffers, Tuunanen, Rothenburger, Chatterjee, 2007) The more specific framework within the realm of design science research partially used in this research project is the "Go design" framework which is a modular generative design framework introduced by Shervin Azadi & Pirouz Nourian. (Azadi & Nourian, 2021) It is a framework for design processes in the built environment and it provides unification of participatory design and optimization to reach mass-customization and evidence-based design. This framework is articulated mathematically through 3 procedures: 1) space-planning, 2) configuring, and 3) shaping. (See figure 9) It frames typical design problems as multi-dimensional, multi-criteria, multi-actor, and multi-value decision-making problems (Azadi & Nourian, 2021) However, in this research only the 2nd (Configuring) and 3rd (Shaping) procedures of the Go Design framework are undergone, the 1st procedure (Planning) is seen as a given.

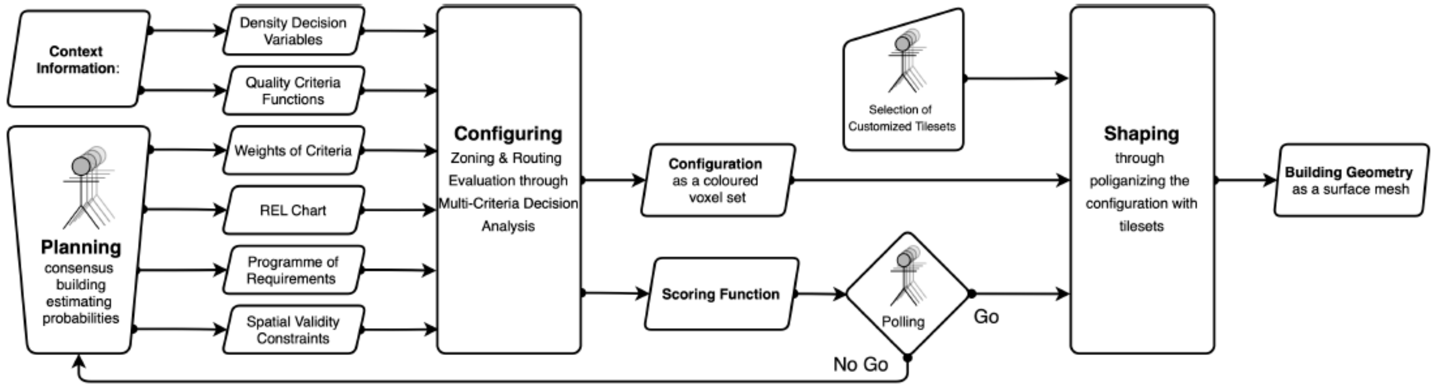


Figure 9: Main flowchart of the Go design framework (Azadi & Nourian, 2021)

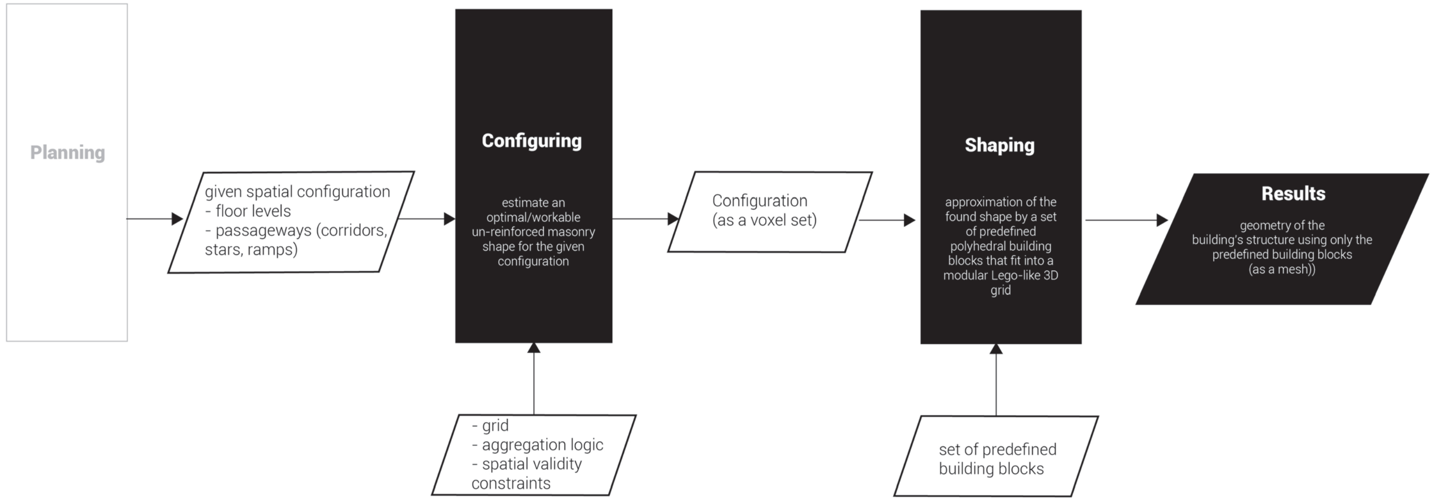


Figure 10: General flowchart for this research, Author

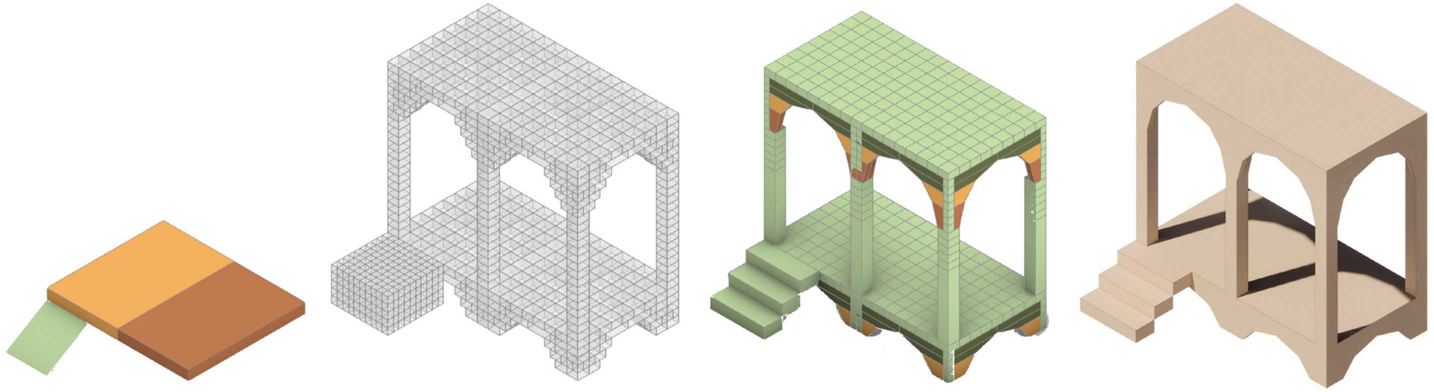


Figure 11: (From Left to right) Spatial Configuration of floor levels and stairs; Voxel approximation of the chambers and floors: Voxel set is approximated with the predefined buildign blocks; Final wooden vault

7.2. PROPOSED METHODOLOGY

7.2.1. PROCESS OVERIVEW

0. The input of the process within the Configuring procedure is a given spatial configuration, therefore the Planning procedure is not a part of this research. The spatial configuration is meant to be a set of floor levels connected with a set of passageways - corridors, stairs, and ramps. (Figure 11)
1. The next step is to design/estimate an optimal/workable un-reinforced masonry shape for the given configuration, possibly separated according to the separate floor levels/rooms. (Voxel set) (Figure 11)
2. The final step is the approximation of the found shape by a set of predefined polyhedral building blocks that fit into a modular Lego-like 3D grid. (Figure 11)

The result of the procedures is a geometry for the desired housing project based on the created building blocks and inputted spatial configuration. (Figure 10) Additionally, all procedures together create a methodology, a meta level game, which are steps that can be taken, and another solution can be found to have a set number of blocks with which variety of valid solutions can be created.
The next subchapter explains the glossary and the used terminology as well as the exact steps taken within the configuring and shaping procedures which directly affect how the initial inputted spatial configuration will be approximated into a geometry for a building structure.

7.2.2. PROPOSED GLOSSARY

- **Voxel grid** – 3-dimensional grid based on ergonomics on which all the predefined building blocks are based, Figure 12
- **Spatial configuration** – A set of floor levels and connecting spaces – corridors, stairs and ramps, Figure 13
- **Building block** - predefined element (part of the set of the final blocks), Figure 14
- **Spatial unit** - A set of predefined elements that create a space, Figure 15

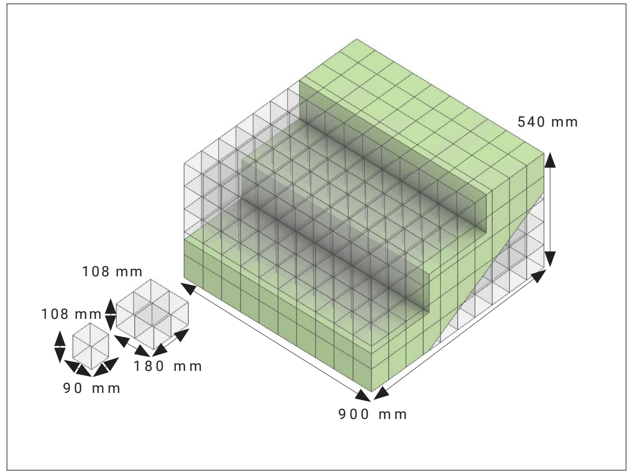


Figure 12: Voxel grid: 90x90x108 mm (Left to Right: voxel grid, column size, stair block)

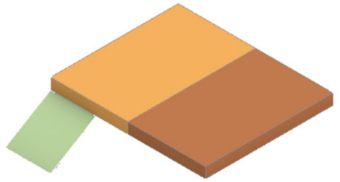


Figure 13: Spatial configuration

Figure 14: Building blocks

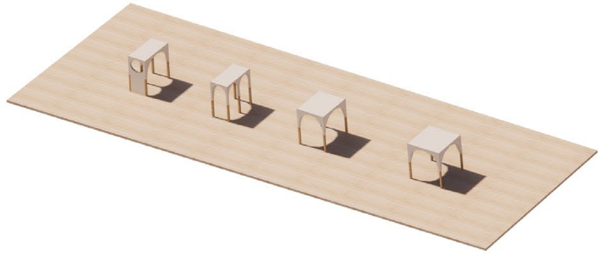


Figure 15: Spatial units

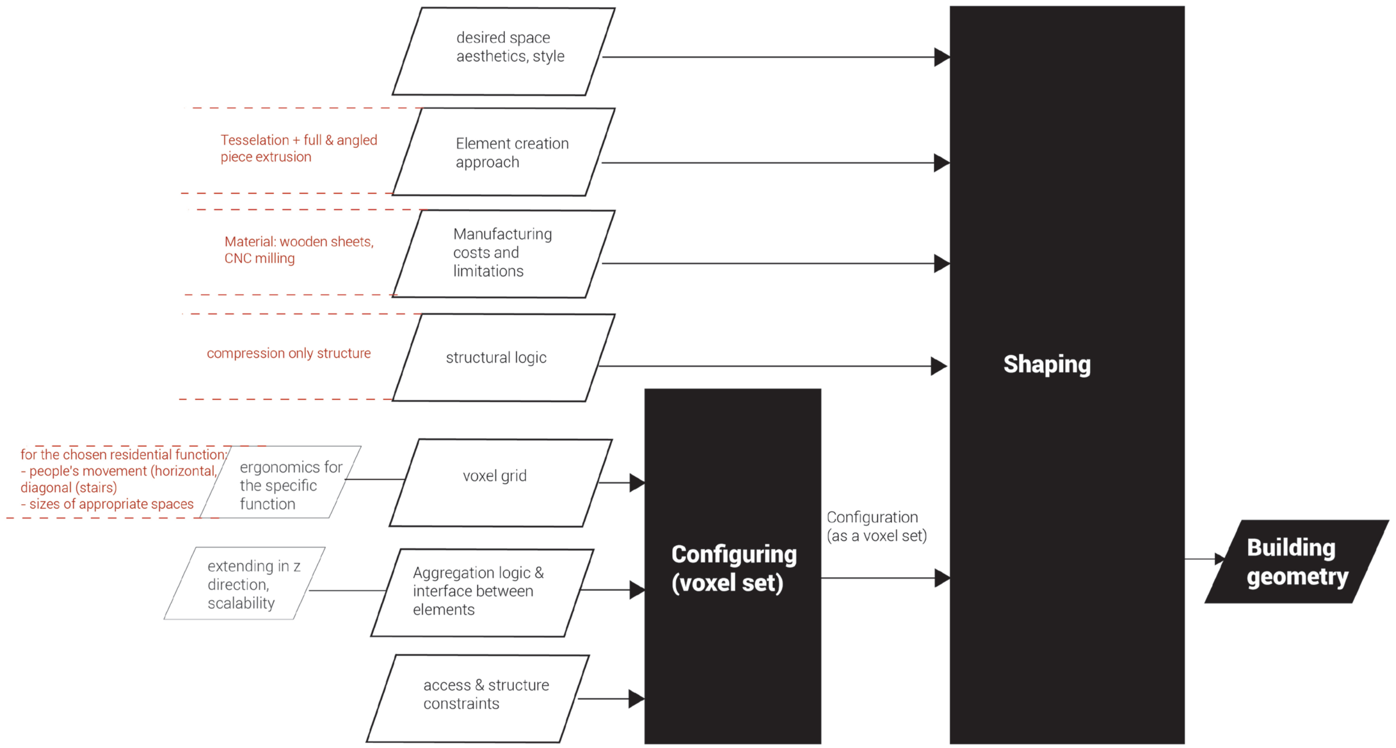


Figure 16 :Zoom in on the Configuring and Shaping procedure flowchart + specific choices in red, Author

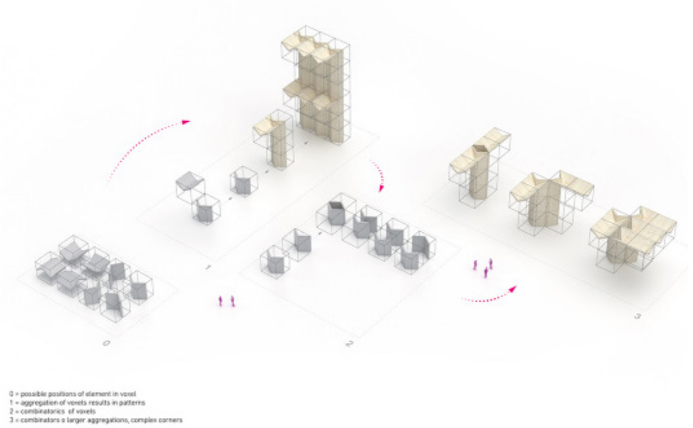


Figure 17: Nuremberg Concert Hall; voxel -> module -> patterns -> combinatorics -> aggregations (Retsin, 2018)

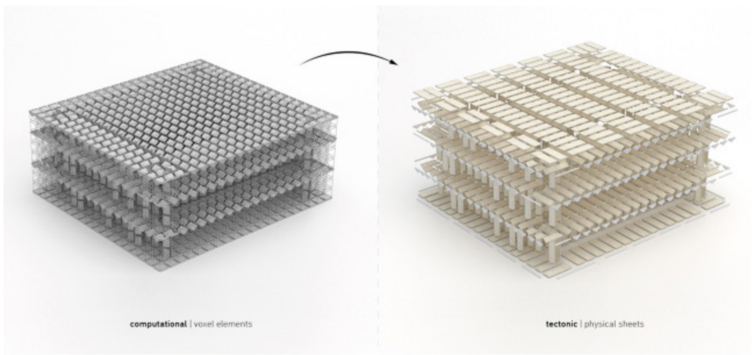


Figure 18: Nuremberg Concert Hall; transition from voxel elements to physical timber sheets (Retsin, 2018)

7.2.3. CONFIGURING & SHAPING PROCEDURES

A more detailed look is taken into the Configuring and Shaping procedures and what kind of logic is implemented there before the actions from the process overview are taken. The overview of these processes can be seen in the flowchart in Figure 16

7.2.3.1. CONFIGURING PROCEDURE

Step 1: Definition of a voxel grid
As mentioned in chapters 2 and 3 in this research paper, the configuring logic is built up on the logic of the Lego (Lego.com, 2022) grid with a real life example of the Belgian "Gablock" (Gablok.be, 2022) that proves how to create walls based on such a logic. This research focuses on how to develop this further and create floors, ceilings & roofs within such a system, because the Gablok system provides a solution for walls and the Lego game pieces only provide the exterior of the structure, but within the Built environment the interior spaces are equally as important. Since the Lego logic is chosen a 3-dimensional voxel grid is defined for the creation of the building blocks as well as for the universal logic of the system based on several constraints.

Step 2: Aggregation logic & interface between elements
Once the voxel grid has been made there are certain aggregation and interface rules and restrictions that have to be taken into account before shaping each element. These rules must provide that it is possible to extend each element upwards in the z direction (and some also in the x and y) and customize the scale of the building (ceiling height, room width etc) (Figure 17)

Step 3: Spatial unit validity constraints
For the configuration to be spatially valid several constraints must be met when configuring. The constraints concern topics such as daylight, access to and from spaces on the same and different levels and, finally, structure. In this research the daylight falls out of scope, however access and structure are tackled.

7.2.3.1. SHAPING PROCEDURE

The procedure of shaping takes the configuration (voxel set) of the configuring procedure and approximates a geometrical representation of the tile set using predefined building blocks. (See figure 18) This section explains the actual steps of designing the building blocks that are predefined and used to translate the voxel tile set from the configuring procedure into final geometry of a building.

Step 1: Structural logic & Scalability
Since the Shaping procedure defines the final shape, material & production of the building blocks it needs to have a structural logic of how the elements work together. The goal for the predefined set of the building blocks is to:

- create a stable compression only structure (test through prototyping and through defining the arch/vault shapes)
- have a dry connection,
- be scalable
- be easily producable

Step 2: Manufacturing costs and limitations:
For example, the shaping procedure faces the constraint of the manufacturing process, more specifically the costs and the limitations of this process. The limitations include the material and its production, meaning the shape of the module must be related to the size of, for example, standard wooden sheets as well as the possible shapes that can be reached with such a material. (see figure 18)

Step 3: Element creation approach
There needs to be an approach of creating the elements in such a way that they directly relate to the type of structure that has been chosen, meaning, the elements must always create a compression-only structure once assembled together.

Step 4: The final shape of the desired spaces
Shaping also specifies more specifically what each type of building block offers within the context of creating a house, how a room will function & look like. These are the final adjustments of the elements.

8. RESULTS

This research aims to create a methodology to approach the design of a limited set of stackable timber elements (that create a structure and the inner shell of the building) which can be configured and assembled into versatile housing solutions that can be mass-customized and produced. Therefore, a systematic approach through the procedures of configuring, and shaping are undergone (described in the proposed methodology section) to achieve a rule-based configurator and a few timber elements that can create many options of valid housing spaces providing variety and affordability. The result is a meta level game meaning the steps described below that have been taken can be a guide to create a different solution, a different game using the same method. Firstly, the results of defining the configuring procedure are presented. Secondly, the shaping procedure steps and results are explained and, finally, the Meta level game is presented.

8.1. CONFIGURING

Step 1: Definition of a voxel grid and its scales.

The voxel grid is based on ergonomics of the type of structure you are creating as well as the appropriate thickness of architectural elements such as columns and walls. For this example, a residential building is taken; therefore, it is limited by how a person moves through spaces: horizontally and diagonally (stairs)(Figure 19) and the different dimensions of spaces and structural elements in a house, such as corridors, small and large rooms, balconies, stairs as well as columns, walls etc. (Figure 20)

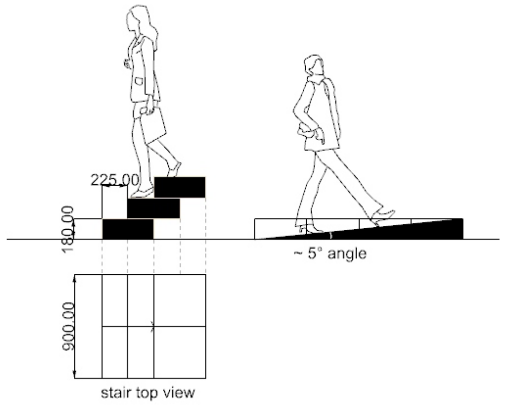


Figure 19: ergonomics of a stair

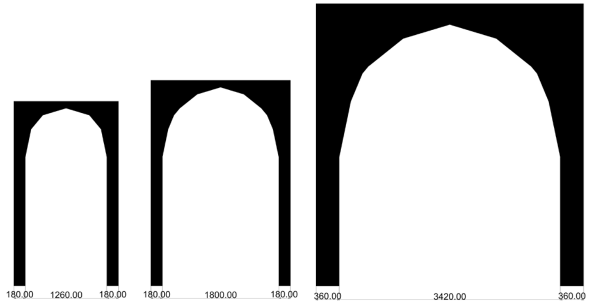


Figure 20: ergonomics of a home and dimensions of spaces & elements

Horizontal constraints (movement & space size):

- comfortable corridor for 1 person: 900 mm
- comfortable run for the stair (30–35-degree angle slope): 225 mm (min)

Vertical constraints:

- comfortable step rise (slope angle 30-35 degrees) 180 mm
- comfortable ceiling height 2880 mm (step size: 180 mm)

Rules for stairs:

- slope 30-35° the most comfortable for stairs
- for 2R+T=60

Therefore, the final voxel grid was defined as a 3-dimensional Voxel grid with its basic cell size 90x90x108 mm (x,y,z) (See figure 21) from which the arches and vaults as well as the stairs can be derived. It follows the proportions of a Lego grid and strives to make appropriate size blocks for assembly.

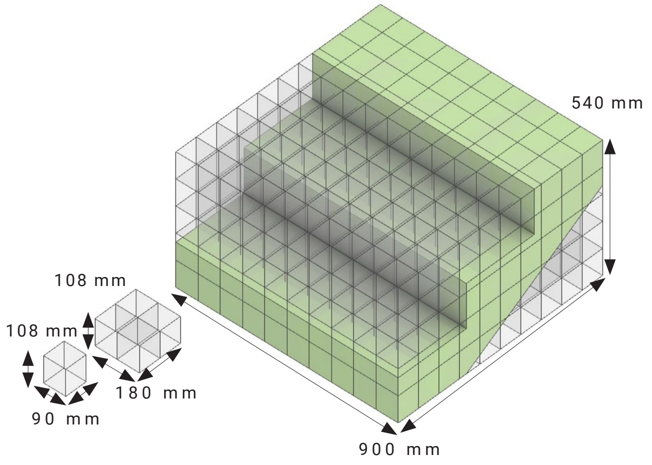


Figure 21: 3-dimensional Voxel grid 90x90x108 mm (x,y,z), column block dimensions 180x180x108 mm, stair block: 900x900x540 mm

It fits the limitations of the ergonomics of a home, and it has the same proportions as a Lego plate.
LegoHeight: 3.2 mm; LegoWidth: 8 mm
BlockHeight: 180 mm; BlockWidth: 450 mm
Proportion H/W Lego= 3.2/8= 0.4
Proportion H/W Voxel grid= 180/450= 0.4

Step 2: Aggregation logic & interface between elements

In order for it to be possible to extend each element upwards in the z direction (and some also in the x and y) and customize the scale of the building (ceiling height, room width etc) certain rules must be passed from the configuring procedure to the shaping procedure. The outer layer of the building block needs to fit the voxel grid fully. More specifically, each separate piece of the building blocks from the outer side needs to fit 1 or more complete voxels, that does not apply to the inner parts. For example, the piece which represents half of the smallest arch is 5 voxels high and 1 voxel wide on the bottom and 2 voxels wide on the top, meaning all these dimensions are full voxels. The actual arch part on the bottom can be freely chosen. (Figure 22)

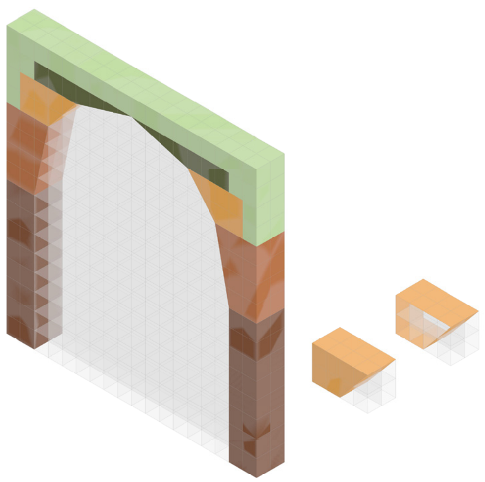


Figure 22: aggregation logic, which surfaces need to fill up full voxels for scalability (left final arch element, middle-building block, right surfaces of the building block on left which need to be full voxels to provide scalability and extension possibilities)

Step 3: Access and structural constraints

Access

- before the start and after the finish of the stairs as well as at the connection between rooms an area of 2x2 voxels at least must be kept empty

Structure

- Base the creation of elements on equilibrium and enough surface overlap between elements. The arch is created from overlaping half of the voxel and the vault is based on a 2x2 voxel grid with 1 full voxel overlap. (Figure 23)

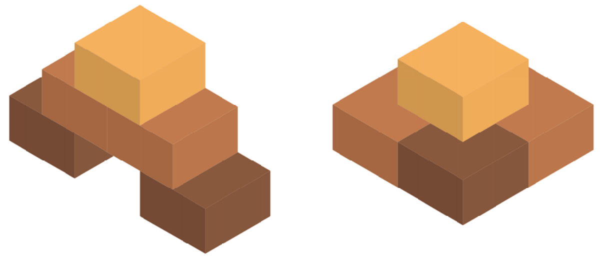


Figure 23: (Left) Arch building voxel pattern, (Right) Vault building voxel pattern

8.2. SHAPING

Step 1: Structural logic & Scalability

The goal is to create building blocks with a dry connection, that can be easily scaled and produced in order to be affordable and provide a wide range of different solutions. Therefore with all the goals mentioned above a dry-fit stackable compression only structure out of wooden blocks (made out of wooden plates) is considered. A stackable structure can have an easy assembly process and a compression only structure can be scaled due to the characteristics of the compression forces. Finally, production of wood and techniques such as CNC milling allow for a fast and easy production process of prefab elements.
Firstly, the rules of a stable arch/vault were followed in order to conclude the necessary shape of the elements.

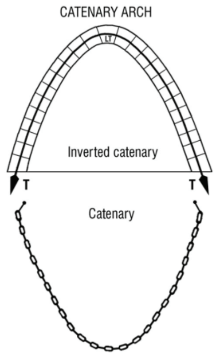


Figure 24: Catenary arch and the mirrored version of it in the shape of a hanging chain (Davis & Maini, 2016)

In the first iteration, the top red piece was one voxel high (108 mm), however, in the second one to ensure stability and easier assembly the top piece was adjusted to 2 voxels high (216 mm)

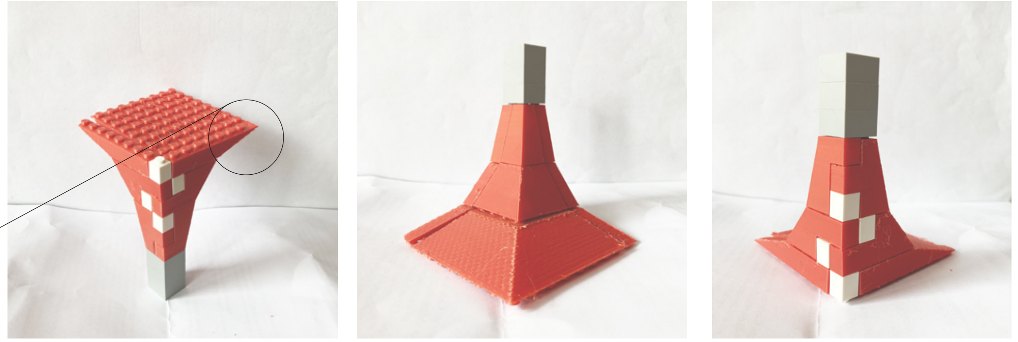


Figure 26: First iteration for prototyping with 3d printed blocks: 1/4th of a vault

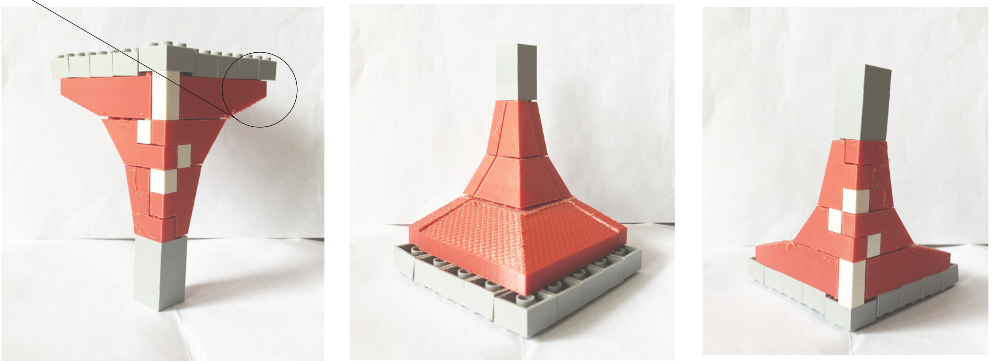


Figure 27: Second iteration for prototyping with 3d printed blocks: 1/4th of a vault

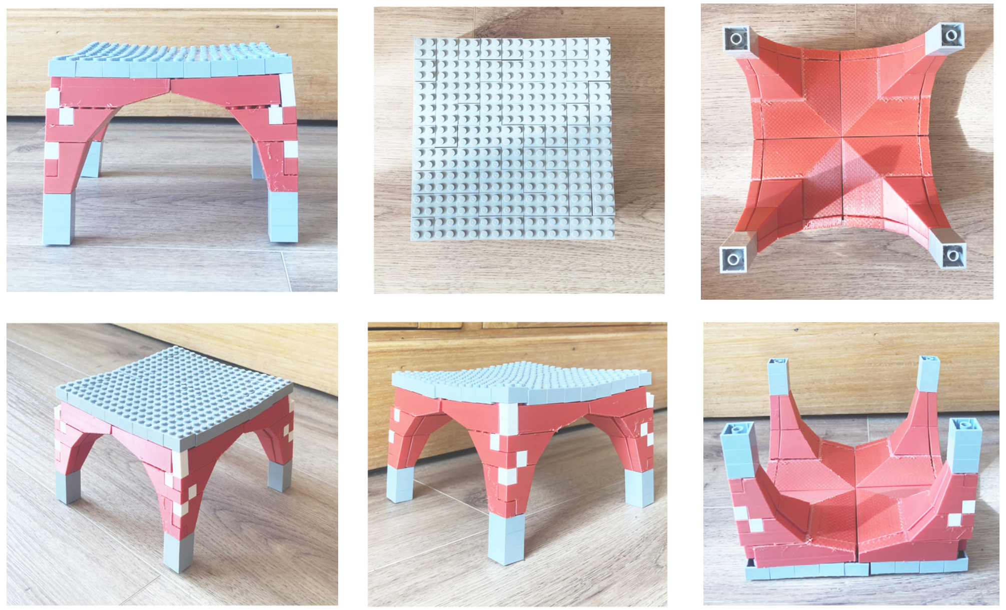


Figure 28: Second iteration for prototyping with 3d printed blocks: full vault

A catenary arch is seen as the perfect arch due to the fact that its shape directly follow the line of thrust of the arch. However, practically and spatially the catenary shape loses a lot of usable space under its piers, therefore a semi-circular arch is prefered. Which aesthetically as well as practically is favoured.

To achieve a stable semi-circular arch several rules must be followed:

- the line of thrust must be within themiddle 1/3rd of the arch section (line of thrust = catenary curve, hanging chain)
- the rule of thumb of a semi-circular arch to achieve stability is that the haunches are loaded and the thickness of the pier is 10 the span. (t=S/10)

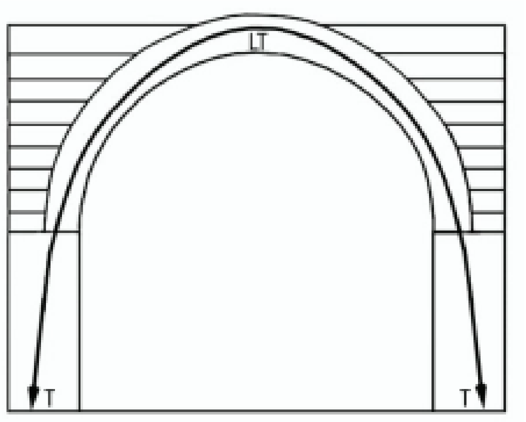


Figure 25: Semi-circular arch with its haunches loaded and t=S/10 (thickness = Span/10) (Davis & Maïni, 2016)

Secondly, a 3d print prototype test was undergone. The test informed about the shape of the vault and its stability as well as the assembly process and critical points in the structure.

There were 2 iterations, the first iteration was hard to assemble and did not reach stability, (See figure 27) However, for the 2nd iteration the top piece of the vault was made thicker in the height direction and achieved stability once assembled all togehter. (See figures 27., 28.)

In Figure 29 you can see what space and ceiling the vault creates if viewed from the bottom, you can clearly see where the 4 parts come together and how the semi-circular shape is achieved through straight edges.

Figure 29: Second iteration 3d printed prototype viewed from the bottom

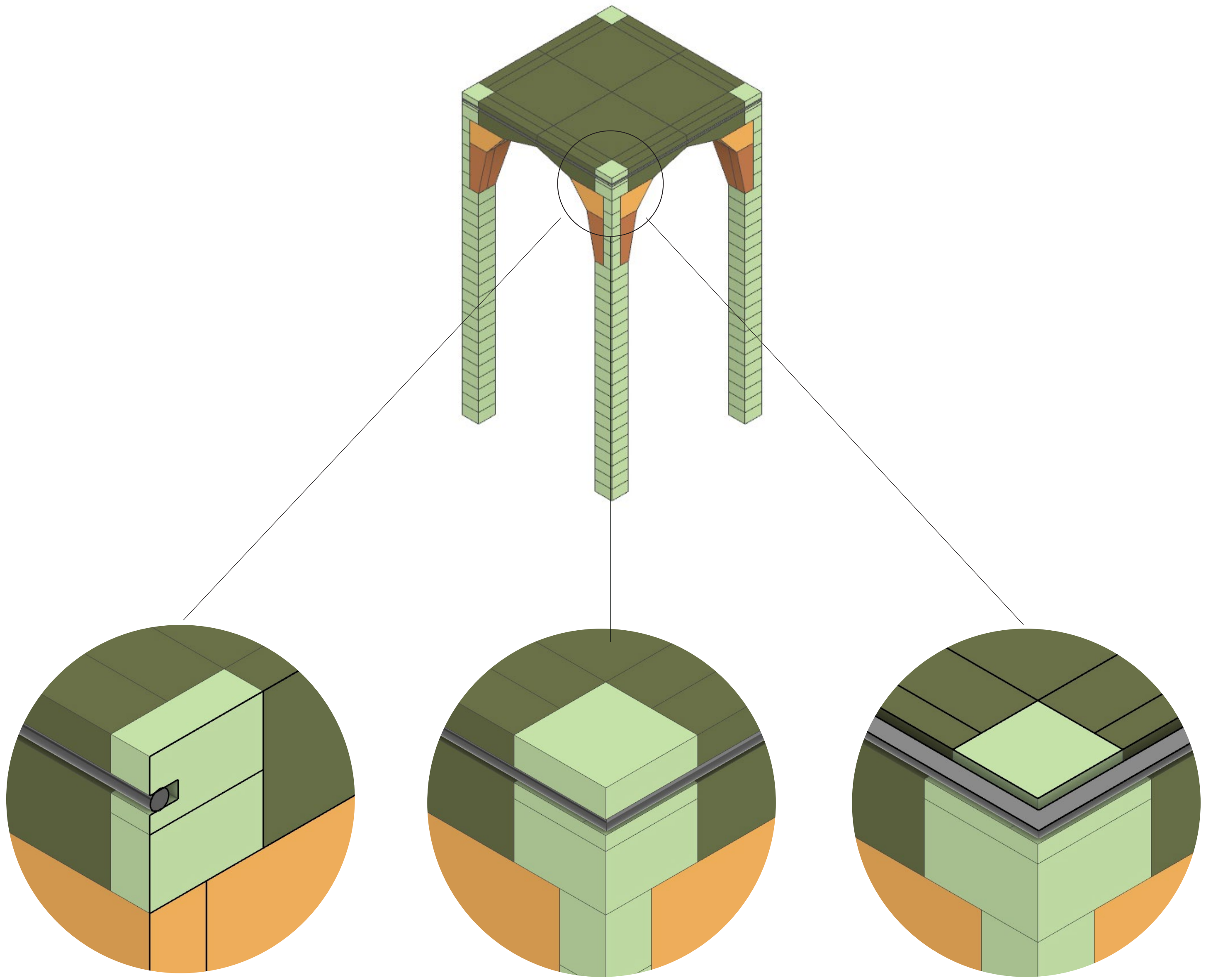


Figure 30: Tension ring on top of the vault with a steel cable (Left to Right) vertical section; 3d view; horizontal section

Additionally to the way how the pieces are shaped and assembled to ensure complete stability due to the thrust forces and external lateral forces a tension ring is proposed as one of the solutions to keep the top layer of the building blocks interconnected. The top layer is the only place where all 4 sides meet and connect, therefore the perimeter of this layer can be a potentially promising spot to place the "tension ring". This additional piece can be in the form of a steel cable . This will ensure not only that the vault can carry its self weight and some additional weight on top, but also take care of the lateral forces and larger forces from the storeys above. This also allows the system to be lighter and weight less for easier assembly and be more efficient in its material use. See Figure 30.

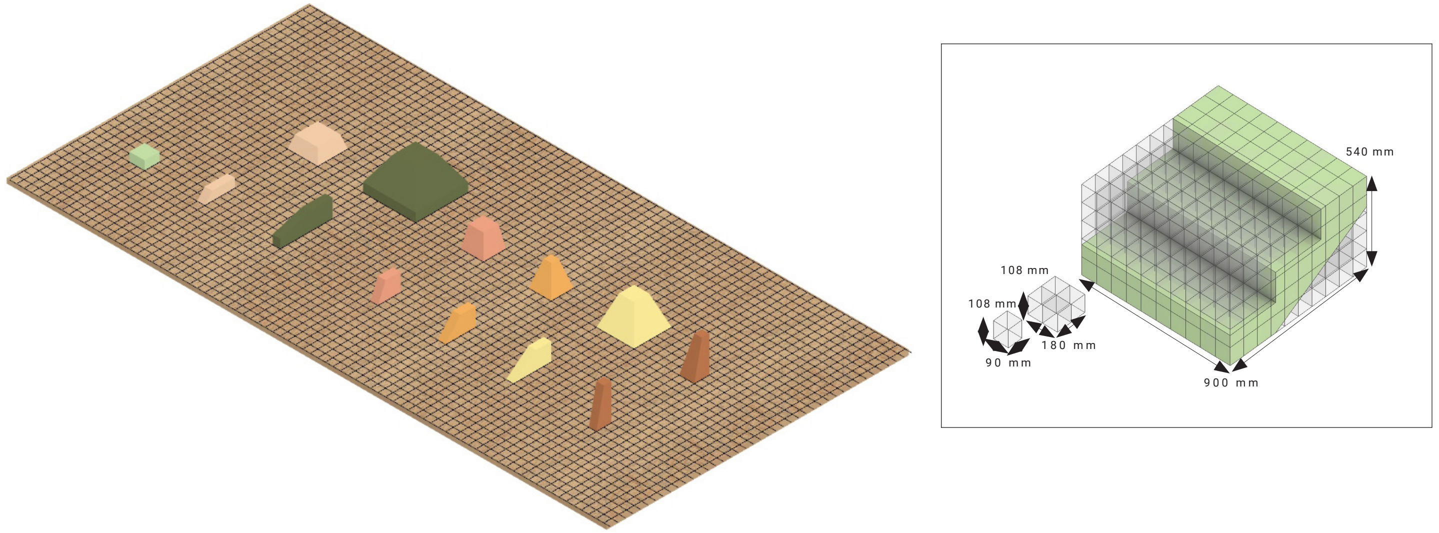


Figure 31: 13 predefined elements for sides and corners within the 90x90x108 mm voxel grid

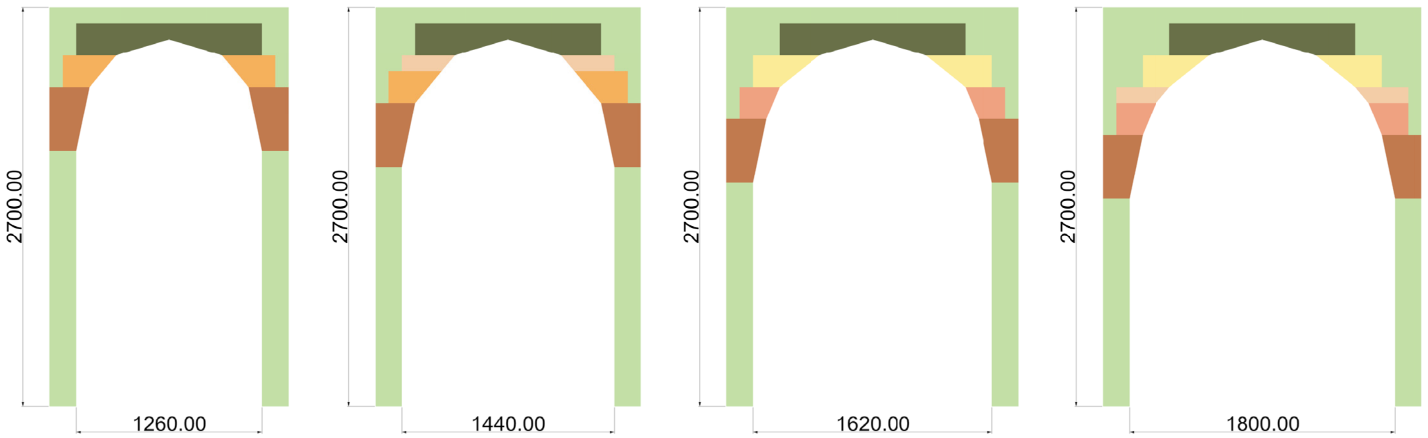


Figure 32: Scalability of the arches & vaults; 4 examples of how the predefined elements can make any arches/vaults within every 180 mm

Finally, the semi-circular arches are built up within the 90x90x108 mm voxel grid, where every 180 mm in the length and width direction a different arch can be made and every 108 mm a different height arch can be made. (See Figure 32) This is achieved by ensuring that every arch every 180 mm uses some of the 13 predefined blocks. (See Figure 31)

Step 2: Manufacturing costs and limitations:

This part is affected by the chosen material – in this case those are wooden sheets. Since CNC milling is the main way how the pieces are manufactured the limitations of this process are taken into account.

1. All elements are made from wooden plates – therefore no massive elements are considered, and the size is limited to the maximum plate size.

2. No curved wooden pieces due to difficulty to manufacture such pieces and the costs involved.

3. Only flat pieces from Plywood 18 mm plates are milled to reduce complexity and avoid angle cuts from the top of the milling table. In Figur 33 you can see how a corner piece is made out of only straight plates with 90 degree angles everywhere. In Figure 34 you can see how it leaves some angled slits, but since it is the internal shell it should not cause any problems.

Step 3: Element creation approach

Two approaches are considered in order to create a predefined set of building blocks that provide variety of architectural housing solutions by making a compression-only structure and that fit the defined voxel grid. .

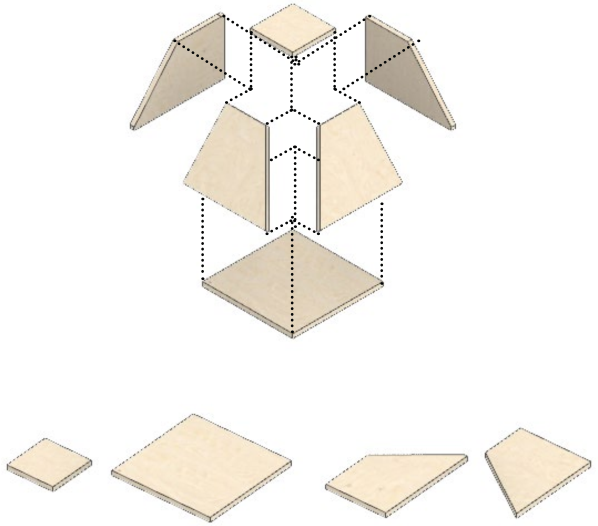


Figure 33: Corner piece build up out of 18 mm straight plywood plates with no angled cuts

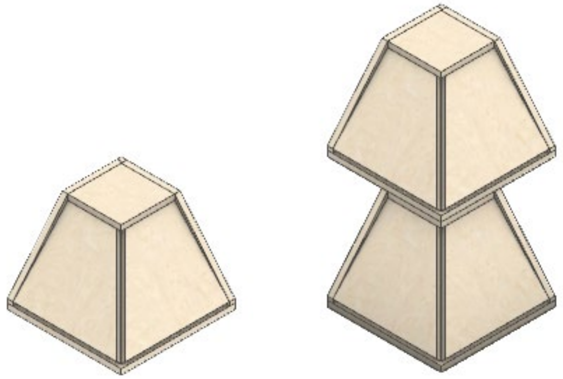


Figure 34: Corner piece assembled with remaining slits in certain edges due to only straight cuts

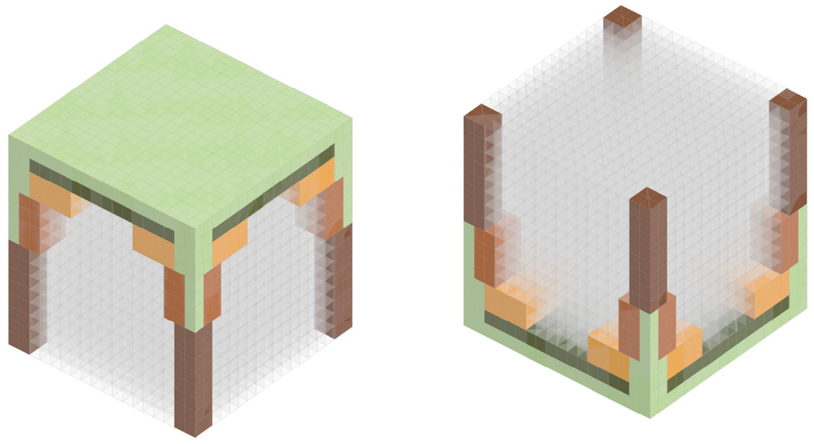


Figure 35: Approximation of a vault with a voxel set in a grid of 90x90x108 mm

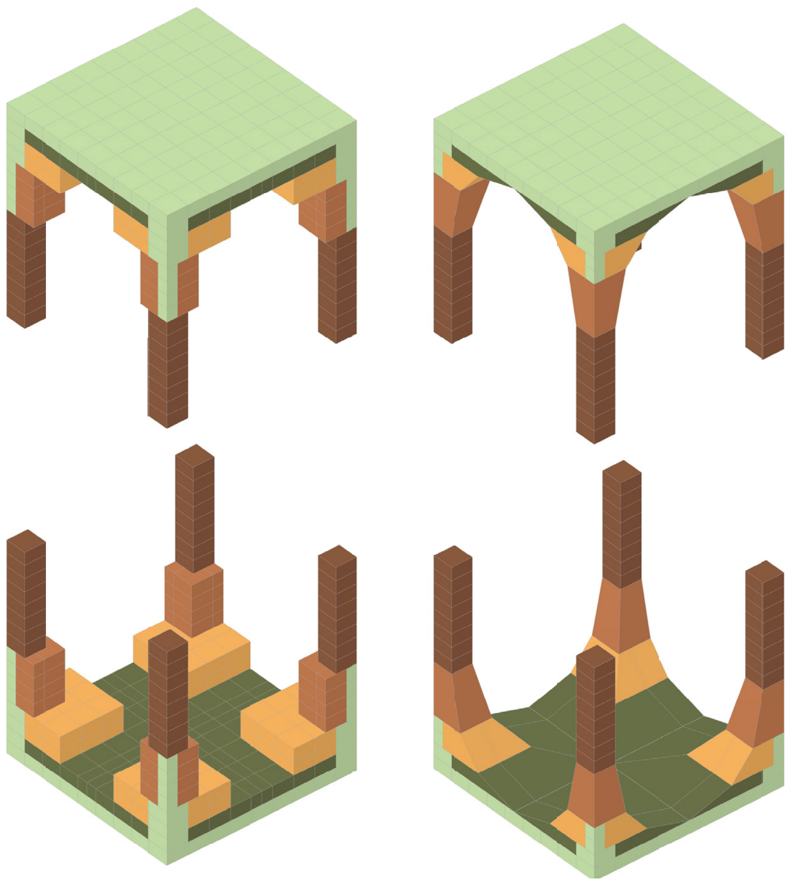


Figure 36: Approximation of a geometry, shaping the voxels with mesh cuts.

1. Approximation by voxels and cutting the meshes to the desired shape. (Approach for standard elements)

The first approach is used for the standard pieces such as the standard vaults & arches. It uses the pattern shown in Figure 19 and approximates a voxel set for the defined space creating a vault with voxels. (Figure 35) Further it defines the desired shape and either fills in or cuts away the voxels with a surface mesh to reach the desired outcome. (Figure 36) This approach is based on the Lego logic and equilibrium

2. Tesselation & design of dry-fit blocks for modular vaulting (approach for special design pieces) (Bitting, Azadi & Nourian, 2021)

It is a generalized computational workflow for generating dry-fit stacking modules from two-dimensional patterns (created using tessellations) in order to construct a dome. Firstly a 2-dimensional pattern is generated and secondly, the triangular parts of the pattern are sorted. Thirdly, in order to index the triangles a logic of pattern rings is created. (Figure 37)

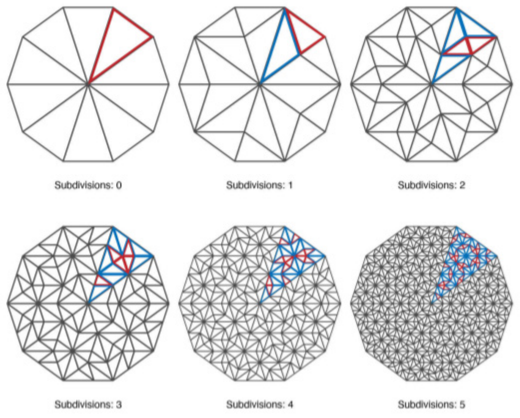


Figure 37: Generated Penrose pattern subdivision method illustrated (Bitting, Azadi & Nourian, 2021)

Fourthly, a method for pattern navigation is developed to select a pair of adjacent triangles and then define one of those triangles as an angled piece and the other as a flat piece to make the way until the center of the dome. (Figure 38) Finally the modules are extruded and pieces have been shaped, and a dome has been created. (Figure 39)

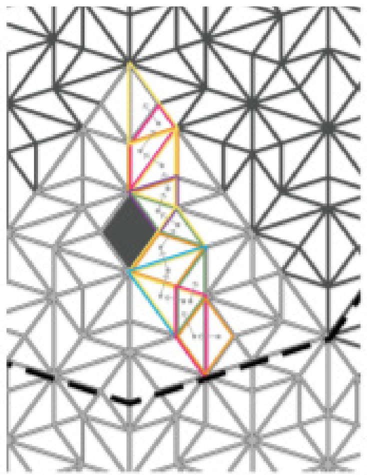


Figure 38: A singular string of triangle pairs progressing towards pattern centroid. (Bitting, Azadi & Nourian, 2021

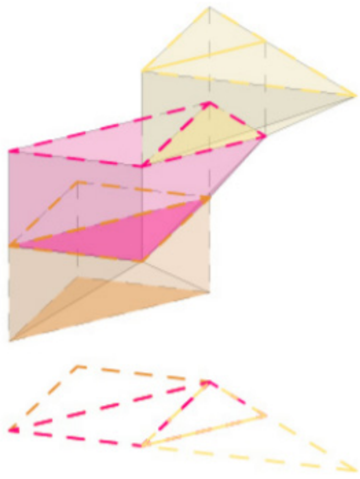


Figure 39: Three stacked modules, and their original geometries projected below.. (Bitting, Azadi & Nourian, 2021

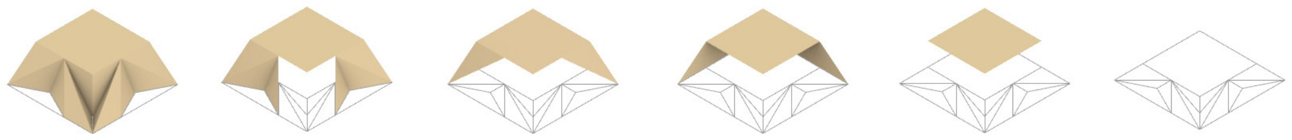


Figure 40: Approximation of a vault with a voxel set, Author

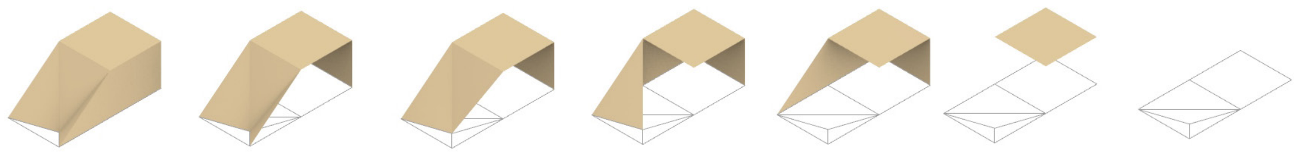


Figure 41: Approximation of a geometry, shaping the voxels with mesh cuts, Author

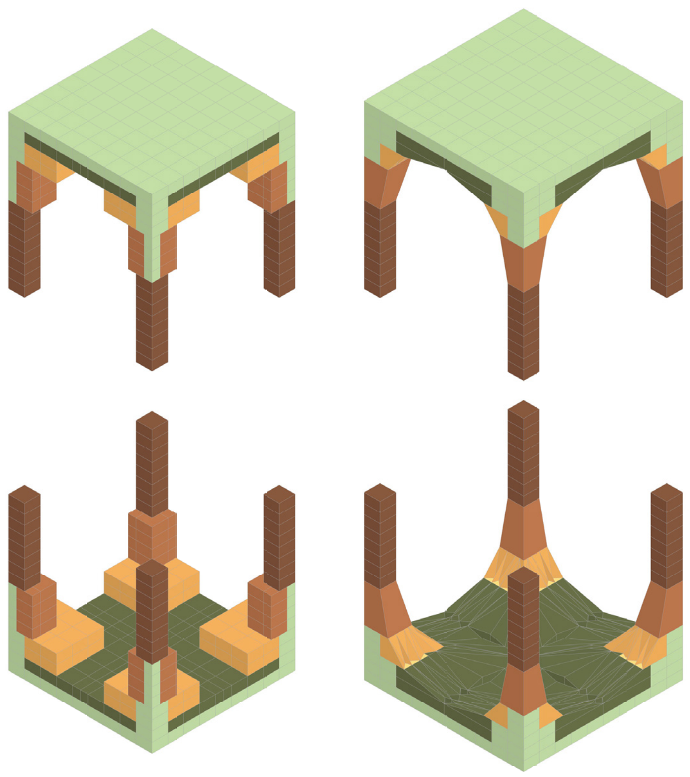


Figure 42: Voxel set and a shaped Diamond vault, Author

Overall, both the pattern shown in Figure 23and the tessellation & extrusion approach allow to fit in the lego grid and design dryfit blocks for ceiling & roof systems to achieve a compression only structure. Few examples of tessellations and extrusions of diamond vault parts for the additional design pieces can be seen in Figure 40&41. The relationship between a voxel set and the final diamond vault pieces can be seen in Figure 42.

The technique of tessellation in gothic architecture can already be traced back from 11th century (Ward, 1915) where ribbed vaults have been displayed through a 2D drawing of a tessellation. (Figure 43)

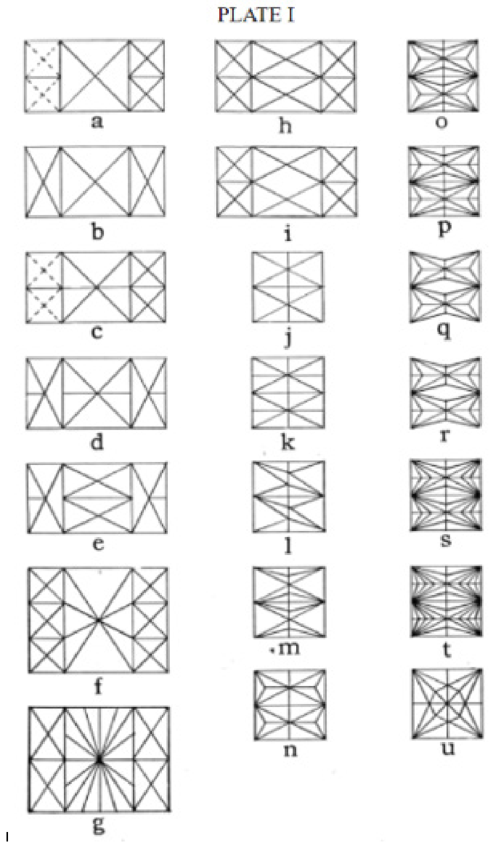
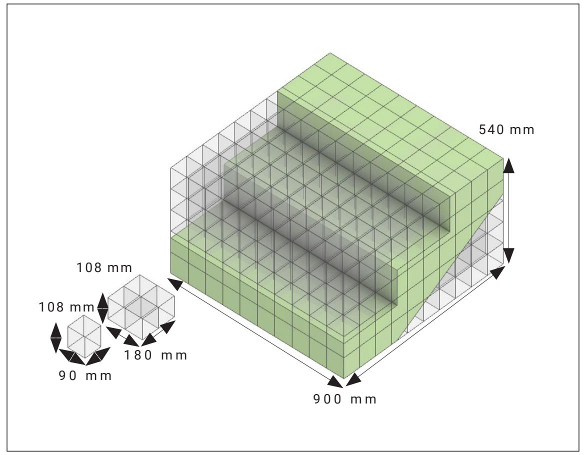
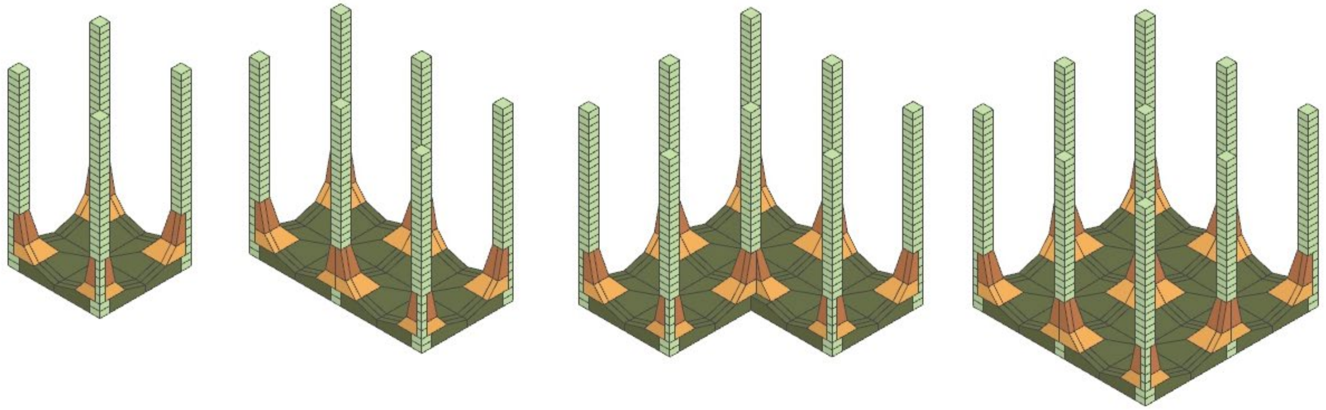


Figure 43: , Ribbed Vaults Over Naves with Square Baysand their tessellations, including (a) Sant Ambrogio at Milan between 1088-1128 (Ward, 1915)





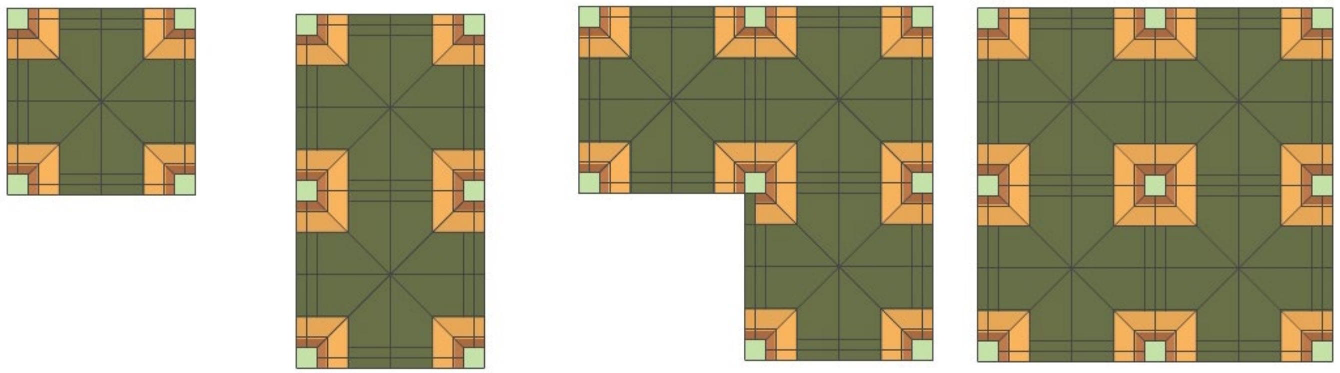


Figure 44: Scalability of the system: (Top to Bottom) Scale and grid; isometric view of 1 vault, 2 vaults, 3 vaults and 4 vaults, top views of extended vaults in 1, 2, 3 or 4 directions

3. Logic for scalability and extendability.

The scalability of the building blocks is achieved by using a 90x90x108 mm voxel grid where all columns are at least 2x2 voxels big (180x180x108 mm). (Figure 44)This ensures that with a side piece and a corner piece you can create 1 vault, you can continue the vault in 1 direction, in 2 , in 3 and in 4 directions. (Figure 45)

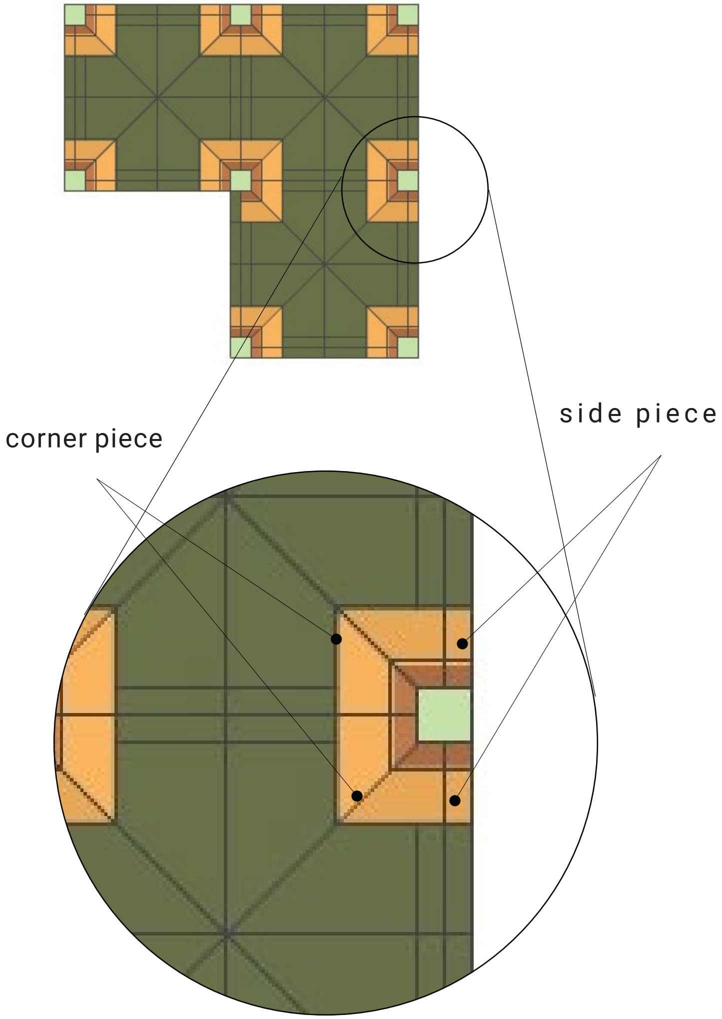


Figure 45: Zoom in into the 3 vaults, corner pieces and side pieces

Step 4: The final desired spaces & design

The final desired architectural elements are:

1. The stairs & their elements (Figure 46)
2. The walls & their elements (Figure 47)
3. The floors/ceilings/roof & their elements (Figure 48)
4. The special floors/ceilings/roof & their elements (Figure 49)

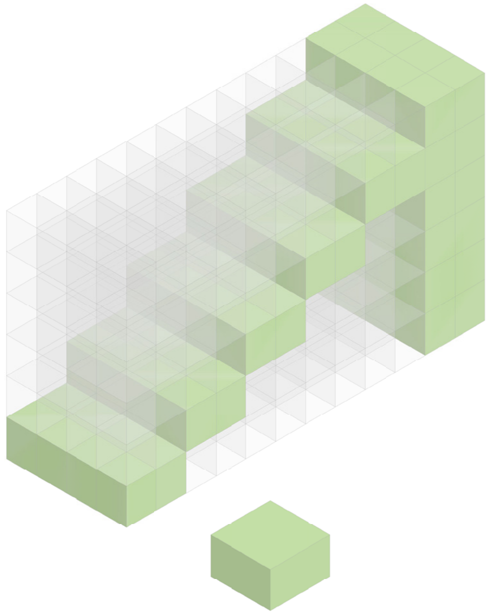


Figure 46: , Stair & the predefined blocks for the stair

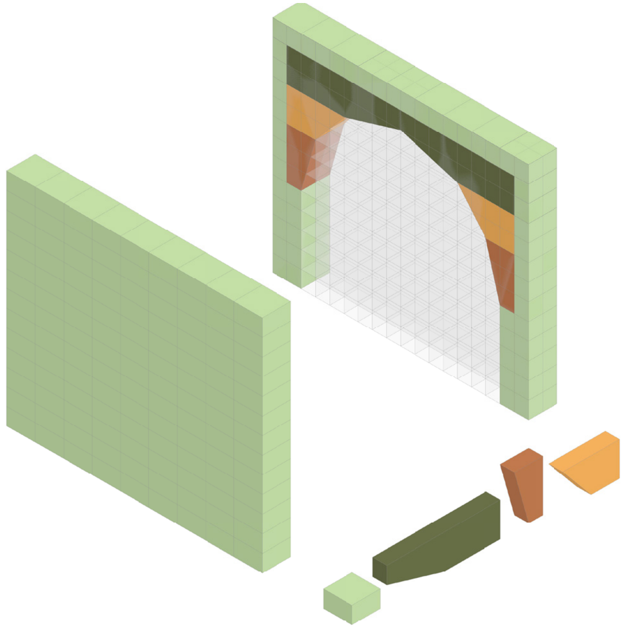
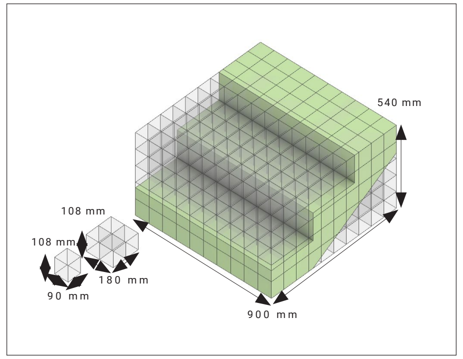


Figure 47: , Wall stacked, wall with opening & wall with storage & the predefined blocks for the walls (providing different slopes for arches)



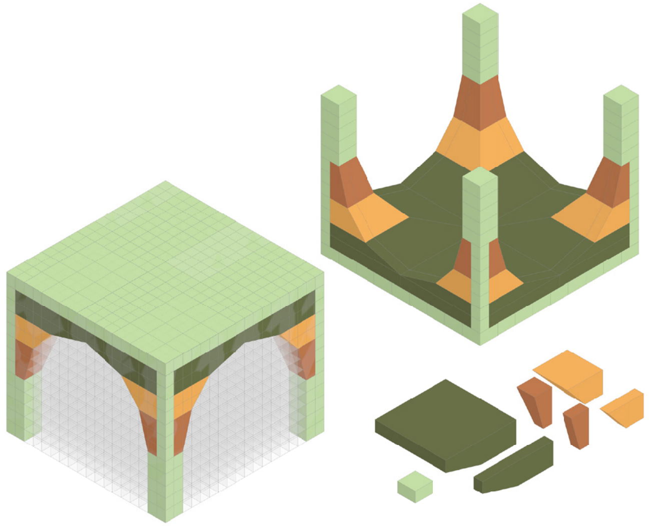


Figure 48: , Vault with openings from top and bottom view, pre-defined building blocks for the vault creation and for different slopes

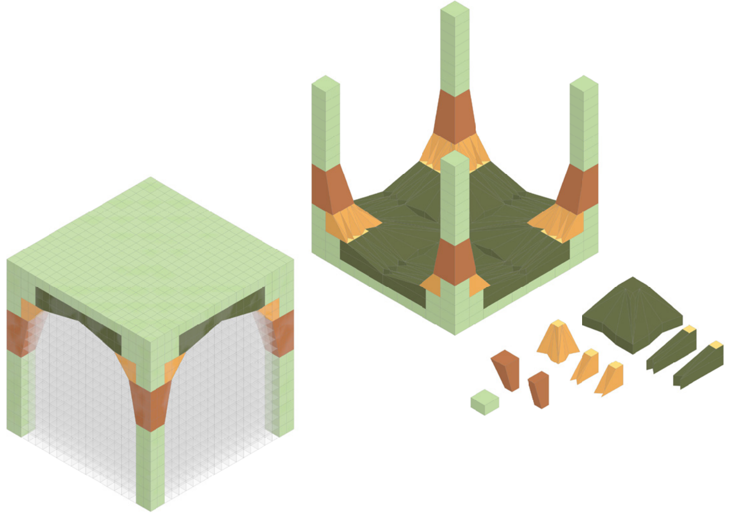


Figure 49 , Diamond Vault with openings from top and bottom view, pre-defined building blocks for the vault creation and for different slopes

8.3. Final building blocks & the possibilities

The possibilities | stairs & walls

Figure 42: stairs & stair elements render, by Author

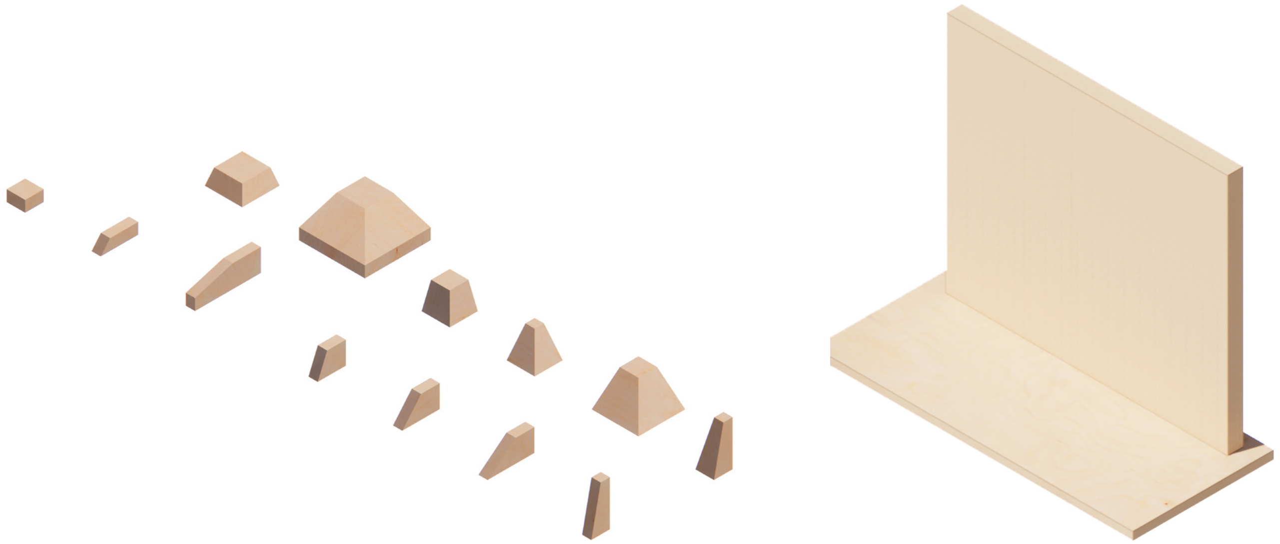
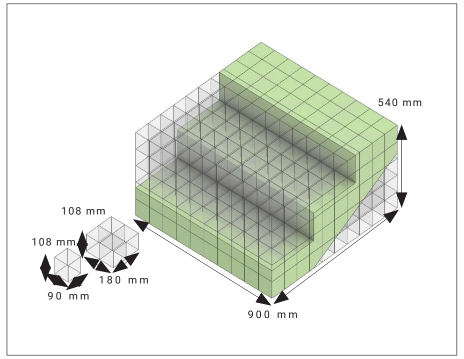
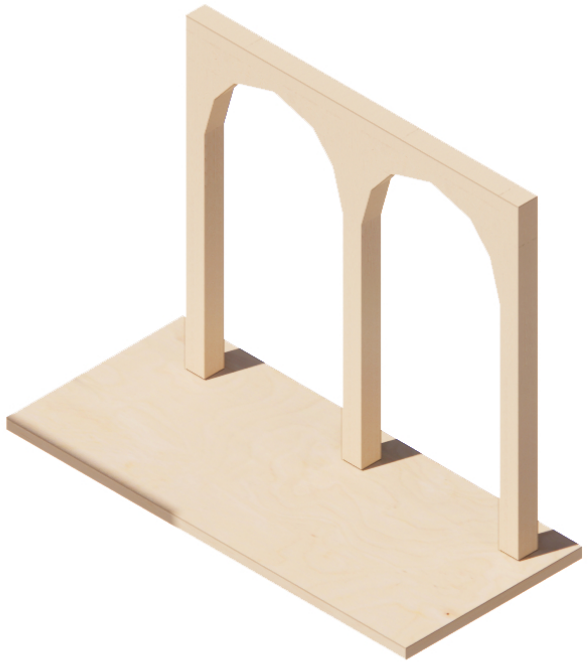


Figure 43: different wall options & wall elements, by Author





The possibilities | vaults

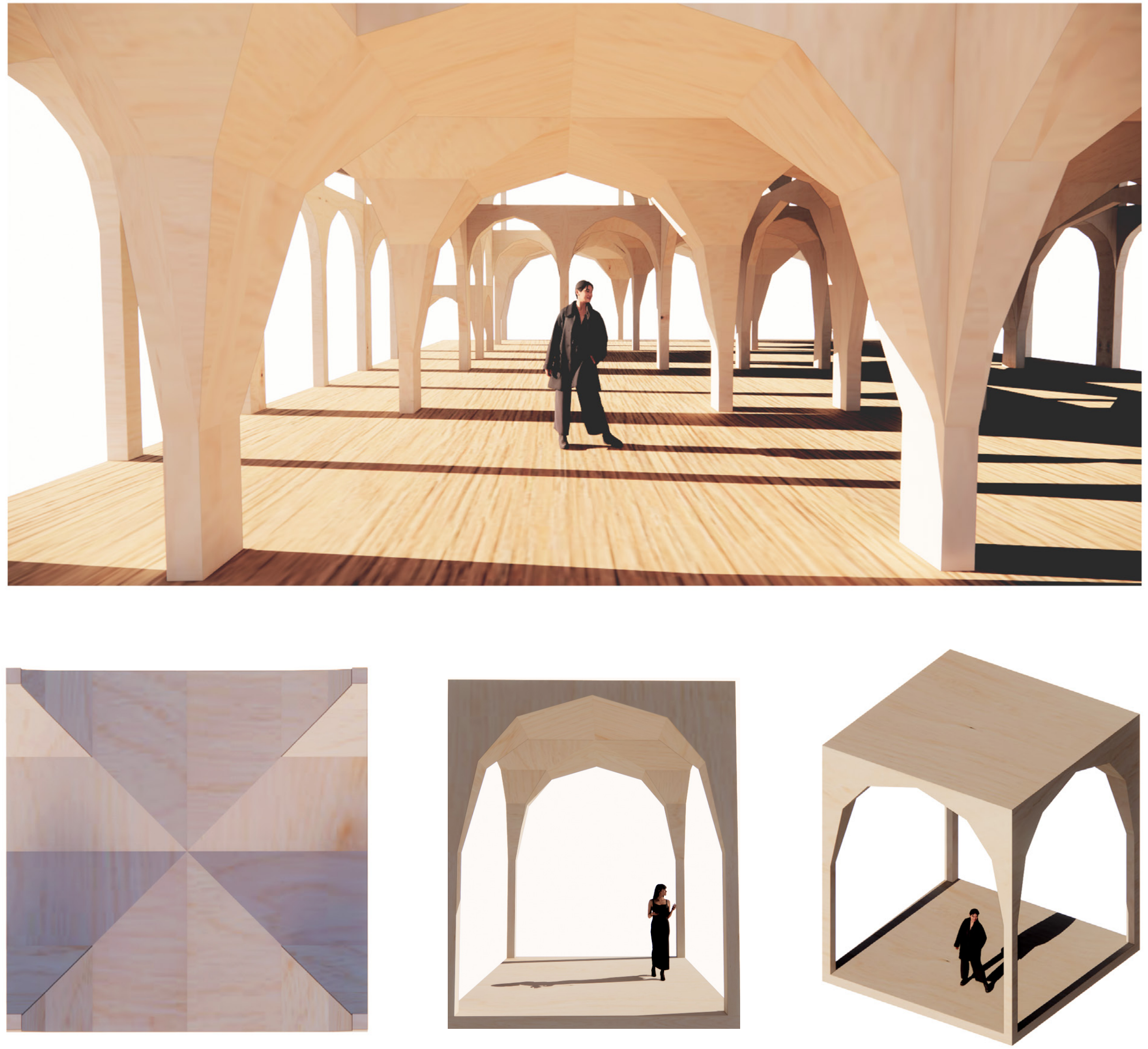


Figure 52: Gothic vault renders, Author

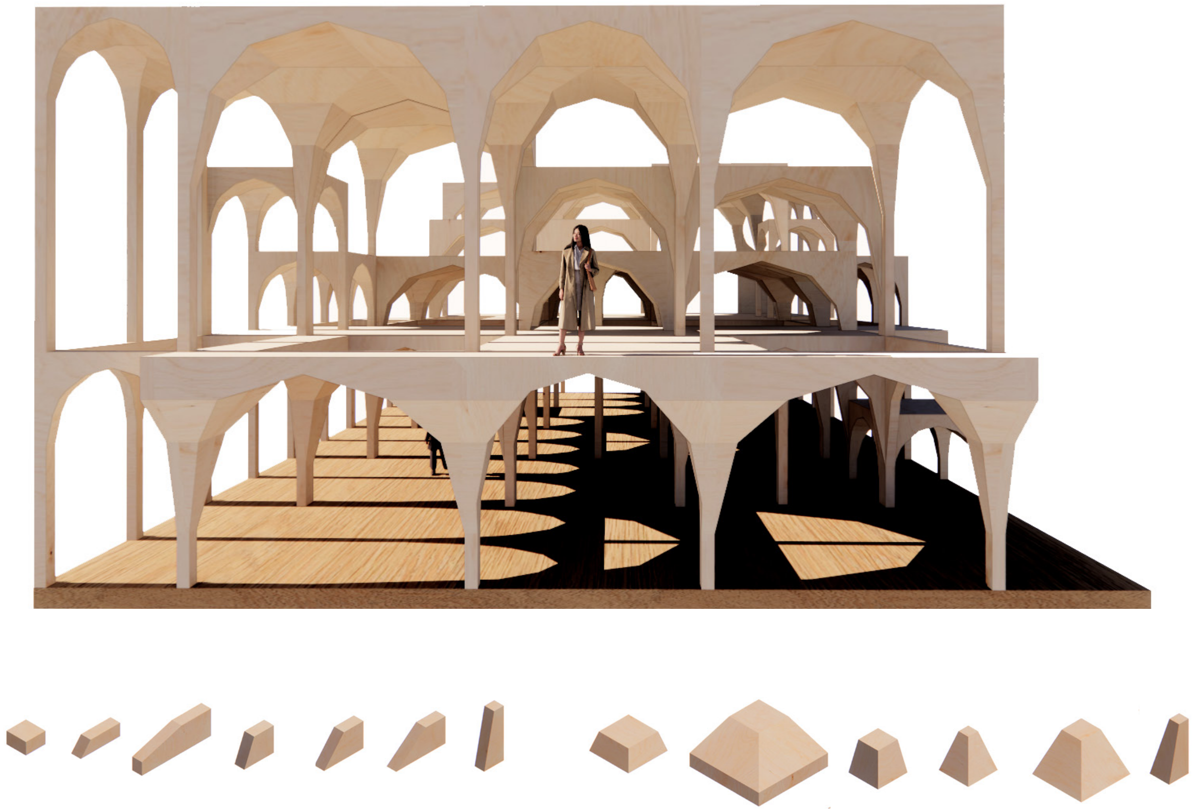


Figure 53: Gothic vault interior perspective render & elements to create the vaults, by Author

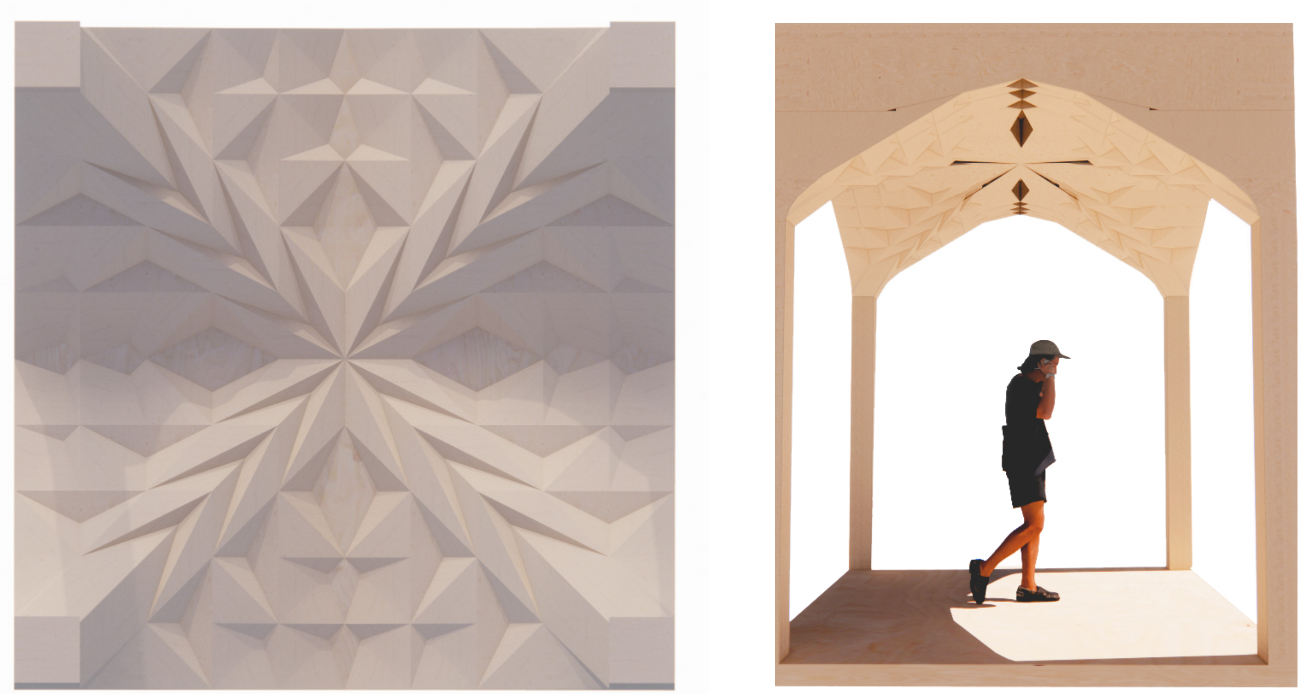


Figure **54**: Gothic diamond vault renders & the elements to make the diamond vaults, by Author

The possibilities | diamond vaults

Figure 55: Gothic diamond vault perspective render 1, by Author

Figure 56: Gothic diamond vault from 8 parts perspective render, by Author

Figure 57 : (From Left to Right) Openings in closed walls; Different levels & heights; corridor space; overhangs, Author

FINAL THEMES

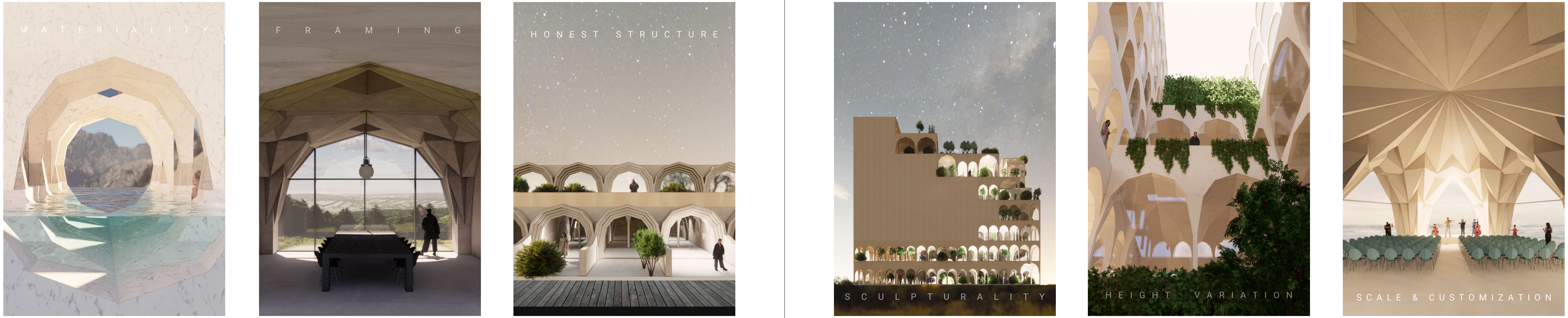


Figure 58 : 6 main themes for the logblock system, an ever evolving catalog

Test case | from building blocks to spatial units to final building structure

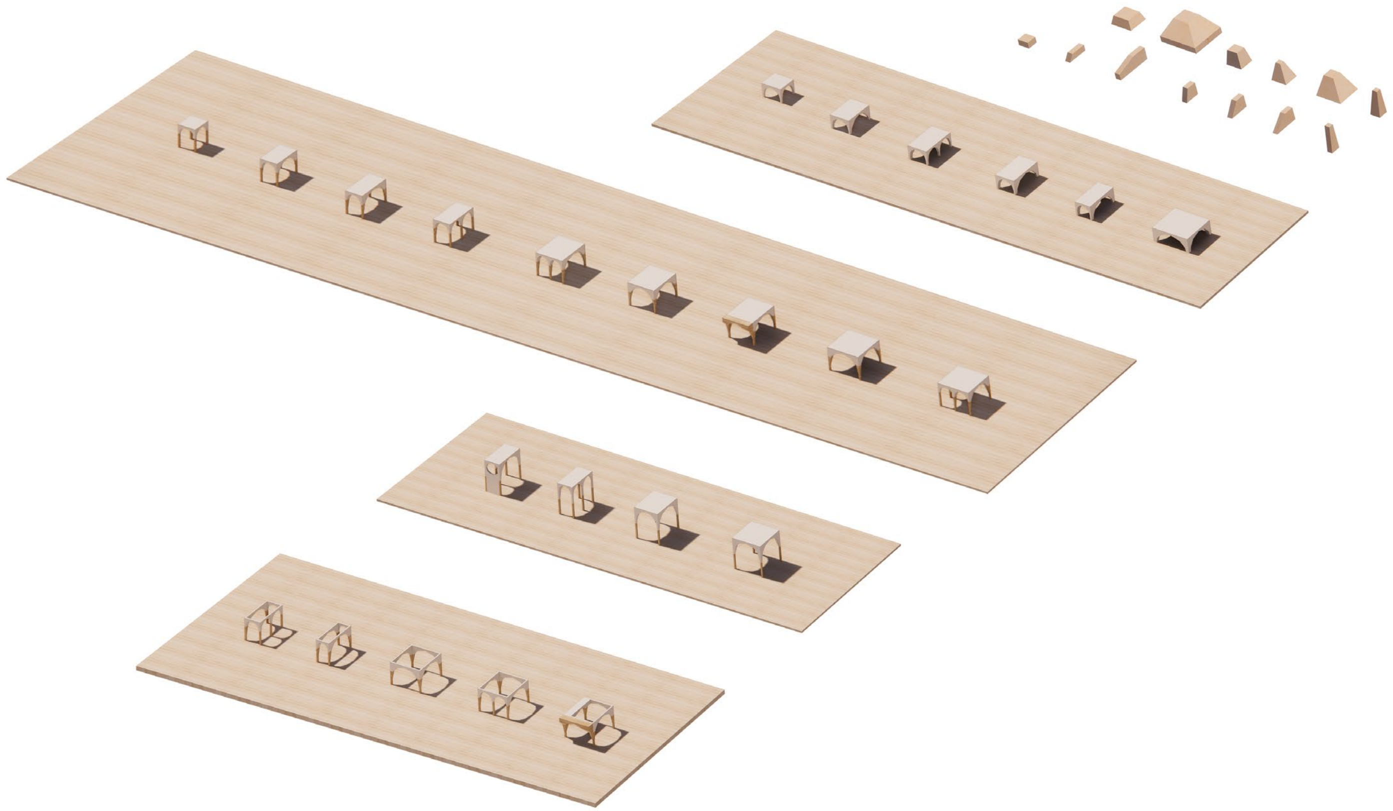


Figure 59: Top - Building blocks, bottom - spatial units, Author

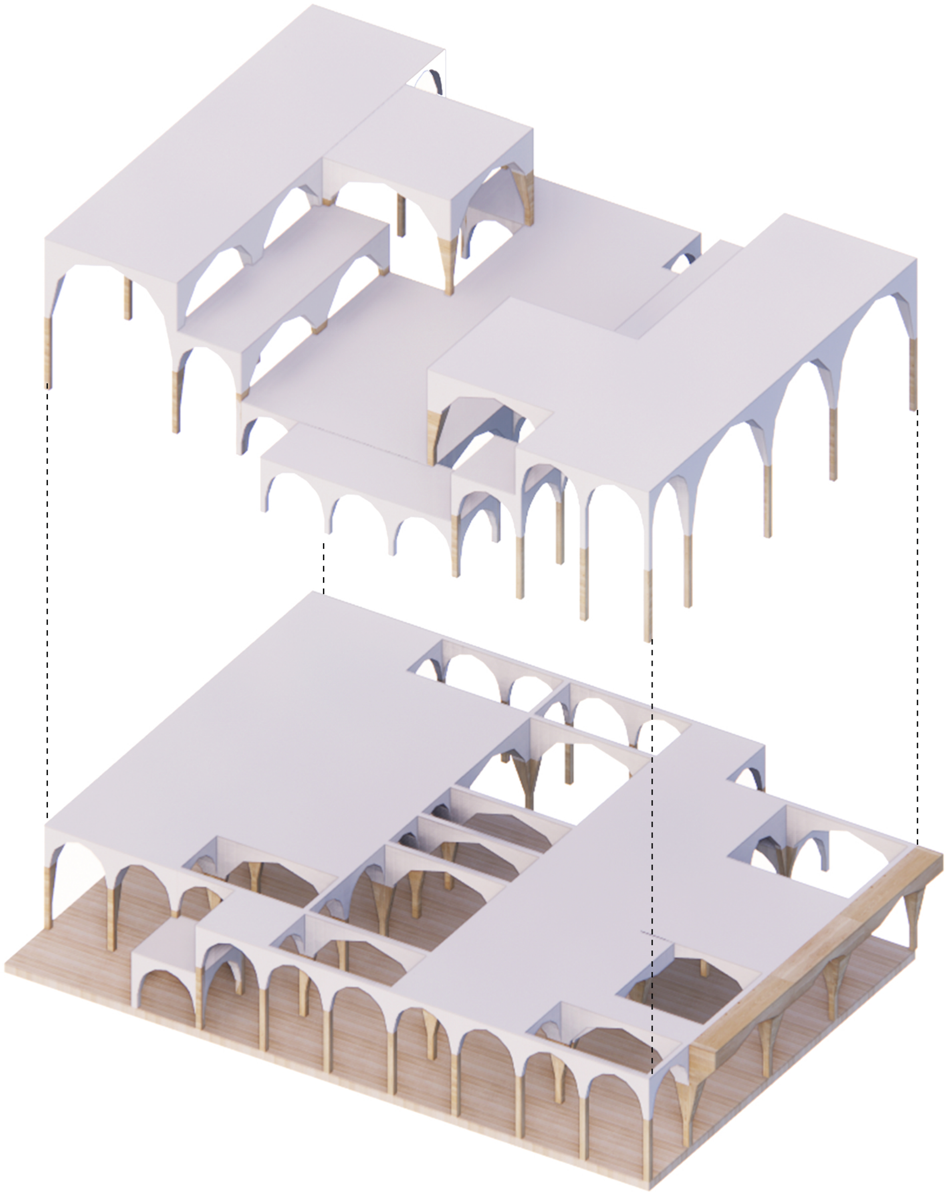


Figure 60: Vault structure exploded, Author

Test case |building structure + final building with facades and finishing

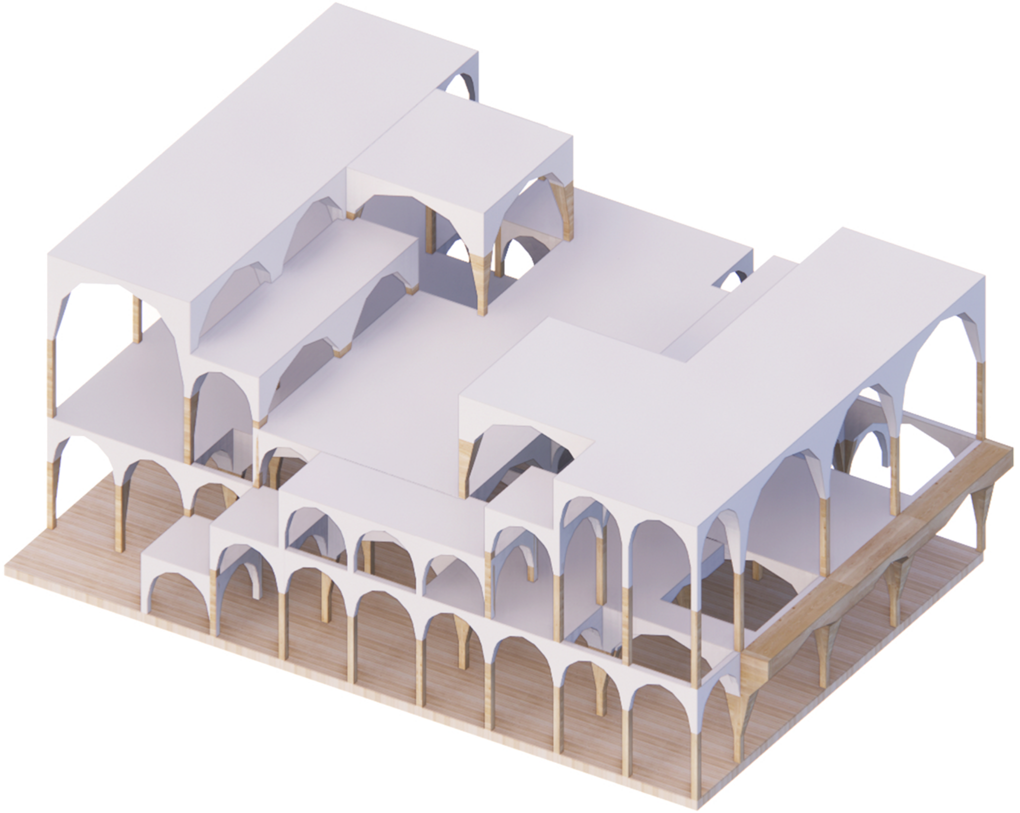


Figure 61 : Vault structure

Figure 62: Final building with facade and finishings

8.4. META LEVEL GAME

Pre-defined steps for the game	Steps as a Guide to create new solutions (you can add your own)
1. Input spatial configuration Floor levels & connecting spaces	
2. Approximate the shape of the spatial configuration according to the configuring logic (this time Lego-like logic) -> voxel set	(Configuring logic): - Voxel grid - Aggregation logic & interface between elements - Constraints (access, structure & other)
3. Approximate geometry from the voxel tile set with the predefined building blocks	(Shaping procedure) - Structural logic - Manufacturing costs and limitations: - Element creation approach (Tessellation & extrusion, patterns) - The final shape of the desired spaces, the aesthetical preference

Figure 63: Meta level game instructions, by Author

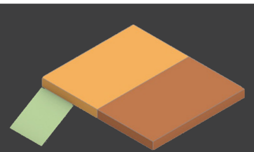
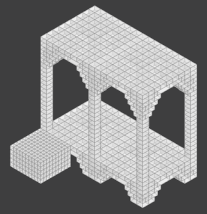
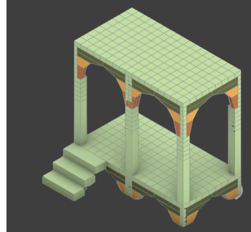
Pre-defined steps for the game	Steps as a Guide to create new solutions (you can add your own)
	
	?
 	?

Figure 64: Meta level game visual instructions, by Author

9. VERIFICATION &VALIDATION

In order to verify the consistency of the created pieces a test case with a given architectural configuration has been undergone, to see if the predefined elements can create solutions for different residential spaces. The test case is simplified into a spatial configuration – floor levels & connection elements (stairs) (Figure 65), then the configuration is approximated with a voxel set (Figure 66). Finally, the voxels are approximated with the pre-defined building blocks that are shaped for final use. (Figure 67&68) and those blocks can be produced out of wooden plates. (Figure 69) The test case can successfully be approximated with the predefined building blocks, yet a larger testing sample should be considered to prove variety of solutions.

In order to analyze the validity of the model (usefulness of the model) it is tested against being:

- Scalable (since architectural projects vary in scale)
- Easily producable
- Accessible

The building system is scalable due to its structural logic – compression only structure and due to the way how pieces have been designed. There are base pieces and pieces for scaling the structure towards the width, length and the height. Finally, the logic of the system is such, that it can be scaled down and scaled up according to the function, this size works for housing, however, for a massive concert hall this grid can be scaled up and still the proportions would stay the same between elements.
The building system is accessible & easily producable due to the chosen material – wooden sheets and the production technique – CNC milling, Also the standard building system as well as the design pieces for diamond vaults consist of straight faces therefore no curved wooden pieces are necessary. Finally, the affordability comes into play once the elements are assembled and it is simple stacking and would not require skilled labor.

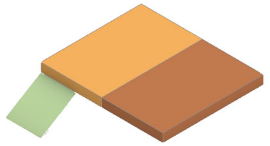


Figure 65: Spatial configuration of the given building

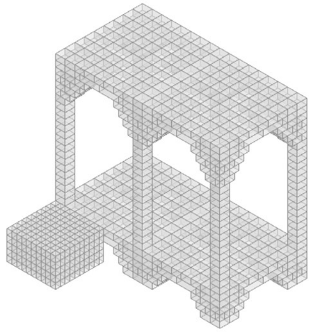


Figure 66: Approximation of the shape of the building with a voxel set

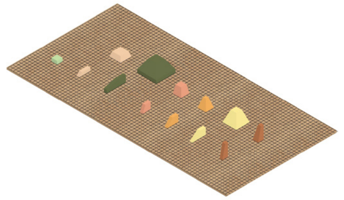


Figure 67: Predefined building blocks

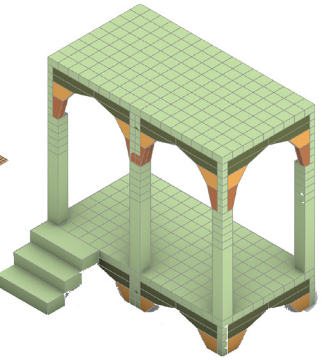


Figure 68: Approximation of the shape of the voxel set with the predefined building blocks

Figure 69: Final wooden vault structure

10. CONCLUSIONS & DISCUSSION

10.1. CONCLUSIONS

In order to design a small set of stackable timber elements to form both a structure and the inner shell of a building that can be configured into versatile, scalable and affordable housing units using combinatorial design and a compression-only structure several steps need to be taken:

- A configuring logic for the elements needs to be defined (In this research a Lego-like logic was chosen) and one of the options for this can include:
  o Defining a grid (taking into account room sizes of a house, but most importantly the dimensions of a comfortable stair and basing the main voxel size on it)
  o Defining an aggregation logic for the interface of elements in order to ensure scalability (in this case several faces of the elements need to be full voxel size to be able to extend all elements to the z directions and in some cases also x&y)
  o Defining access and structural constraints (in this research access meant leaving certain amounts of voxels open near stairs and connections of spaces, for the structure a compression only structure is assumed and certain patterns for equilibrium are chosen)
- Shaping logic in order to be able to create the final building geometry
  o Structural logic needs to be defined and prototyped and continued from the configuring procedure, this should allow for a scalable structure therefore a compression only structure is chosen.
  o The manufacturing technique and production limitations should be known which can be based on choosing a material and the way the elements will be produced (in this research wooden sheets and CNC milling is chosen) and basing the shaping of separate pieces on the maximum material product size and limitations of manufacturing.
  o An element creation approach needs to be defined to move away from the voxels and get towards a precisely shaped wooden structure. This can ensure architecturally and ergonomically valid and versatile spaces due to correct dimensioning of pieces and shaping pieces in such a way that several angles of vaults/arches can be found and that different widths & heights of spaces can be easily found. (in this research tessellation and extrusion is used as well as patterns based on
  o Rules of how the spaces should aesthetically look like and what style they should follow should be defined to finish off the element shaping.
- Once the Configuring logic and Shaping of the pre-defined building blocks is done a way of inputting a given floorplan needs to be found – in this research a spatial configuration is defined which consists of floor levels and connecting elements/spaces – stairs, ramps & corridors. And then this configuration undergoes the configurator steps and the voxel set is approximated with the predefined building blocks.

These steps can be seen as a meta level game (See chapter 8.3.) and the configuring and shaping procedures can lead to different results if different choices are made, also the configuring and shaping procedures themselves can be adapted. Overall, the research was succesful and a set of predefined elements was found which allows for versatile and easily producable and scalable wooden structures.

10.2. DISCUSSION

The results of this research can be tested further more thoroughly with different given configurations of different architectural styles in order to test if more building block types are necessary. The research has found valid solutions that have been tested for vaults that are the same size in 2 directions, but prototyping is necessary to test if non symmetrical vaults need any adjustments and additional pieces. All of the elements should be further technically worked out stating the appropriate connections and build up. Different interlocking systems should be tested for easier assembly. The specific size of the elements could be analyzed in order to increase the efficiency of production and material use. Meaning how does the size of the elements fit on the wooden plates in order to have less waste of the material. Overall, the research is a start into creating a full building system for housing that can also become a building system that by scaling it can accomodate other functions. However, several steps need to be taken to further detail the pre-defined blocks.

10. REFERENCES

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