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Makers Bazaar

A system to revitalize the urban infrastructure of the Zaatari Refugee camp

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The following report describes the design of a workflow for the urban redevelopment of the Al Zaatari refugee camp in Jordan. Due to the prolonged necessity of the camp and the regional and local properties, a more permanent urban structure is sought. The first chapter details the analysis of the design exercise: The problem statement and the regional potentials, the design goals and the vision, as well as a proposal for a new design, are all included in this chapter. The methodology to be used for the design is described at the end.

INTRODUCTION 01

1.1 PROBLEMS & POTENTIAL

To get oriented on the challenges and possibilities in the design area, the urban, architectural, and material conditions are analysed - initially in the entire class, and afterwards by the group. These analyses are described in detail in chapter 2 - Research & Analysis.

From these analyses and the first impression of the situation, several characteristics are identified as the most important problems and potentials within and around the camp:

Problems:
- Lack of stable revenue sources for private camp inhabitants
- Lack of urban structure, leading to informal growth of the camp over the years
- Unbalanced distribution of the camp infrastructure
- Inefficient education system
- Camp as an enclosed community detached from its surroundings
- Poor architectural quality due to the scarcity of resources
- Crime and violence rates in the camp are high

Potentials
- Skills and mercantile drive of the refugees
- Informal roads formed over time with less dense plots around them
- Different densities of commercial and other activities
- Presence of different vehicular connections and logistic hubs

The high crime rates and lack of stable revenue in the camp coupled with the mercantile drive of the camp inhabitants, give a hint to the direction taken with the proposed design.

1.2 DESIGN GOALS & VISION

The vision for the redevelopment of the camp is a method and not a singular building. To give the camp inhabitants a way to learn new skills while at the same time revitalizing the camp economy, this must both host the existing mercantile side of the camp, while at the same time educate the next generation in a craft that directly benefits the camp. The goals are as follows:

The design must:

- Provide a system that could help restructure the urban fabric of the camp
- Contribute to the improvement of education and development of new skills
- Provide the means to improve the architectural quality of the camp

The proposed building can host different kind of educational and commercial functions, depending on the theme of the building. These are then centered around key locations throughout the camp to give these districts a defining characteristic.

Figure 01: Design goals (own image)

1.3 DESIGN PROPOSAL

The proposal is to find key locations, called centralities, within the camp and build a system that uses the typology of the bazaar to gradually connect these elements.

The redevelopment process consists of four phases:

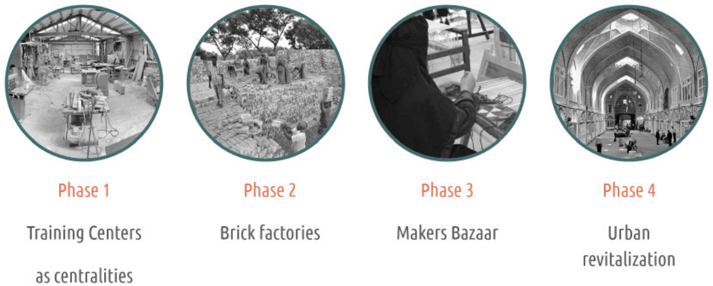


Figure 02: Development phases (own image from final presentation)

Starting out, a training center is needed to educate people in brick making and masonry. When a brick factory is added to the camp so that building materials can now be supplied locally, the urban redevelopment around the centralities can take off.

The design focuses on one such centrality, in the restructuring towards a makers bazaar that combines commercial and social functions with a brick makers space.

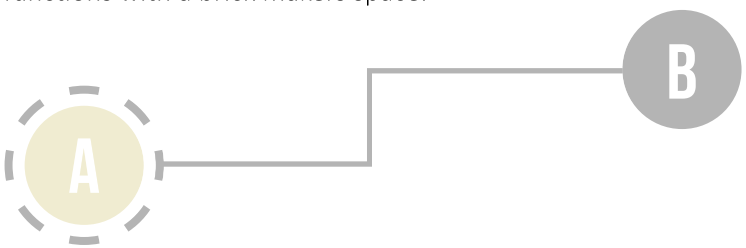


Figure 03: Centralities scheme (own image)

1.4 METHODOLOGY

In order to reach the desired results a systematic approach was followed. Our Methodology (as predented in figure 04) initiates with the Research and Analysis of the camp on an urban scale. There is also research conducted about the architectural elements of the camp in the existing situation as well as a more broad analysis of the bazaar typology in the middle east. The research and analysis part concludes with the research on the given material and its properties, meaning the adobe earth block.

From our research and analysis, we identify the problems and potential of the given case study and we move to our design proposal. After clearly formulating our goals, we develop the program of requirements in a detailed table and we define the relationship of the spaces through a rel diagrams and several bubble diagrams. This step helps us to understand the required space and its particularities.

After developing our urban growth strategies in the form of goals and rules, we choose one centrality of the bazaar to apply our program of requirements. For this purpose, a Layout tool is developed that computationally results in the design of our floor plan.

The shaping process initiates from this plan and is influenced by the properties of the material and the structural analyses that run in parallel. At the end of this process we result with the 3D configuration.

At the last phase of this project we look into the constructability of our design, where different systems and techniques are investigated in order to reach our final construction sequence. The detailing part plays an important role in this process.

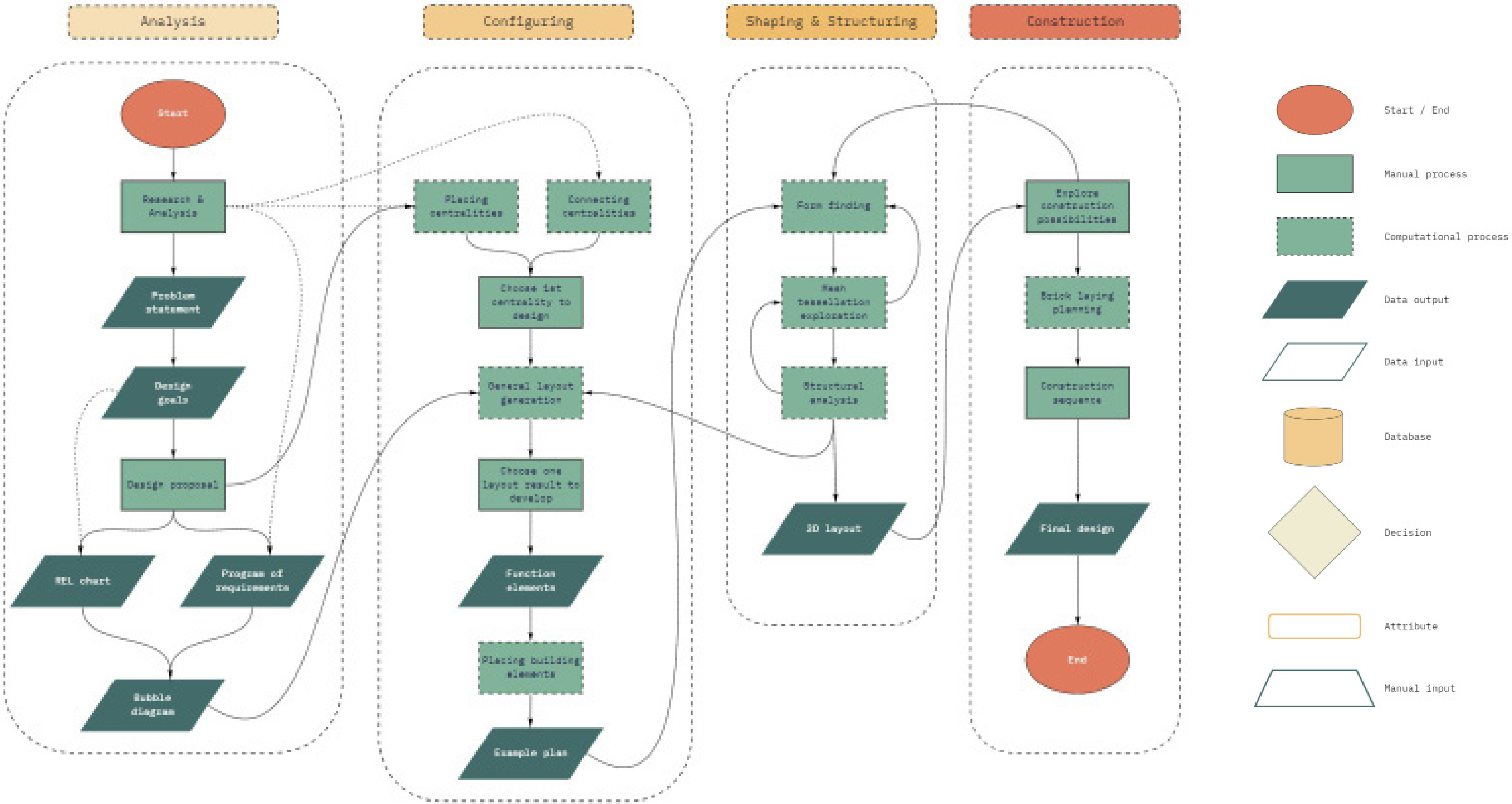


Figure 04: Overall flowchart of the project (own image)

Research and analysis covers the results of all the research done in preparation for the design process, as well as any analyses that have an effect on the final design. First, the urban context is explained. After this, the local and regional architecture are briefly summarized. Finally, an overview of the available materials is included

RESEARCH & ANALYSIS 02

2.1 URBAN ANALYSIS

The main concept of the Makers Bazaar is to function as an active system, able to restructure the urban fabric of the camp and grow with it. It is evident that the urban scale is significant for our project and thus we decide to start our analysis from this point.

Focus was given on the existing infrastructure and the distribution of the different functions of the camp. For this purpose, multiple sources were used to verify the found information, as well as the report from the previous year's projects. After gathering all this information, the main functions and their location were illustrated and color-coded on a map. In figure 00 we can also see the main road networks outside the camp, as well as the possible connections with the neighboring cities.

If we zoom in this map we can identify an uneven distribution of the main functions around the camp area. Most of them are located in Districts D3, D4 and D5. This can be explained from the different stages of expansion of the camp from the north-west side to the south-east side.

The road network is also notable. The primary roads are the ones that distinguish the different districts, while the secondary roads define subplots inside those districts. A lot of informal roads are also observed, resulting from the spontaneous adjustments of the people on their housing units and from the pedestrians' circulation inside the camp. These observations will help us set our urban growth goals through the bazaar typology.

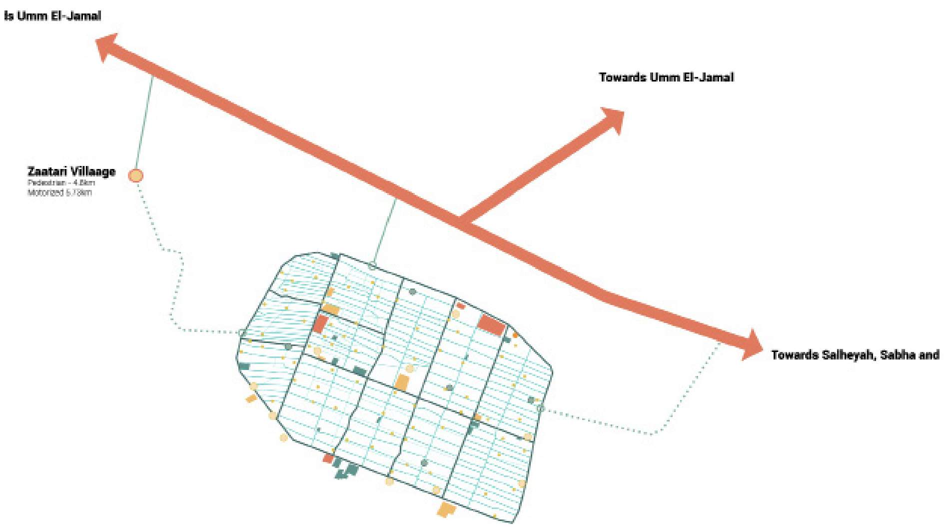


Figure 05: General area analysis - Functions & Connections (own image)

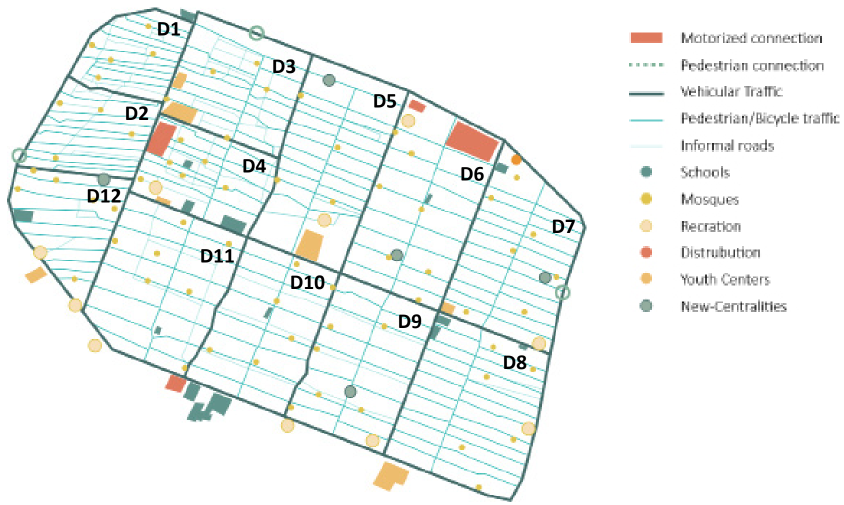


Figure 06: Illustrated map of Zataari camp (own image)

2.2 ARCHITECTURAL ANALYSIS

As described in the urban analysis, the camp has a main regular grid structure. This structure is infilled with two distinct types of housing, pictured on the right. The camp was initially made of tent units, but as it grew and facilities increased, more adequate caravans were added. After almost 10 years, the camp residents have reorganized and repurposed these in varying degrees to claim space and create smaller, family-owned courtyards. The low quality of these available shelters are the cause of health and safety concerns to the camp's structure.

Historically, the area has long been inhabited and knows a rich cultural and architectural tradition to take inspiration from. The main area of study was that of the bazaar typology. Several observations were derived from this research:

- Bazaars are key nodes in trade routes
- Bazaars highlight the intersection of functions
- Arcs, domes, and vaults are common architectural elements
- Organically develops but functionally organized
- Users add improvised shading in bazaars when it is not provided by the structure
- Bazaars sometimes have flexible spaces and allow transitional space usage
- Social interaction is as important as exchange of goods
- Some bazaars are covered, have second floors that can optionally be closed off
- The spine of the bazaar defines the circulation and urban structure of the surrounding area

For the makers bazaar design, the leading principle is the flexibility with which the shared spaces can be claimed and reclaimed. By providing a structure to use, the bazaar can redefine the urban context.

Figure 07: Caravans, tents, and hybrid shelters. Photo: Kaity Kawar/IRC

Figure 08: Bazaar of Isfahan. Image source: Mohammed Gharipour, 2012

2.3 MATERIAL ANALYSIS

The material analysis concerns all the materials currently in the camp, and all materials that feasibly can be imported into the camp.

Besides the caravans and tents provided by UNHCR, the inhabitants have often modified, expanded or altered their homes with improvised building methods. These often utilize the following materials:

- Scrap tires
- Corrugated sheets
- Discarded or repurposed water tanks
- Foam- or woodchip boards from dismantled caravans
- Cinderblocks
- Plastic or cloth tarps

After these artificial materials, some natural resources in the area are also suitable for construction. The camp residents have used rocks, gravel and stones in augmenting their houses. The ground is presumed to have enough clay and silt to be used for bricks and adobe structures. An in-depth look at the design of the brick and it's composition can be found in chapter 5.

Water is scarce since the camp is located in a desert. For this reason, water is imported by the UNHCR. Temperature regulation is also an issue in the climate, which is why earthy architecture has traditionally been used to build in the region. The large thermal mass from these compression-only structures provide a cooler interior climate during the day while keeping a stable temperature during cold nights.

Figure 09: Varied scrap material availability. Photo: Getty Images/AFP

Figure 10: Commonly available construction materials. Own image

In the configuring chapter, a general layout for the design is generated. First the methodology will be shortly discussed. Then, the logic behind the placement of centralities and the urban growth are explained. The program of requirements and it’s associated REL chart are then used to implement the steps needed to finally generate a layout for the design. This process is expanded upon at the end of the chapter

CONFIGURING 03

3.1 METHODOLOGY

After having completed the research and analysis process, we proceed to the configuration part of our project. The configuration process starts by placing the centralities that are going to constitute the nodes, from which the bazaar is going to develop and expand. Since in the context of this project, we are going to cover the design of one centrality, after the computational process for finding possible centralities, we are going to choose one of those to develop further.

After zooming in to the centrality we chose, the design process starts by defining the program of requirements, from which we then derive a REL chart and a bubble diagram, in order to specify in more detail the relations of the spaces. We then proceed to the application of our computational layout tool, which is producing results based on the requirements of each space. In the first phase of this tool, we get alternative configurations of the main functions, as areas, from which we choose manually one example that best fits our design vision. The seperate functions as well as the whole configuration, are based on a standard grid which is formed by individual cells.

After choosing one product of the first phase we move to the second phase of the layout tool, where, after several iterations through all the cells of the configuration, we result in a unique code of the edges of each one of them. This unique code depends on the relation of the different functions as well as on the rules and restrictions for each specific function. According to the code of all the edges, a 2D plan is produced for the whole design.

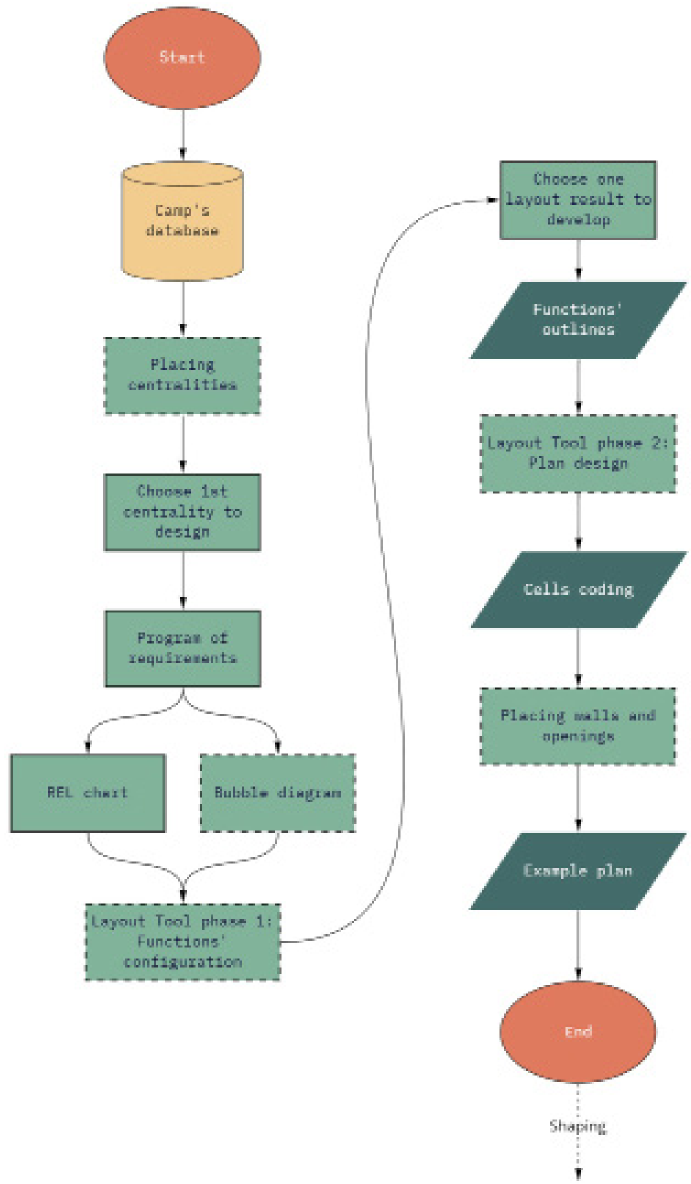


Figure 11: Configuration process - overall flowchart (own image)

3.2 CENTRALITIES EMERGENCE

As a centrality is defined, a spot of the area under study, that emerges as a point of interest due to its position in relation to other functions and to the circulation network and to its distance from sources of significant goods.

The centralities are envisaged to emerge in strategic places in order to contribute to the more uniform distribution of infrastructure throughout the camp and to form the nuclei of development of the bazaar as a functional and social space.

In order to computationally describe the origination of those centralities, we developed a grasshopper definition. As a first step, we depicted the information that we got from the camp's database in the form of the existing circulation network - divided into primary, secondary, and informal roads - and of the spots of interest as points. As spots of interest are considered: the distribution centers, the youth centers, the schools, the cultural spaces, and the mosques.

After highlighting the existing infrastructure we manually assign a radius of influence to them by category. The radius of influence depends on the importance of the function, its relation with the future bazaar functions, as well as its frequency throughout the camp, and it is divided into two categories: low and high influence *(figure 14)*. As a result, the available area outside this "zone of infrastructure" is chosen *(figure 15)*. Subsequently, a maximum distance from the gates and the water sources is defined and the intersection of these circles with the available area constitutes the space that is adequate for the emergence of a centrality *(figure 16)*. The centrality can be placed on any road intersection within this area. This process is also described in the flowchart on the right.

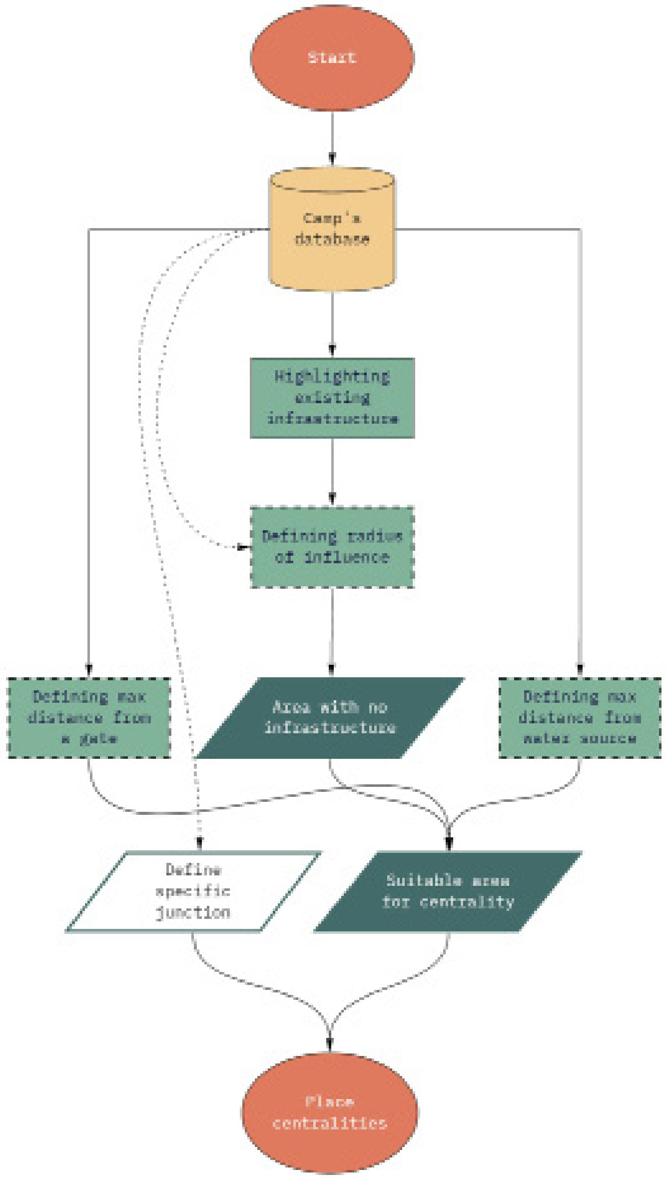


Figure 12: Emergence of centralities - grasshopper script flowchart (own image)

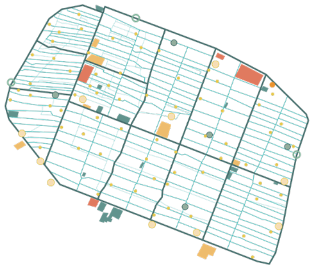


Figure 13: Existing infrastructure

Figure 14: Define radius of influence

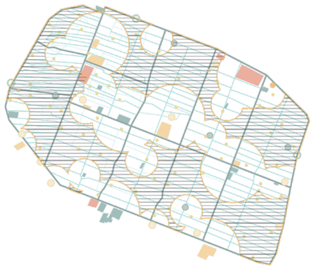


Figure 15: Highlight are without infrastructure

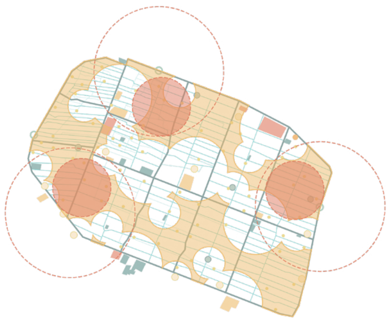


Figure 16: DIstance from gates & water source

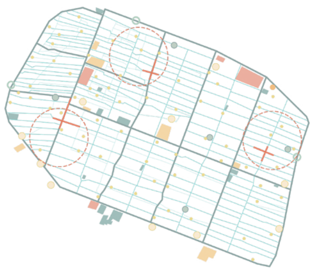


Figure 17: Define specific junction

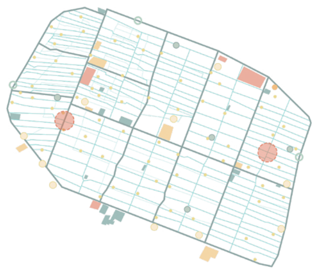


Figure 18: Centralities emergence

3.3 URBAN GROWTH

Based on our vision to revitalize the urban structure of the Zaatari camp, the bazaar is envisaged to become a polycentric structure, growing from the emerging centralities that are spotted in the locations described in the previous chapter.

As the camp grows bigger and evolves through time, more centralities, smaller or bigger, emerge and the bazaar tends to grow from them to connect and form an urban functional, commercial and social system. This system subsequently affects the growth of the other functions of the camp, resulting in a well-structured functional space.

The path that is being formed while the bazaar grows, as well as the placement of buildings along it, are being defined by a set of rules. These rules can be summarized as:

- finding the shortest path between two centralities
- balancing attraction and repulsion forces as short and long distances from other functions
- following as much as possible the existing road network to cause interventions with less disturbance
- avoid moving more permanent structures
- ensure evenly distributed open spaces

Some secondary rules concern mainly the functions of the bazaar itself and include the need of a caravanserai of every 100 shops, the existance of an atrium at the prinicipal cross-roads, and the link of it with a small or big courtyard and the connection of the educational space to this courtyard.

As the course required to focus on the design of one of the centralities and move to the building scale, an algorithm for the visualization of the urban growth fell out of the scope of this project for the moment.

For this reason, we did not manage to invest too much time on this but we developed a grasshopper script for a simplified version of the creation of a path between two centralities. This definition will be explained in brief here through the flowchart in *figure 25* and some illustrated diagrams but it can be found as a whole in appendix X (figure 00).

This definition take the centralities and the several other functions as points. Firstly, the shortest path between AB is created *(fig. 19)*. Then this line is divided into points and a field of vector forces is formed according to repulsion or attractions forces. If we need to get closer to a certain function then the vecor starts from the point on the line AB while if we need to keep distance from a function the vector ends in this point *(fig. 20)*. The points are repositioned according to these forces *(fig. 21)* and then snapped to the existing road network *(fig. 22).* Then, the points are connected in a row and if this line coincides with the road it becomes a path, while if it forms a diagonal it is reserved for an open space *(fig. 24).*

There is still a lot of room for further development that is going to be discussed in more detail in the Reflection chapter.

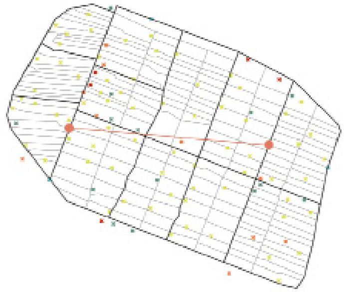


Figure 19: Connecting centralities - line AB

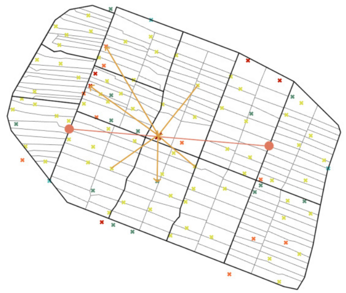


Figure 20: Create field of vector forces

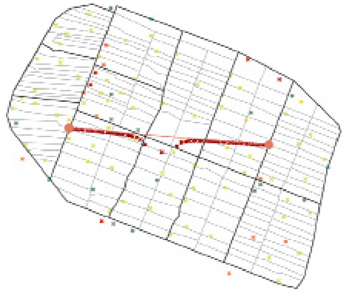


Figure 21: Reposition points

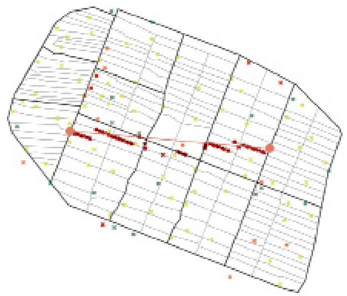


Figure 22: Snap points to existing grid

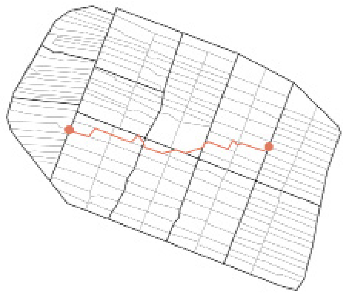


Figure 23: Connect snapped points

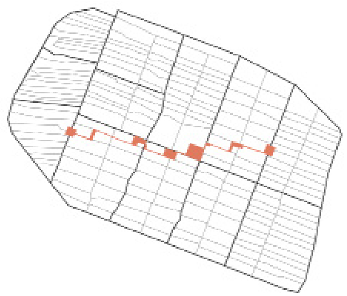


Figure 24: Create path and open spaces

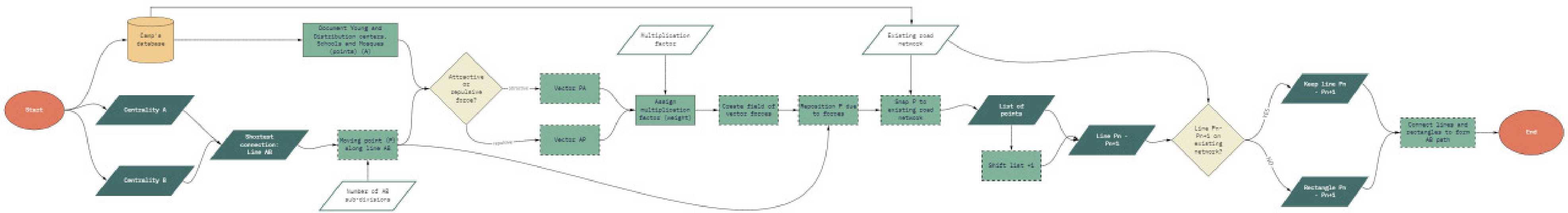


Figure 25: Simplified urban growth definition - flowchart (own image)

3.4 PROGRAM OF REQUIREMENTS

After choosing one centrality to design, the first step is to define the program of requirements. The table on the right illustrates all the primary and secondary functions with their basic characteristics. For each function, among others, we define its minimum area, its accessibility, estimated operating hours, and the production of noise. These characteristics let us define also the relation of these functions, that is translated into numbers in the REL chart below and into a more diagrammatic form in the bubble diagram *(figure 28), which was produced with the help of the Syntactic tool for grasshopper.*

		Area (m2)	Noise (generation)	Definition of space	Open/semi-closed/closed (to sky)	ceiling hight	Day light intensity	Accessibility	Open hours	Main Function
Commercial	Food retail	10-14m2	yes	Fixed	closed	2.7m	low	public	During the day	Yes
	Craft	20m2	yes	Fixed	closed	2.7m	low	public	During the day	Yes
	Tech	10m2	yes	Fixed	closed	2.7m	low	public	During the day	Yes
	'Café / Restaurant	10-40m2	yes	Fixed	closed	2.7m	low	public	During the day	Yes
Logistics	Caravanserai	400m2	yes	Modular	semi-closed	(if roof 5)	high	Private	Always	Yes
	Acces to Road	x	yes	x	open	x	high	Public	During the day	No
	Storage (workshop)	60m2	no	Fixed	closed	2.7m	zero	Private	Never	No
	Storage (shop)	7m2	no	Fixed	closed	2.7m	zero	Private	Never	No
Others	Atrium	200m2	yes	Modular	semi-closed	6-10m	medium	Public	During the day	Yes
	Learning space	150m2	no	Modular	closed	3.2m	high	Semi-public	During the day	Yes
	Workshop	200m2	yes	Fixed	semi-closed	4m	high	Semi-public	During the day	Yes
	Housing	30m2	no	Modular	closed	2.7m	medium	Private	x	No
Connectors	Buffer space	50m2	yes	Modular	open	x	high	Public	During the day	No
	Courtyard	100m2	no	Modular	open	x	high	Semi-public	During the day	No
	Passageway	x	yes	x	closed	6-8m	low	Public	During the day	Yes

Figure 27: Table of functions and their characteristics (own image)

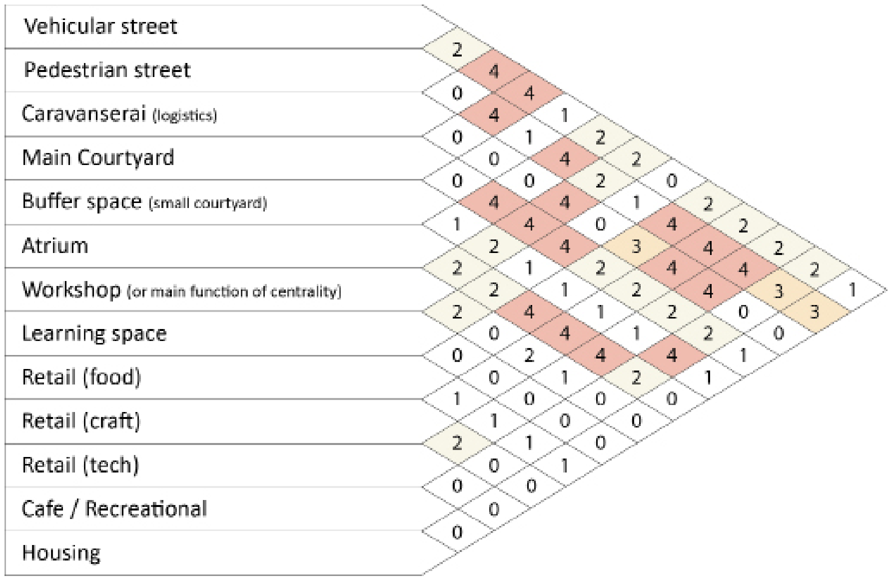


Figure 26: REL chart (own image)

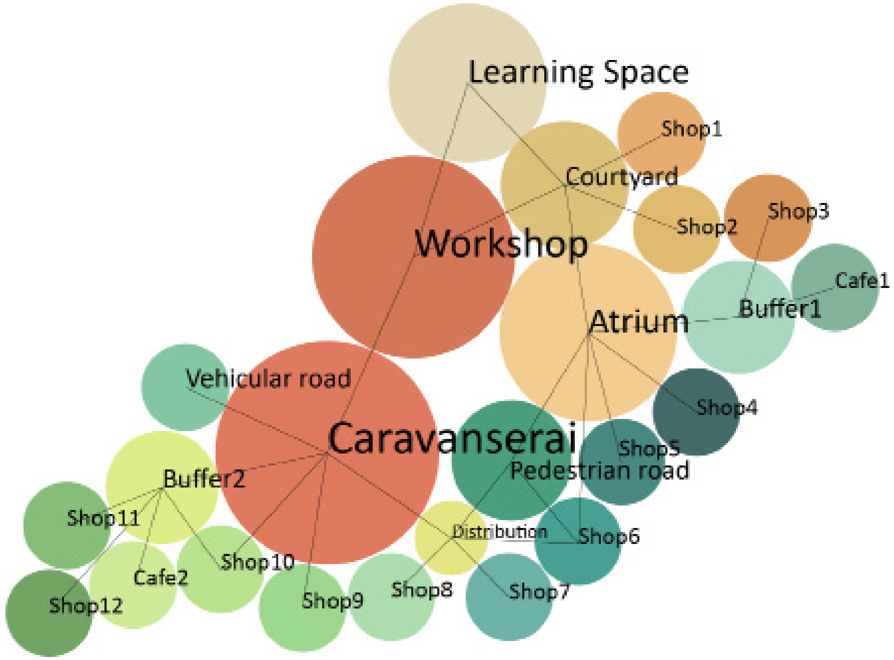


Figure 28: Bubble diagram (own image)

3.5 LAYOUT TOOL

The detailed development of the program of requirements, as well as the subsequent rel and bubble diagrams, assisted in understanding the scale and the identity of the needed spaces and the relationship with each other. In this phase of the design we developed a Layout tool in order to reach a plan design that serves all the requirements of the spaces through a computational process. This tool includes two phases. In the first one, the available space is translated into a grid from square cells and the configuration of the functions, as areas, is taking place. In the second phase, we iterate through the cells of each function area in order to assign walls and reach a plan design.

3.5.1 Phase 1 - Functions' configuration

This part of the Layout tool was developed mainly in grasshopper with the parallel developments of some python components. The full definition can be found in on the Git repository.

In this part of the report, its functionality of this tool is going to be presented through the main flowchart *(figure 29)* and illustrated diagrams, representing the steps.

The input that is required from the user at this stage, is the functions and their respective minimum areas in form of lists. The grid size is also part of the input but is mainly being influenced byt the shaping and construction processes that are going to be presented at the next chapters. The random seed can be altered by the user and it triggers the production of another alternative since it affects the XxY ratio of the function areas and their placement on the plot.

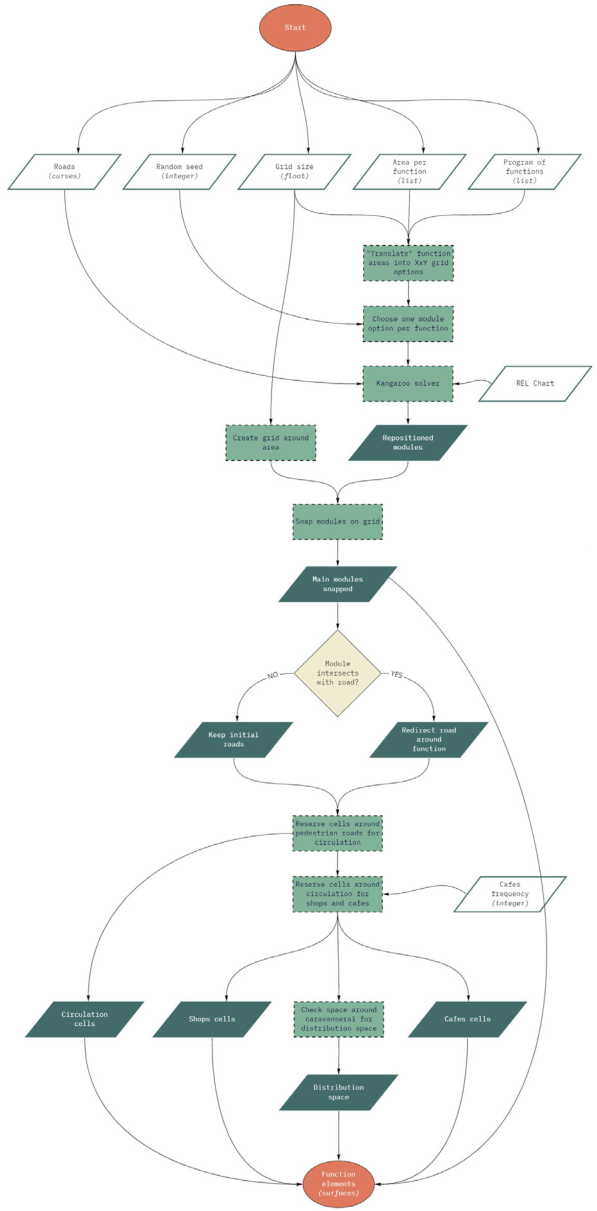


Figure 29: Layout tool - Pase 1 - flowchart (own image)

The first phase of the Layout tool can be summarized in the following steps:

step 1: The list of functions and areas are being translated into surfaces based on XxY grid ratios.

step 2: The functions that take most of the space and are more rigid in their shape are selected. The distance goals between those functions, as well as their distance from spots of interest, like the junction or the vehicular road, are being determined according to the rel chart which was presented in the previous chapter. These distance goals are being measured from the centroids of the functions and are fed into a kangaroo solver that is then initialized in order to bring the system into equilibrium, with the solution that best serves the combination of all the goals.

step 3: The surfaces resulting from the solver are being snapped to the grid of the area, based on proximities to the grid vertices and to rules about aligned/shared edges.

step 4 (optional): If one of the main functions intersect with a road, then this road is being redirected around the function.

step 5: The circulation space is being defined. Cells for circulation are being added on the main pedestrian axes and together with the courtyard and the atrium, they form the circulation network.

step 6: Shop units are being added around the circulation areas to form the bazaar elements and the courtyard shops.

step 7: Some of the shop units are occupied by cafes, according to user’s input about the frequency of cafes.

step 8: the remaining space between the caravanserai and the commercial areas are defined as distribution/ buffer space.

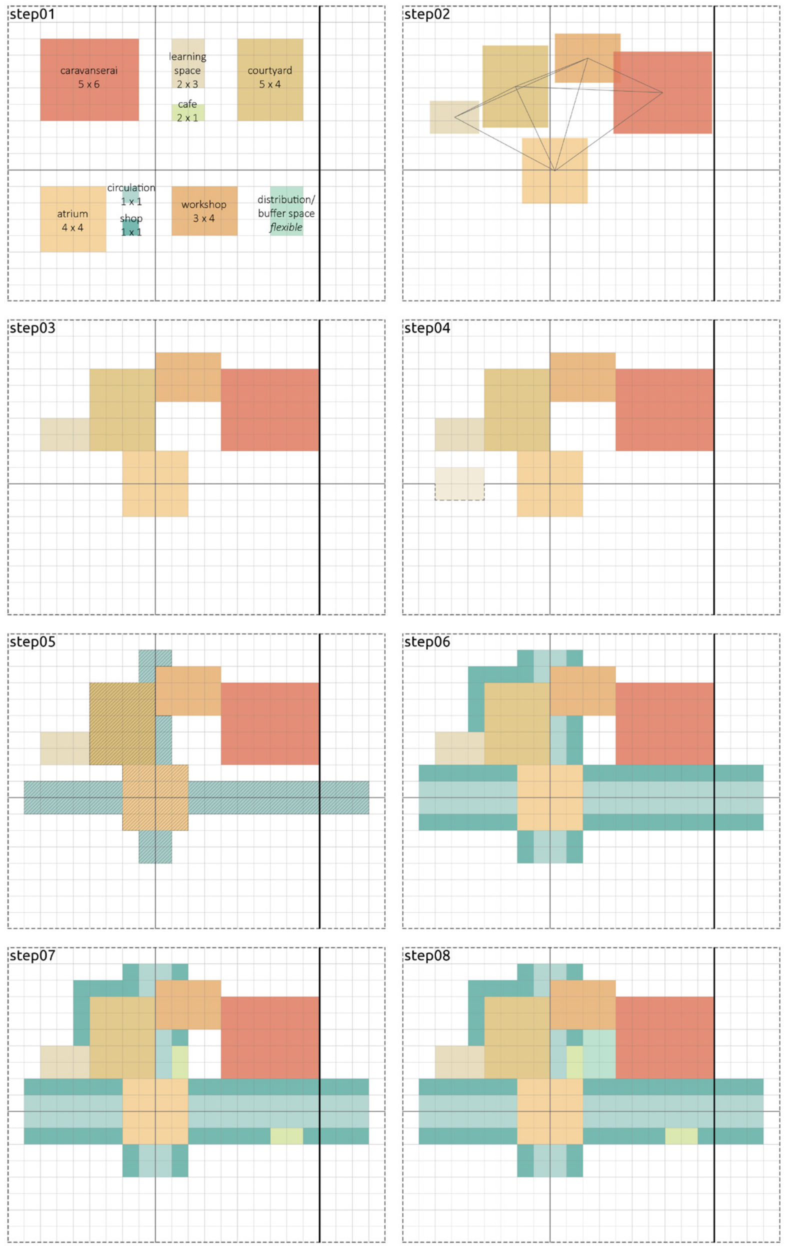


Figure 30: Layout tool - Pase 1 - Steps illustrated (own image)

3.5.1 Phase 2 - Plan design

After the functions are defined, a plan is generated from this input. Briefly, the workflow is as follows:

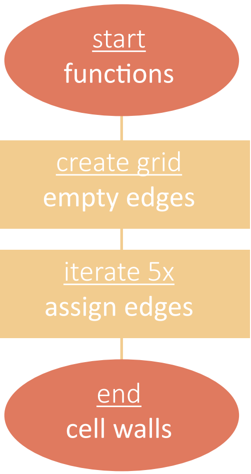


Figure 31: Plan design workflow in brief (own image)

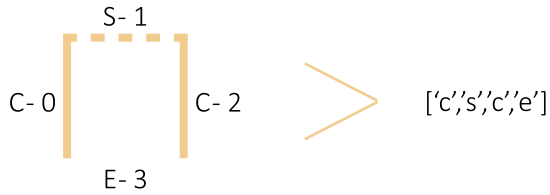
First, an empty grid of cell edges is created for each cell by creating a nested list with empty walls of length "gridsize":

['e','e','e','e'] * gridsize

Here, each value represents the currently state of the walls of cell like so:

'e' = empty, a not-yet assigned cell edge
'o' = open, a cell edge that must remain open
's' = semi-open, an edge that must by passable, but partly closed
'c' = closed, a closed cell edge

Each edge of a cell is a position in the list:



In this way, the script can iterate through the current list of wall edges and assign them new values as needed, as well as evaluate the values in neighbouring cells and edges by their index. A class is written to assign initial attributes to cells for easier access later on. Below is the flowchart for this part of the script.

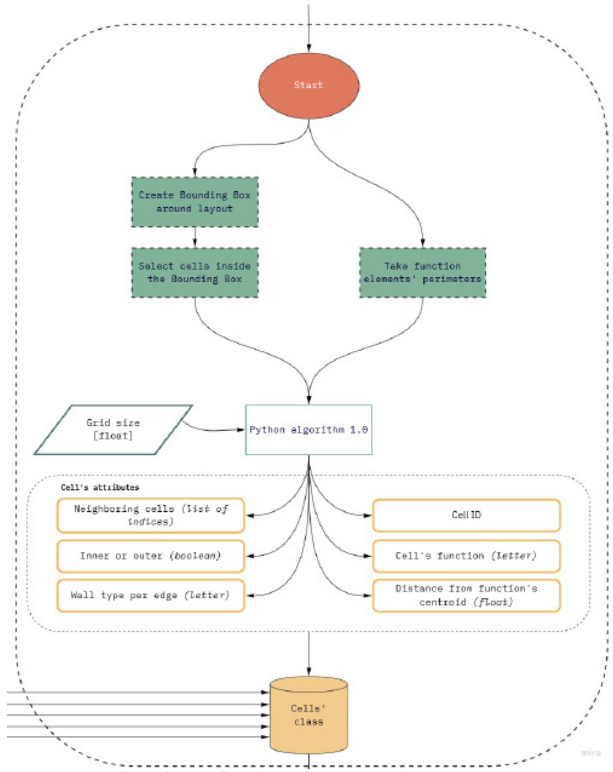


Figure 31: Cell atributes flowchart (own image)

All the cells inside the bounding box of the layout output are selected. The cells are then given an ID, the neighbouring cells are found, whether it is on the inside of it's function or on the edge, what it's function is, what the distance is to the centroid of the function, and what it's current wall type is. The wall type is not to be confused with the cell edge type. Here, wall type means whether the cell is U-shaped, L-shaped, I-shaped, II-shaped, enclosed, or free. These values depend on it's neighbours and help later on in the process when assigning stairs.

The first iteration finds the edges of all functions that have an arcade-like structure. If the edge is next to another function that, according to the REL chart, should be connected, the cells are opened up. If the cells should have no connection, they are closed off. The chart shows user input as an option for a more refined result, but this was skipped in the eventual implementation due to time constraints.

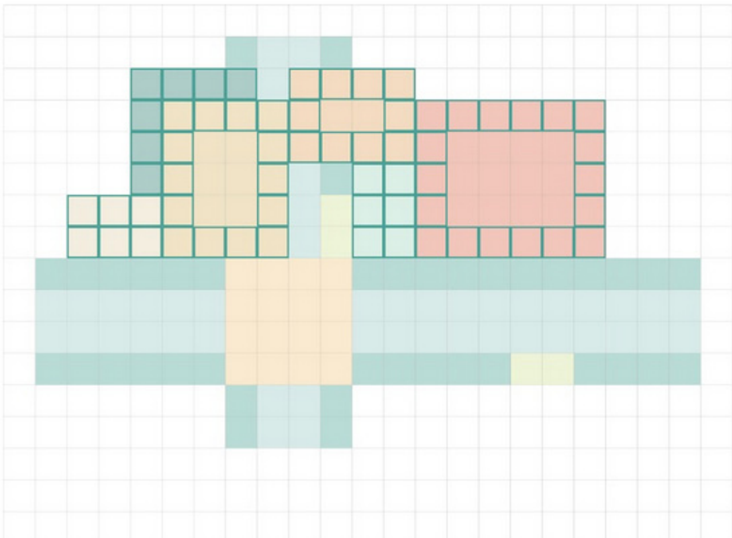


Figure 32: Affected cells of first iteration (own image)

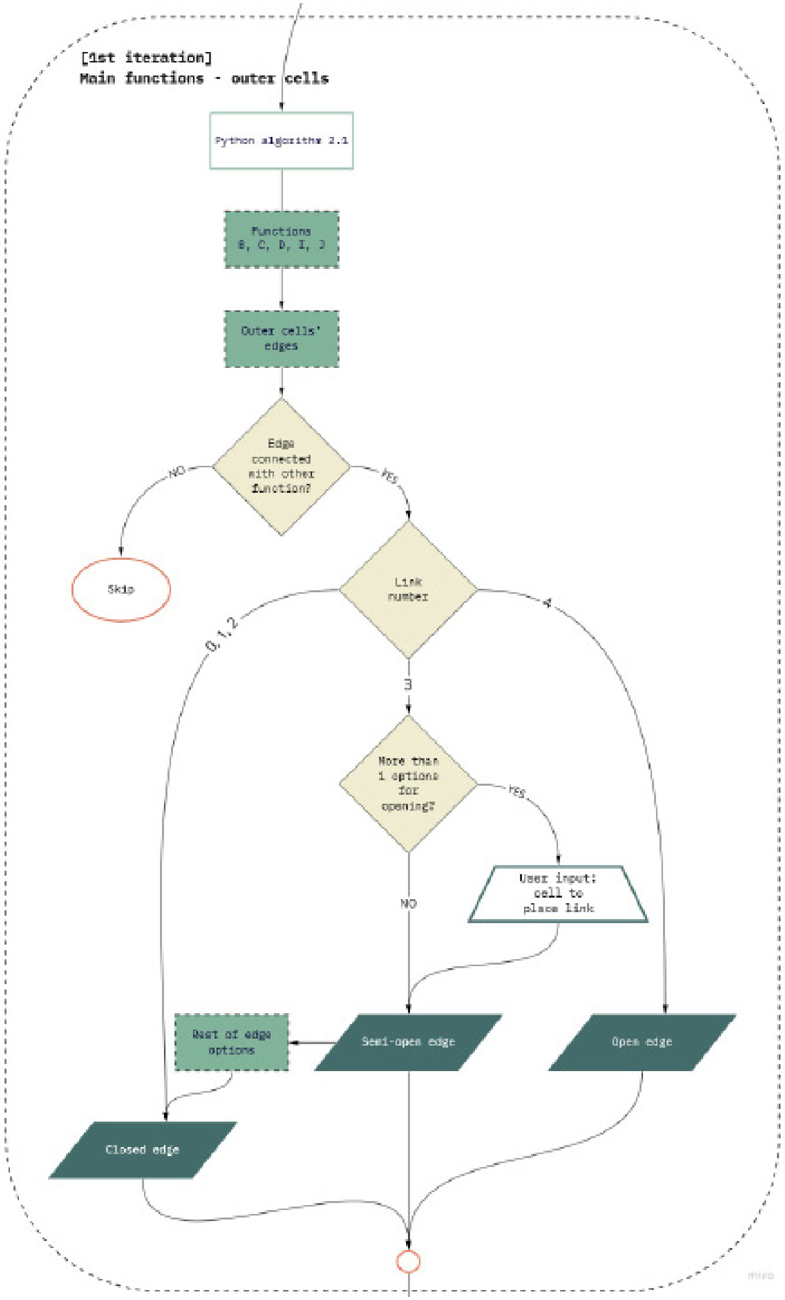


Figure 33: First iteration flowchart (own image)

Once the outer cells of the main functional spaces are defined, the next step is to find all the self-standing modules. Due to having different requirements for the needed connection between the public bazaar units and (semi) private functional spaces behind them, unique combinations are found for this function which is why it is treated seperately. The main axis of the bazaar is kept free by assigning these their own unique function (G).

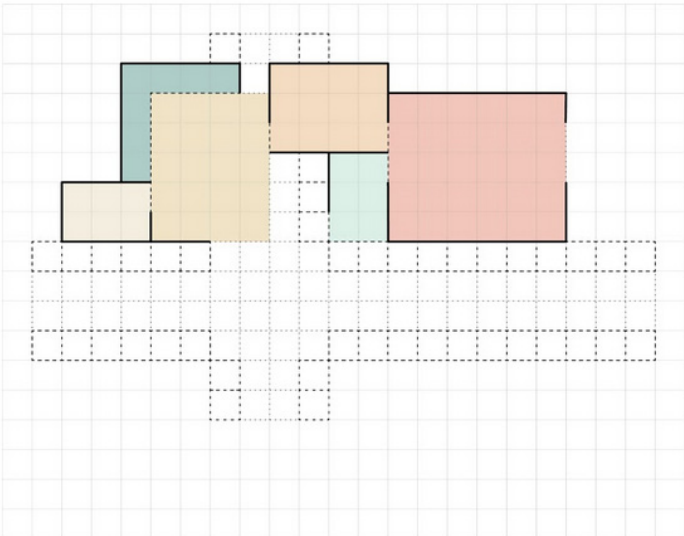


Figure 34: Results of second iteration (own image)

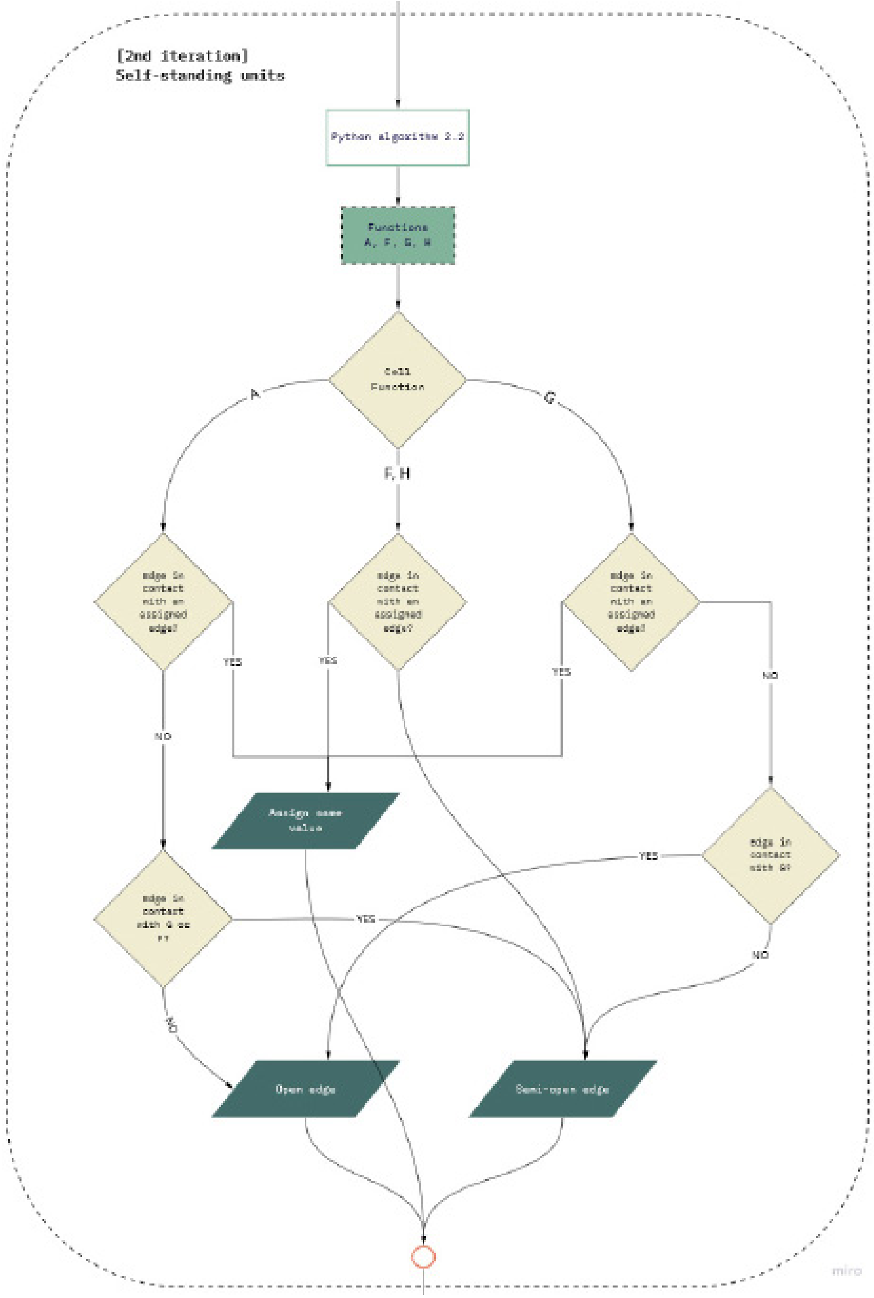


Figure 35: Second iteration flowchart (own image)

The third iteration places the stairs in all functions that have a reuquirement for stairs. The carevanserai and workshop both have a second floor and need stairs. By finding any cells labeled as 'L' shaped, the corners of the function is found. Then the user is asked to choose from the remaining stairs which make the most sense to them, as can be seen in *figure 36*:

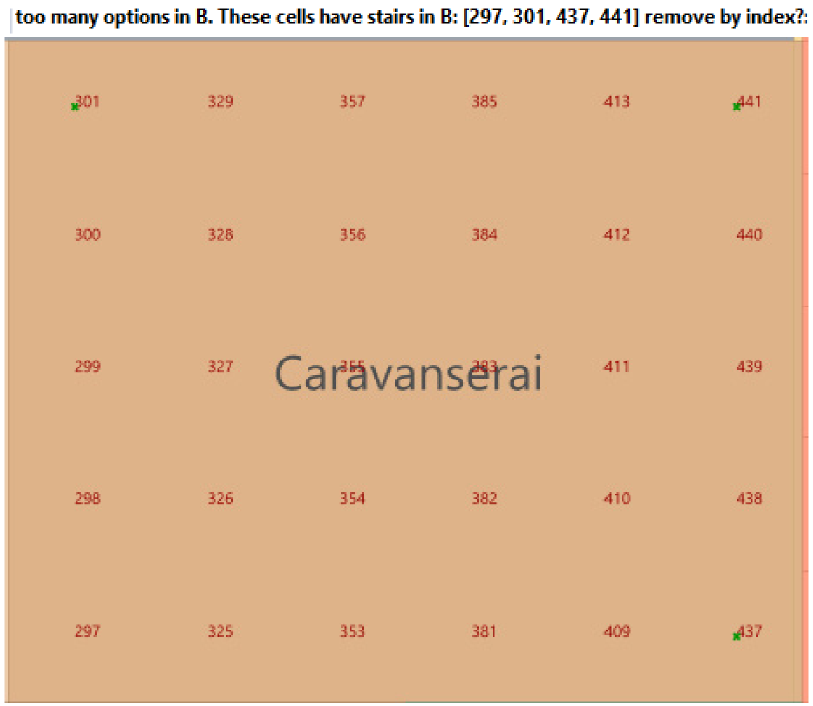


Figure 36: Typing '0' into the Rhino console removes cell 297 as an option for the stairs (own image)

Once the stairs are chosen, the user once again gives input on the rotation of each stair module with by providing the index of the side that is to remain 'open'. The rest of the cells are closed off.

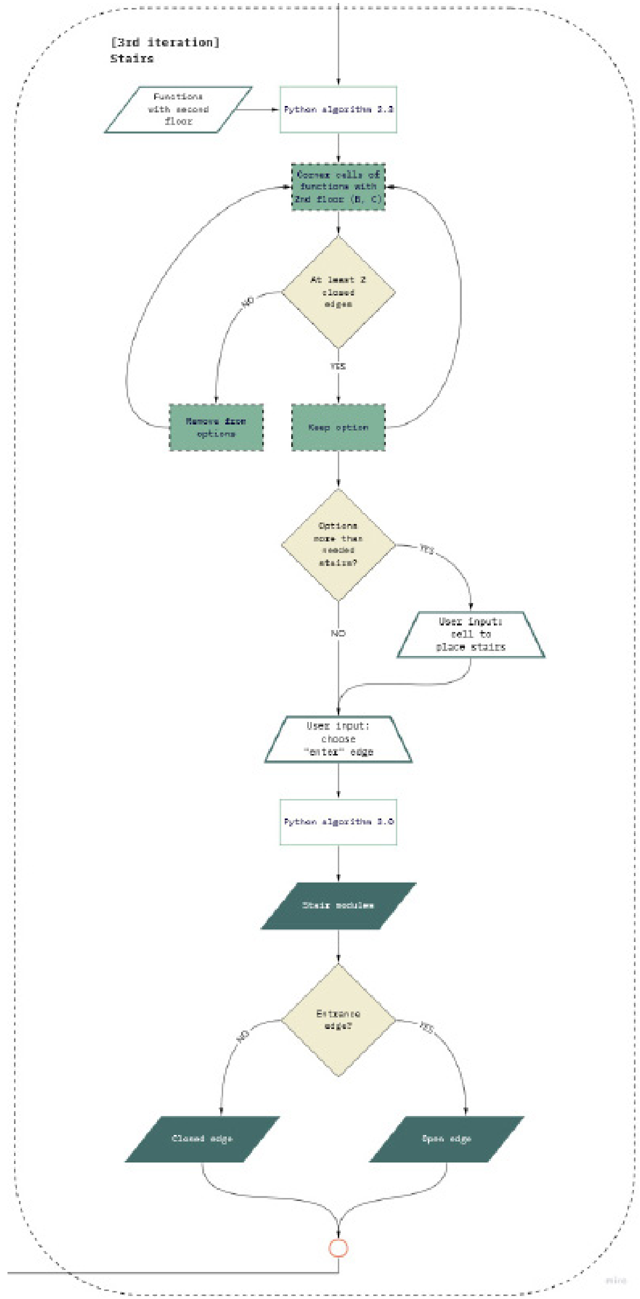


Figure 37: Third iteration flowchart (own image)

After defining the stairs locations, the inner courtyards of functions that have a courtyard are cleared out. If the cell to be removed is bordering a shop unit, it gets a semi-open edge. Otherwise, the edges are either opened up or take on the value of their neighbouring edge if that edge is already defined. This ensures that the connections between neigbhouring cells make sense from a construction and useability perspective.

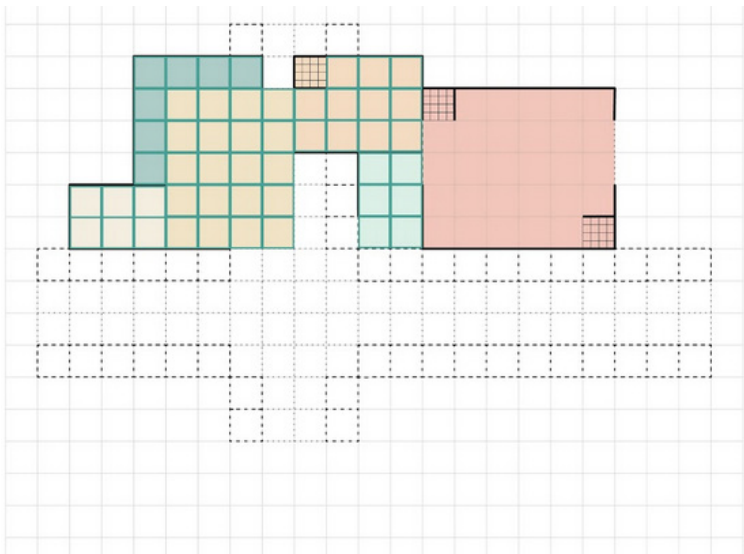


Figure 38: Affected cells of fourth iteration (own image)

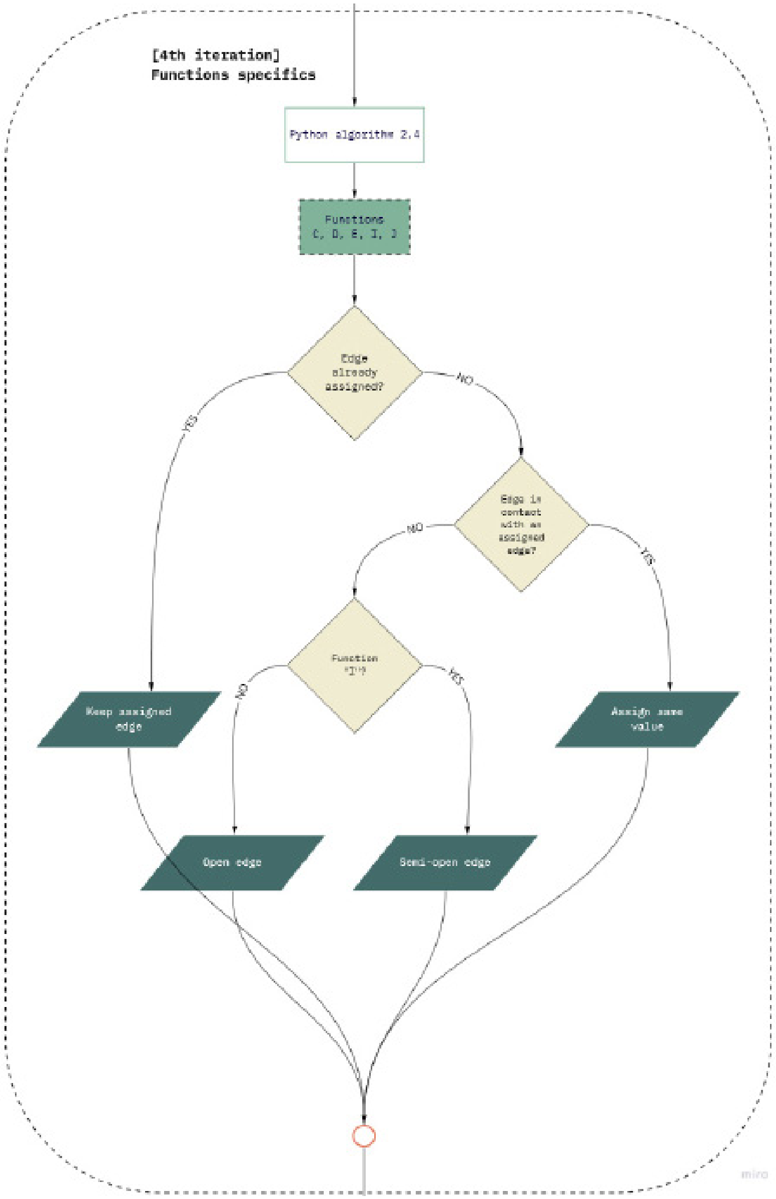


Figure 39: Fourth iteration flowchart (own image)

The final iteration gives the carevanserai's remaining cell walls their type. Storage units are created along the edge of the carevanserai by finding all outer cells and making the walls semi-open. The center courtyard is cleared, all the while taking the previously created walls into account. The final result from these iterations looks like *figure 40:*

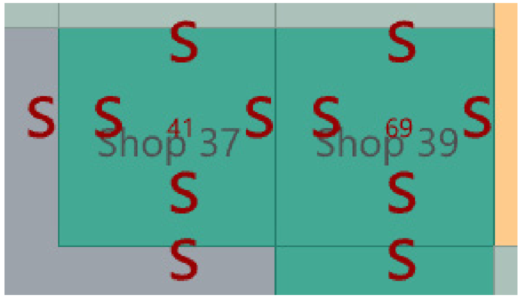


Figure 40: Dry output from configuration script projected on plan view (own image)

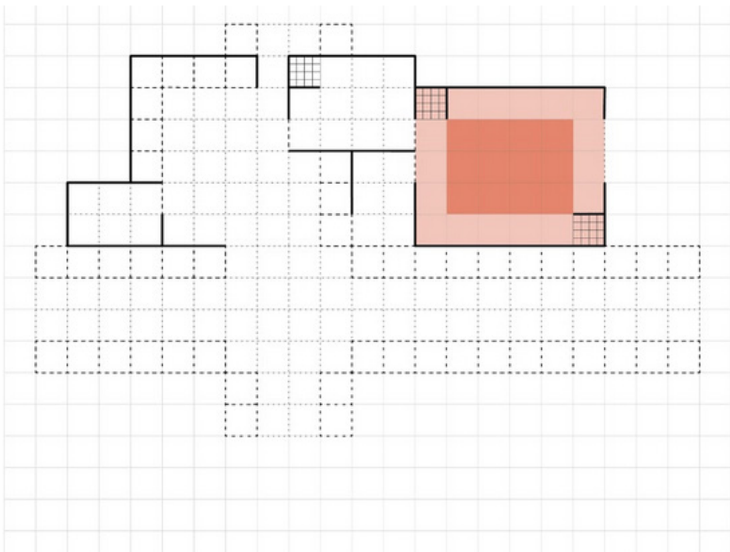


Figure 41: Affected cells of fifth iteration (own image)

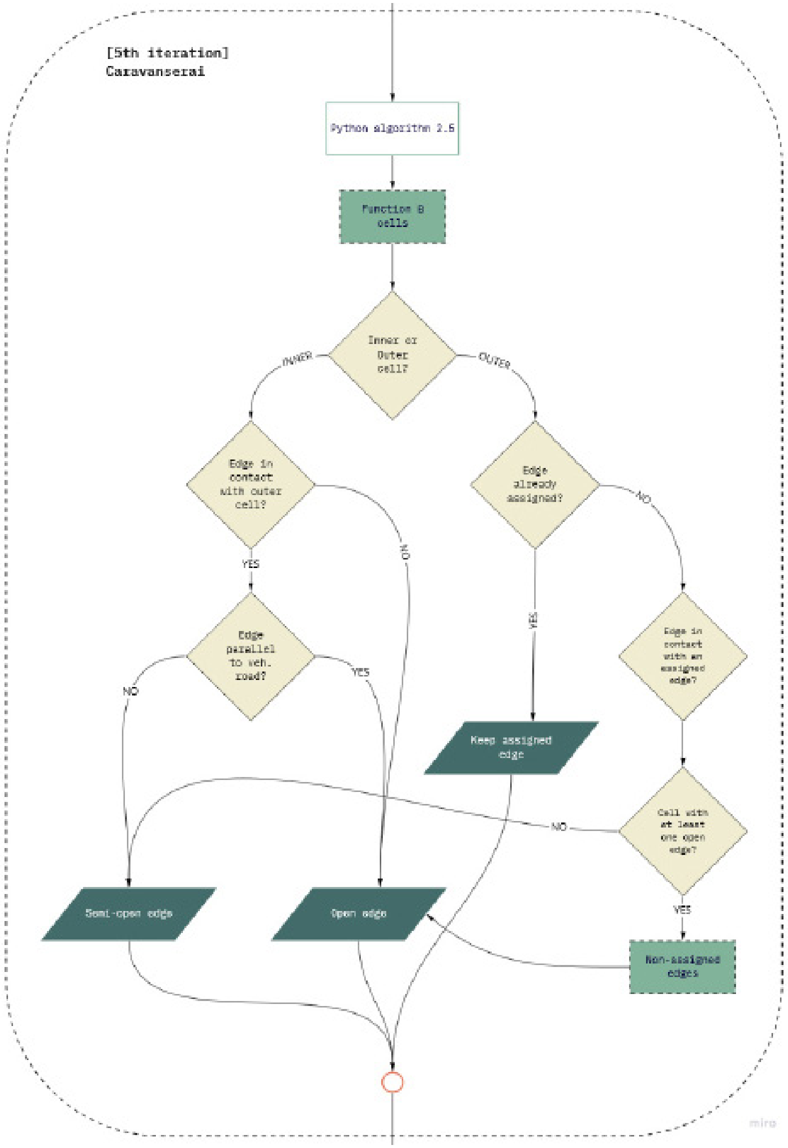


Figure 42: Fifth iteration flowchart (own image)

Conclusion

A configuration was succesfully generated using the logic described above. Unfortunately, translating the raw results into automatically generated maps or models proved challenging. Due to time constraints, it was not possible to merge the wall module library with the configuration script, so the plan as well as the final design had to be manually generated.

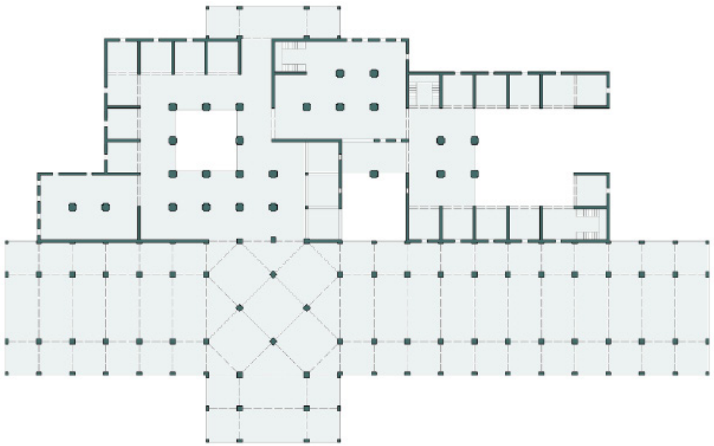


Figure 43: Final floor plan (own image)

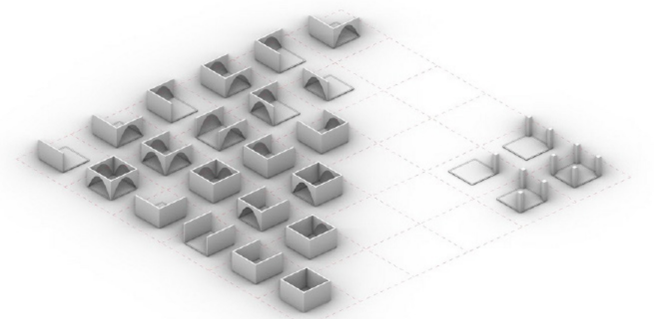


Figure 44: Wall modules (own image)

The library of elements that is implemented into the configuring tools is in this chapter developed and structurally tested. The form-finding process focuses on the optimization of two different typologies of roof shapes and analyzes them in order to determine their optimal thickness. Only after the shaping process has produced structurally safe elements, it has been possible to move to the construction phase of the design.

SHAPING & STRUCTURING 04

4.1 GENERAL CONCEPT

Our general concept for the project originates looks at the design of the bazaar to be an urban restructuring module. Large covered galleries of the Tabriz bazaar formed one of our earliest inspirations, which has a more structured character covering a width of a regular street *(Figure 45, Left)*.

We wanted to merge this structured approach with the informality of the other bazaars in the camp as well as other regions in Jordan and middle eastern countries. The informal structure of these bazaars gives much room for shopkeepers to customize their space and add character *(Figure 45, right).*

A schematic cross-section *(Figure 47)* helped us determine the heights and spans of the roofs and minimum widths needed for the street below. The spans were then rationalized into multiples of 0.3m, which was considered later as a starting point based on a brick size detailed later in the construction process *(Figure 46).*

Structured

Informal

Figure 45: Image of the Tabriz Bazaar and a typical Bazaar in Amman, indicating a kind of hybridization intended to be used in the project.

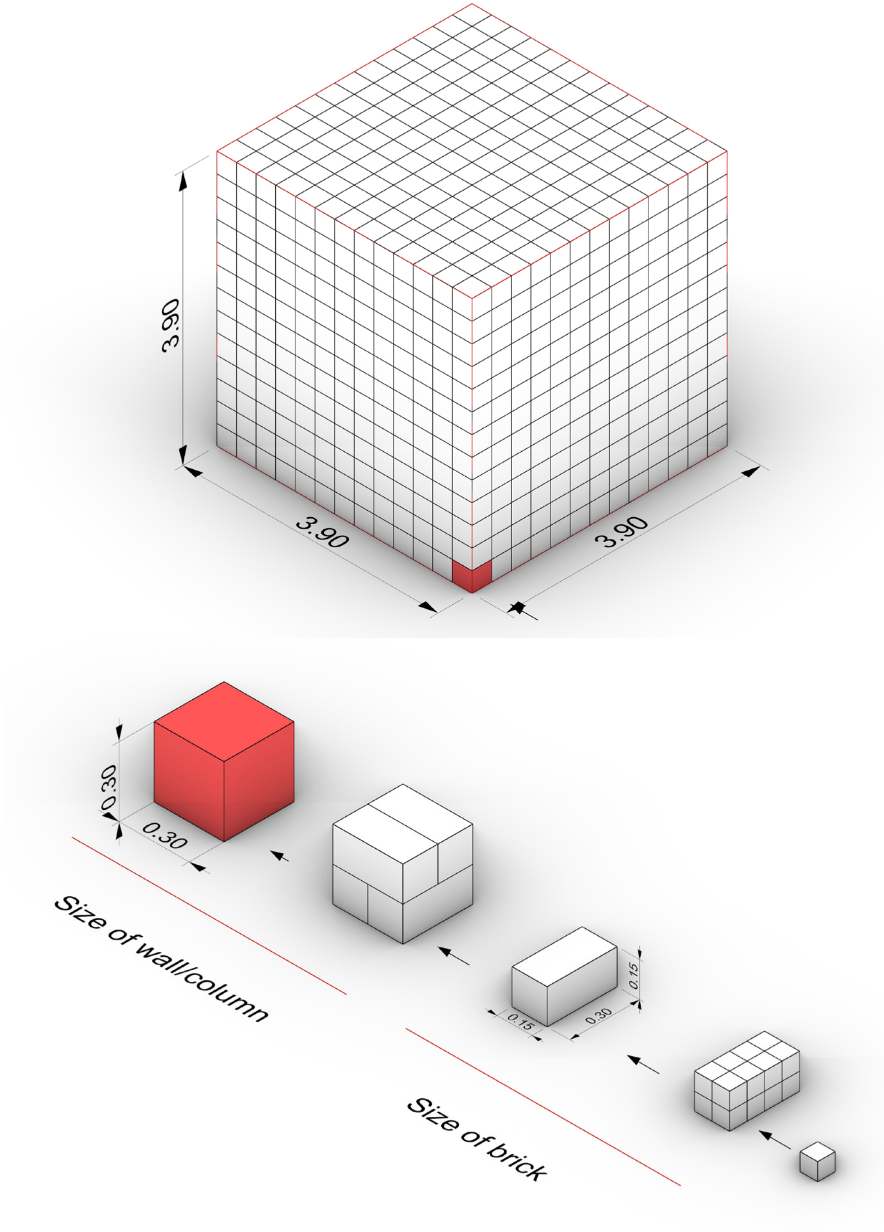


Figure 46: Figure explaining the scaling of Voxels from a brick to a building unit.

This idea was then generalized to:

1.Shops flanking either side of the street with a covering for shopkeepers to modify and use according to their needs *(Figure 47, Top left)*.

2.Large covered roof covering the width of the street, which shades it from the harsh Jordanian sun and other elements *(Figure 47, Top left)*.

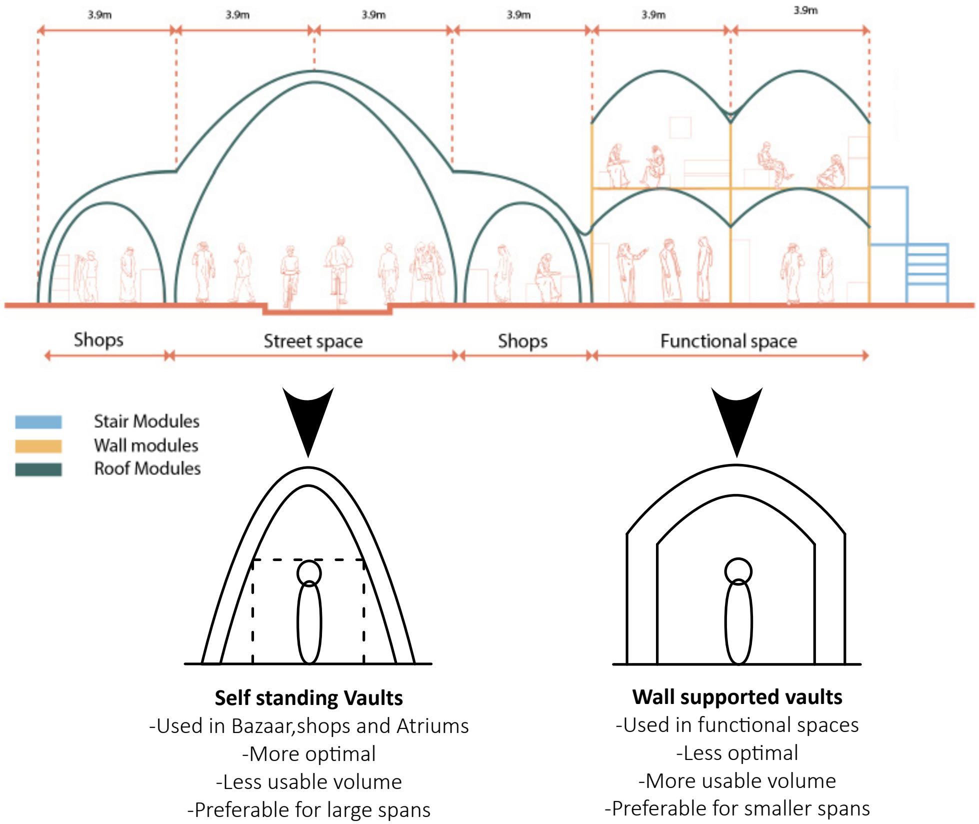


Figure 47 : Diagram indicating a schematic crossection of street with the structural systems.

3. A more structured system for the rest of the development enclosing more functional spaces such as learning spaces, caravanserai, housing, and learning spaces *(Figure 47, Top right).*

Due to the large span of the bazaar, the roof structure had to be as optimal as possible and for the functional spaces, a simplified system is preferred to adapt to the various conditions of the floorplan *(Figure 47, bottom left and right)*.

A categorization of all the building elements before and after the shaping process ins detailed in *Figure 48*.

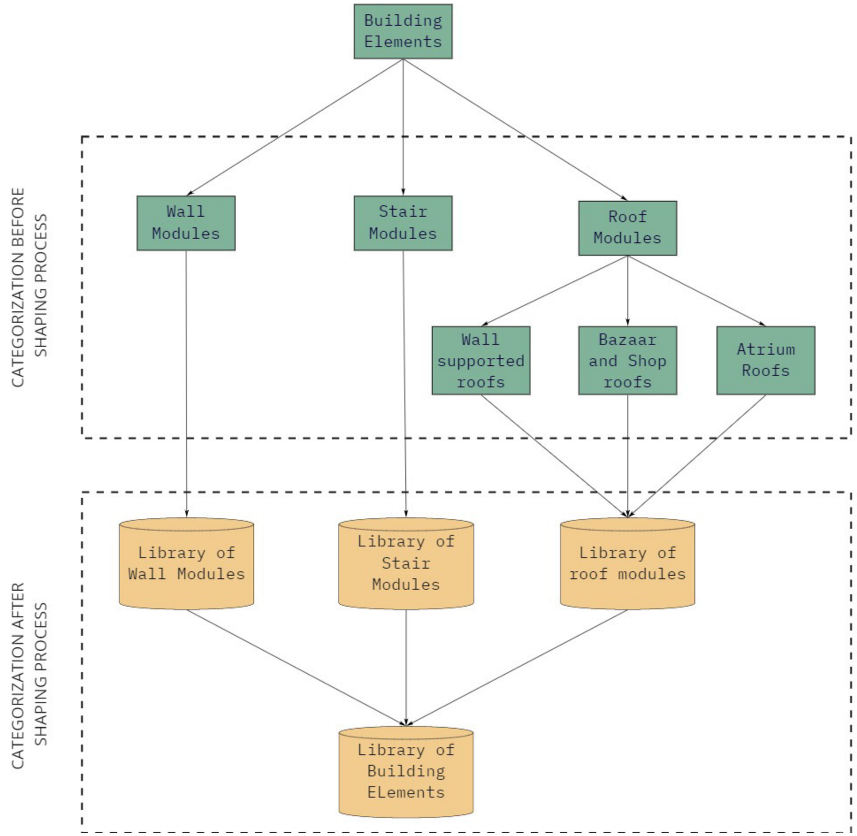


Figure 48 : Flow chart of the categorization of building elements before and after the shaping process.

4.2 BUILDING ELEMENTS - WALLS

The final product of the configuration process is a 2D plan, consisting of grid cells which edges are assigned the code C for closed, S for semi-open, and O for open. The transition from the 2D plan to 3D space is achieved through our shaping process and the introduction of our building modules library. The first category of this library is the wall modules.

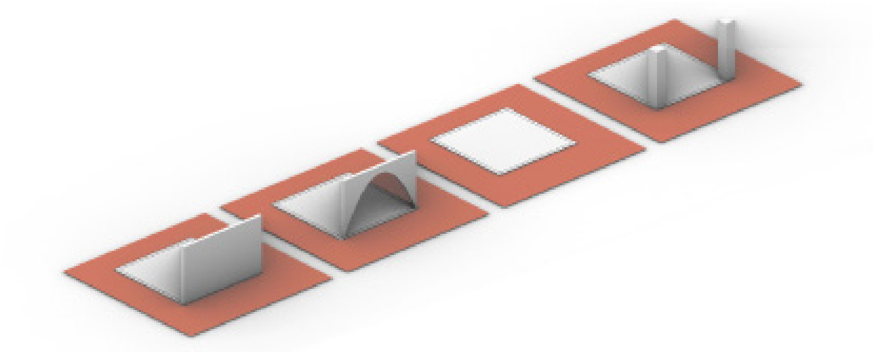


Figure 49: from left to right: C-closed, S-semi open, O-open, columns

4.2.1 Wall modules types

As mentioned above, the principal categories of the walls are three: C represents a closed solid wall, S represents a semi-open wall, ie an arced opening that can either remain open or be assigned a door, and finally, O represents a totally open edge *(Figure 49)*.

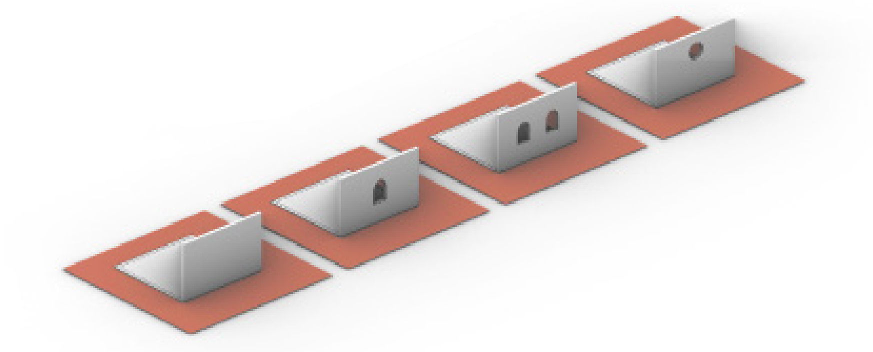


Figure 50: from left to right: C0 type, C1 type, C2 type, C3 type

Considering the need for windows, the C category is subdivided into four different modules, C0 remains the solid wall without an opening, C1 is a solid wall with a single arched opening, C2 has two of these openings, while C3 has a single circular opening *(Figure 50)*.

When two or more open edges intersect in a junction that will need to support a roof, then a column element is being placed there *(Figure 49)*. If this junction is located in an open space (e.g. a courtyard) then it remains empty.

The elements C0, C1, C2, C3, S, O and the column can be placed in any possible combination on the edges of one cell in order to create a wall module *(Figures 51-52)*.

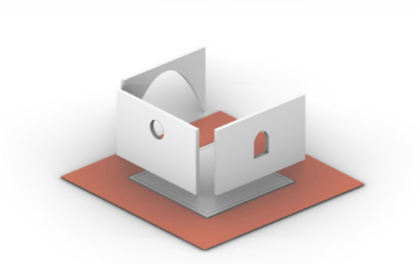


Figure 51: Wall module - example 1

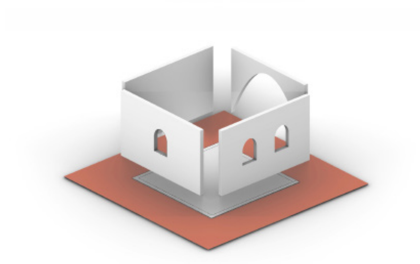


Figure 52: Wall module - example 2

4.2.2 Wall modules placement rules

From the Layout tool, we already have the example plan in the form of cells, whose edges are assigned their code (C, S, O). For each cell we can place any wall module that comes in accordance with this specific coding. Since C1, C2, and C3 are all variations of the closed edge can be placed in any edge assigned as C. An example is presented in the figure below.

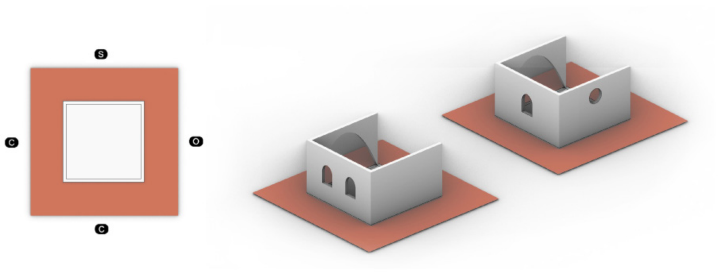


Figure 53: example of a cell and possible wall modules to place on it

The configuration grid is based on a logic of a tartan grid. Following that logic, each cell has an inner offset, equal to half of the wall thickness. In this way, when two wall elements connect, they form the wall with the final thickness.

As a consequence, only two identical elements can connect with each other and no element can be left unpaired. This applies also for the sub-categories of the closed walls, where every type should be paired with the exact same type, similar to the domino pieces logic.

An example of this wall modules placement logic is illustrated on the diagrams on the right.

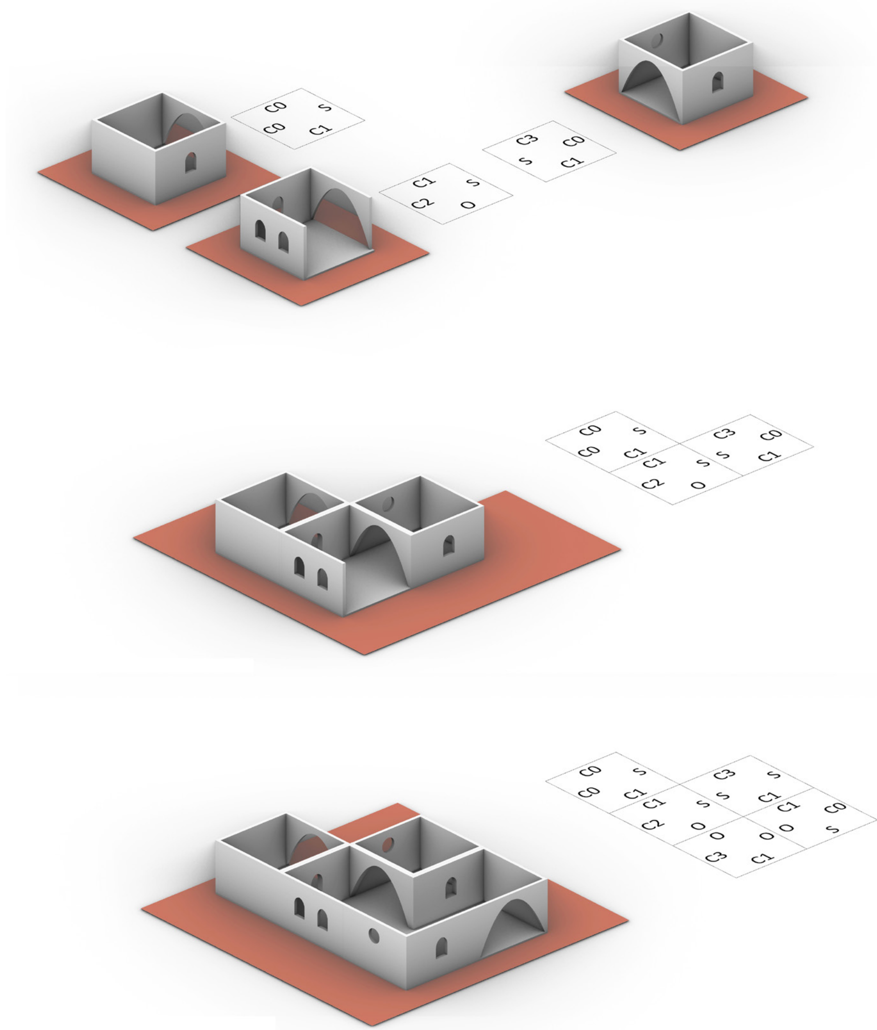


Figure 54: example of wall modules placement rules

4.2.3 Wall modules library

It becomes evident that are numerous alternatives of possible combinations of the C, S & O elements. This results in an extended library of wall modules that are all formed by the same principal elements. In *Figure 55* the wall modules without the C-variations are presented, while in *Figure 56* there is a sample of the extened wall module library

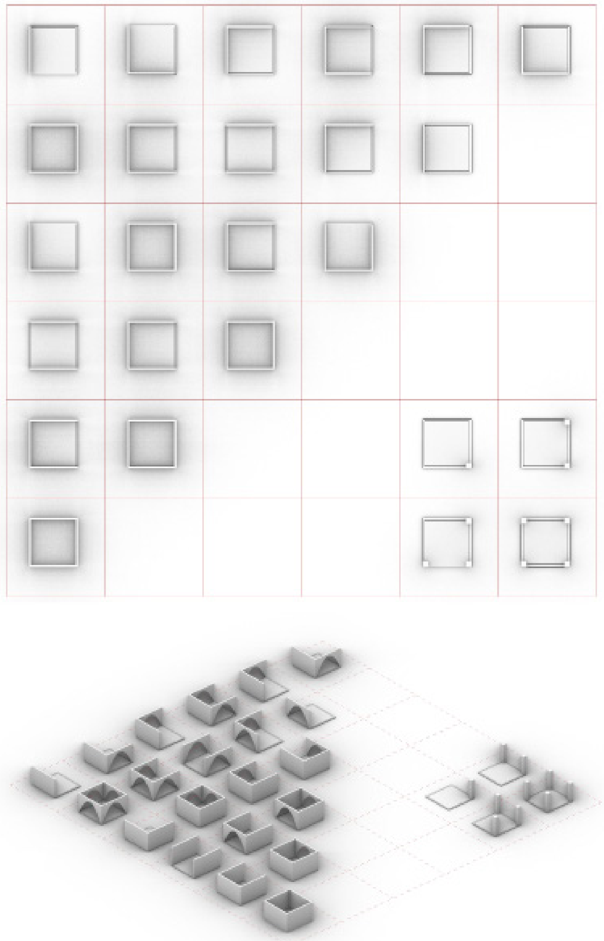


Figure 55: Principal walls library

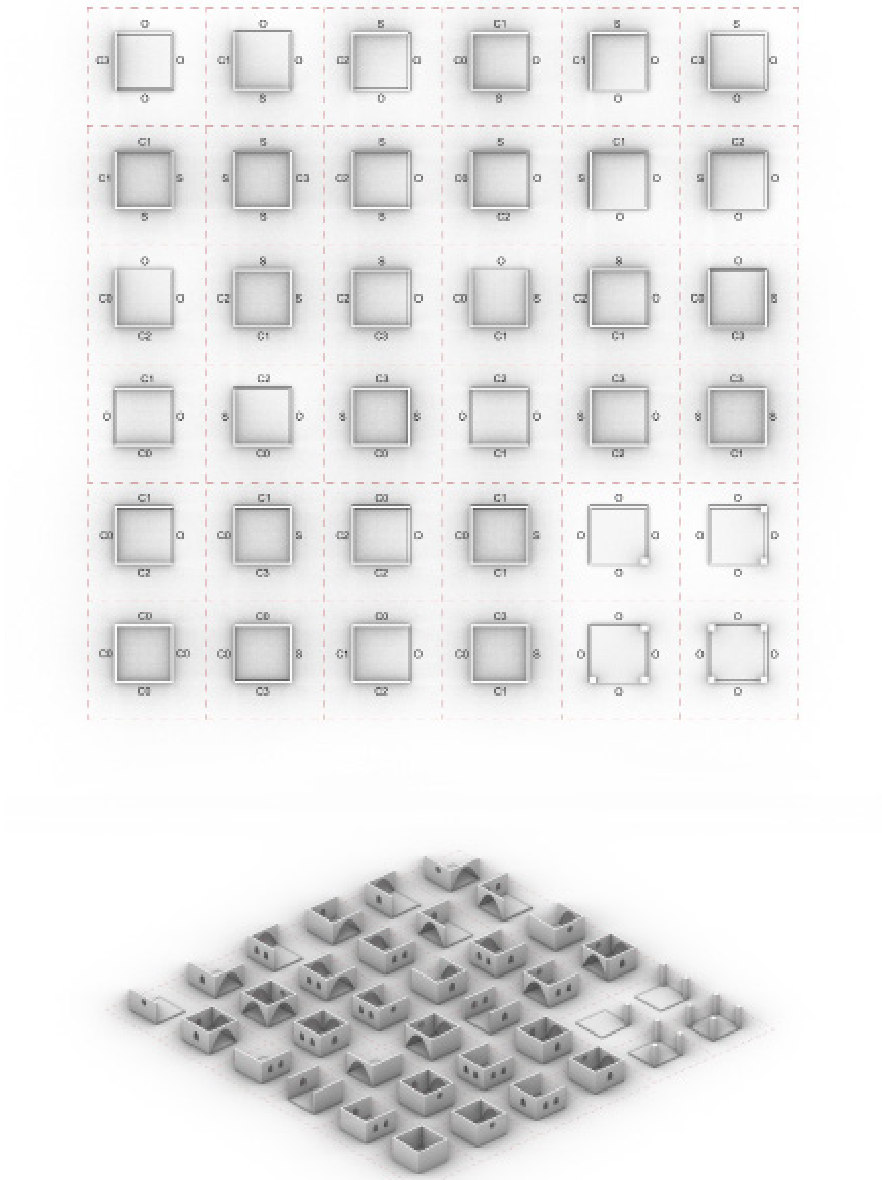


Figure 56: Sample of the extended walls library

4.3 BUILDING ELEMENTS - STAIRS

A key element to move from the 2D to the 3D scale, are the stair modules. The stairs are being placed in the locations determined during the configuration proces , they are generated from a pyhton algorithm and visualized through a grasshopper definition.

4.3.1 Stairs generator algorithm

As mentioned above, for the generation of the stair modules a python algorithm has been developed and then for the visualization of the results a grasshopper definition. The extended scripts can be found in the Appendix. In this paragraph the main logic of this algorithm will be presented in the form of a flowchart *(Figure 57)* and diagrams *(Figure 58)*.

From the layout tool we already know the cell in which the stair needs to be placed, as well as the orientation of the entrance and the exit. At the first step of this process, the chosen cell is divided into 16 sub-cells and then the user chooses the sub-cells that are going to be the first and the last step of the stairs *(Figure 58- step 01)*. For the purposes of this part of the report and to facilitate the clarity for the reader, for this paragraph the sub-cells are going to be mentioned simply as cells.

After the first step a repetitive process begins where, initiating from the starting cell and inputting the rest of the cells in the availability list, we find the neighboring cells (cells that share an edge with the current cell) *(Figure 58 - Step 02,04,06)* and randomly choose one *(Figure 58 - Step03,05,07).* The chosen cell then becomes the current cell and is being removed from

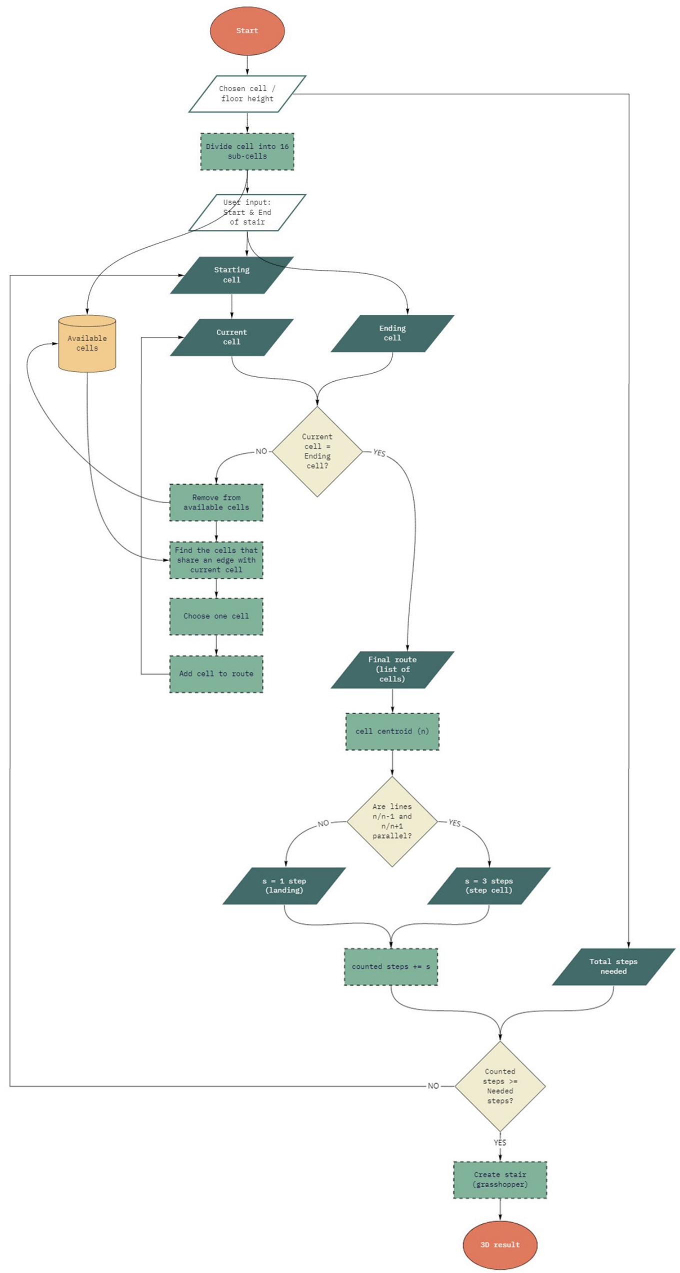


Figure 57: Stairs generator algorithm flowchart

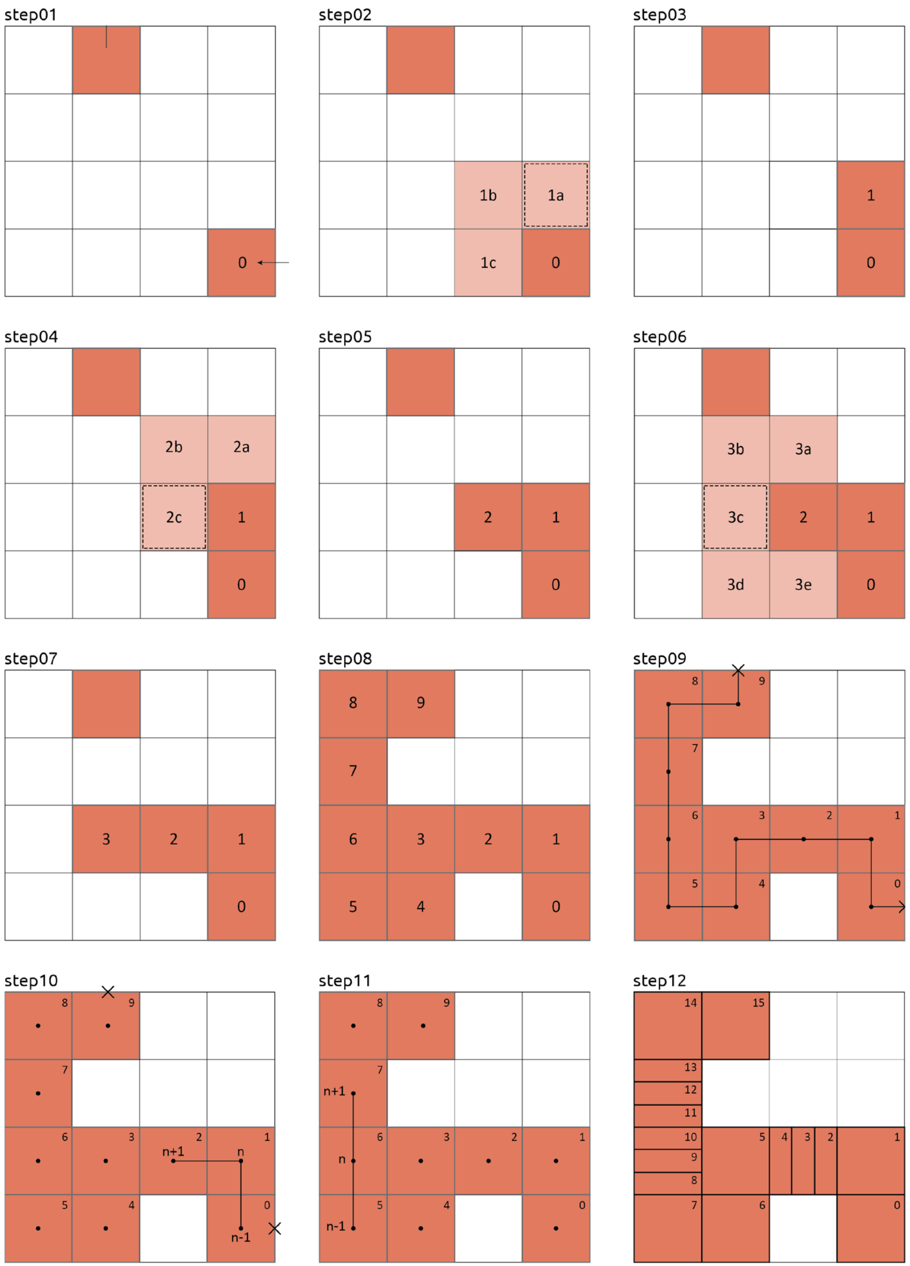


Figure 58: Stairs generator steps illustrations

the availability list. This process is being repeated until we reach the final cell *(Figure 58 - Step 08)*. As a final result we get the ordered list of cells, as the “route” of the stairs.

The next step is to evaluate if this route is feasible, that is if this sequence of cells allows the creation of enough stairs to bridge the required height. This is being checked by dividing the cells into landing-cells, that can count only as one step, and step-cells, that count as 3 steps. To evaluate this we create the lines among the centroids of the cells and then check the lines n- n-1 and n- n+1. If these two lines are parallel *(Figure 58 - Step 11)*, then cell n can have up to 3 steps, while if they are not *(Figure 58 - Step 10)*, the n cell is counted as a landing. At the end of this evaluation, if the steps are enough the stair is being created through a grasshopper definition that gets as input the list of cells and the categorization of the cells. If the steps are not enough the algorithm goes again to step 0 and produces another solution to evaluate.

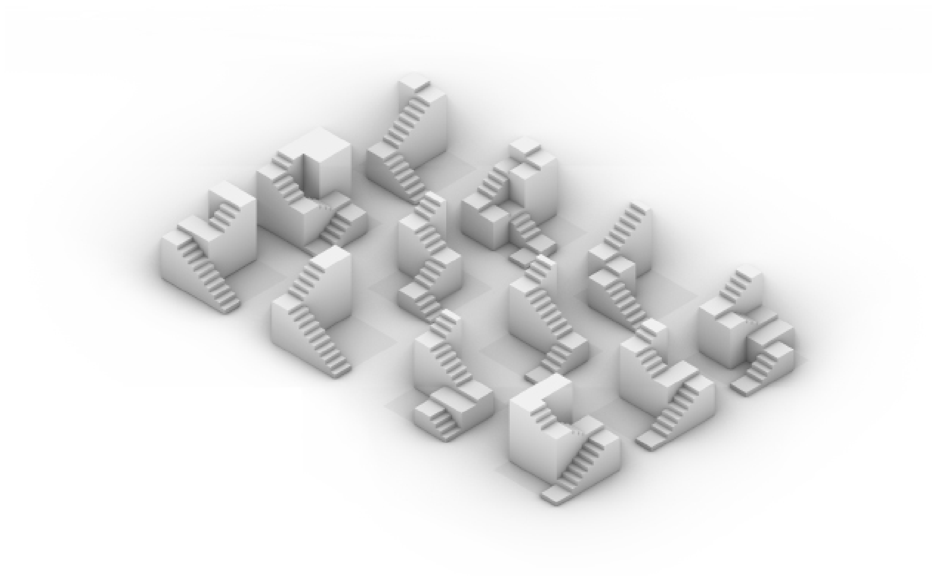


Figure 59: Stairs generator results for the same situation

4.3.2 Stair modules library

The stair generator algorithm that was presented before, makes it possible to produce many different results for the same situation.

For this reason we set different calculations in order to be able to compare the different produced alternatives. These calculations include:

- the total cells used for the route
- the volume of the stair module
- the total length, as projected in a XY plane

Another option for future developement, is to consider the height of the landings in case there is a semi-floor available.

Based on the fact that for each unique situation another stair module could be more adequate, we result in a very extended stair module library.

As a consequence, for the purposes of this report, we chose one solution for every combination of starting and ending cells that is presented on this chapter.

Figure 60: Sample of stair modules library - Top view

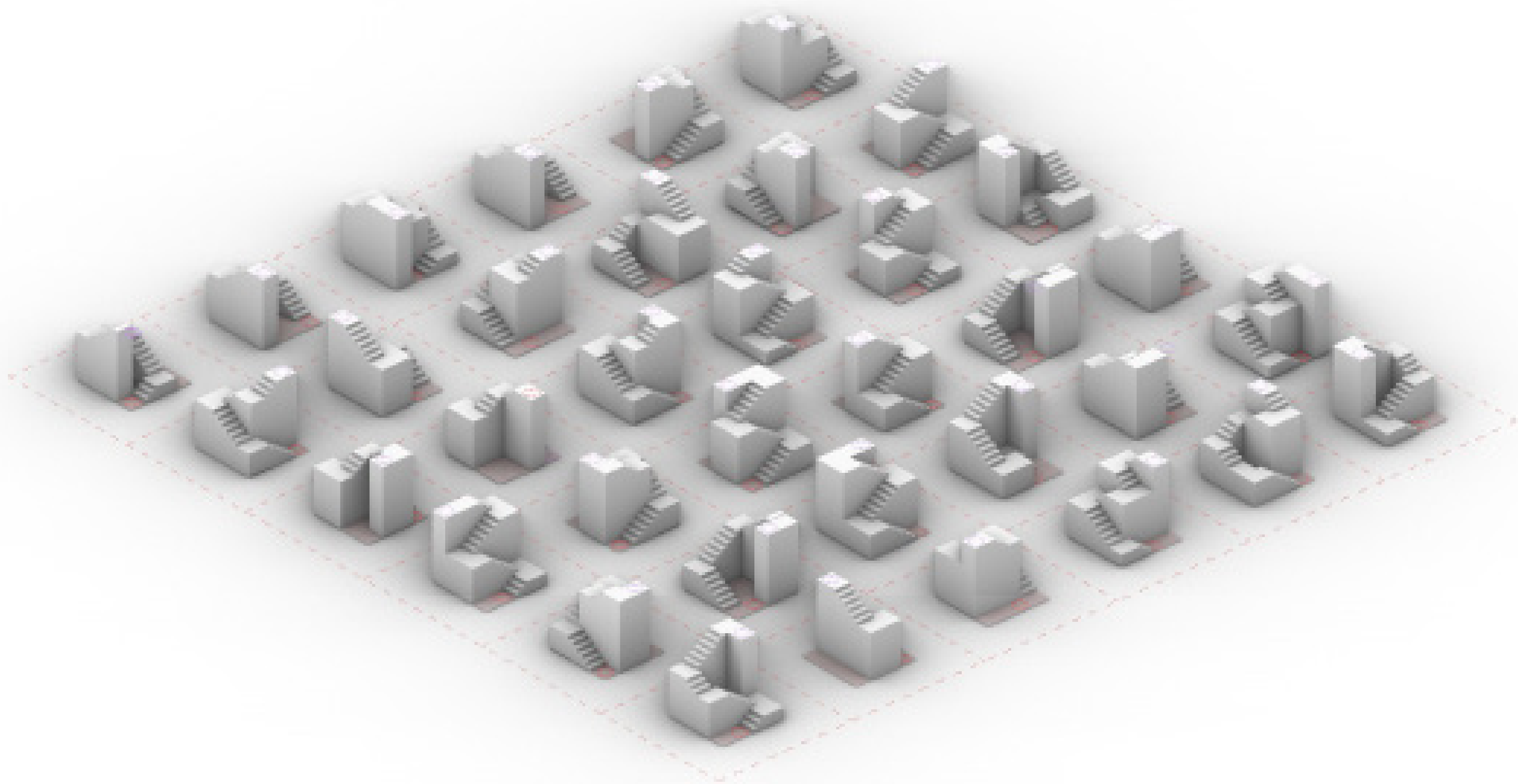


Figure 61: Sample of stair modules library - Isometric view

4.4.1 Methodology

The form-finding process began with exploring tessellation patterns within a square cell to understand its behavior with different subdivision patterns, subdivision levels, and anchor points.

The general workflow we employed for the form-finding is to create lines on rhino or grasshopper and using the weaver-bird lines to mesh components to make meshes. These basic meshes were then further subdivided using the WB constant quad subdivision method, as shown in *(Figure 63)*. Small scripts were made to test out different forms including the kind of anchors it needed, with also possibility of real time feedback such as roof heights to get better control of the shapes.

For the later stages, the subdivision and detailing of the tessellation were done manually after a basic understanding of the inter-relations of the subdivisions to the final roof form. The subdivided mesh was then input to the kangaroo physics solver to perform the dynamic relaxation. An overview of this is shown in a flow chart *(Figure 62)*. We did some initial tests on square vaulted structure with open arches on all sides formed our form-finding basis and became a basis for developing the rest of the design modules as detailed in the next sub chapters.

For the structural analysis, finalized forms were baked and analyzed in Karamba. Although this manual intervention meant more time, it was efficient for us to document our process on the shapes which had potential and helped in going back and forth as it was a continuous and parallel process.

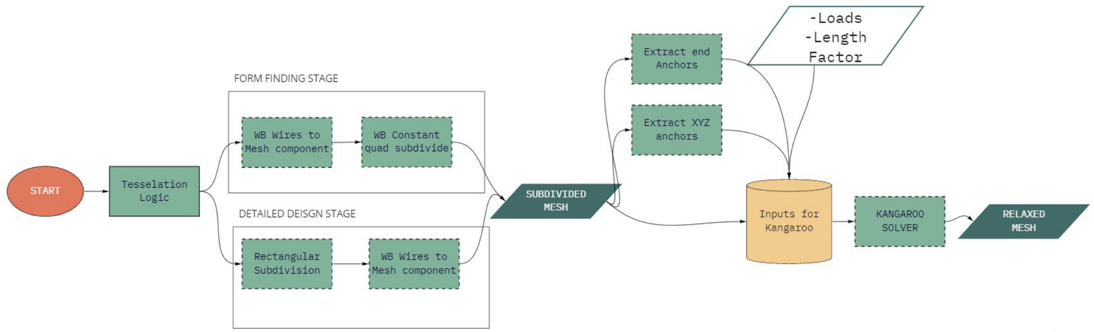


Figure 62: Flowchart of the general form-finding setup using Kangaroo Physics dynamic relaxation solver.

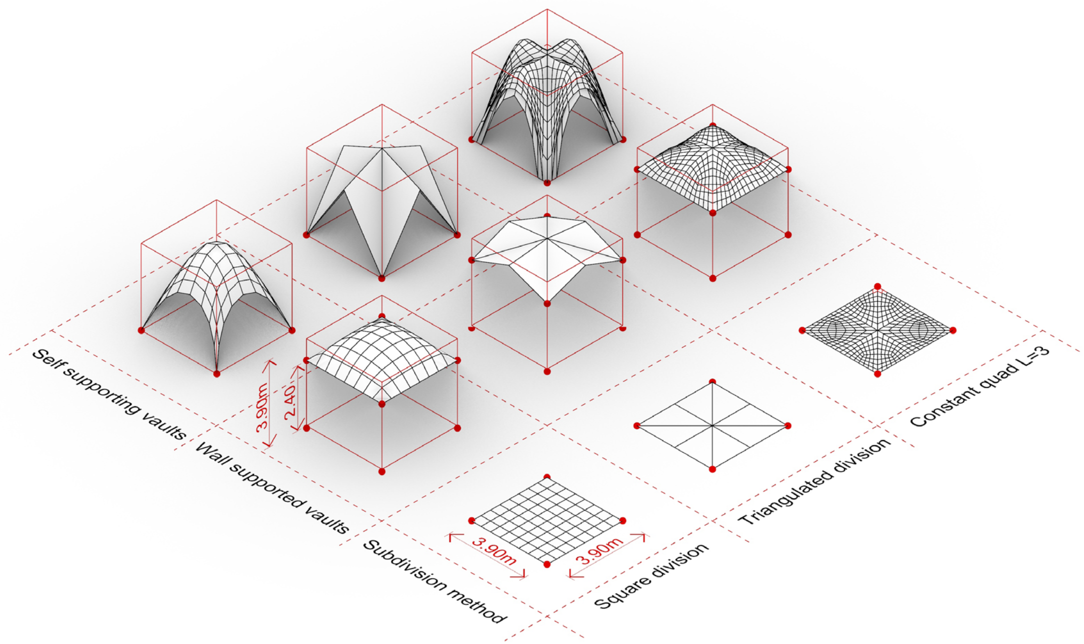


Figure 63: Results of initial tests simulating the two different roofing systems used in the camp.

4.4.2 Tessellation logic

After the initial tests, the behavior of the influence of primary tessellation lines and the secondary subdivided lines were more apparent. The primary lines influence the shell's shape, similar to the ridge, valley, and hip lines of a sloping roof *(Figure 64).*

A tessellation logic for each cell could then be developed based on the logic of the layout tool, where each cell is assigned a wall condition on its location and adjacency conditions with its neighboring cells *(Figure 65, top)*. The roof tessellations could also follow a similar logic, and the results are compiled in *Figure 65*. This logic is used throughout the form-finding process to connect cells, disconnect cells, create ridge/valley conditions.

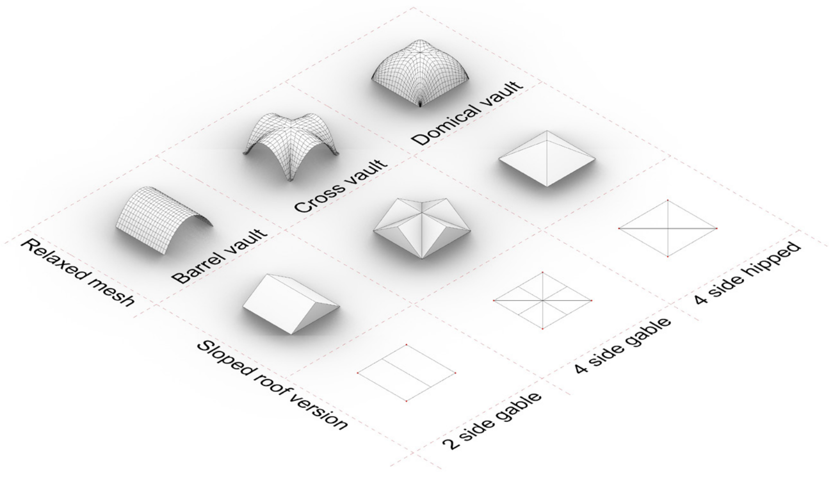


Figure 64: Image showing the comparison between a sloping roof and relaxed mesh with the same undivided tessellation grid.

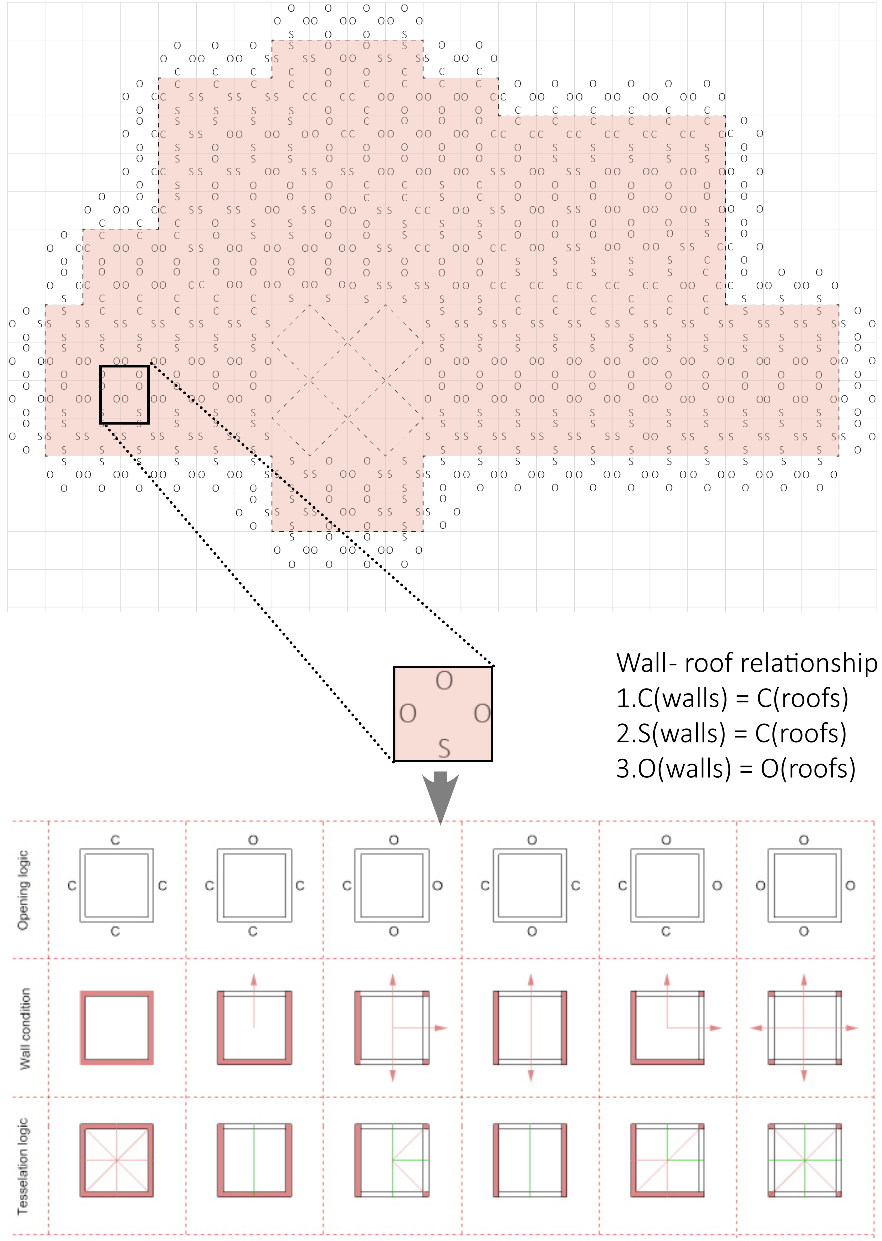


Figure 65: Image showing the link between the floor plan and the tessellation logic.

4.4.3 Workflow

The flow chart below gives an understanding of how the entire shaping process took place after the concept was finalized. It is mainly organized into 3 stages, that is Form finding, feasibility check and detailed analysis as shown in flow chart. *(Figure 66)*

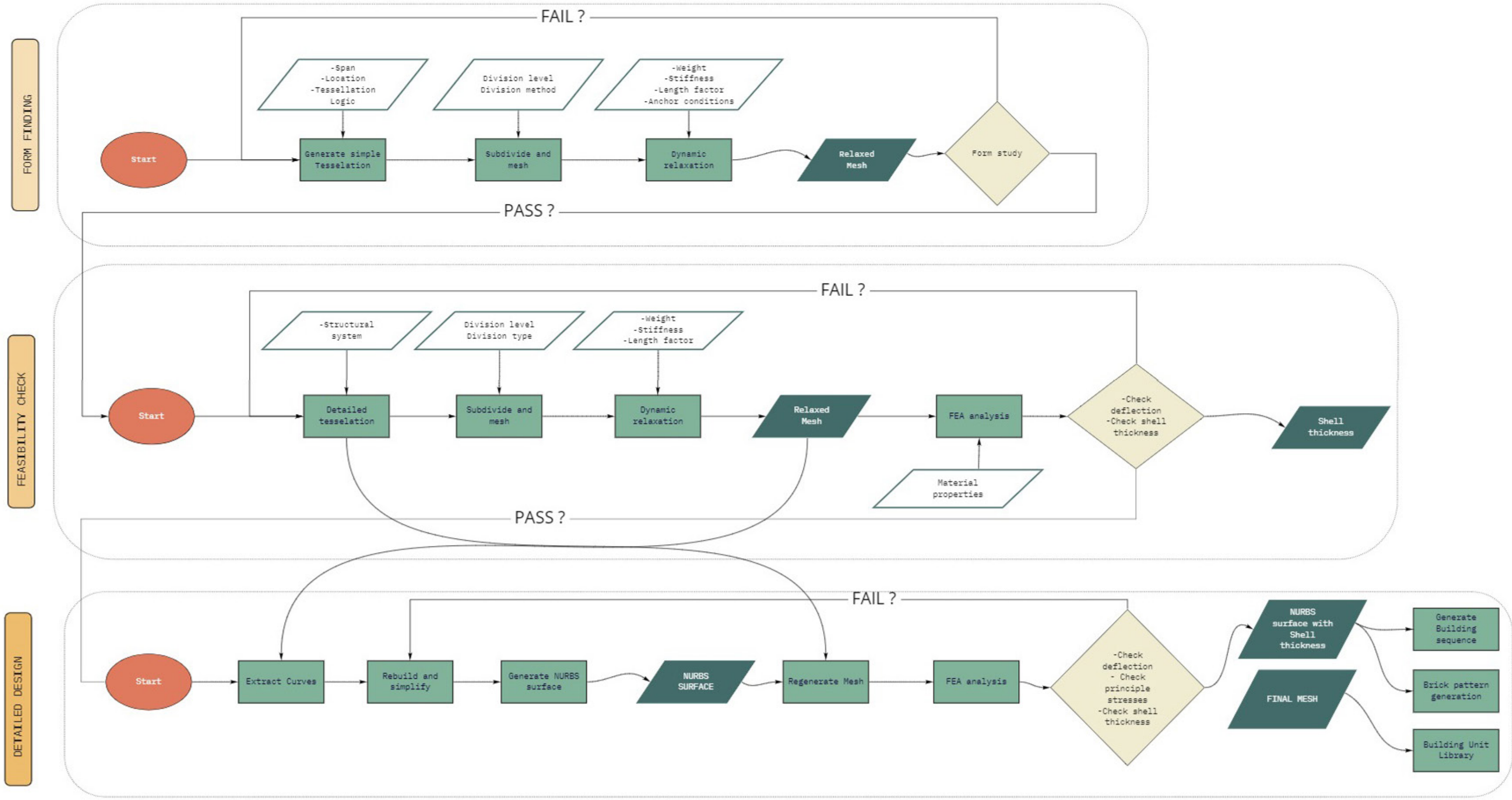


Figure 66: Flowchart indicating the roof shaping process organized into 3 main stages.

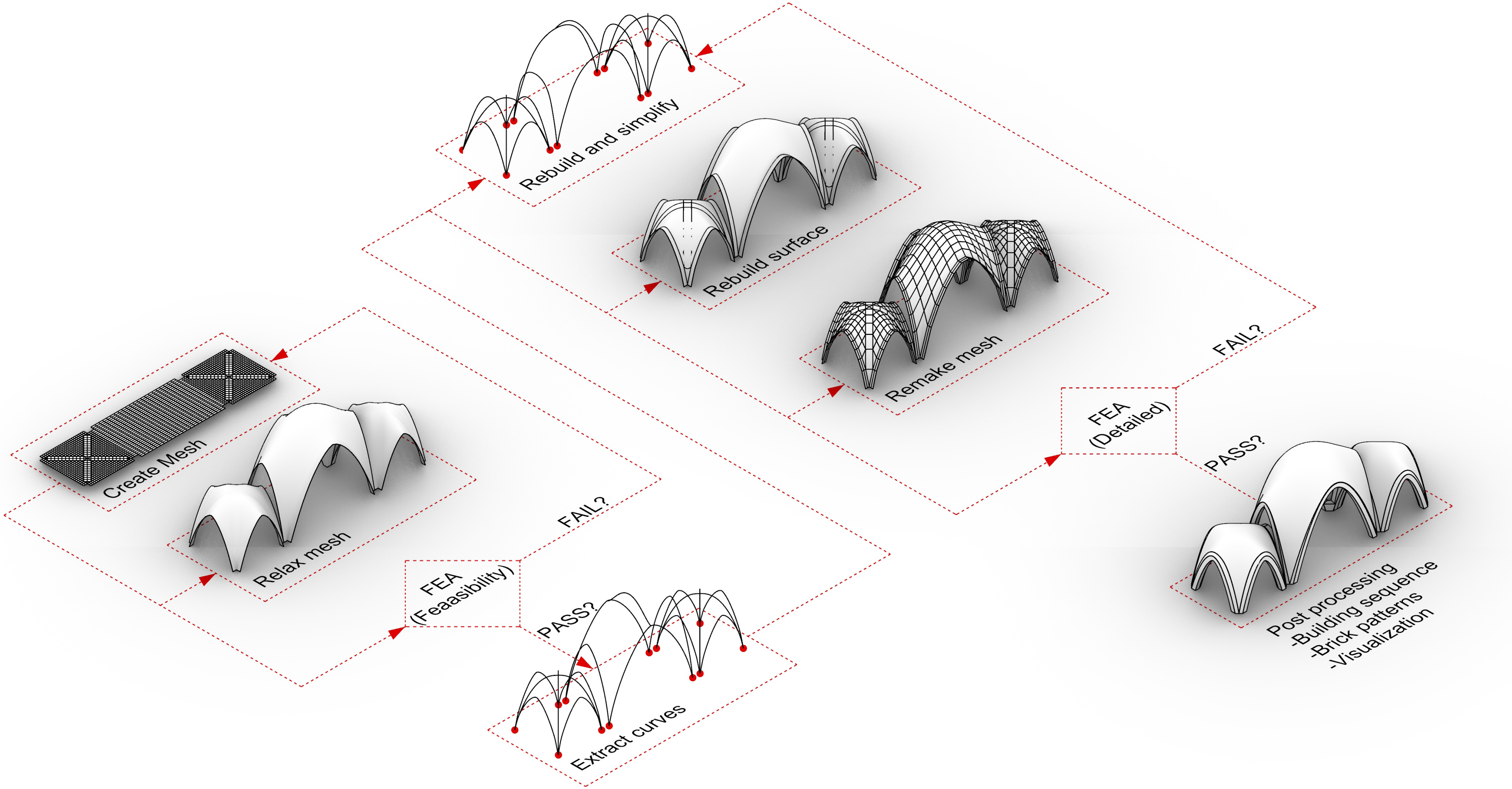


Figure 67 : Isometric view of showing the refinement of one of the iterations based on the above flow chart.

4.4.4 Form finding and feasibility

4.4.4.A-Wall Supported Roofs

For the building units, the roofs were perceived to be wall supported, and therefore the tessellation logic can be directly used onto different cell conditions. The resulting shapes are shown in *Figure 68.*

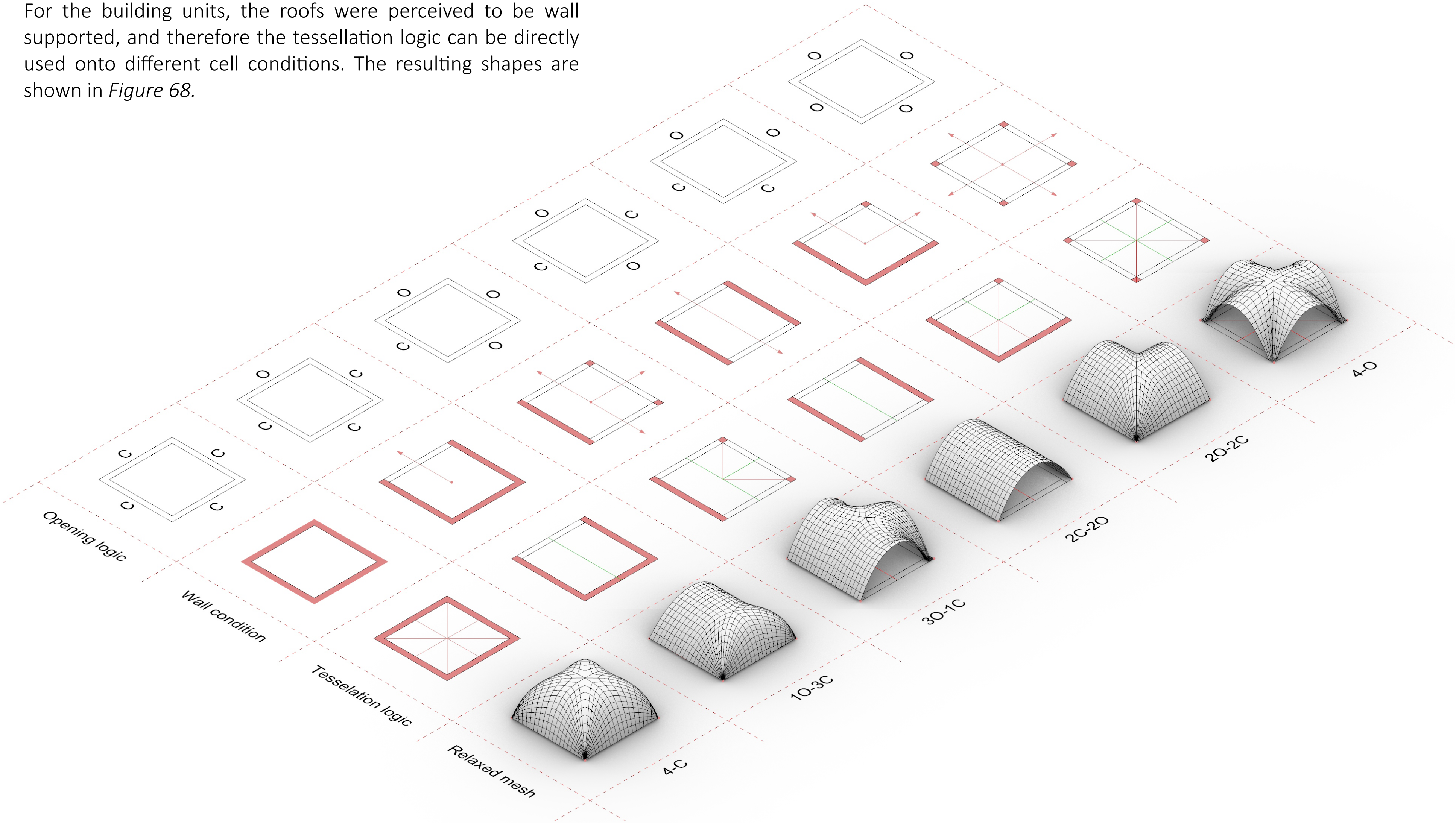


Figure 68: Subdivided and relaxed meshes as per the tessellation logic derived earlier.

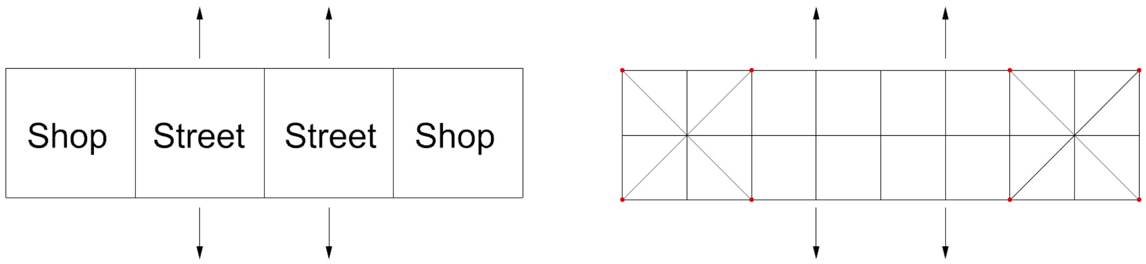
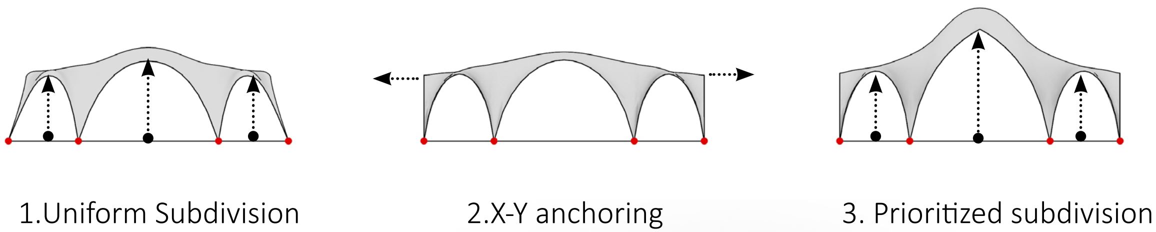


Figure 69: Derivation of the basic tessellation grid.



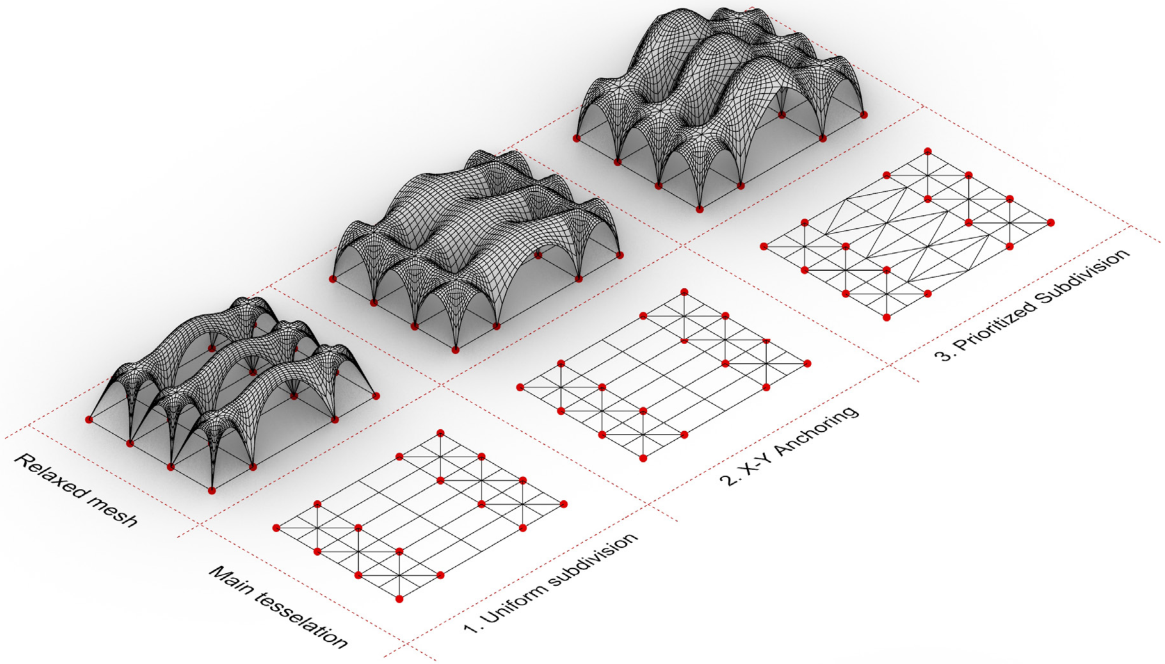


Figure 70: Isometric view of the form finding stages of the Bazaar.

4.4.4.B-Bazaar and Shop Roofs

As detailed in our concept, the bazaar unit had a large span of 7.2m and repeated many times over. A more optimal shape was preferred to reduce material consumption. Nevertheless, as large roofs can also result in lateral forces, a buttress system similar to churches was conceptualized, as shown in *Figure 71*.

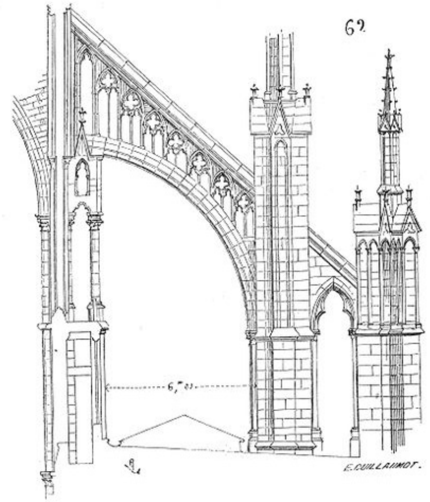


Figure 71: A typical crossection of a buttress. (Source : pintrest.com)

Therefore, the buttress would not only serve as additional stability elements but would also be designed in a way to ensure the space it encloses is usable as shops. Since the shops are always conceived to be flexible spaces, a concept such as this could work provided minimum heights are maintained.

The form-finding process began with an initial tessellation grid. *(Figure 69,Right)* , which comprises two open cell roof conditions bridged by a linear roof(Step 1,*Figure 70*). To avoid the edge faces of the structure to slope inwards, the subdivided mesh's edge points were anchored in the X and Y direction and allowed only to relax in the Z direction(Step 2, *Figure 70*).

A higher ceiling height for the bazaar street was preferred as it encloses more people in terms of pedestrian and bicycle traffic. Dynamically relaxing the shop units connected to the bazaar units gave results with very shallow results. In order to not customize the relaxation settings for each individual element, a prioritized subdivision was used instead to localize forces and achieve the required heights.

The bazaar roof was subdivided more to have more point forces pushing the roof higher(Step 3, *Figure 70*). Nonetheless, this form resulted in structures that were becoming more dependent on each other for stability, and hence the meshes needed to be split at the junctionsTherefore the option of relaxing the two different roof structures separately with individual relaxation settings was explored(*Figure 71*,left). But during this process, much tweaking was required to get the two meshes to match at the edge, but still resulted in inaccuracies(*Figure 71*,right).

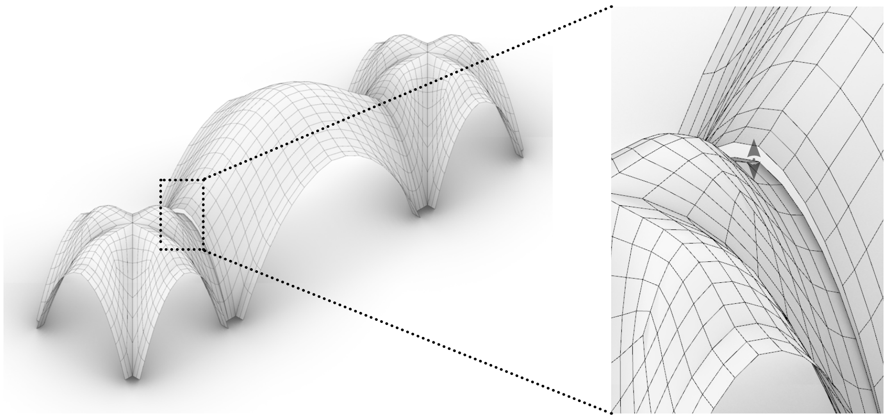


Figure 71: Image of dynamic relaxed mesh with individual settings for separating the modules.

Moreover, daylight and ventilation strategies had to be figured out, which meant that it was more sensible to split the roofs altogether with a gap between the two roofs. Therefore, an initial FEA feasibility analysis was performed to check if both the roofs can span on its own with reasonable wall thicknesses. Once this confirmation was made, another iteration where the two roofs were relaxed individually with different force settings, but this time deliberately created a gap between the roofs (*Figure 72*). The gap can be left open or partially covered as detailed in the later chapters.

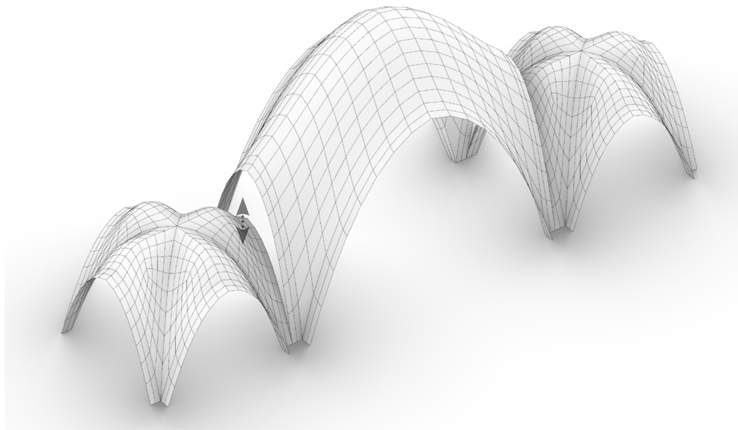


Figure 72: Image of dynamic relaxed mesh with individual settings creating a deliberate gap between the roofs.

Once a workable relaxed form with a suitable height and curvature was achieved in the form-finding stage; a more detailed approach was looked into to further develop the meshing process. The meshing process is customized based on how close the resulting mesh could result in a shape that suits our construction logic.

In the shop units' initial form exploration process, a building system based on ribs and peripheral arches was conceptualized.

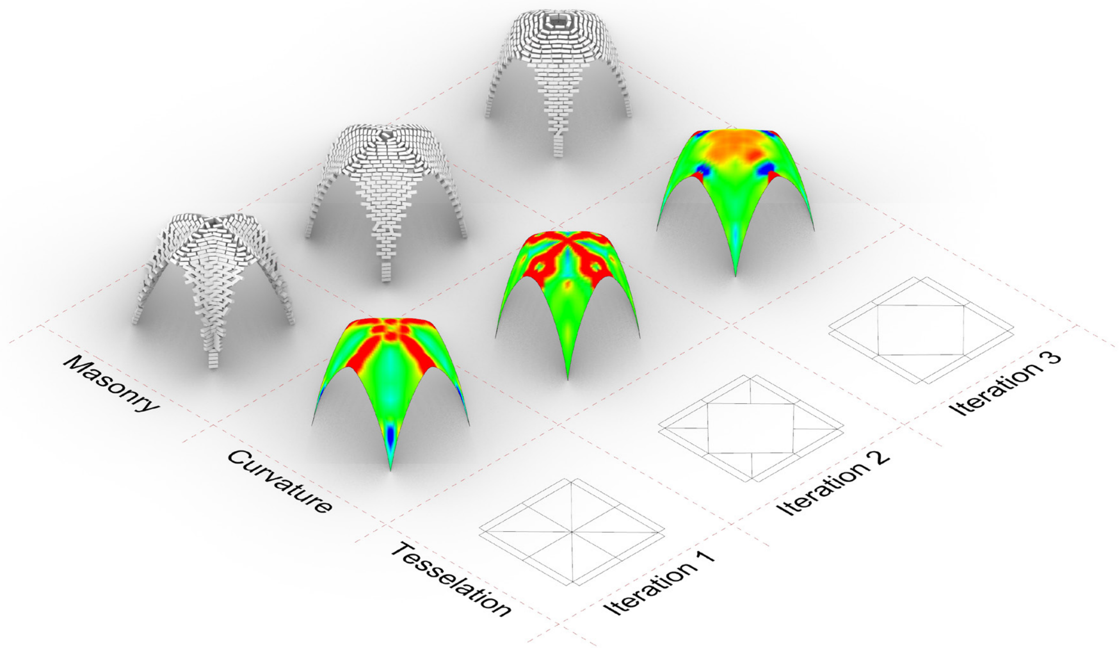


Figure 73: Evolution of the basic tessellation towards reducing negative curvature and forming a more buildable option.

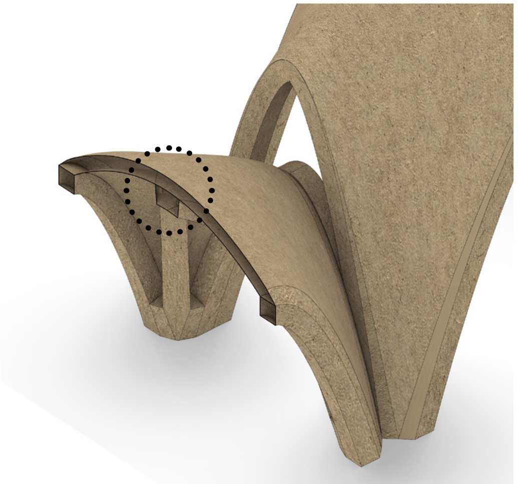


Figure 74: Typical crossection of a ribbed vault indicating the doubling of thickness.

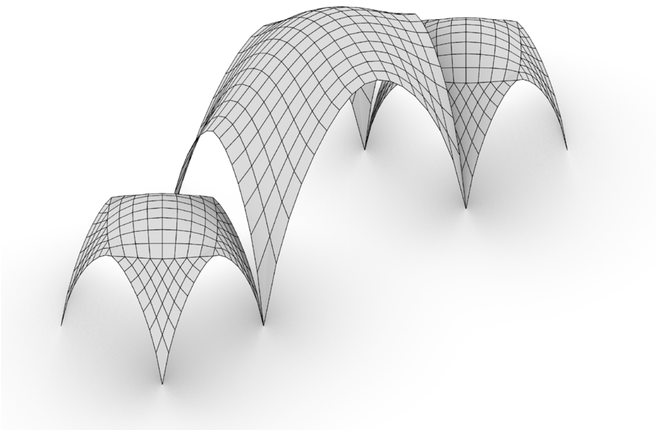


Figure 75: Final mesh after refinement of shop units.

The shape resulted in valleys formed at the intersection *(Figure 73)*. With this in mind, a more detailed tessellation grid was developed, respecting the tartan grid rules and our smallest module of 0.3X0.3.

In the later stages of design, the construction sequence was simplified using arches only for the edges and the rest of the shell built using a doming principle. This was to avoid doubling of shell thickness at the ridges *(Figure 74)*. The shells needed to have a minimum thickness of 0.3 m due to climatic conditions, and the ribs also needed the minimum thickness to support on its own. Moreover, the negative curvature at the valleys resulted in intricate brick patterns involving many cut bricks *(Figure 73)*. Hence the tessellation pattern was further developed. Although this does not follow the initial tessellation logic, it still respects all sides' rules being open.

The detailed mesh with this logic was developed. We ran some FEA tests of all these options to check for displacement and shell thickness before narrowing down one option. The final relaxed geometry then chosen for the bazaar is as shown in *Figure 75*. The mesh was then sent for further detailed refinement and analysis.

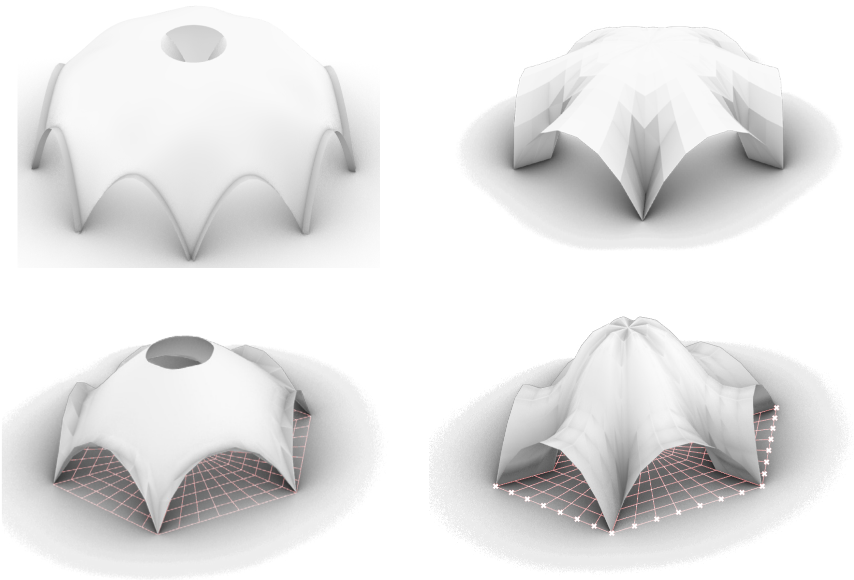


Figure 76: Some results of the initial form-finding explorations for the atrium based on polygonal floor plans.

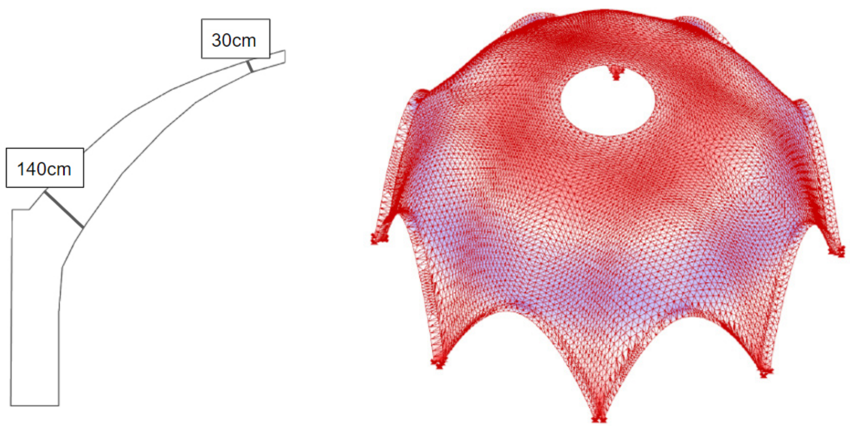


Figure 77: Initial FEA test of the 15.6m domes showing the high tensile forces at the top of the arches and the minimum crossection required to be able to withstand these forces.

4.4.4.C-Atrium Roofs (Adobe 2.0)

The bazaar and shop units were designed as a modular self-standing and repeatable element happening on the streets. Crossroads and junctions need to be treated. We looked at this as an opportunity to develop something that breaks away from the rest of the project's structure as an element that identifies the development as a "centrality" or node. Hence the concept of the atrium came about. For this, the initial iterations were looked at going for polygonal based forms at the crossroads *(Figure 76)*. One option that seemed interesting from the form-finding studies was to look at a large spanning dome supported on the edge arches of the bazaar *(Figure 76, Top left)*. This would reduce the scaffolding required as a system of corbeling the bricks or building the dome as continuous self-supporting compression rings. As we did a feasibility test with the loading conditions, the dome structure was found to be less feasible because of the sheer amount of material it will require at the base to resist the tensile forces acting on the structure *(Figure 77)*. An option of optimizing the cross-section of the shell was also explored. Even with this approach, the dome's base needed walls of at least 140cm, which made it less feasible.

The alternate approach looked at having four anchors in the middle, which pulled the roof down *(Figure 78)*. Here, the atrium could be conceived to be an extension of the bazaar units, yet breaking the structure creating new and exciting junctions and shapes.

After the initial form-finding options of the atrium, we aimed to reduce the number of unique conditions and simplify the building system during the feasibility study. With this approach, the roof structure could be further subdivided into individual components and simplified into more or less similar shapes used in other project areas.

This way, the construction technique would remain the same but just used at a different scale, making it more feasible than the dome structure.

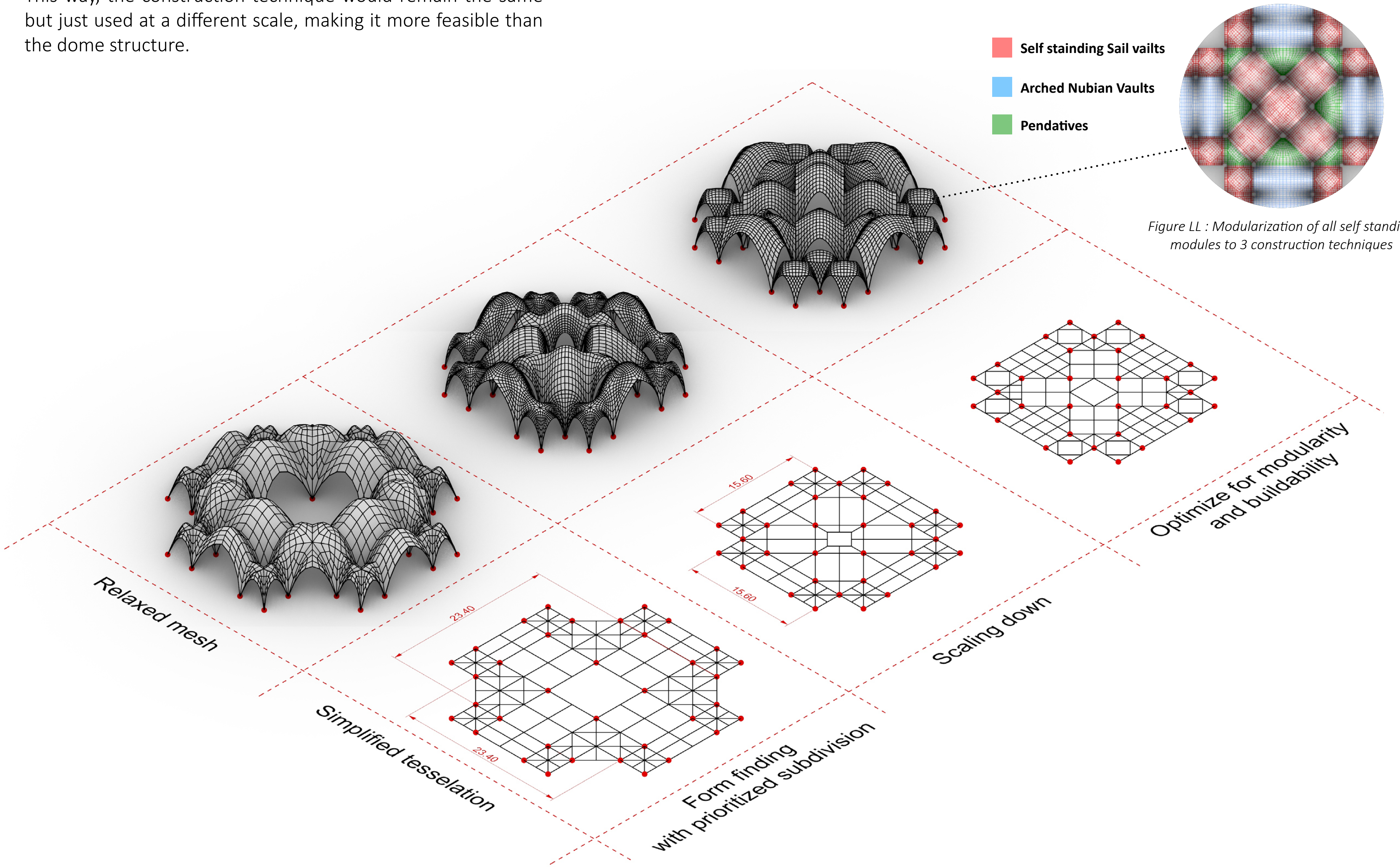


Figure LL : Modularization of all self standing modules to 3 construction techniques

Figure 78: Form finding evolution of the atrium form with middle anchors.

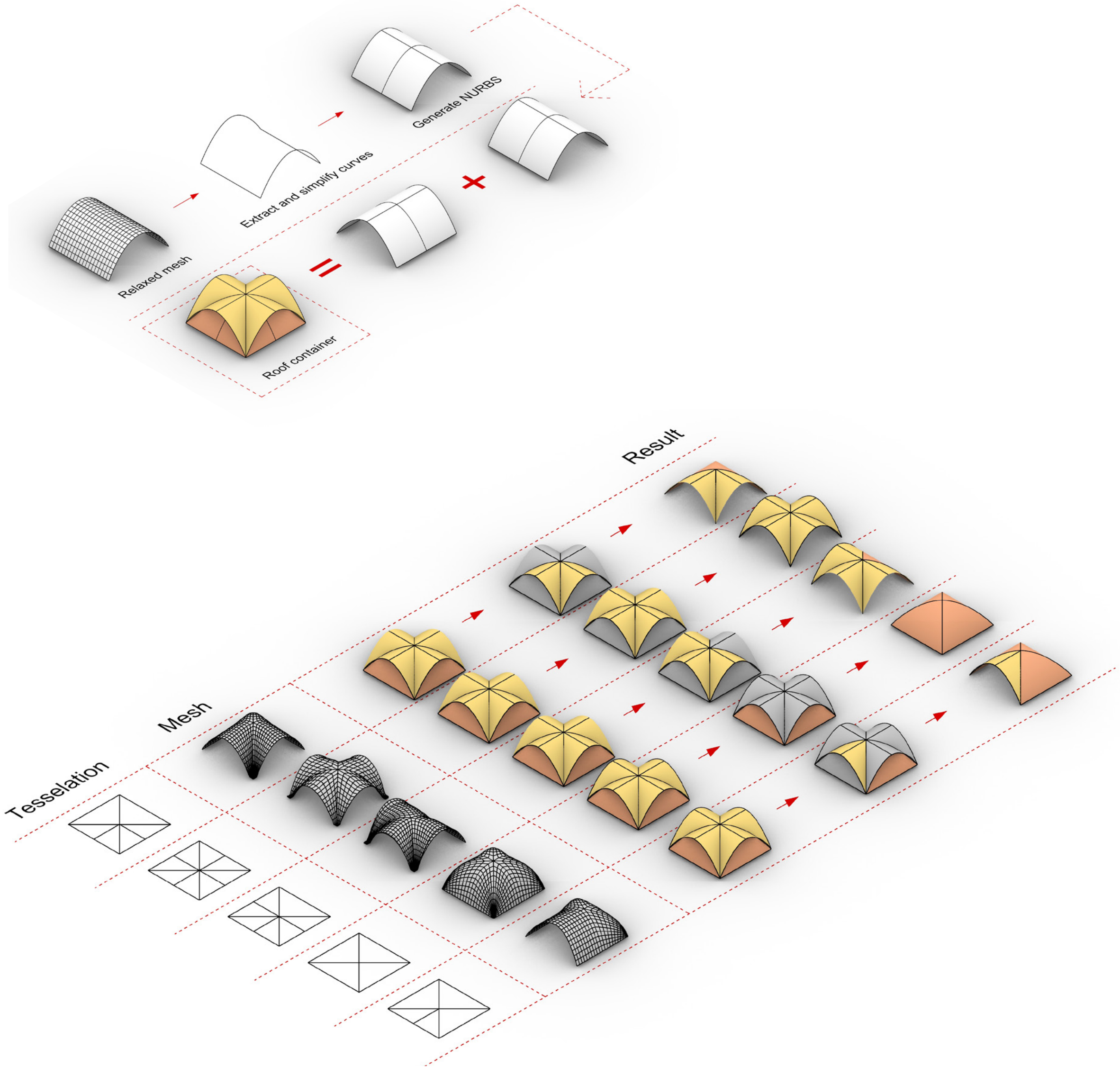


Figure 79: Diagram showing the formation of all roof typologies using the container concept.

4.4.5 Detailed design

In the detailed design stage, the dynamically relaxed mesh results are slowly modified and rationalized to be easily buildable and recreated using a manual modeling process, thereby giving a primary indication of how these shapes can be realized into built form.

<u>4.4.5.A-Wall Supported roofs</u>

For the building units, an alternative approach was used. The simplest option with 2 sides 2 closed was simplified into 3 point curves. A "roof container" was created by creating a hybrid surface of 2 of the roof surfaces. Based on the Closed and open cell logic of the layout tool, additional surfaces from the roof container was kept or removed. The grey colour surfaces indicates which parts were removed. The rest of the geometries were modelled using the same unit as shown in *Figure 79*. The resulting surfaces were used in the brick making scripts and subsequently this logic can also be used in the layout tool when geometries are being referenced.

4.4.5.B-Bazaar and Shop roofs

Figure 80 shows how the tessellation was refined from the form finding stage to the detailed design stage. 0.3m offsets are given within each grid, except for the middle to accommodate the arches.

Figure 81 indicates the various steps used during this stage from form finding to the final shape and *Figure 82* shows in detail the how the shape was refined. This process was used to rationalize all of our building geometry, which could then be used to Re-mesh and analyze in a more detailed manner as it is the shape closest to the final buildable version of the shell.

Figure 81 shows the initial mesh and the final rationalized form of the bazaar, atrium, and the building unit roofs.

These processes were applied to all the roofs to generate the final NURBS surfaces which were remeshed and sent for final FEA analysis and used in the brick making scripts to generate brick patterns.

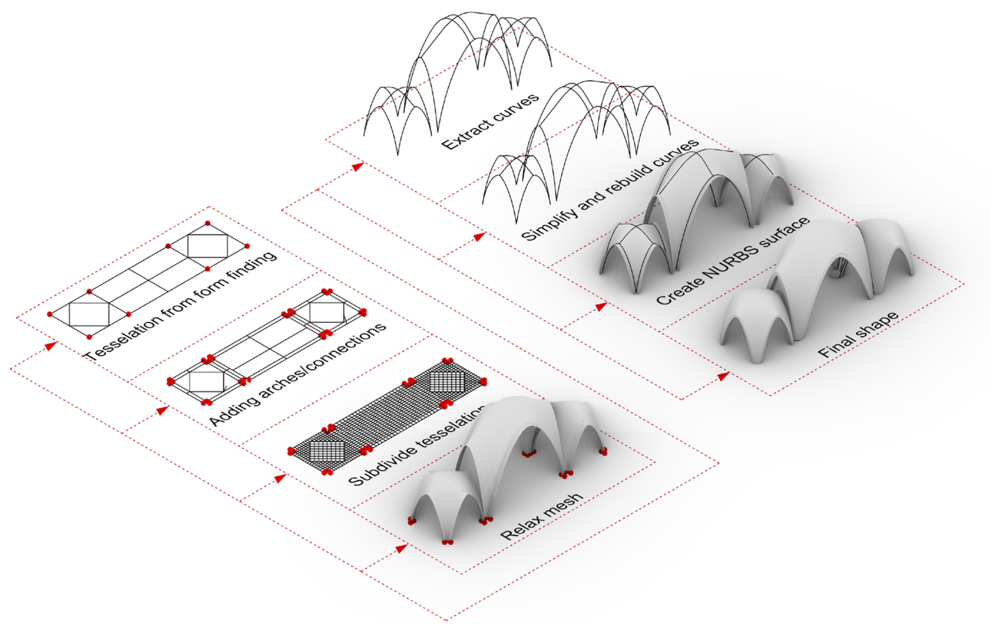


Figure 81 : Diagram showing the various stages of refining the Bazaar unit in the detailed design stage.

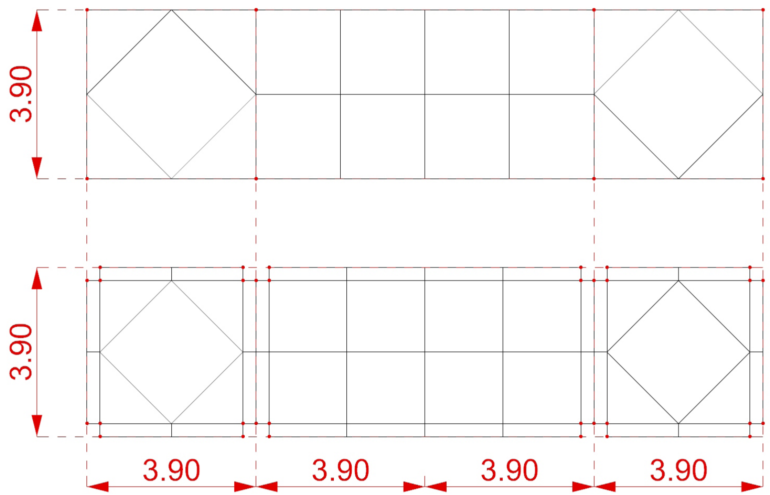


Figure 80 : Drawing showing the refinement of the tessellation

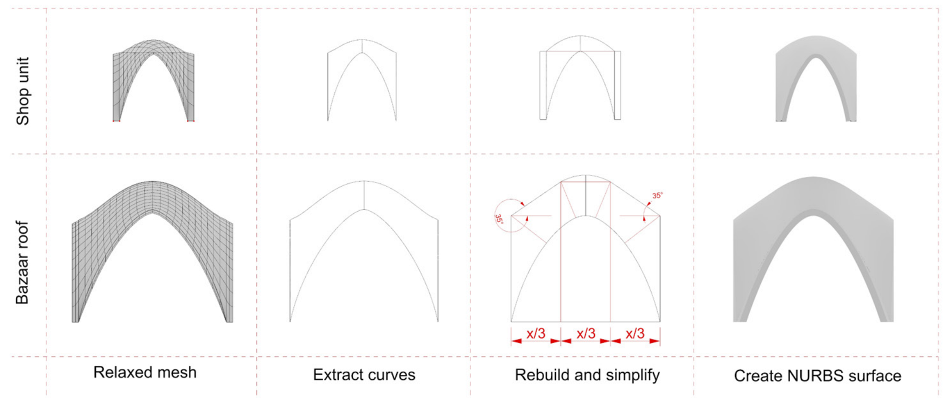
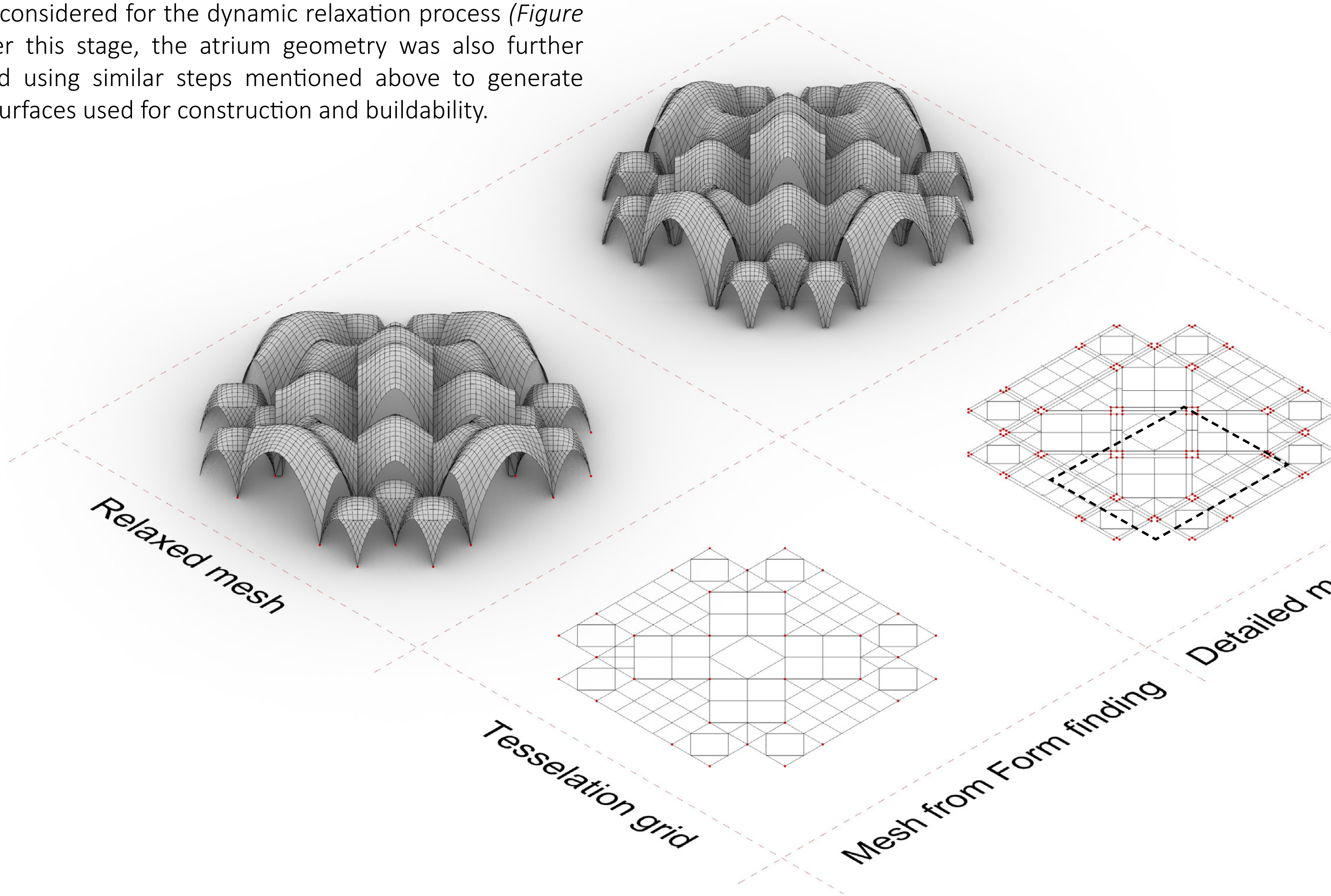


Figure 82 : Drawing showing the manual simplification involved in refining the bazaar roof and shop units.

4.4.5.C Atrium roofs (Adobe 2.0)

The atrium was also refined in consideration to the tartan grid. The arch offsets had to be varied in the diagonal arches to keep to the strictness of the grid. But since the units within the atrium could be self standing, the arches could be considered to be shared between shapes and hence the "doubling" of arches was not considered for the dynamic relaxation process *(Figure 83)*. After this stage, the atrium geometry was also further simplified using similar steps mentioned above to generate NURBS surfaces used for construction and buildability.



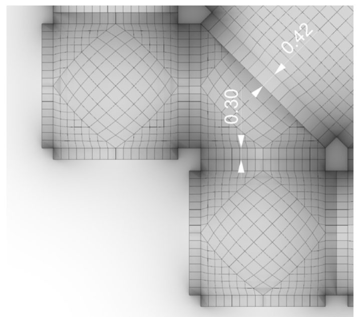


Figure *FF: Picture indicating the change in grid size from the orthogonal and diagonal mesh lines.*

Figure 83: Refining the tessellation pattern of the atrium

4.4.6 Roof modules library

Finally the collection of all the refined meshes can be categorically organized as shown in *Figure 84* which can be then called out by the layout tool to be placed in the respective location. A NURBS version of the same can also be used, which can then connect to the brick pattern making and constructibility stages of the project.

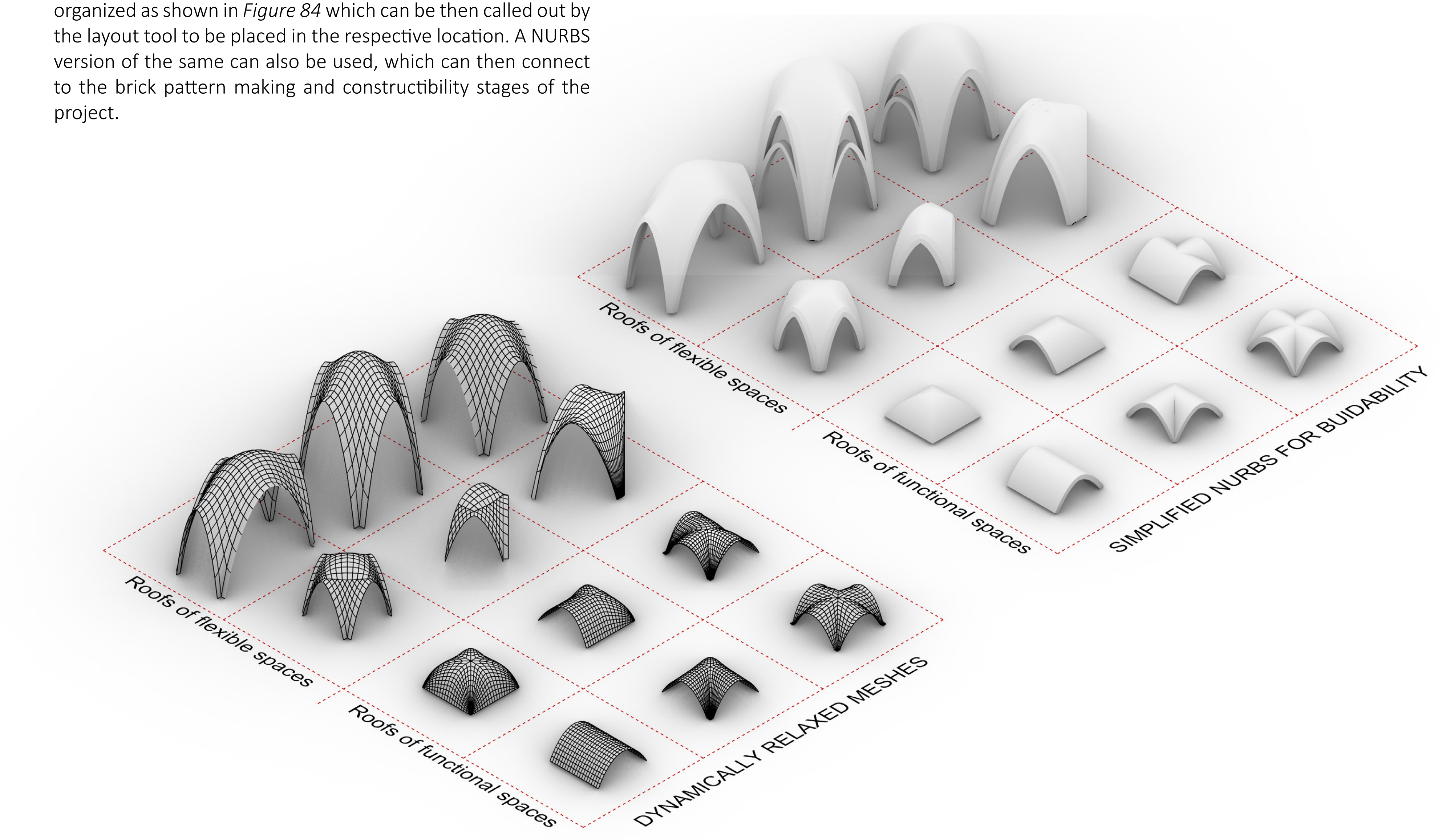


Figure 84: Library of all roof elements

4.5 STRUCTURAL ANALYSIS

4.5.1 Material properties

Significant scenarios from our building modules library have been considered for a deeper structural evaluation. The first step necessary to perform a realistic analysis and optimization of the shape and thickness of each building element, has been determining reasonable material properties for adobe. Due to the current situation, it has been impossible to produce and study the properties of our own earth mixtures and blocks. For this reason, existing literature and the structural reports of the students from Earthy 2019/20 have been reviewed and considered as reference for the choice of suitable material properties *(Fig.86)*. In addition to this, the different typologies of earth bricks have been evaluated according to mechanical, environmental and construction properties *(Fig.87)*.

The result of this evaluation has shown the advantages of using manually pressed unstabilized CEB. In fact, higher mechanical properties balance the slightly higher cost and complexity of production.

This production system influences the density, which has been therefore derived from the literature review on compressed earth blocks.

Other properties as Young’s module and strength of the material should be higher than for adobe, but for consistency the data for adobe bricks produced by one of the groups from Earthy 2019/20 have been considered to be the most reasonable and complete.

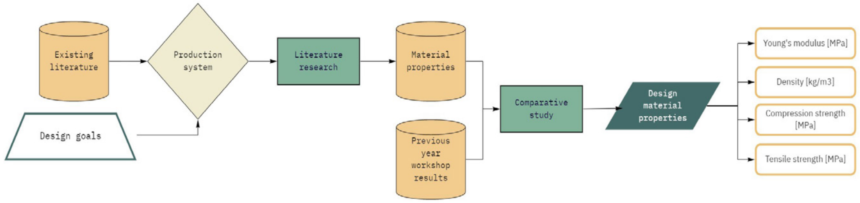


Figure 85: Material properties flowchart

The lower values of strength and stiffness and strength have been accepted as additional safety factors. The final material properties that have been used as one of the inputs for the FE analysis are summarized in *Figure 88*.

Source	Brick type	Pressing method	Density [kg/m3]	Compressive strength [MPa]	Tensile strength [MPa]	Young's modulus [MPa]
Physical, Mechanical and Durability Properties of Soil Building Blocks Reinforced with Natural Fibres	Soil block stabilised with fibres	Pressure gauge	1780	2,1	0,3	
Mechanical properties and hygroscopicity behavior of compressed earth block filled by date palm fibers	Compressed earth blocks filled with palm fibres (5% cement)	Hydraulic press	1450	8	0,85	
Thermal and Structural Properties of Compressed Earth Brick (Laterite Soil)	CEB	Hydraulic press	1687,2	14,8		
Analysis of the mechanical properties of compressed earth block masonry using the sugarcane bagasse ash	CEB with sugarcane bagasse ash	Mechanical press	1930 - 2020	2,42		
Compressive strength of compressed earth block masonry	CEB	Manual press	1800-1850	3,2		
Group 1 (Earthy 2019-2020)	Adobe	Hand pressed		6	0,6	80
Group 2 (Earthy 2019-2020)	Adobe	Hand pressed	1452	3	0,3	211
Group 5 (Earthy 2019-2020)	Adobe	Hand pressed	1500			150

Figure 86: Brick properties evaluation

Type of bricks	Forming procedure	Mechanical properties	Biobased mixture	Cost of production	Ease of production	Total evaluation
Unstabilized adobe	Handmade molded	- -	+	+ +	+ +	+ + +
Unstabilized compressed earth blocks (CEB)	Manual press	+	+	+	+	+ + + +
Unstabilized compressed earth blocks (CEB)	Mechanical / hydraulical press	+ +	+	-	-	+
Stabilized earth blocks	Manual press	+	-	-	+	+
Stabilized earth blocks	Mechanical / hydraulical press	+ +	-	- -	-	- -

Figure 87: Production systems evaluation

Density [kg/m3]	1700
Young's modulus [kN/cm2]	21
Compressive strength [kN/cm2]	0,3
Tensile strength [kN/cm2]	0,03

Figure 88: Chosen material properties

4.5.2 Loading conditions

In setting up the environment for the FE analysis, loading conditions represent the last necessary input. These have been specified into three different load cases:

- *Dead Load*: self weight of the tested shapes has been considered and calculated according to the chosen density of compressed earth blocks.
- *Live Load*: a value of live load usually considered for residential buildings has been taken into account. This has been considered enough for the single-storey part of our design, as access on their rooftop would happen mainly in case of maintenance. The value has been doubled for two-storeys modules, to meet more suitable requirements for public spaces.
- *Lateral Load*: wind load has been approximated for Jordan and used in the analysis of structures directly exposed to it.

The exact values of the loads and the safety factors that have been applied to each of them in the load combination can be seen in *Figure 89.*

After evaluatin the local climate, additional snow load was not considered necessary for the structural design and analysis.

Load case	Magnitude [kN/m2]	Magnitude [kN/cm2]	SF
L0	/	/	1,2
L1	2	0,0002	1,5
L2	0,2	0,00002	1,5

Figure 89: Chosen loading conditions

4.5.3 Detailed analysis

The flowchart illustrates the different steps of the structural analysis that has been performed on the main elements of the building elements library.

The three inputs which have been described in the previous sections are used to build the model for the FEA in Karamba. When the model is ready a test thickness is set and the analysis is performed.

In order to consider a shape and thickness good enough to move to the next phases of design, four parameters are checked after each simulation:

- *Compression*: when tested without lateral load, the shape has to show 0% utilization in tension, proving to be an only-compression structure.
- *Utilization:* when tested with the complete load combination, utilization in compression has to be as high as possible but below 100%.
- *Principle stresses:* principle stresses in the two directions have to be below the strength threshold of the material in both compression and tension.
- *Displacement:* the maximum displacement has to be below the value of span/200. Displacements are checked both in X, Y and Z directions.

According to this workflow, only if all these boxes are ticked it is possible to proceed to the next steps. In any other case, the test thickness or the input shape have to be changed.

After performing the analysis, it has been clear how difficult it is to achieve particularly high values for utilization in compression. This is due mainly to the poor quality of the material and to the minimum brick size which has been taken into account. Moreover, tensile stresses have been often the leading factors in increasing the thickness. This increase leads to lower utilization factors, which have still been accepted.

In the next pages, the main results of the analysis for each module are presented.

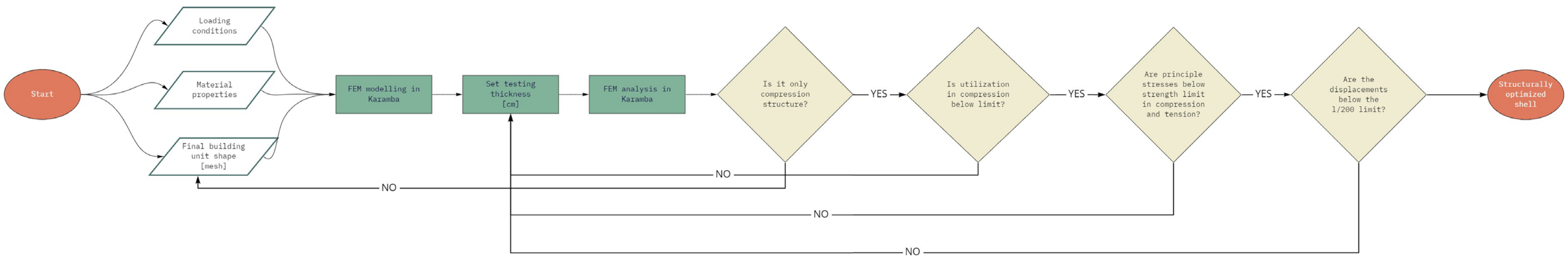


Figure 90: Structural analysis flowchart

4.5.3.A Shop roof

Final thickness [cm] : 30

The illustrations show the result of the analysis for utlization and principle stresses in first and second direction.

The utilization scheme consider lateral load, too. For this reason some localized light tension (green-coloured) can be observed. According to the colour coding of the legend for stresses, if there are no bright orange or dark green spots on the shell, the stresses are within the acceptable range provided by the material properties. The extremes of this stress domain can be seen also in *Figure 91*.

Maximum displacements in X, Y and Z direction can be seen in *Figure 92* and compared to the maximum displacement allowed.

Principal stress 1 [kN/cm2]		Material strength [kN/cm2]
Compression	0,02	0,30
Tension	0,02	0,03
Principal stress 2 [kN/cm2]		**Material strength [kN/cm2]**
Compression	0,10	0,30
Tension	0,00	0,03

Figure 91: Principle stress analysis

Span (l) [cm]	360
Limit	l/200
Max displacement [cm]	**1,8**
L0	
Δx [cm]	0,04
Δy [cm]	0,04
Δz [cm]	0,21
L1	
Δx [cm]	0,02
Δy [cm]	0,02
Δz [cm]	0,1
L2	
Δx [cm]	0
Δy [cm]	0,11
Δz [cm]	0,15
Max possible displ.	
Δx [cm]	0,06
Δy [cm]	0,17
Δz [cm]	0,46

Figure 92: Displacement analysis

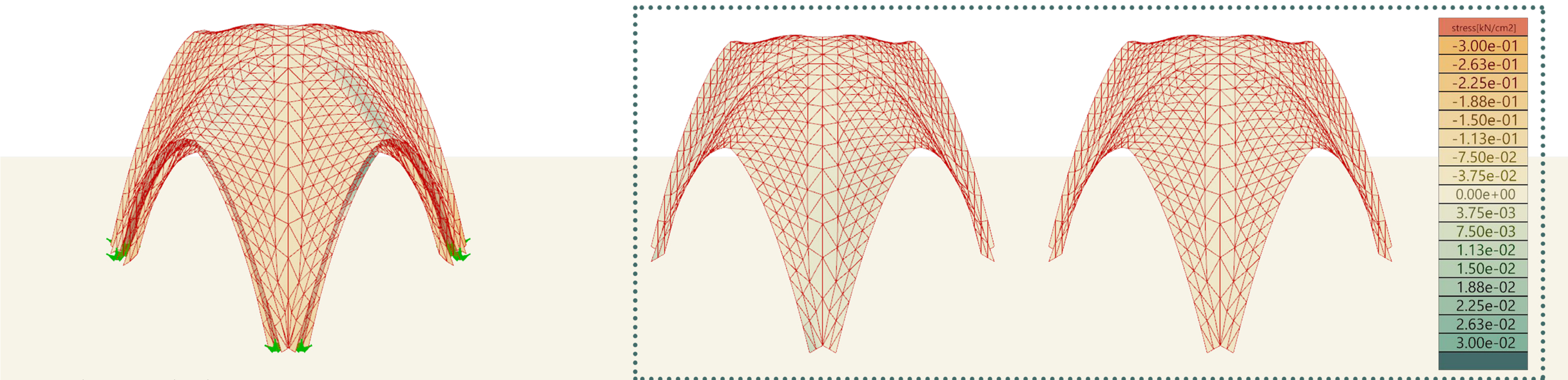


Figure 93: Shop structural analysis

4.5.3.B Bazaar roof

Final thickness [cm] : 40

The illustrations show the result of the analysis for utlization and principle stresses in first and second direction.

Figure 94 shows the comparison between maximum stresses and the allowable strengths of the material.

Displacements in X, Y and Z direction for each load case are compared to the maximum allowable displacement in *Figure 95.*

Principal stress 1 [kN/cm2]		Material strength [kN/cm2]
Compression	0,02	0,30
Tension	0,02	0,03
Principal stress 2 [kN/cm2]		**Material strength [kN/cm2]**
Compression	0,11	0,30
Tension	0,00	0,03

Figure 94: Principle stress analysis

Span (l) [cm]	720
Limit	l/200
Max displacement [cm]	**3,6**
L0	
Δx [cm]	0,18
Δy [cm]	0,12
Δz [cm]	0,64
L1	
Δx [cm]	0,06
Δy [cm]	0,04
Δz [cm]	0,23
L2	
Δx [cm]	0
Δy [cm]	0,20
Δz [cm]	0,21
Max possible displ.	
Δx [cm]	0,24
Δy [cm]	0,36
Δz [cm]	1,08

Figure 95: Displacement analysis

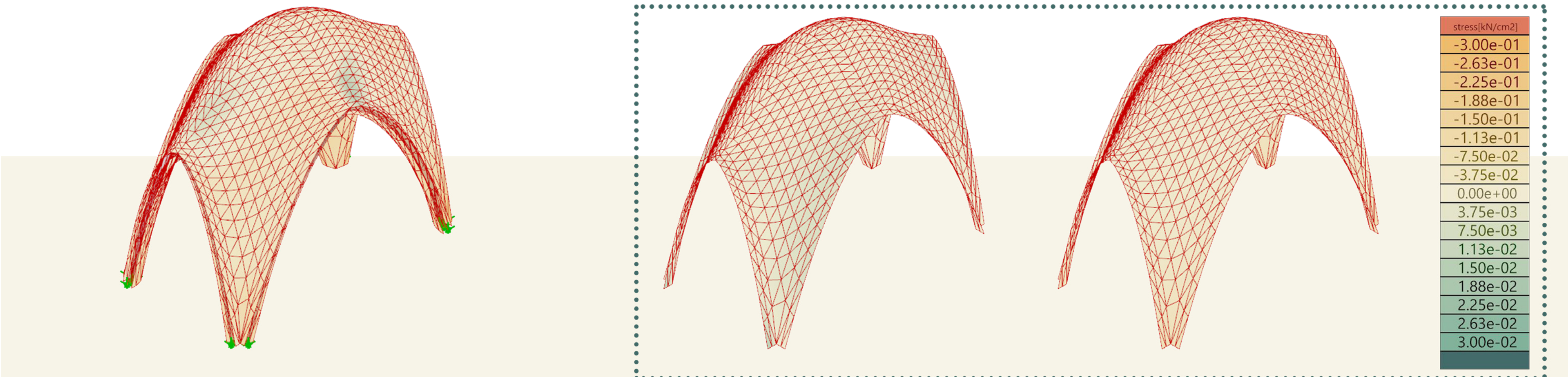


Figure 96: Bazaar structural analysis

4.5.3.C Hand calculations

The first results from the FE analysis have been verified through hand calculations, in order to guarantee the accuracy of the model for future simulations.

For both the shop and the bazaar modules hand calculations are performed for axial compressive stress at the supports. Only dead load is considered.

The same density used as input for the FEA is considered in approximating the total weight of the shell. The weight is then divided equally into the four supports and used to calculate the axial stress. The dead load's safety factor is then applied.

The result of these calculations is compared to the compressive stress calculated in Karamba.

$$Density = 1700\frac{kg}{m^3}$$

$$A_{shop} = 2 * (30 * 30)cm = 1800\ cm^2$$

$$\boldsymbol{\sigma_{shop} = 0.024\frac{kN}{cm^2}}$$

$$A_{bazaar} = 2 * (40 * 40)cm = 3200\ cm^2$$

$$\boldsymbol{\sigma_{shop} = 0.045\frac{kN}{cm^2}}$$

$$Load = 15.630e3 * 0.098 = 153.174\ kN$$

$$Load_{support} = \frac{Load}{4} = \frac{153.174}{4} = 38.293\ kN$$

$$\sigma_{support} = \frac{Load_{support}}{A} = \frac{38.293}{1800} = 0.021\frac{kN}{cm^2}$$

$$\sigma_{SF} = \sigma_{support} * 1.2 = \boldsymbol{0.025\frac{kN}{cm^2}}$$

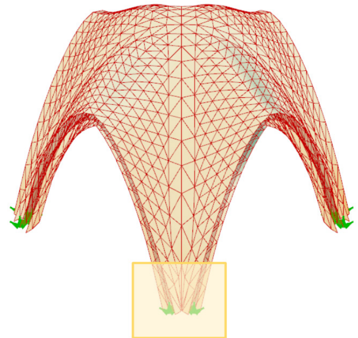


Figure 97: Shop hand calculations

$$Load = 42.233e3 * 0.098 = 423.680\ kN$$

$$Load_{support} = \frac{Load}{4} = \frac{423.680}{4} = 105.920\ kN$$

$$\sigma_{support} = \frac{Load_{support}}{A} = \frac{105.920}{3200} = 0.033\frac{kN}{cm^2}$$

$$\sigma_{SF} = \sigma_{support} * 1.2 = \boldsymbol{0.039\frac{kN}{cm^2}}$$

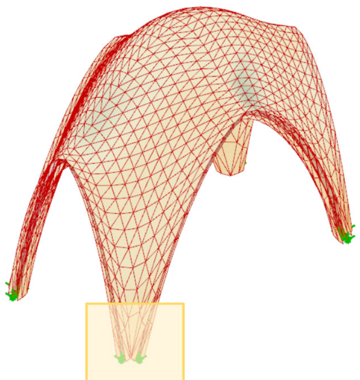
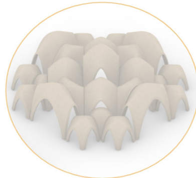


Figure 98: Bazaar hand calculations

4.5.3.D Atrium roof 1



Final thickness [cm] : 30

The illustrations show the result of the analysis for utilization and principle stresses in first and second direction.

Four types of different modules are built separately, but they have been modelled together, as they eventually rest one on each other. *Figure 99* shows the comparison between maximum stresses and the allowable strengths of the material.

Displacements in X, Y and Z direction for each load case are compared to the maximum allowable displacement in *Figure 100*.

Principal stress 1 [kN/cm2]		Material strength [kN/cm2]
Compression	0,02	0,30
Tension	0,03	0,03
Principal stress 2 [kN/cm2]		**Material strength [kN/cm2]**
Compression	0,11	0,30
Tension	0,00	0,03

Figure 99: Principle stress analysis

Span (l) [cm]	720
Limit	l/200
Max displacement [cm]	**3,6**
L0	
Δx [cm]	0,28
Δy [cm]	0,28
Δz [cm]	0,78
L1	
Δx [cm]	0,14
Δy [cm]	0,14
Δz [cm]	0,39
L2	
Δx [cm]	0
Δy [cm]	0,54
Δz [cm]	0,37
Max possible displ.	
Δx [cm]	0,42
Δy [cm]	0,96
Δz [cm]	1,54

Figure 100: Displacement analysis

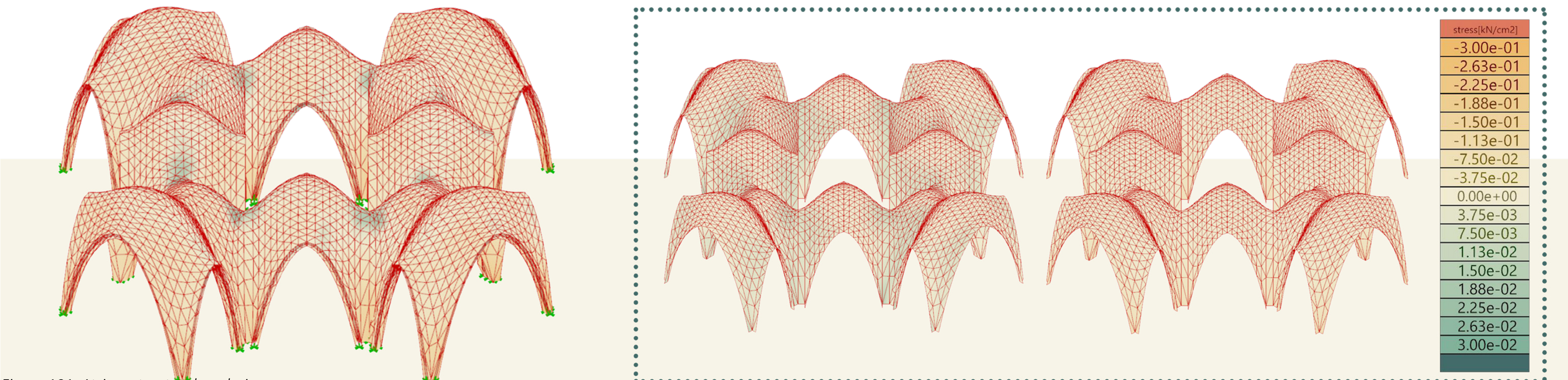
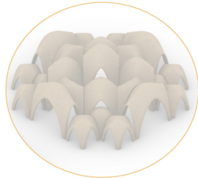


Figure 101: Atrium structural analysis

4.5.3.E Atrium roof 2



Final thickness [cm] : 60

Due to its height, the central vault requires a shell thickness of 60 cm.

Figure 102: stress comparisons to compressive and tensile strength of the material.

Figure 103: displacements in X, Y and Z directions for all the load cases compared to maximum allowable displacementes.

Principal stress 1 [kN/cm2]		***Material strength [kN/cm2]***
Compression	0,01	0,30
Tension	0,02	0,03
Principal stress 2 [kN/cm2]		***Material strength [kN/cm2]***
Compression	0,10	0,30
Tension	0,00	0,03

Figure 102: Principle stress analysis

Span (l) [cm]	640
Limit	l/200
Max displacement [cm]	**3,2**
L0	
Δx [cm]	0,26
Δy [cm]	0,26
Δz [cm]	0,81
L1	
Δx [cm]	0,13
Δy [cm]	0,13
Δz [cm]	0,40
L2	
Δx [cm]	0
Δy [cm]	0,74
Δz [cm]	0,43
Max possible displ.	
Δx [cm]	0,39
Δy [cm]	1,13
Δz [cm]	1,64

Figure 103: Displacement analysis

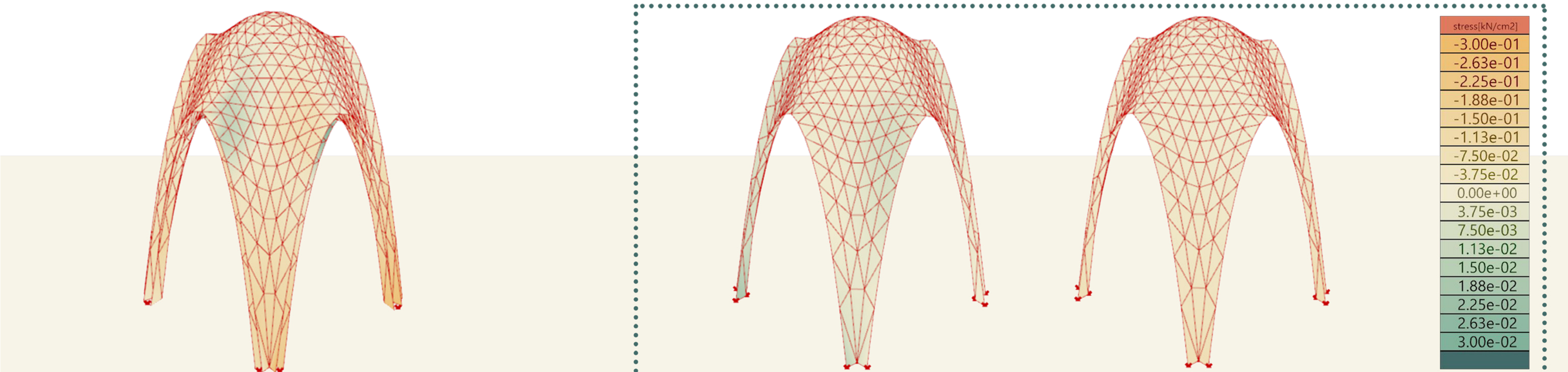
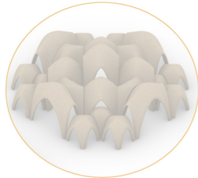


Figure 104: Atrium vault structural analysis

4.5.3.F Atrium roof 3



Final thickness [cm] : 30

The corner module of the atrium it is very similar to the shop module in terms of shape and structural behaviour.

Figure 105: stress comparisons to compressive and tensile strength of the material.

Figure 106: displacements in X, Y and Z directions for all the load cases compared to maximum allowable displacementes.

Principal stress 1 [kN/cm2]		Material strength [kN/cm2]
Compression	0,01	0,30
Tension	0,01	0,03
Principal stress 2 [kN/cm2]		**Material strength [kN/cm2]**
Compression	0,05	0,30
Tension	0,00	0,03

Figure 105: Principle stress analysis

Span (l) [cm]	640
Limit	l/200
Max displacement [cm]	**3,2**
L0	
Δx [cm]	0,04
Δy [cm]	0,04
Δz [cm]	0,20
L1	
Δx [cm]	0,02
Δy [cm]	0,02
Δz [cm]	0,10
L2	
Δx [cm]	0
Δy [cm]	0,05
Δz [cm]	0,08
Max possible displ.	
Δx [cm]	0,06
Δy [cm]	0,11
Δz [cm]	0,38

Figure 106: Displacement analysis

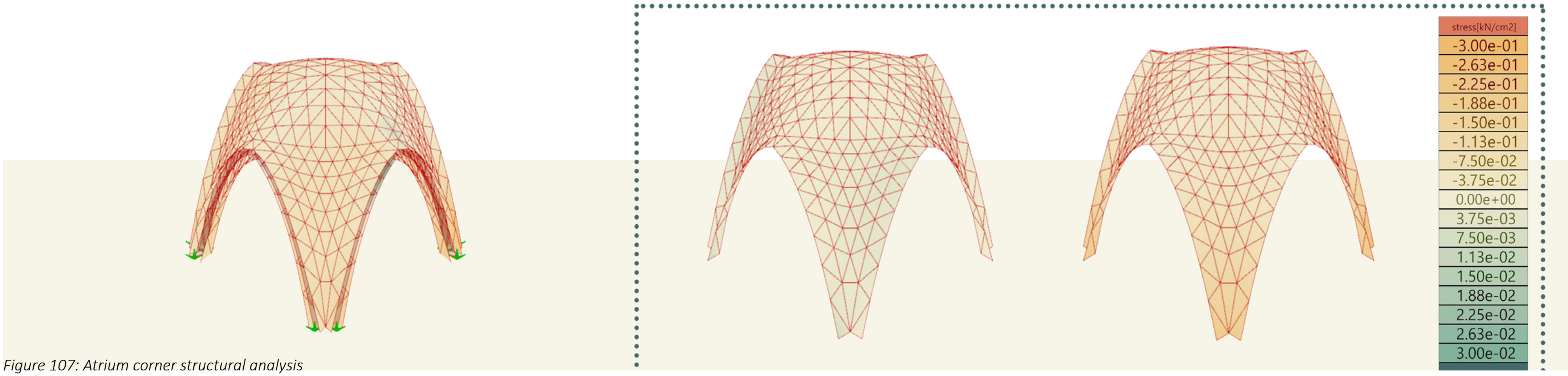


Figure 107: Atrium corner structural analysis

4.5.3.G Wall modules

Final column dimension [cm] : 90x90
Final wall thickness [cm] : 30

Considering the more structured part of the design, composed by wall and roofs modules, analysis have been performed to understand the dimensions of both.

Tests have been performed with loads for one and two storeys, as this possibility is allowed by our configuration tools. On the side, many options are evaluated and stresses in principle direction 1 are reported for both the scenarios. Due to the lateral thrust of the vaults, column size increases to 90x90 cm.

For what it concerns wals, the linear supports and the balance of lateral thrust that happens between neighboring roofs made it possible to achieve a thickness of 30 cm in all the options.

1	Axial stress 1 storey [MPa]		Material strength [MPa]
	Compression	0,37	3,00
	Tension	0,23	0,30
	Axial stress 2 storeys [MPa]		Material strength [MPa]
	Compression	0,48	3,00
	Tension	0,30	0,30
2	Axial stress 1 storey [MPa]		Material strength [MPa]
	Compression	1,42	3,00
	Tension	0,24	0,30
	Axial stress 2 storeys [MPa]		Material strength [MPa]
	Compression	1,80	3,00
	Tension	0,30	0,30
3	Axial stress 1 storey [MPa]		Material strength [MPa]
	Compression	0,15	3,00
	Tension	0,23	0,30
	Axial stress 2 storeys [MPa]		Material strength [MPa]
	Compression	0,26	3,00
	Tension	0,25	0,30

Figure 108: Axial stress analysis

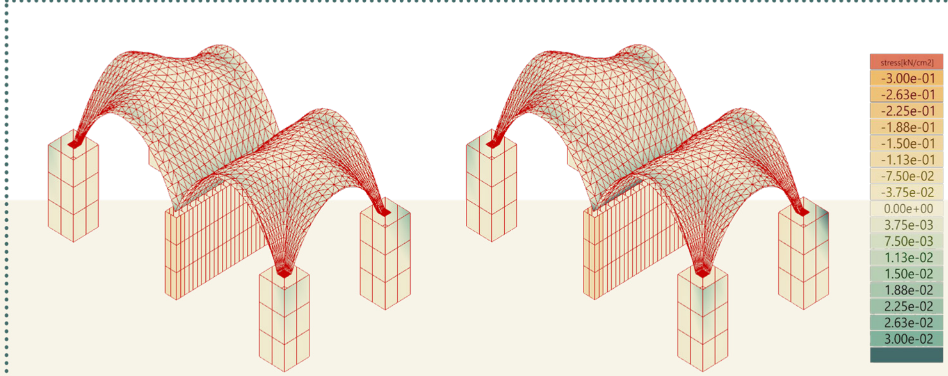


Figure 109: Scenario 1 structural analysis

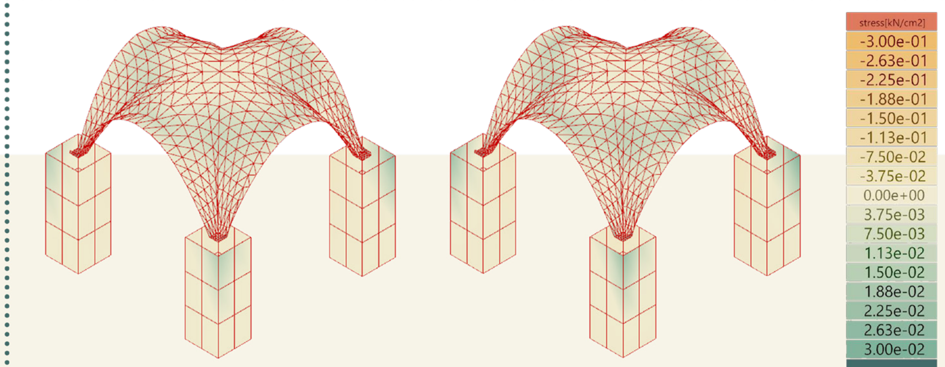


Figure 110: Scenario 2 structural analysis

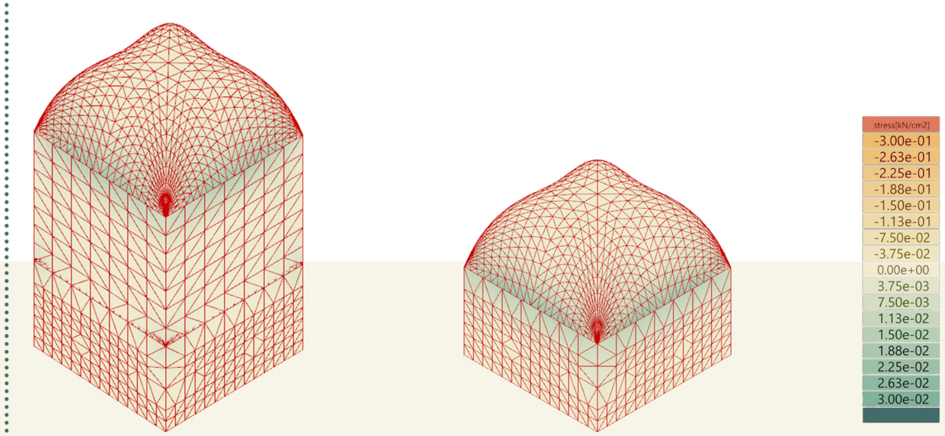


Figure 111: Scenario 3 structural analysis

4.5.3.H Wall supported roofs

Final thickness [cm] : 30

The roof elements have been structurally tested separately from the vertical elements. This has been done to avoid the inaccuracies often involved in modelling the supports. Loads for the two-storeys option have been used for the simulations, as considered to be the worst possible scenario.

In *figure 113*, displacements and stresses in both principle directions are are classified for all the roof options.
Those values have to be compared to:
- *max. compressive stress = 0.3 kN/cm2*
- *max. tensile stress = 0.03 kN/cm2*
- *max. displacement = 1.8 cm*

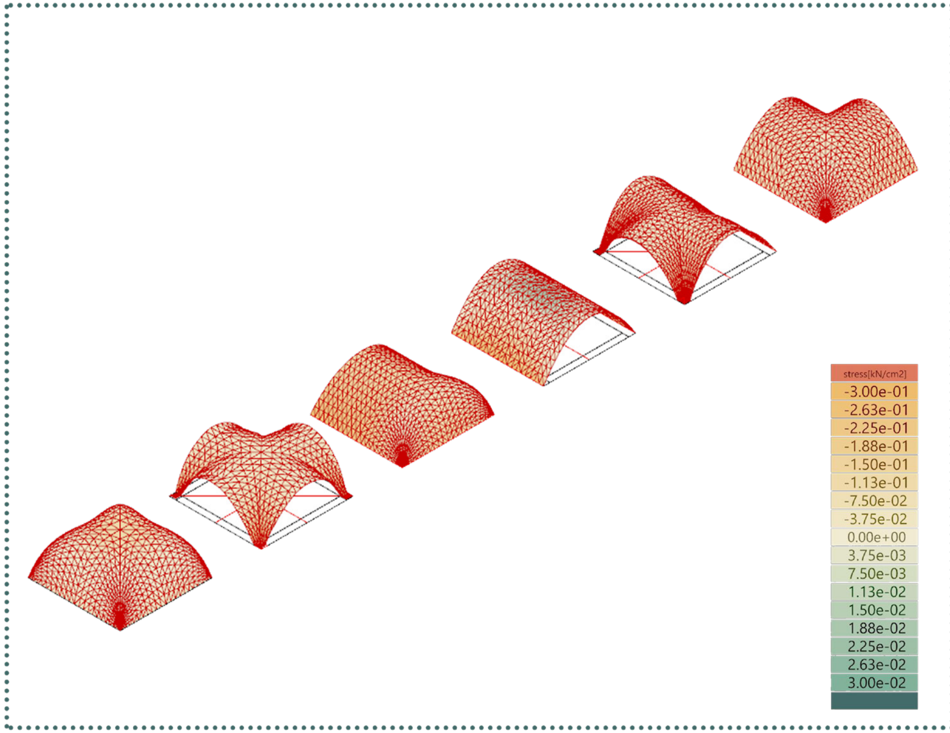


Figure 112: Wall supported roofs structural analysis

	Displacements			***Principal stress 1 [kN/cm2]***		***Principal stress 2 [kN/cm2]***	
Roof type	*x*	*y*	*z*	*Compression*	*Tension*	*Compression*	*Tension*
1	0,03	0,03	0,18	0,01	0,00	0,01	0,00
2	0,05	0,05	0,41	0,02	0,01	0,04	0,00
3	0,04	0,03	0,14	0,01	0,00	0,01	0,00
4	0,03	0,01	0,12	0,00	0,00	0,01	0,00
5	0,21	0,04	0,28	0,02	0,02	0,05	0,00
6	0,06	0,08	0,24	0,02	0,01	0,05	0,00

Figure 113: Wall supported roofs structural analysis

In the last phase of the design, the results of the shaping process are detailed. This has meant understanding and simplifying the construction system of each element, studying the brick composition and analyzing the brick patterns. Details for other relevant topics such as rainwater management and climate design are also shown in this chapter.

CONSTRUCTION 05

5.1 BRICK COMPOSITION & SIZE

5.1.1 Brick composition

Material properties are related to the proportions of materials used to mould the earth bricks and curing time and conditions. Literature research shows that typically mixtures are composed by sand (40 to 70%), clay (15 to 60%) and water (8 to 12%)(*Bowen, 2017*). Reinforcements can be added to enhance compressive strength or ductility. For consistency, the mixture considered by the same of group of students from Earthy 2019/20 is taken as starting point *(Figure 114)*.

Clay	30%
Fine sand	30%
Coarse sand	40%
Water content	*10%*

Figure 114: Chosen mixture

Although all the analysis have been performed with the basic material properties to ensure safety, the possibility to add reinforcement in the mixture of the most stressed bricks has been takent into account. In order to choose the type of reinforcement, solid waste flows within the camp have been considered. According to *Saidan (2016)* beside organic waste, the most common categories in commercial areas are: paper and cardboard (17.67%), plastics (13.91%), textiles (5.10%). *(Figure 115)*
For this reason based on availability, on the most compressed bricks 1% reinforcerment with the following materials is suggested:

- straw
- paper pulp
- textile fibres

Based on availability, additives can be applied on the bricks to waterproof them (linseed oil, lime, animal fat).

Table 3
Average percentage composition per area category at Zaatari camp in 2015. Source: MoMA (2015b).

Waste categories (%)	High populated Districts	Low populated Districts	Commercial Area	Zaatari (Average)	Average MSW in Municipalities[a]
Organics	55.84	52.60	49.65	52.70	59
Paper and cardboard	5.60	3.74	17.67	9.00	14
Plastics	11.39	13.23	13.91	12.85	10
Leather, wood, textile and rubber	11.57	13.99	5.10	10.22	10
Metal	3.69	3.70	7.08	4.82	5
Aluminum	0.27	0.32	0.65	0.41	
Glass	0.90	0.81	2.04	1.25	4
Inert material	0.04	0.37	0.23	0.22	5
Special Waste (Hazardous, etc.)	0.17	0.45	0.20	0.28	6
Miscellaneous-Bread	0.35	0.41	3.09	1.28	
Miscellaneous - Nappies	10.18	10.38	0.38	6.97	
Total	100.00	100.00	100.00	100.00	

[a] Average MSW compositions percentages in the 100 Municipalities in Jordan.

Figure 115: Zaatari waste composition (Bowen, 2017)

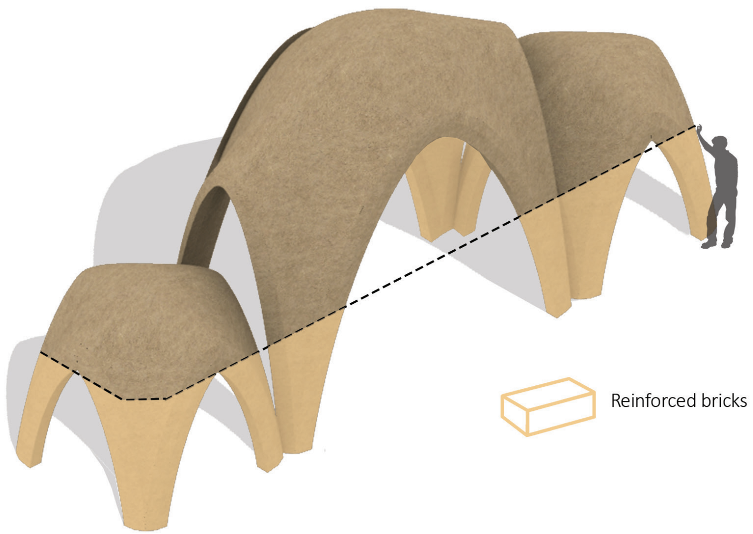
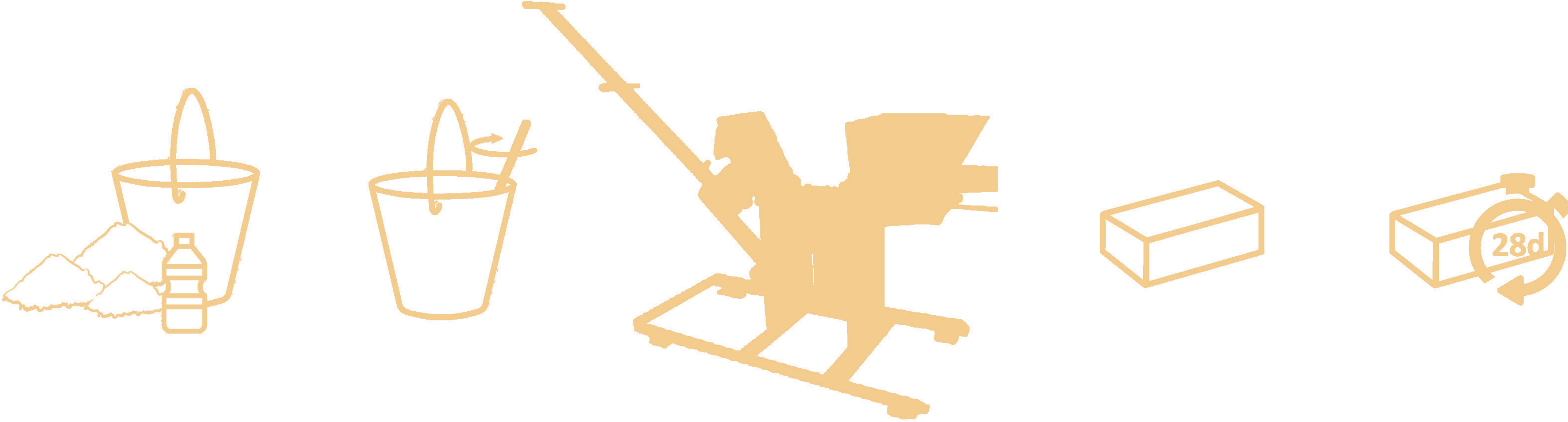


Figure 116: Height-related criteria for brick type disposition



<u>Ingredients</u>

<u>Standard mixture</u>
Clay 30%
Fine sand 30%
Coarse sand 40%
(Water 10%)

<u>Reinforcements</u>
(based on availability)
1% straw
1% paper pulp
1% textile fibres

<u>Mix them</u>

Dry ingredients are mixed first.
Water is then gradually added and mixed with the other ingredients.

<u>Press them</u>

<u>Cure them</u>

The bricks are cured for 7 days in the shadow to avoid uneven shrinking. Is preferred to let them cure for 21 days more, but can be used after 7.

Waterproofing after drying:
(based on availability)
Linseed oil
Hydraulic lime
Animal fat

Figure 117: Brick production instructions

5.1.2 Brick sizes

The list of instructions presented in the page above represents the main steps to be followed in order to produce the compressed earth blocks. These rules could be further developed, based on parameters like the hand press that would be used in the actual construction or more detailed curing conditions.

To move to the constructing phase of the design, the brick making logic has been further developed into brick patterns and brick sizes *(Figure 118)*. Starting point in this process has been a 16 voxels brick. One of those voxel represent the smallest unit of our 3.9x3.9m grid. The dimensions of the brick have been later optmized for masonry, in order to allow a 12mm joint between two layers and still achieve a wall thickness of 300mm.

A last variation on the size has been done to design bricks for roofs and arches. Their reduced height means lower weight and higher accuracy in approximating the curvature of the roofs. As it can be noticed, only the height is changed so that the same hand press can be used to produce both the bricks. These components are used to develop and to detail the two building systems of which the design is made of.

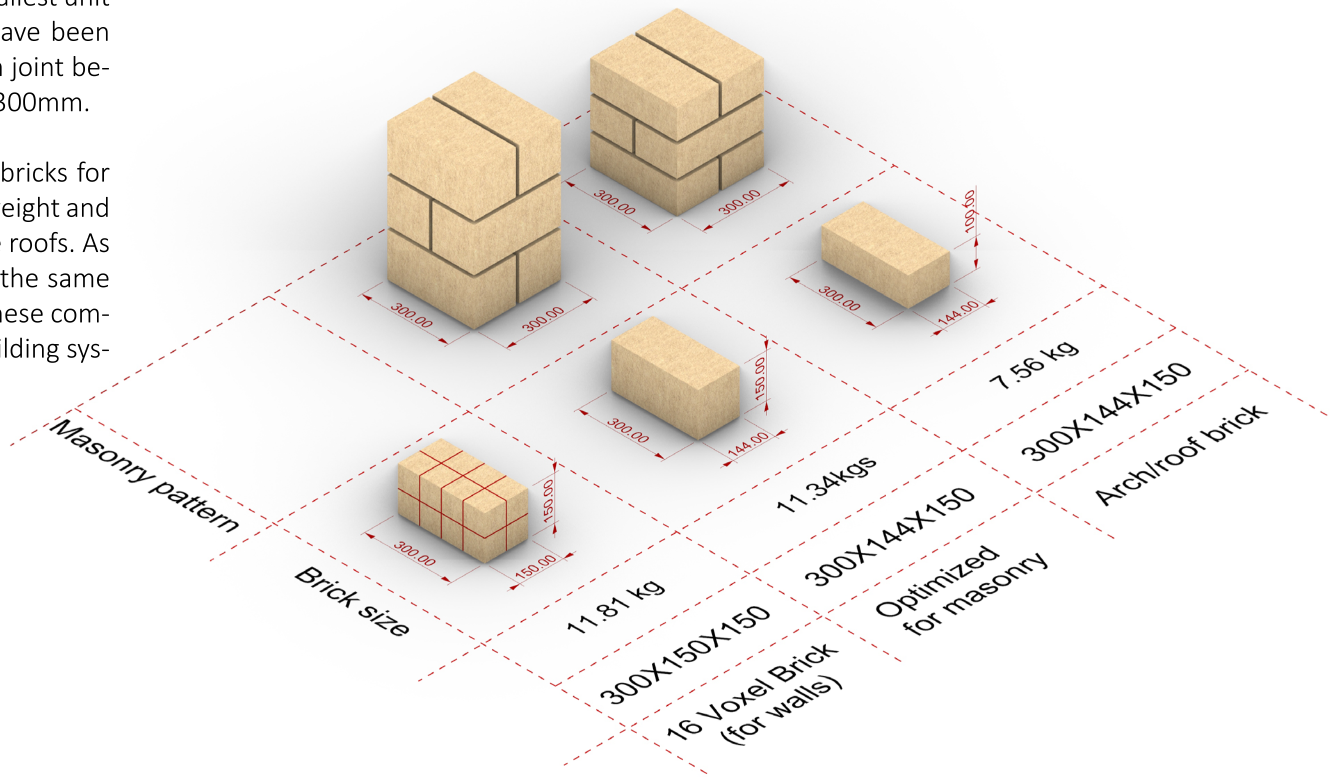


Figure 118: Brick patterns and chosen brick sizes

5.2 TOOLS & EQUIPMENT

An analysis of the resources present in the camp based on literature and photographs has shown the diffuse availability of corrugated sheets and scrap wood pieces. Images demonstrate also relevant construction skills within the camp. Visual proofs of these discoveries can be seen in *Figure 119*.
These elements, together with other basic instruments have been collected and illustrated to provide the workers with a clear toolset for construction *(Figure 120)*.

Figure 119: Materials and skills availability

Figure 120: Construction toolset

5.3 CONSTRUCTION SEQUENCE

5.3.1 Walls

Brcik layout for the walls :

The walls have a specific brick sequence. This sequence is made out of four layers that can be repeated by the builders to achieve a hight of 2.4meters. The first layer is made out of a repeating pattern of one brick that lies across the wall followed by 2 bricks parallel to the wall. The brick that lies across the wall provides stability and connection between the 2 bricklayers. The second layer is made out of a ''stair'' pattern of brick lying in a parallel way to the wall direction. The pattern is shifted at every layer of the wall to assure as mush connections between the bricks as possible. The easy to build pattern is adapted to the grid size that has been defined (3.9x3.9). The bricks used for this pattern are 300x144x100 bricks.

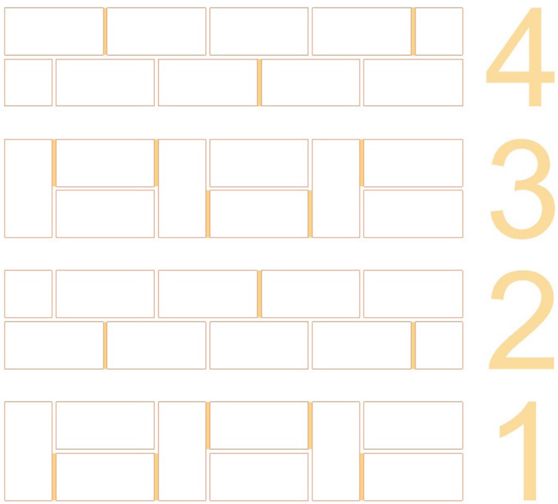


Figure 121: Brick laying pattern sequence

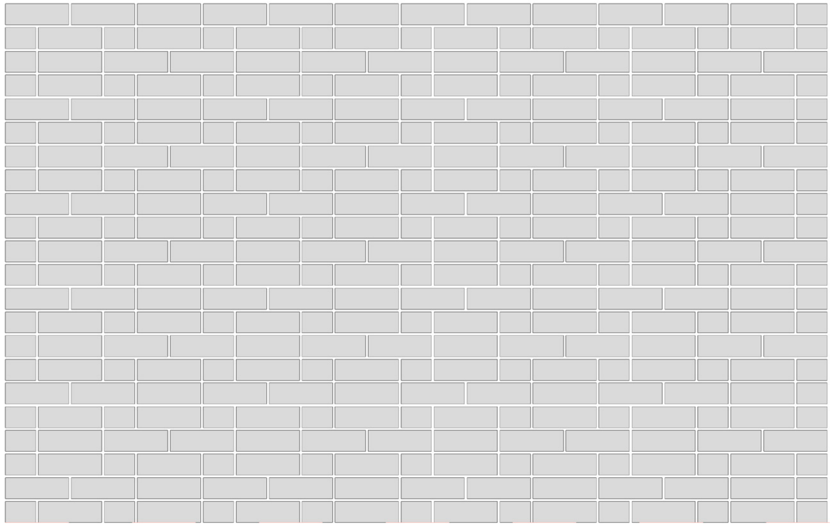


Figure 122: Front view wall

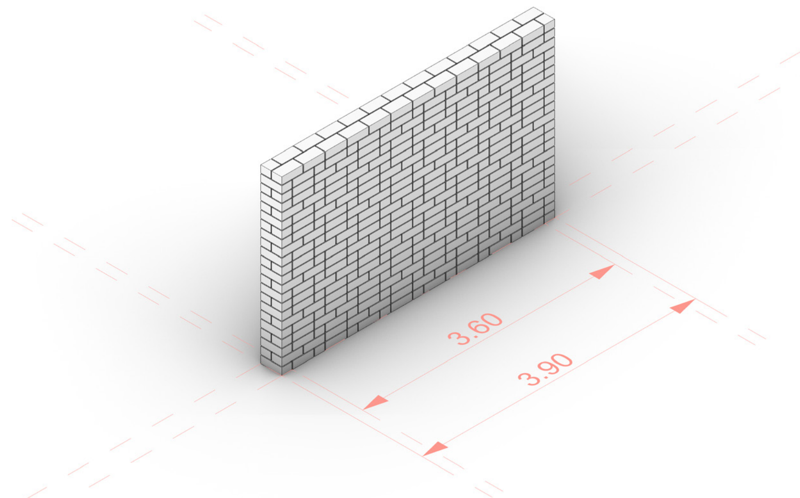


Figure 123: Brick wall

T and L section :

The corners of the building ensure stability, therefore they and their brick pattern are important. The pattern used in the design is adapted to the grid and fit in the modularity plan. For the L-section, the pattern provides a connection between the walls on every layer. For the T-section, the walls are connected on every layer as well. An important rule to follow in order to achieve stability in the corner is to not create windows to close to the corners.

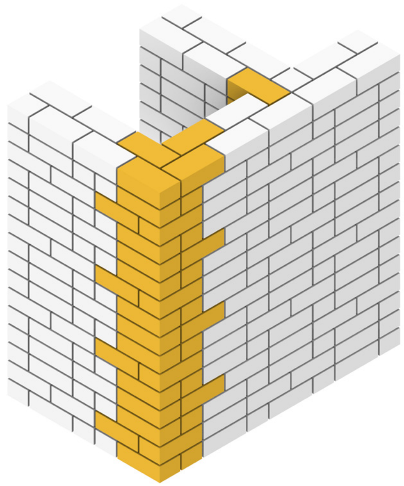


Figure 125: Brick pattern L-Section

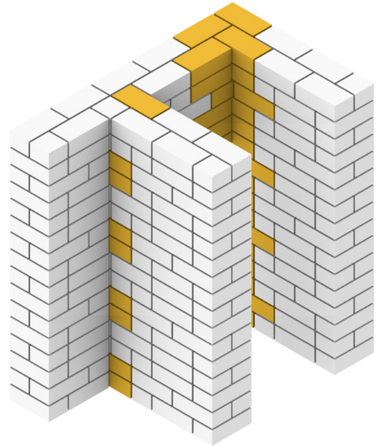


Figure 126: Brick pattern T-Section

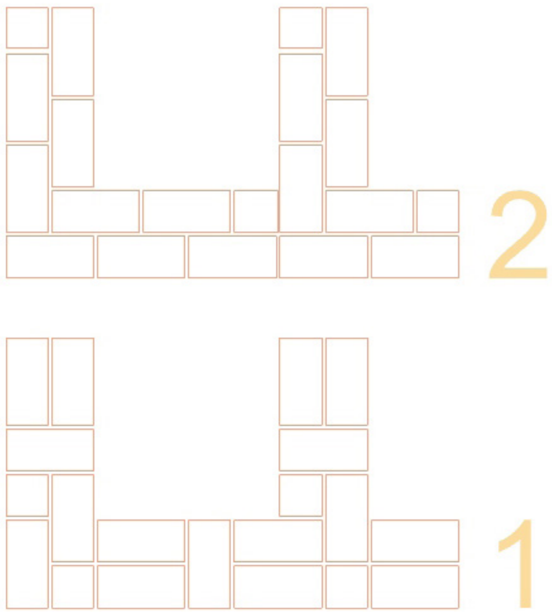


Figure 124: Brcik pattern T & L section

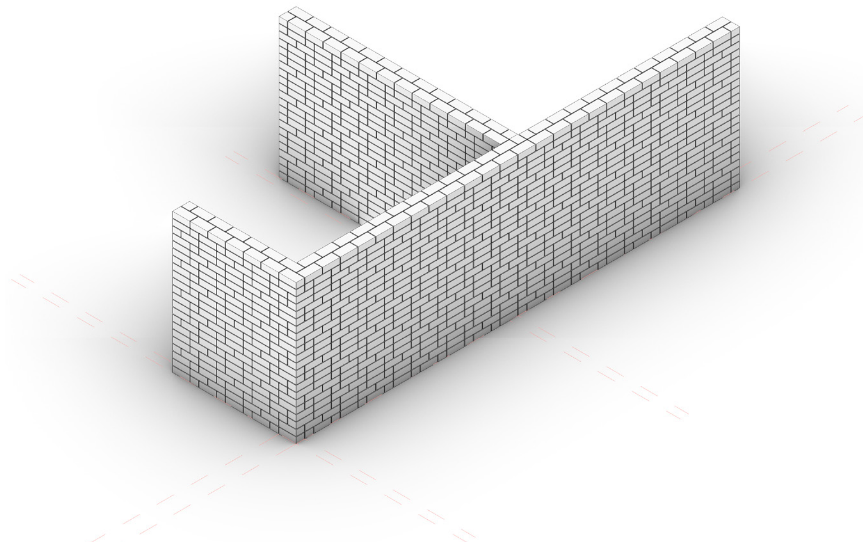


Figure 127: Brick wall

Fundation :

As any other building, brick buildings need a foundation. The foundation of this building is made ot out stones that can be found aound the camp.

Figure 129: Foundation grid

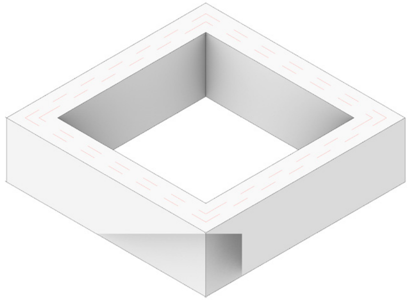


Figure 130: Foundation block

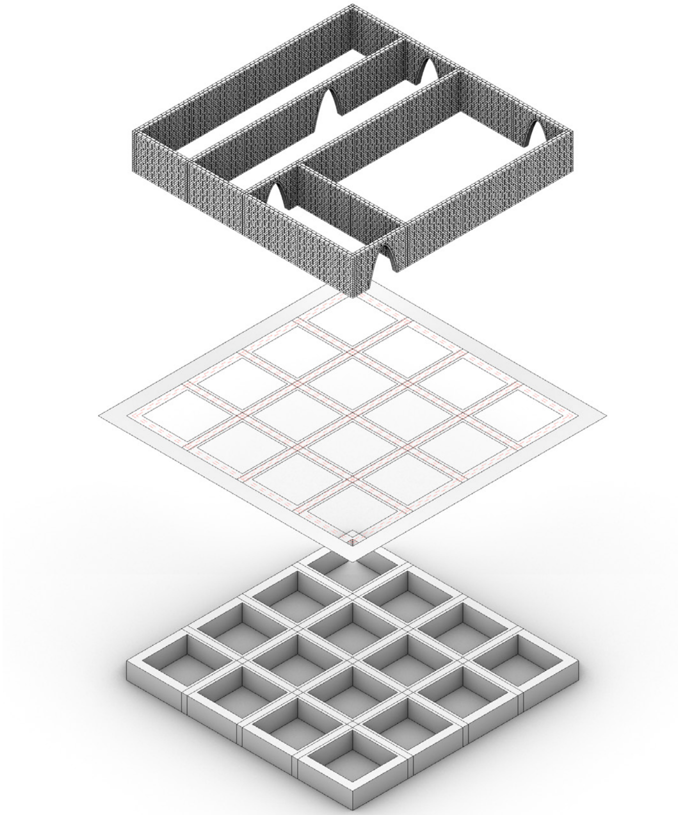


Figure 128: Foundation axo

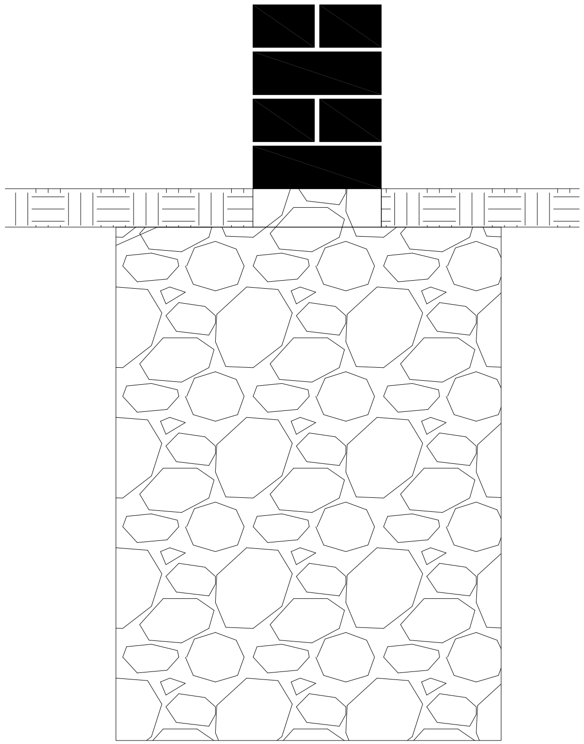


Figure 131: Foundation detail

5.3.2 Windows & Doors

Two different types of windows are used in the design. Both are built with the help of a car wheel. The wheel provides support that can be used to place the brick. By using this technique a repeatable shape can be made. The first one is the arched window and is used in active spaces where people spend time. The second window is round one. This opening is mainly used is logistics spaces to ensure ventilation and light.

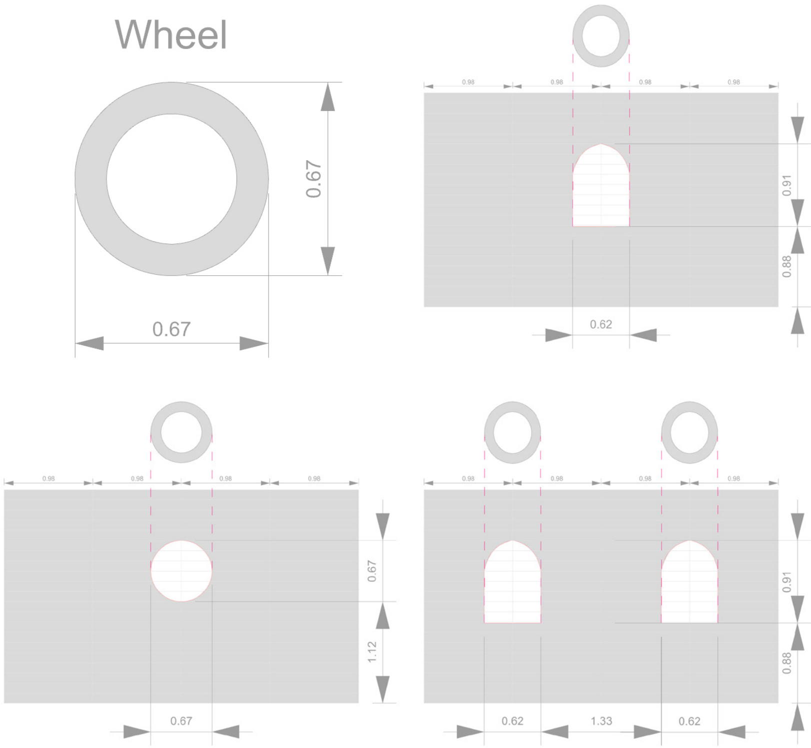


Figure 132: Image legend

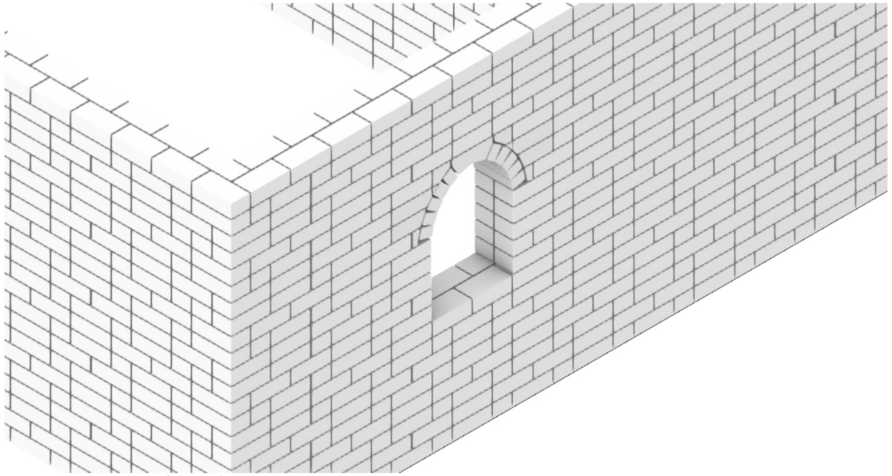


Figure 133: Image legend

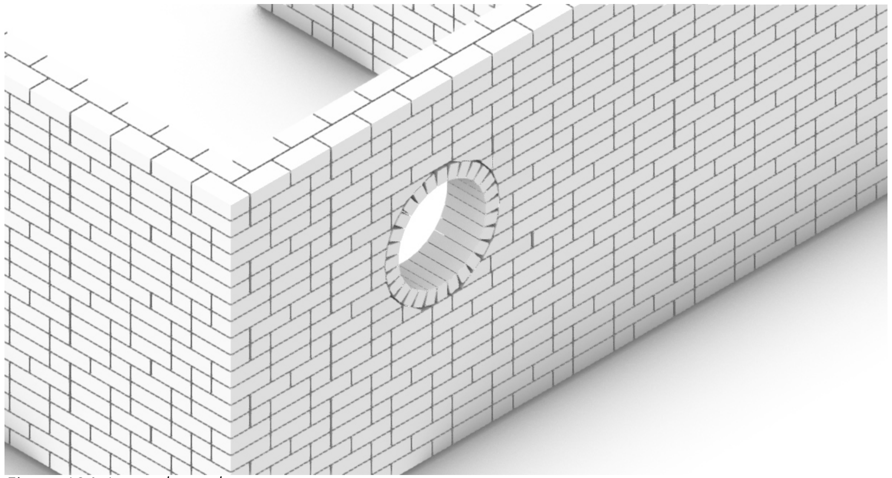


Figure 134: Image legend

Door opening:

The door opening is used between spaces and as an entrance into the building. This module provides a smaller opening to the module library and can be used when as a back entrance or as opening in an open space. It is built by using the same techniques used to build the catenary arches to avoid complexity.

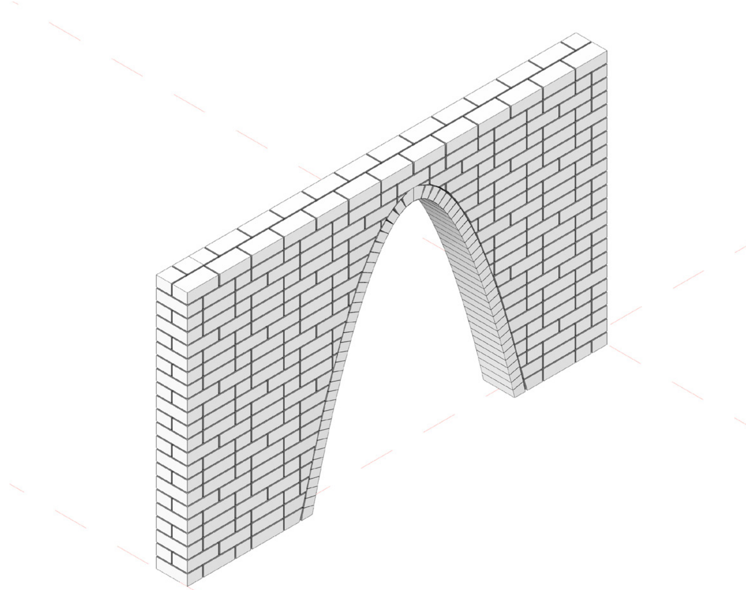


Figure 136: Door opening

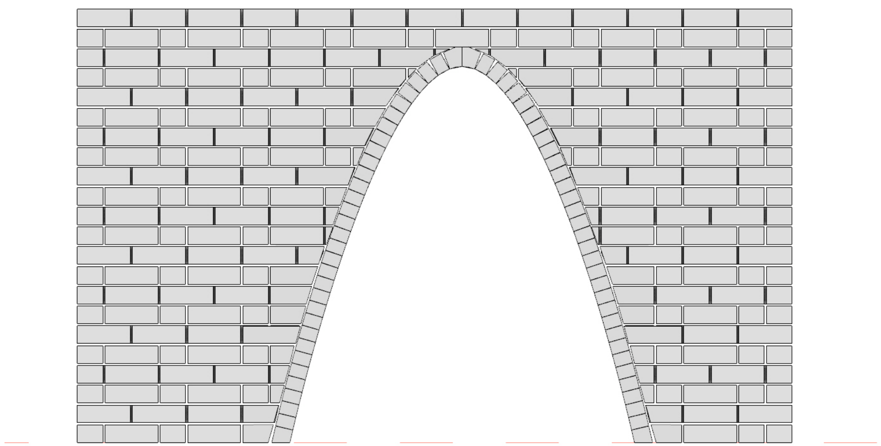


Figure 135: front view door opening

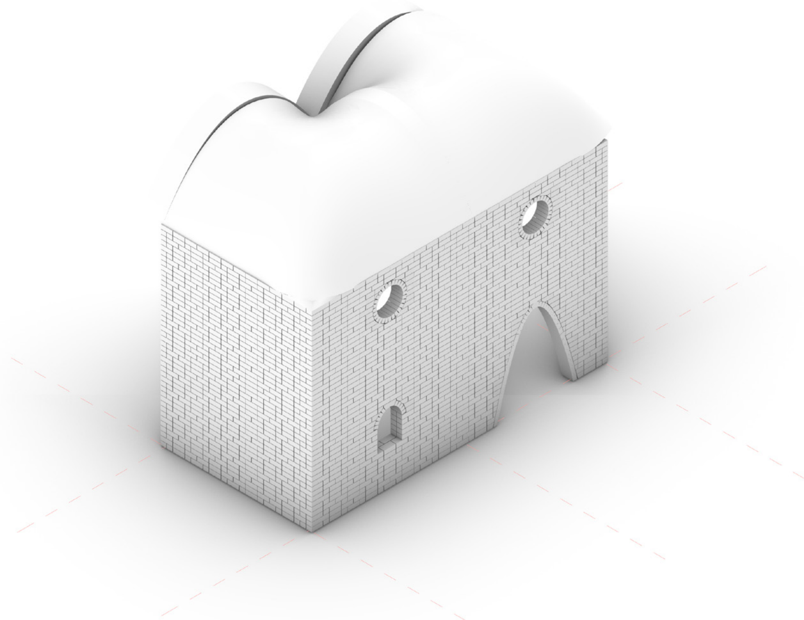


Figure 137: Opening overview

5.3.3 Technique - Self Standing Sail Vault

The location of the sail vaults are indicated in the keyplan in *Figure 140*. All the vaults follow a common construction sequence listed below. With increase in scale, the sizing of the Jig members and number of supports increase, but the basic principle remains the same *(Figure 138)*. For additional references for the correct curvature of the bricks, corrugated sheets can be bent and clamped to the arches *(Figure 139)*.

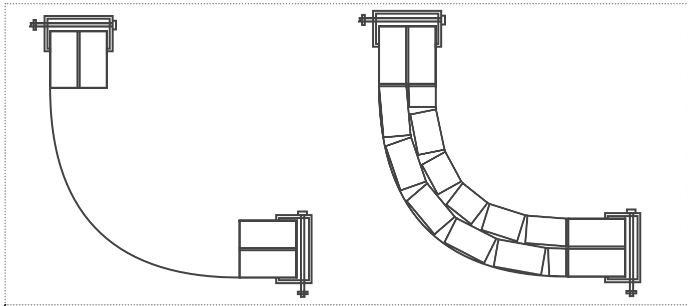


Figure *139: Referencing template for curved shapes using corrugated metal sheets*

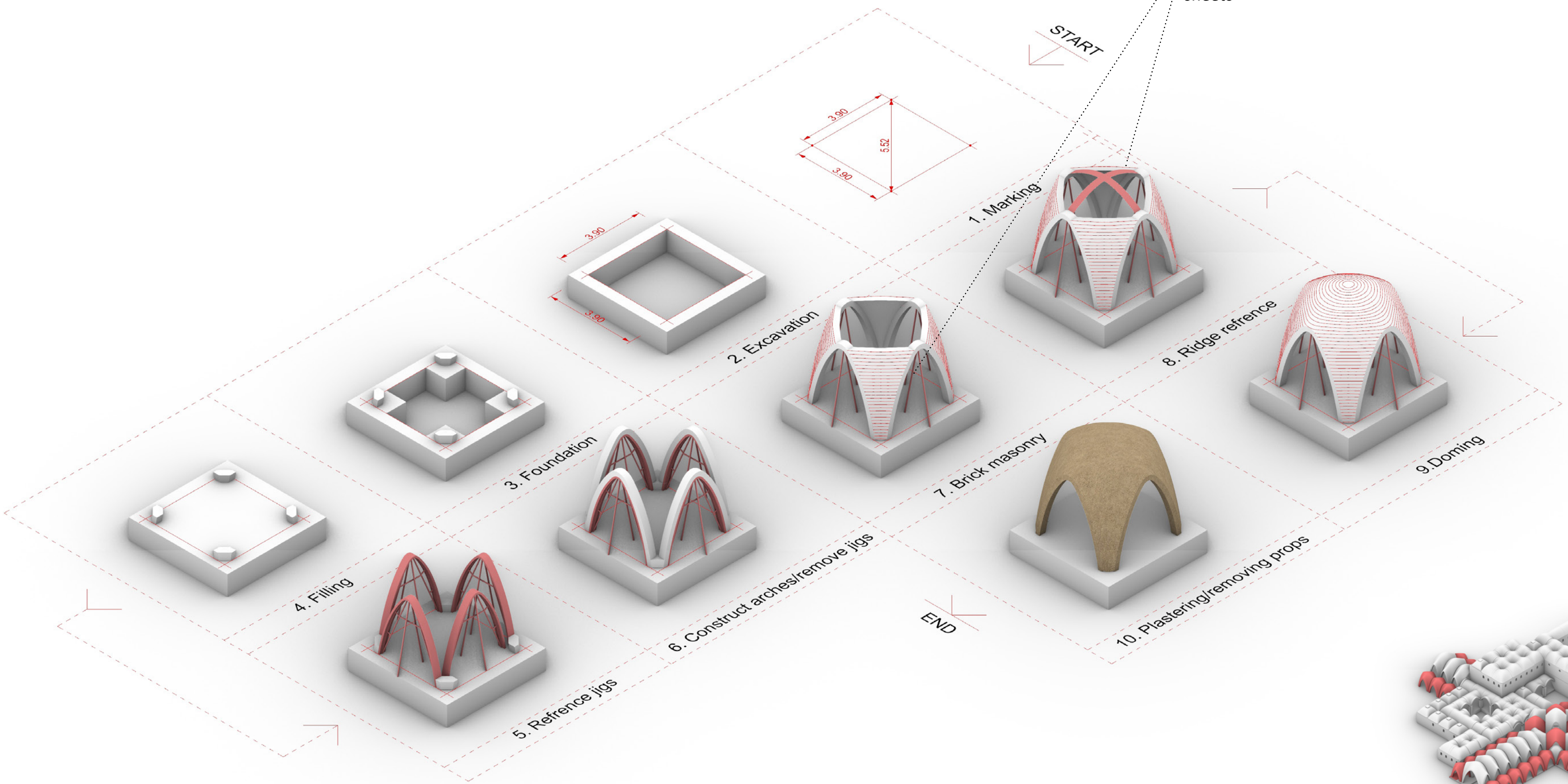


Figure *138: Construction Sequence of the Self standing Sail vaults used in Bazaar and atrium*

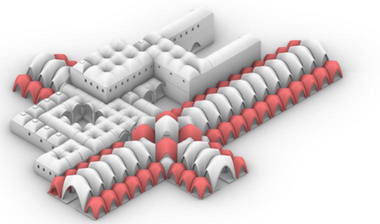


Figure *140: Location of Self standing Sail vaults*

5.3.4 Arched Nubian Vault

The arched Nubian Vaults are used as connecting elements between the shops to create a large covering over the street as shown in *Figure 142*. The construction technique is similar to a Nubian vault where the vault is constructed while resting on a surface. Here, Instead of a wall, it would be an arch with a prop support *(Figure 141)*.

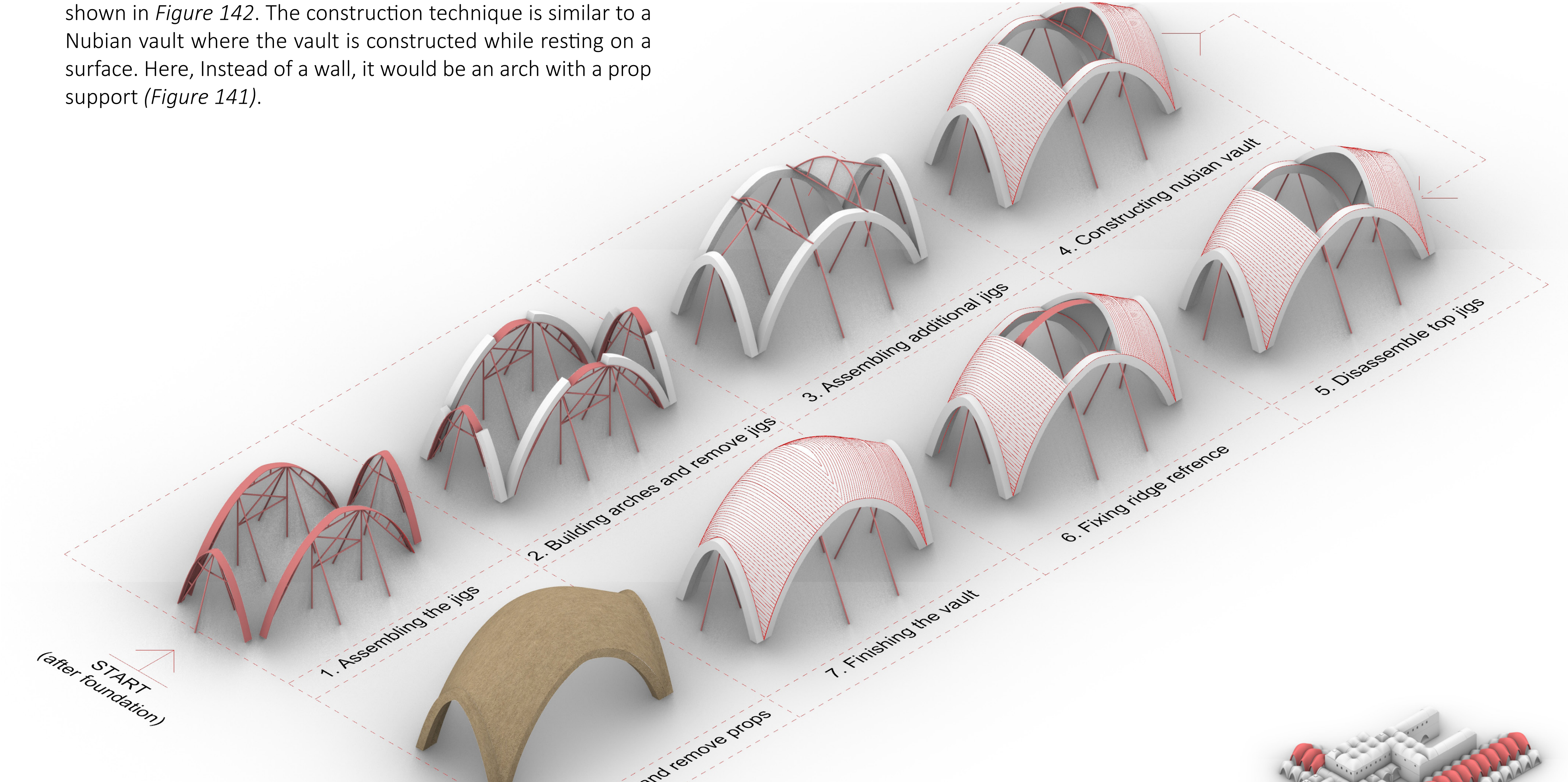


Figure *141: Construction sequence of the Arched Nubian Vaults used in the Bazaar*

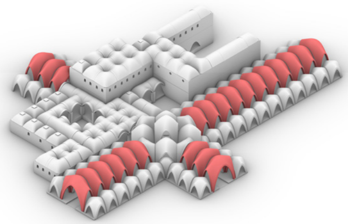


Figure *142: Location of Arched Nubian vaults*

5.3.5 Bazaar and shop roofs

The composition of the bazaar unit consists of 2 self standing sail vaults and 1 arched Nubian vault *(Figure 144)*. The sequence of completing this is detailed in *Figure 143*.

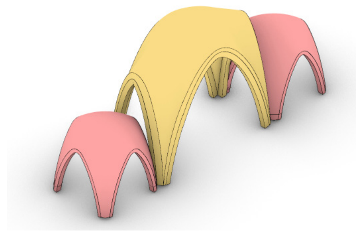


Figure *144 : Composition, 2X Self standing sail vaults and 1X arched nuian vault*

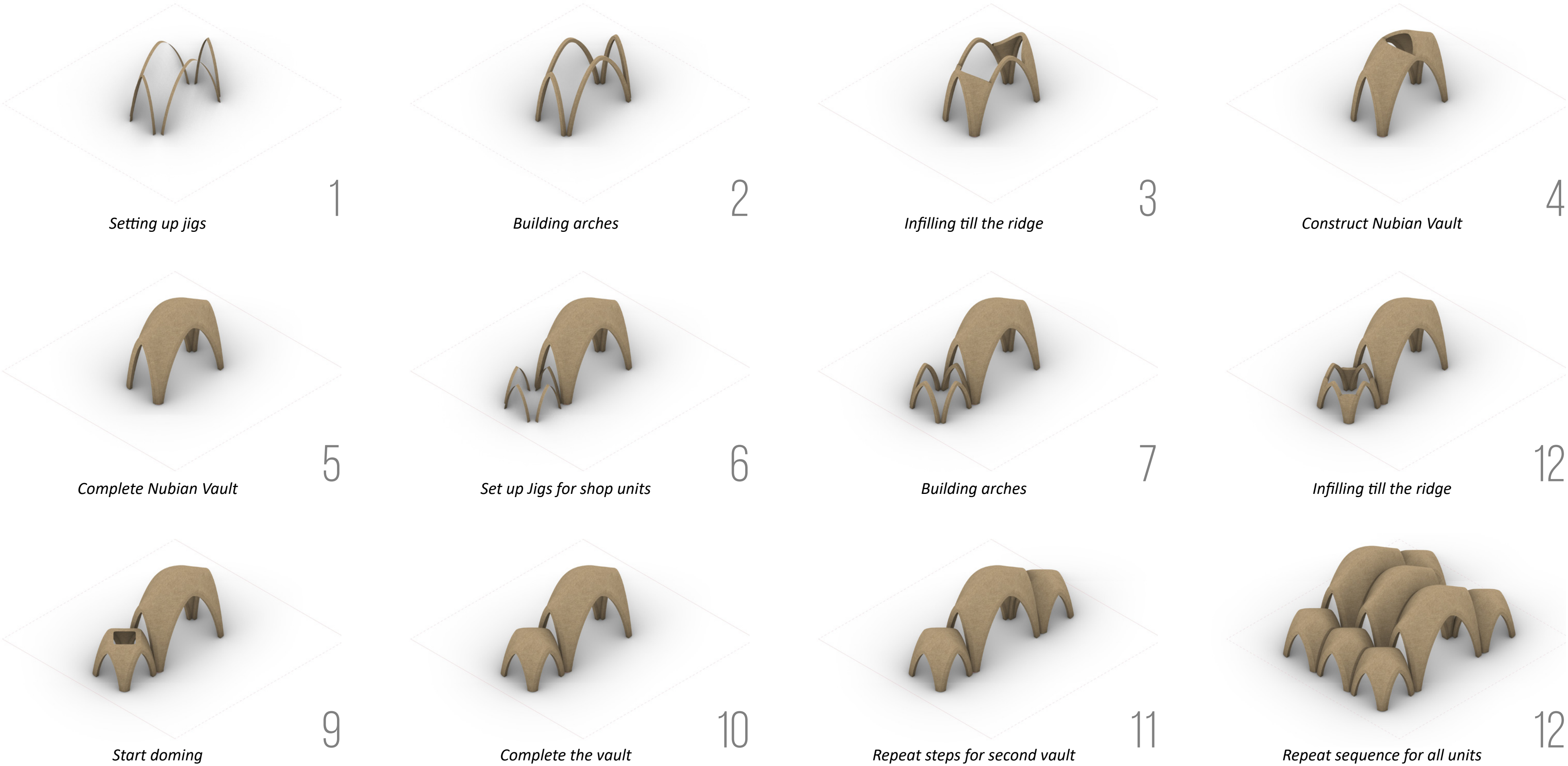


Figure *143: Construction sequence of the entire bazaar element*

5.3.6 Atrium Roofs

The atrium consists of 5 self standing vaults and 10 pendatives *(figure 146)*. The sequence of building the atrium starts from the center and sequentially move towards outside. This is done so that its easier to get material to the inside of the atrium in the beginning and easy access to the larger roof heights *(figure 145)*.

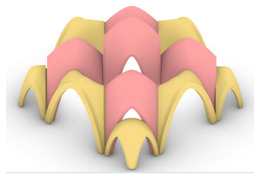


Figure *146 : 2X Self standing sail vaults and 1X arched Nubian vault*

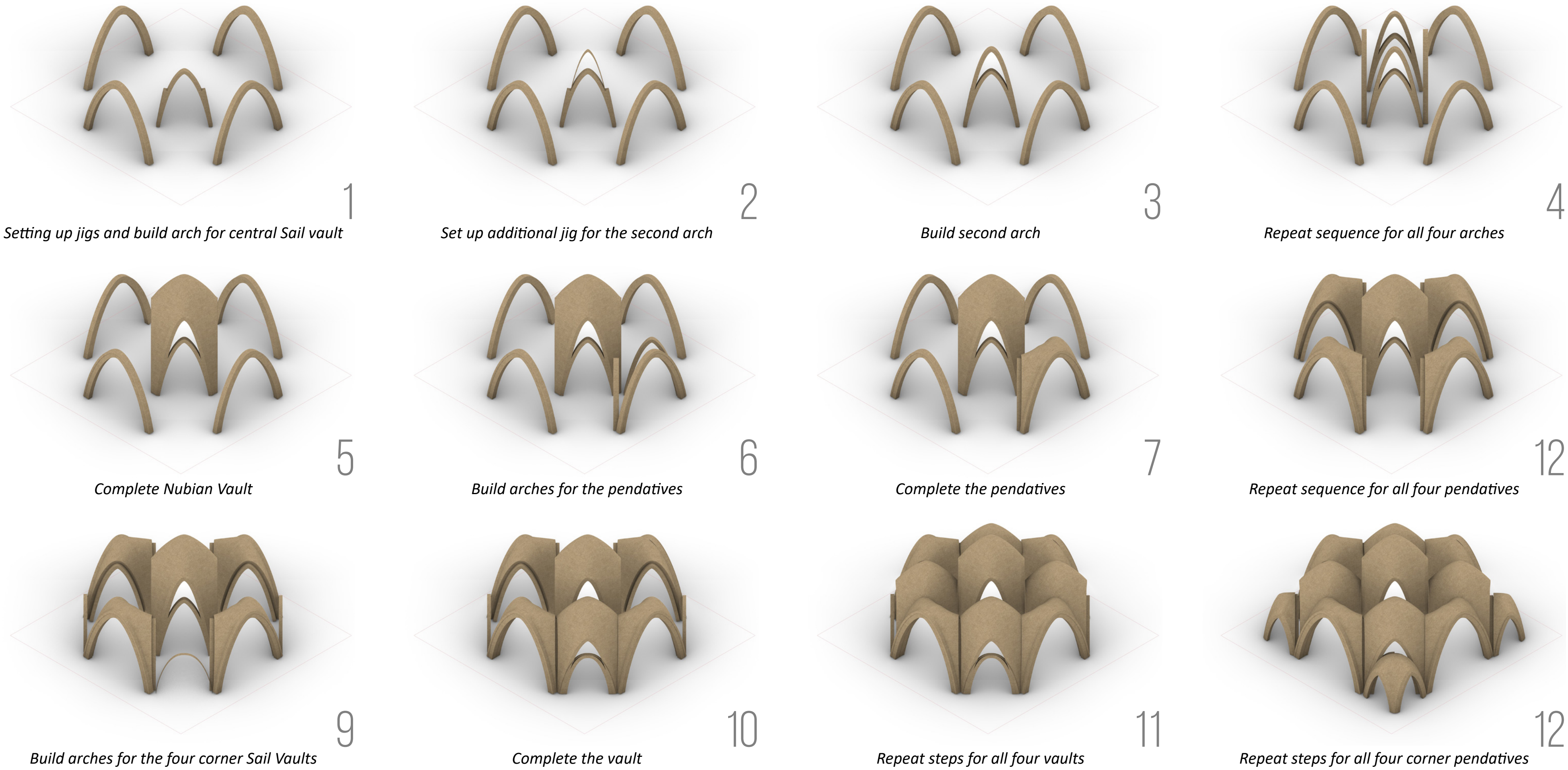


Figure *145: Construction Sequence of the entire Atrium*

5.3.7 Wall supported roofs

The jig system developed to ensure the buildability of the self-standing roofs of the bazaar could be applied also for the wall supported vaults. However, considering how the design has been splitted into two quite different parts already from the beginning of the shaping process, the possibility of implementing an alternative construction system for the wall supported roofs has been explored.

Due to the limited amount of time and the effort already put into perfectioning the main jig system, this solution has been investigated on a more conceptual level and lacks of final detailing. Therefore, more research could still be done in this direction.

The idea behind the construction system is the development of a limited amount of blocks that can be assembled to approximate the shape of the six vaulted roofs and used as temporary formwork for their construction. Gypsum is considered as main material. The pros of such solution are mainly its simplicity, which is required by the unskilled labour available on the site, and its educational value. In fact, the pieces can be assembled and disassembled even on the ground, giving the chance to explore all their possibilities and get acquainted with the shapes they generate.

The development of the pieces takes as inputs the tessellations of the vaulted roofs and their systematic classification which has been previously showed in the shaping and structuring phase.
One quarter of the basic cell (3.6x3.6 m) of the tartan grid is considered. This 0.9x0.9 m cell represents the smallest sub-module of the design (used already for stairs and columns). Within this sub-module, the 2d tessellations is used to derive the shape of the pieces, as it is possible to see in *Figure 147.* The options considered are: diagonal rib, secondary rib and edge arch.

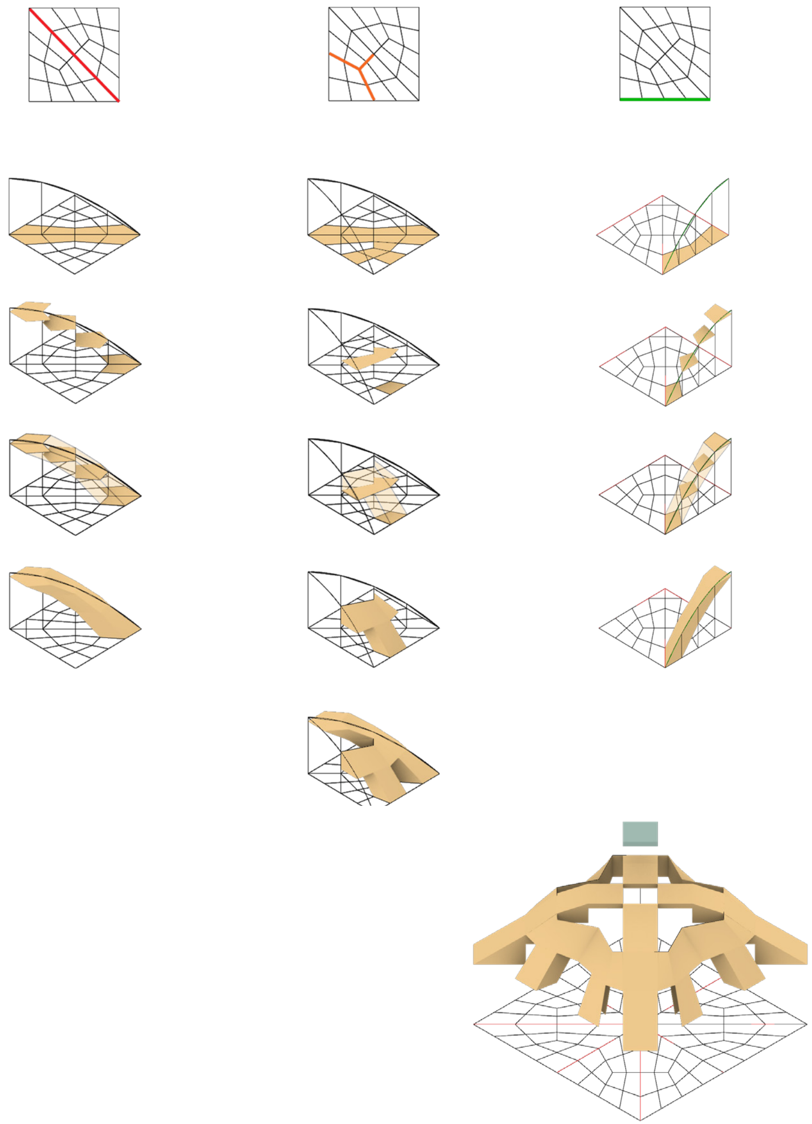


Figure 147: Modular elements construction process

The only input necessary beside the tessellation is the height in the center of the vault, which is used to create the reference curve to approximate. The cells of the tessellation are then moved to different control points of the curve, based on their position. The modular pieces are then created by lofting one of these moved cells and its neighboring one.

The pieces developed at first can approximate the curve, but would be complicated to produce, as they are all complex shapes that cannot be moulded. For this reason, a rationalization process of the shapes has been performed. Considering the limited span, the secondary ribs have not been considered necessary for construction. For this reason, only the diagonal rib and the edge arch have been simplified.

The main simplification criteria has been developing elements that could be moulded. All edges have been translated into straight lines. The starting and ending point of this simplification can be seen in *Figure 148.*

The goal of the process was to achieve elements easier to produce and stack on top of each other, while still giving a good approximation of the vault.Finally, a corner piece and keystones for the different options based on the singularity points of the tessellations have been developed.

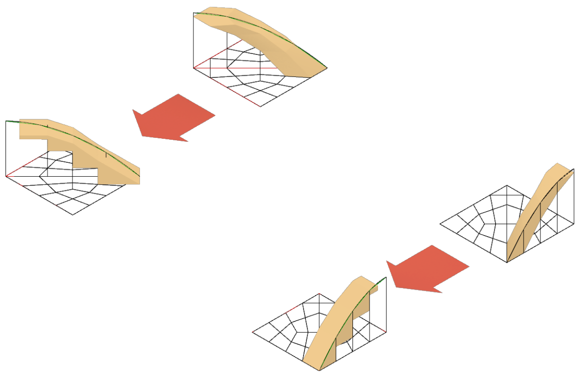


Figure 148: Modular elements simplification process

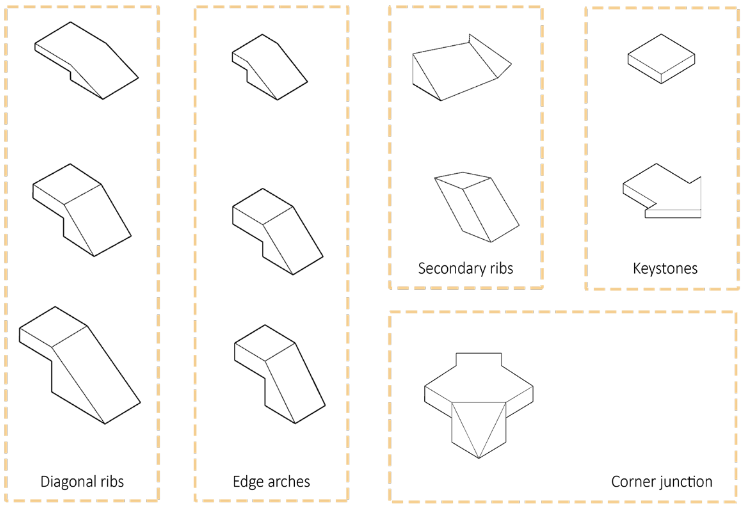


Figure 149: Modular elements library

The final library of elements *(Figure 149)* is composed of a total of eleven pieces that are enough to give an approximation of the six vaulted roof options and work as guidelines for their construction. As secondary ribs are not considered necessary, only nine different elements are required.
In the next page, it is possible to see how these elements are combined to accomodate all the roofs conditions, and how this relates to their tessellations and supports. Both in the first and fourth row, the vaults edges are classified in *open* and *close*, condition which is related to their supports.
This classification has influenced the roofs from the shaping process up to construction.
As previously said, more research has to be done in respect of the feasibility and detailing of this solution. Some subjects could be:

- interlocking system
- optimization of size and weight
- optimization of shape to avoid sharp and fragile edges
- durability

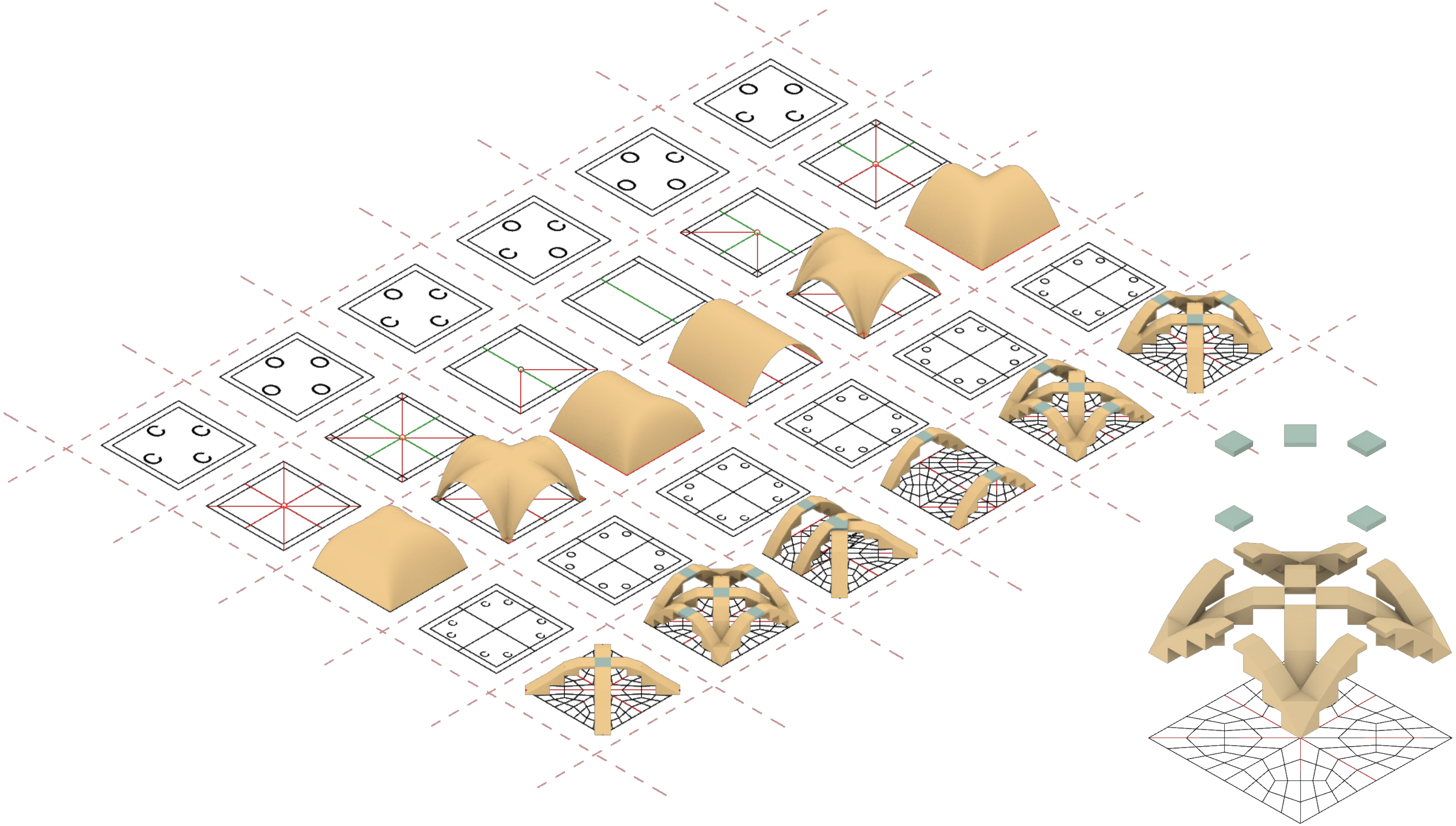


Figure 150: Roof classification and application of modular construction system

5.3.8 Brick Pattern Making

The most challenging part of the sail vault construction is the brick layering. During the form finding process different systems for contouring the surfaces were explored, which dictate how the bricks will be laid(Figure 151). After some initial tests, it was evident that the first pattern(Figure 151, Left) resulted in many bricks being cut in the valley and hence this approach was scrapped. We chose the second option(Figure 151,right) of contouring the bricks horizontally to minimize the problem. The same contouring logic was optimized by reducing the negative curvature in the surfaces as shown in the Form finding stage.

We then resorted to an iteration which had the least negative curvature to not only avoid cutting of bricks, but also simplifying the curvatures the bricks need to follow while filling the gaps between the 2 arches.

After the contouring principle was finalized, two approaches were looked into for the brick distribution pattern:

1. The first approach(Figure 152, Left) looked at categorizing the curves based on length and type and generating the pattern accordingly. For example, curves in the bottom which can accommodate only one brick, considers only one brick and curves on top are further categorized and pattern is generated based on whether the curve is closed or non closed. This method is more real representation of the construction sequence, but fails to complete the pattern with gaps resulting between the arch and the brick.

2. The second approach(Figure 152, Right) looks at rebuilding the entire surface and contouring it and extracting out the extra bricks based on a boolean function. Although the pattern in this looks more complete, you can notice that the base of the shell has inaccurate staggering at the base of the vault, which is not an accurate representation of how it will be eventually built.

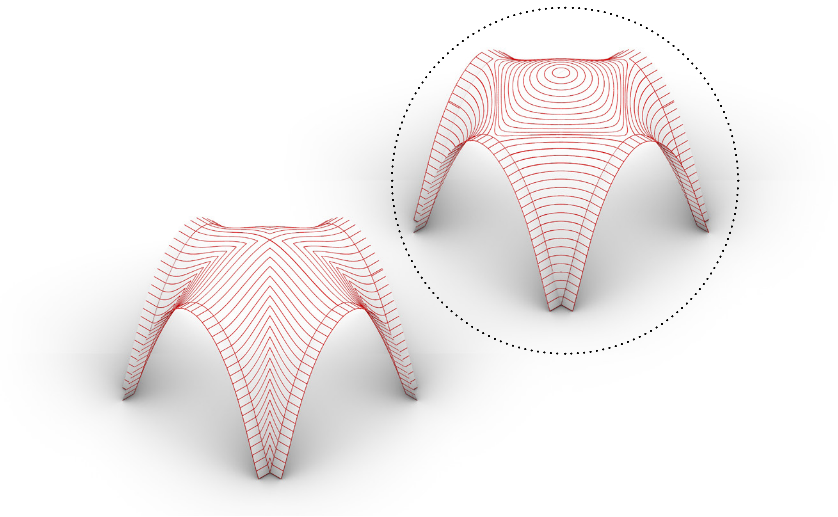


Figure *151: Exploring 2 contouring approaches for the self standing square vaults*

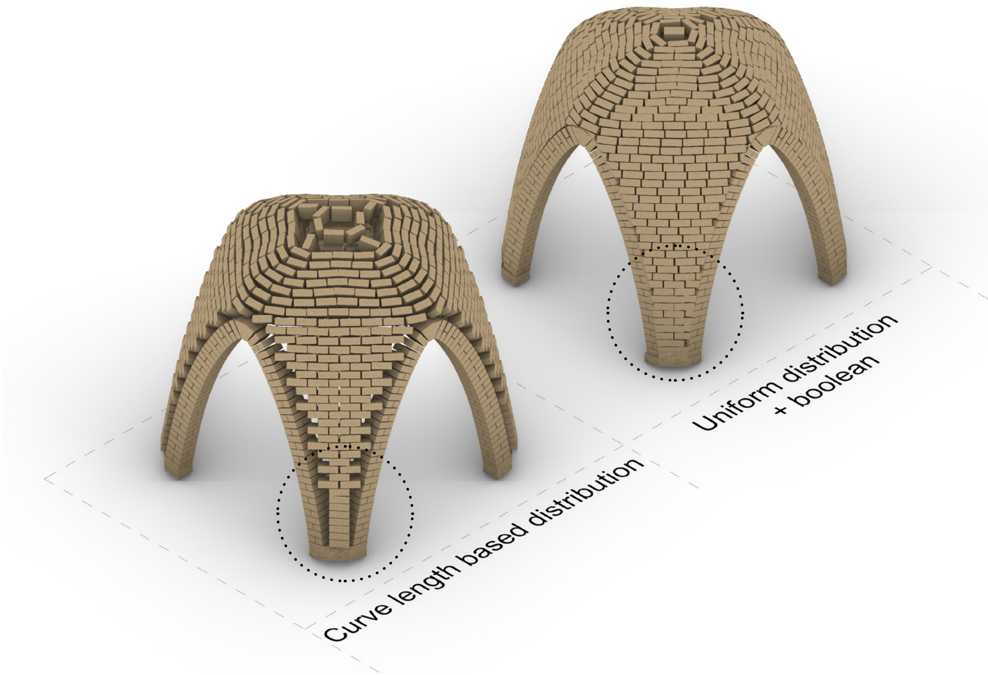


Figure *152: Exploring 2 approaches to the self standing square vaults.*

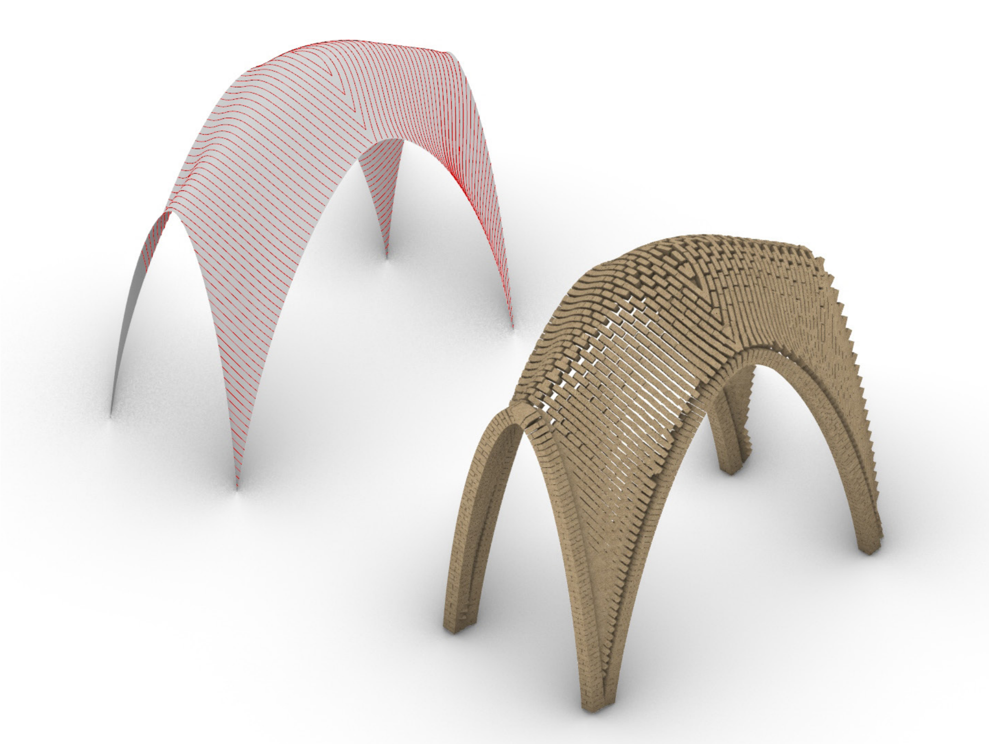


Figure 153: Brick pattern of the arched Nubian vault technique

For the arched Nubian Vault, the same script was used with a modification in the contouring process. The pattern was generated for half the surface and the second half was mirrored and a cutting plane in between trimmed the bricks at the middle. A similar approach would be used during the construction as the vaults would start from the sides and reach towards the middle where the bricks need to be cut based on what is required.

A crucial detail which needs to be developed is how the bricks rest on the side arches. As now there is a clear gap between the Arch and the vault. As the vault needs to “rest” on the side arches, there is no way to avoid this issue. An alternate option is to widen the arch by introducing another course of bricks with an upturned brick to lock the edge bricks in place and avoid unnecessary fillings as shown in the detail(Figure 155).

The brick patterns for the Wall supported roofs are generated using the same method as how the roofs were simplified. The barrel vault pattern was rotated and joined or cut to form the different shapes(Figure 154).

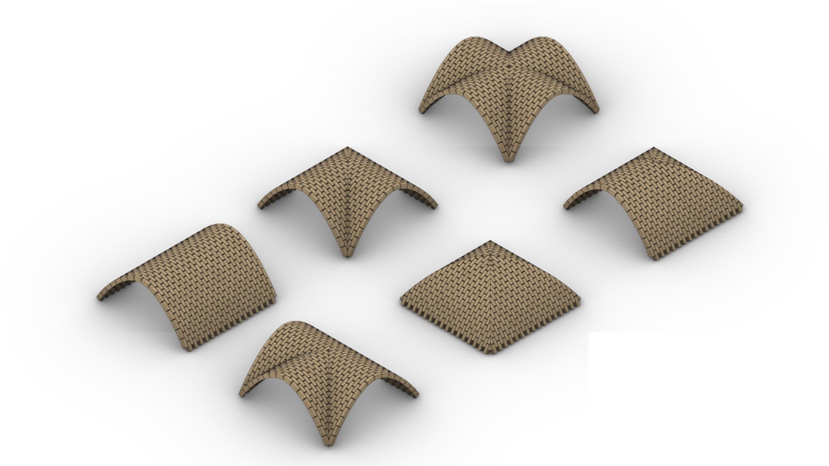


Figure 154: Brick patterns of the wall supported roofs.

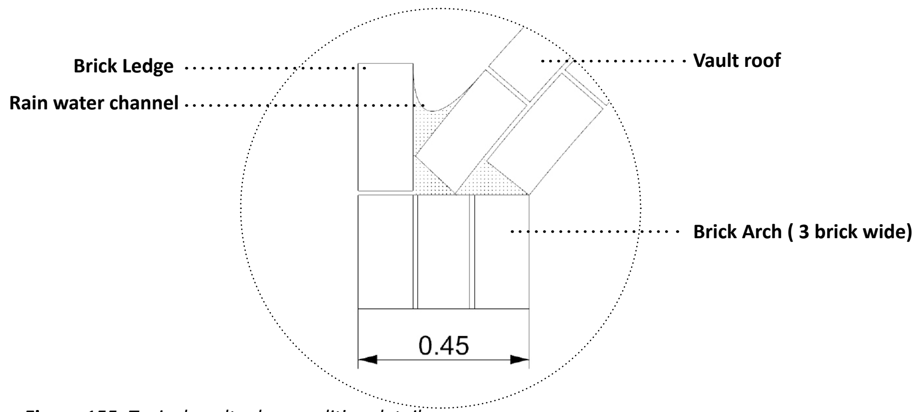


Figure 155: Typical vault edge condition detail

5.4 BUILDING SYSTEMS

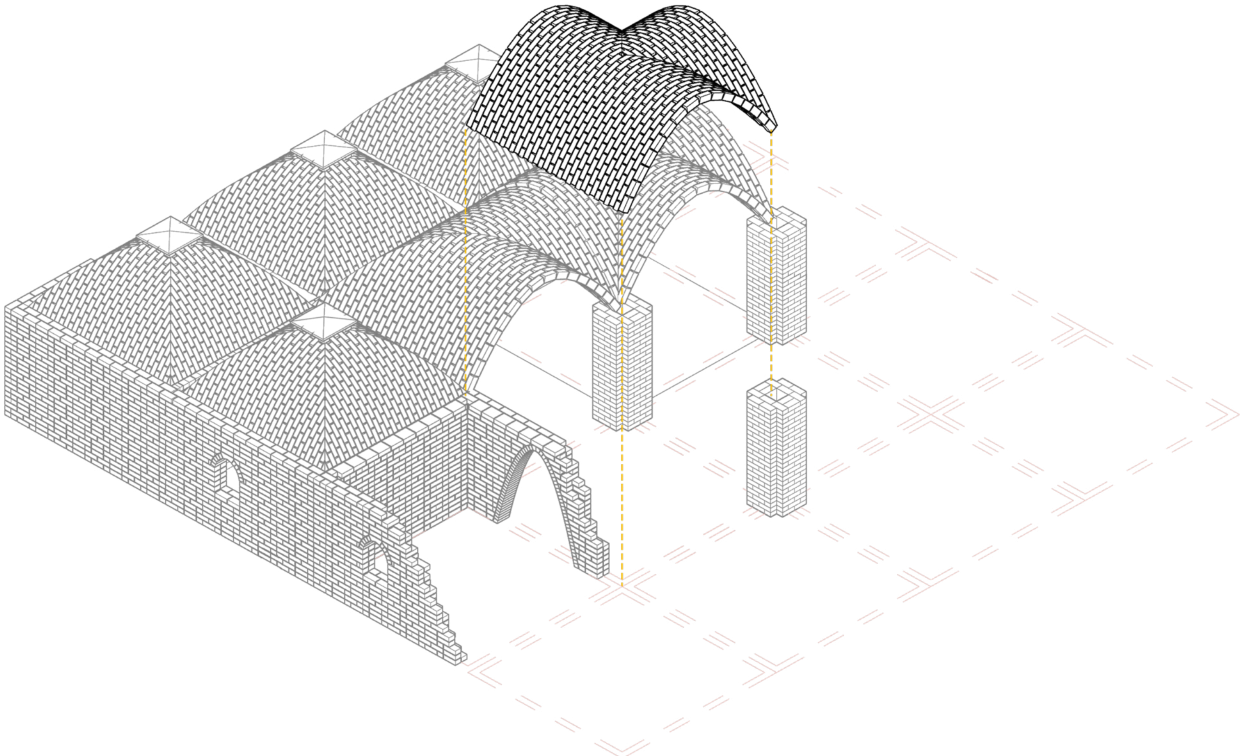


Figure 156: Wall-based building system, one storey

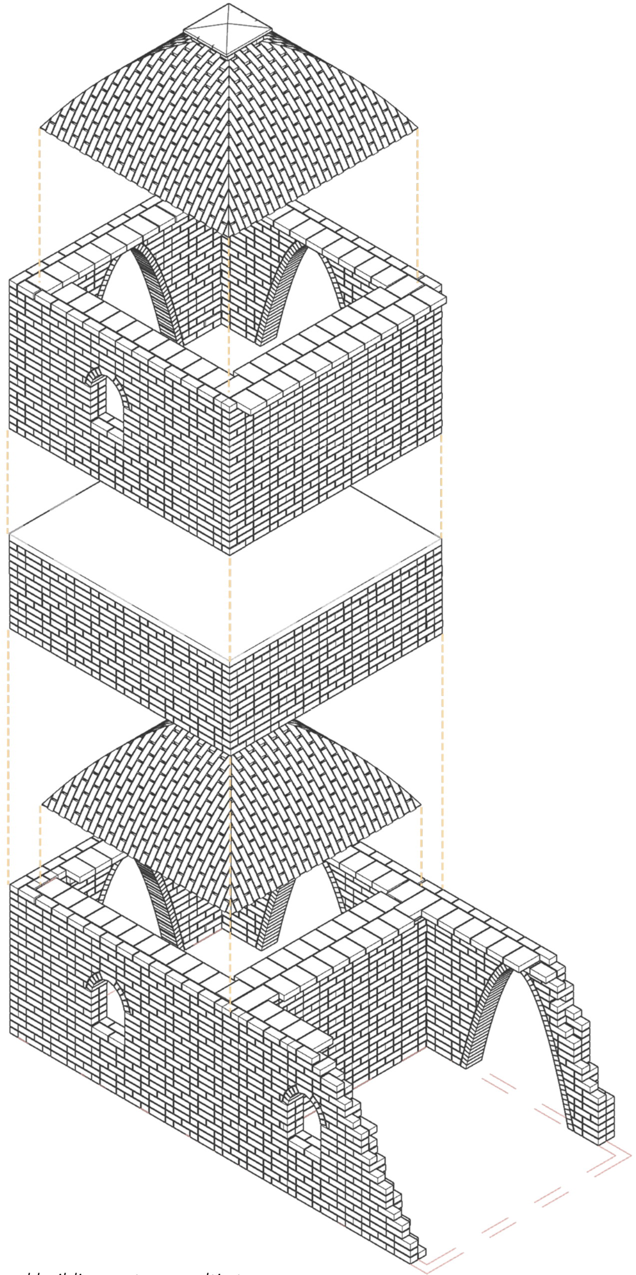


Figure 157: Wall-based building system, multi-storey

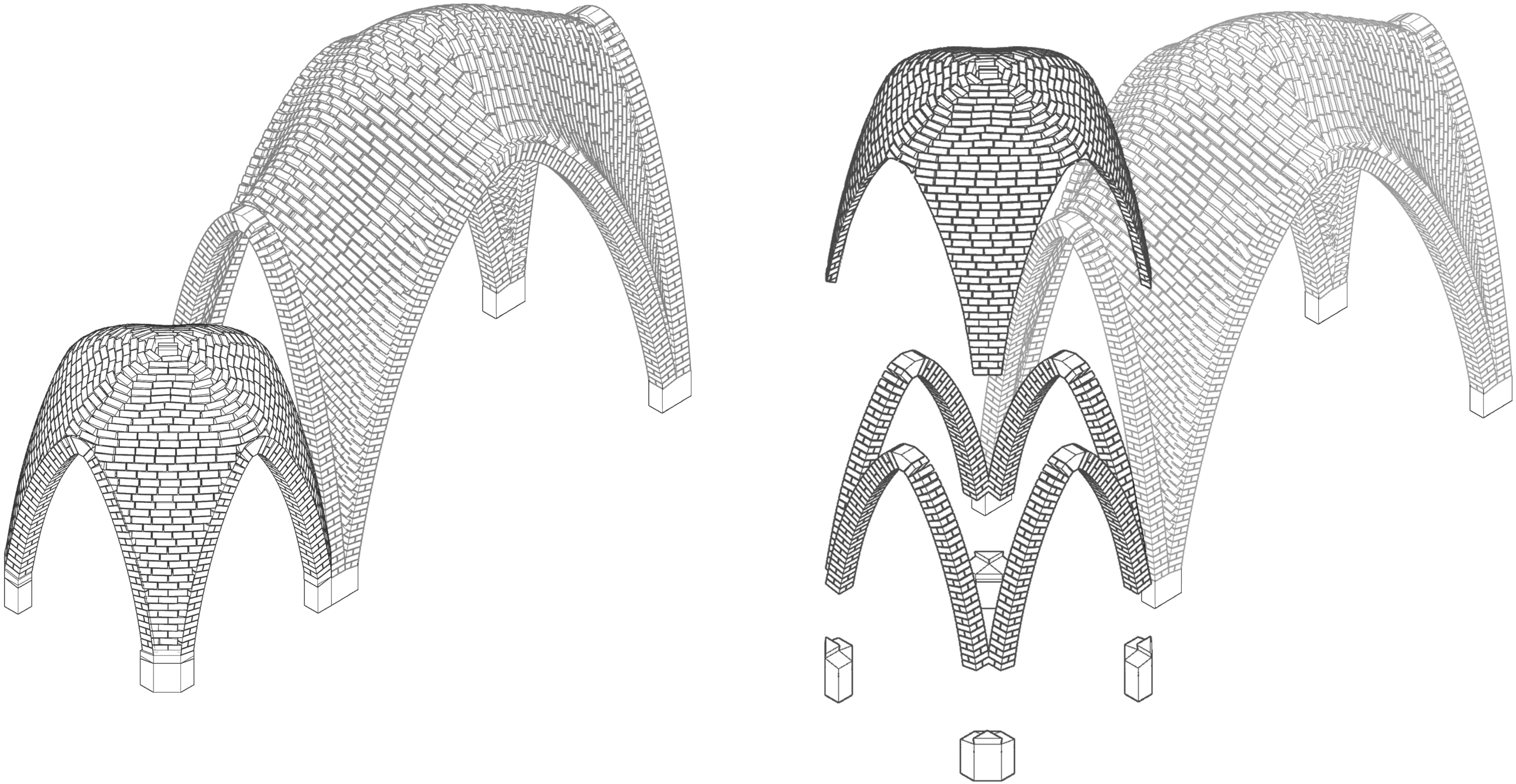


Figure 158: Self-supported building system

5.5 DETAILS

Next to the shaping and constructing phase of our design, an initial process of detailing has been performed on it. Different topics have been addressed, to ensure the feasibility and success of the project.

5.5.1 Rainwater management

For the roofs of the wall-supported building system in particular, a rainwater management strategy has been necessary. Knowing that such a strategy could be potentially integrated in the computational logic with which our layout tool assigns roofs to wall modules, the research has been limited to more standard options that could in the meanwhile represent a solution to this problem. The first idea to collect and discharge water at the valleys generated when four roof modules meet on top of a column has been to integrate a gutter into it, so that the water could then flow through pipes located in the floor and be discharged *(Figure 159).*

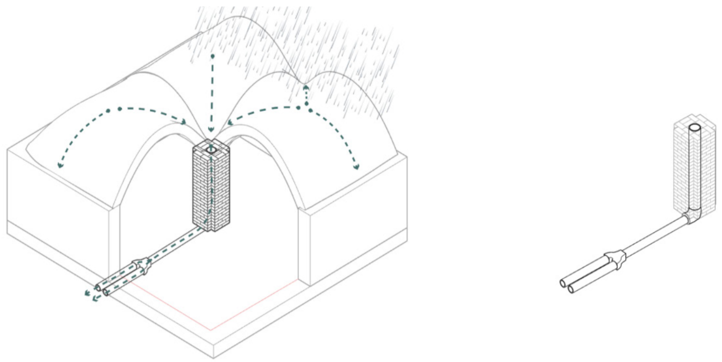


Figure 159: Rainwater management: integrated gutter

This solution meets our design goals, but from a practical point of view shows many drawbacks. Bringing rainwater inside the building and being the integrated gutter difficult to access and mantain, it is easy to predict infiltrations and similar other issues.
Other solutions have been therefore explored, consisting in different ways of creating a roof surface separated from the ceiling shape. This final surface could provide the waterproofing and the slope necessary to redirect the water outwards.
Two different variations have been considered:
- create the slope with earth filling on top of the existing roof structure. Apply mud plastering as finishing layer;
- build segments of columns on top of the ones on the ground level and use them as supports for an indipendent brick roof structure *(Figure 160).*

However, no structural simulation has been done on any of these final solutions, so their feasibility has still to be determined.

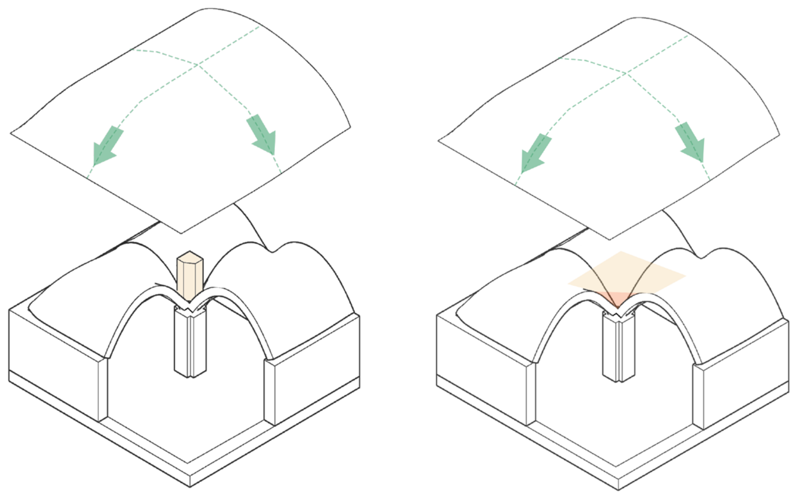


Figure 160: Rainwater management: indipendent roof surface

5.5.2 Climate Design: thermal mass & ventilation

Different choices within the design process has been influenced by the will of achieving comfort inside the different spaces.
The first of these decisions has been to set the wall thickness to a minimum of 30 cm, considered to be the threshold necessary to provide enough thermal mass. This value has been considered for the roof elements as well.
Natural ventilation has been another parameter believed to be paramount for the success of the project. This requirement has been approached in different ways for the two parts of the design:

- *Wall-based building system*. Beside designing different options for vertical openings, an analysis of the roof has been performed. The climatic advantages of a domical shape have been taken into account and brought to the design choice of using such a roof shape wherever possible. Additional top openings have been implemented to avoid heat trapping and allow for natural air circulation. To do not let water in, half bricks are used to support a cap made of customized flat bricks covered with waterproofing mud plaster as the rest of the roof. When needed, a similar solution can be applied also to the rest of the roof options *(Fig.161)*.

- *Self-supported building system.* These elements are used to configure a covered street and spaces for temporary shops. As this is considered to be an outdoor area, air circulation is less controlled. However, the thermal mass of the shells produces a cooling effect on their interior space, while the difference of height between the shop and the bazaar units allows the warm air to flow outwards and to be replaced by new fresh air. Residual heat could still be trapped in the higher part of the bazaar roof, but due to its height the risk of it affecting the user's comfort is considered to be neglectable *(Fig.162)*.

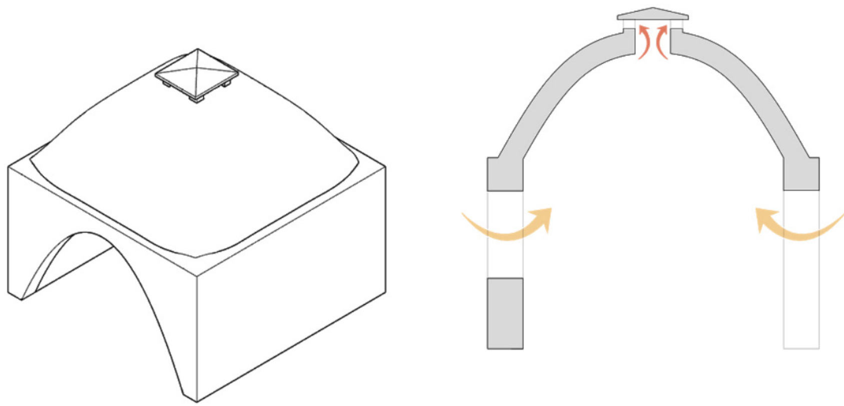


Figure 161: Wall-supported building system ventilation scheme

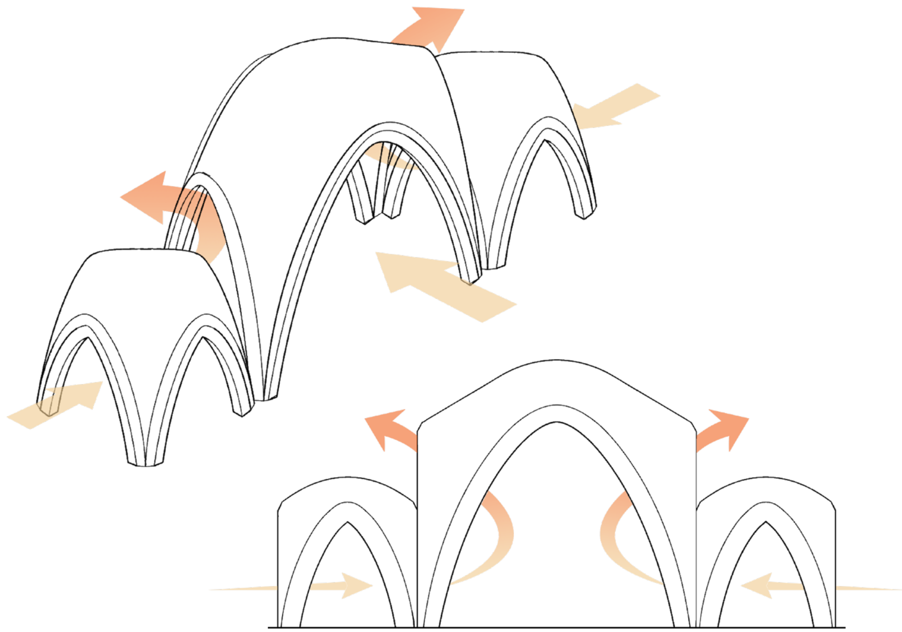
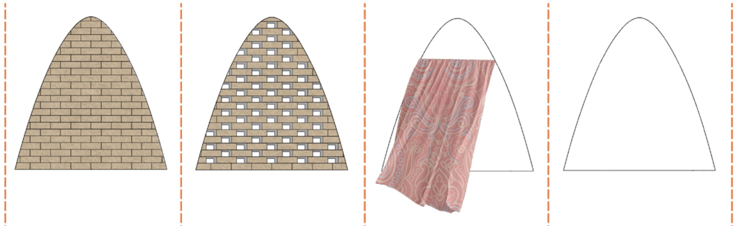


Figure 162: Self-supporting building system ventilation scheme

5.5.3 Bazaar and Shop roofs

Many elements in the self-supporting roofs needed to be at least partially detailed to proof the feasibility of such shapes.
One these has been about the height difference between the shop and bazaar units. Those openings have been designed to allow daylight and natural ventilation, while avoiding noise trapping. Being an outdoor space, no thermal insulation needed to be considered. According to these requirements, many filling options have been compared and evaluated *(Fig.163)* to eventually make a design decision about it. As shown in the table, fabric results to be the best option, being a shading device that does not add any load to the structure, while still allowing air circulation.
Rainwater has been another issue to address in proximity of those openings. To avoid water infiltrations, mud is modelled on top of the units, to build a lifted edge and redirect the water towards the sides of the modules.
The last topic that been researched has been optimizing the usable space within the shells, to avoid architectural vanity.



	Solid wall	Jali pattern	Curtain	Basic opening
Shading	++	++	+	--
Daylight	--	+	+	++
Lightweight	--	-	++	++
ase of construction	-	--	++	++
iding noise trapping	--	+	+	++
Air circulation	--	+	++	++
inwater protection	++	++	-	--

Figure 163: Bazaar openings evaluation

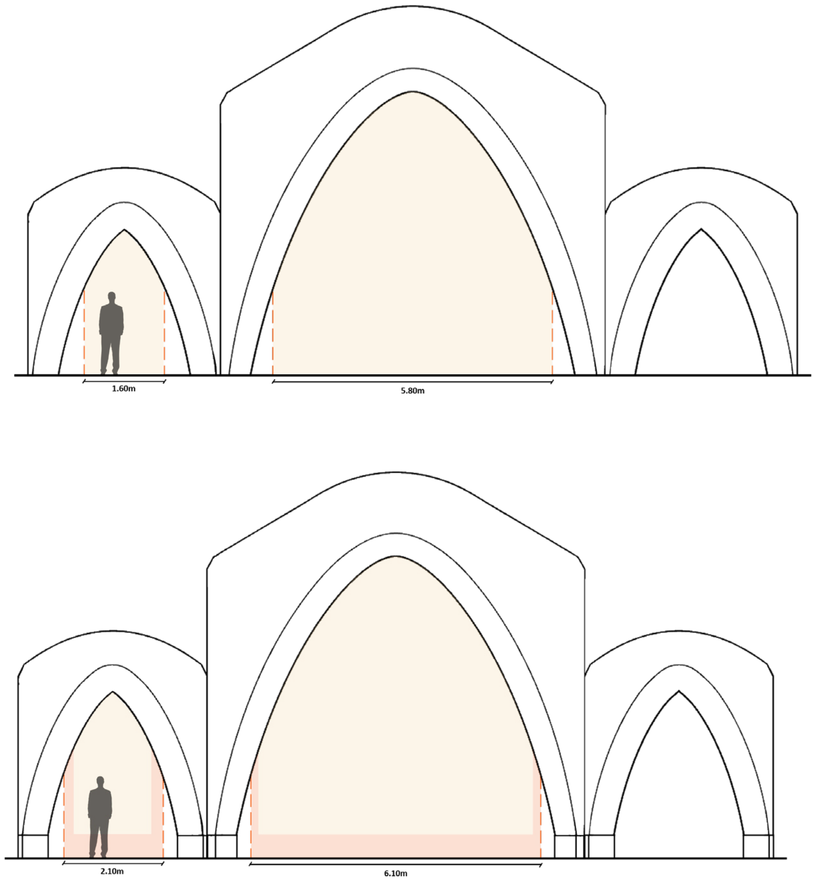


Figure 164: Self-supporting roofs usable space analysis

As it can be seen in *Fig.164*, the shells have been lifted on foundation blocks which are 50 cm high. This decision increases even more the walkable space. Leftover space can be used for storing goods. This solution appears better than completely replacing the shells, as previous calculations resulted in 90x90cm columns. This dimensions would generate a usable space equivalent to the one already available with shells.

This section shows the result of the overall process. As the main goal was not to develop a single design but a system that could generate and fit multiple options, the following pages represent just a possible iteration which is used to show how all the elements of the design come together into a functional and realistic architecture.

CHOSEN ITERATION 06

6.1 PLAN EXAMPLE

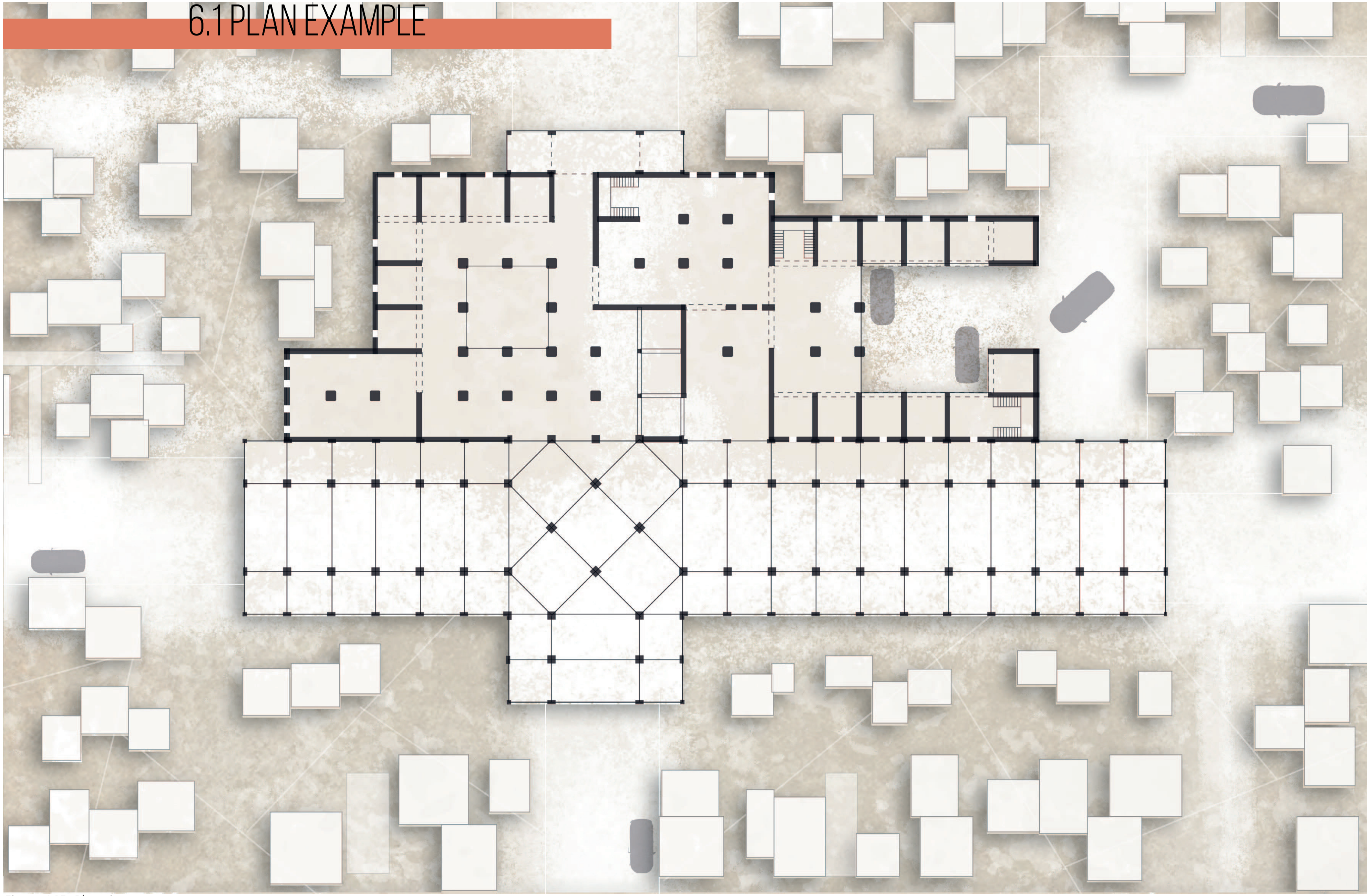


Figure 165: Plan view

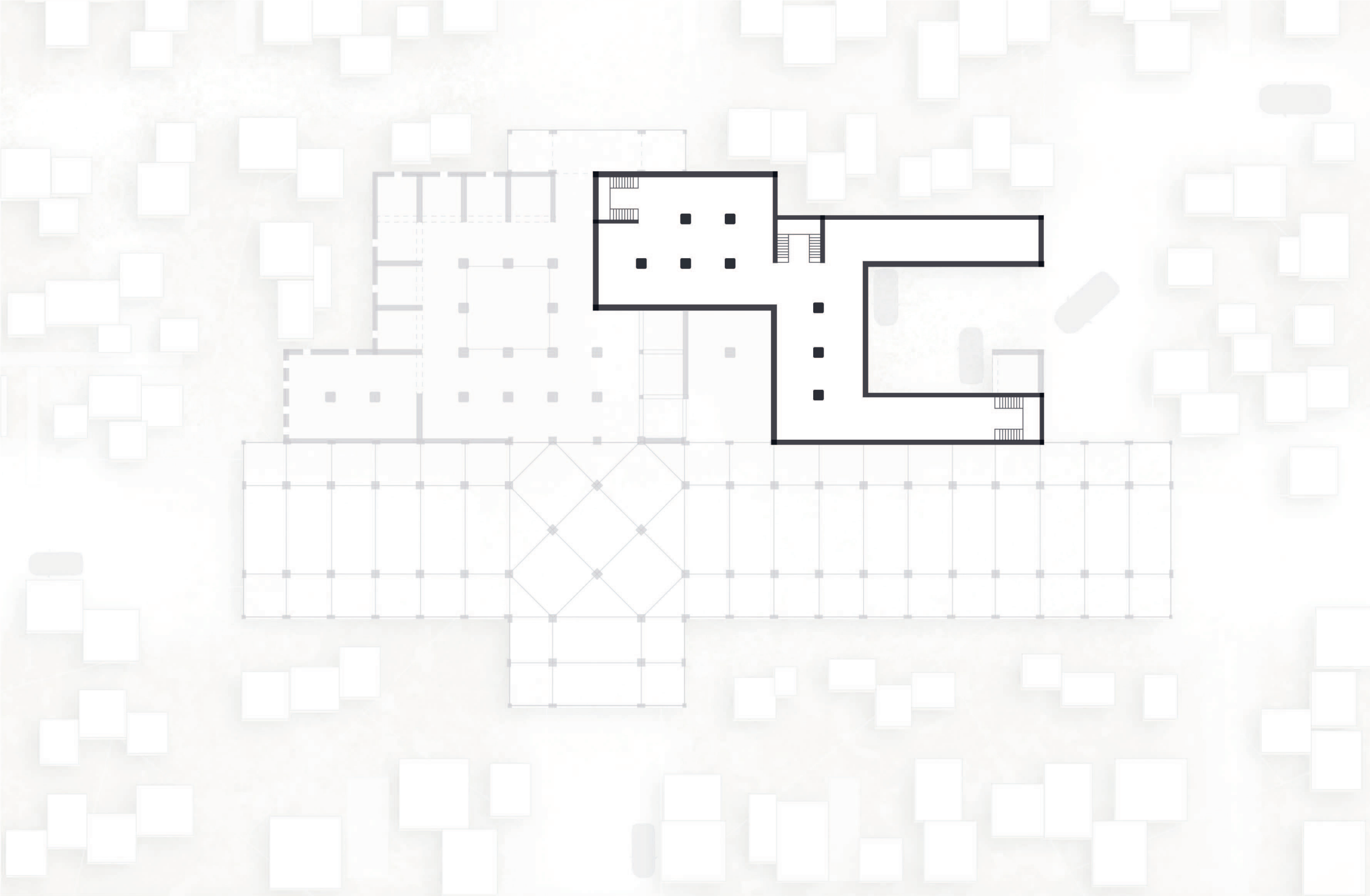


Figure 166: Plan view, second floor

6.2 ISOMETRIC VIEW

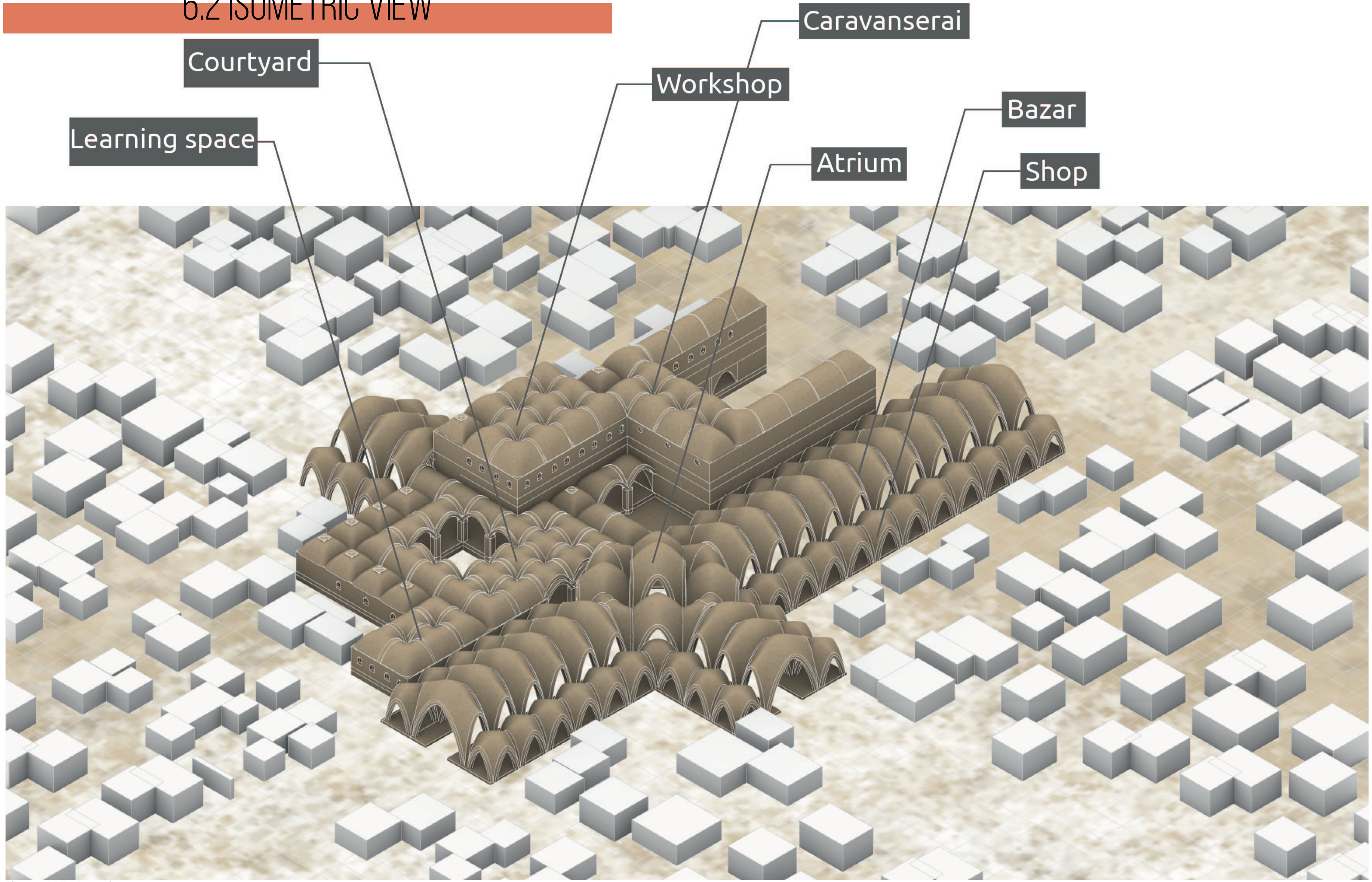
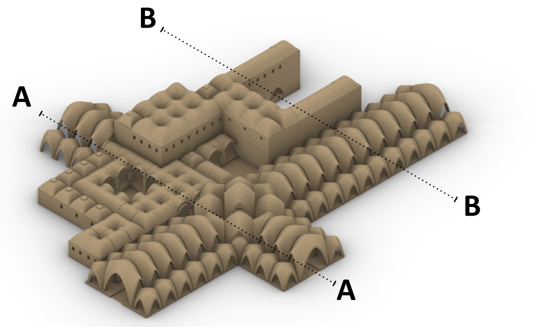


Figure 167: Overview

6.3 SECTIONS



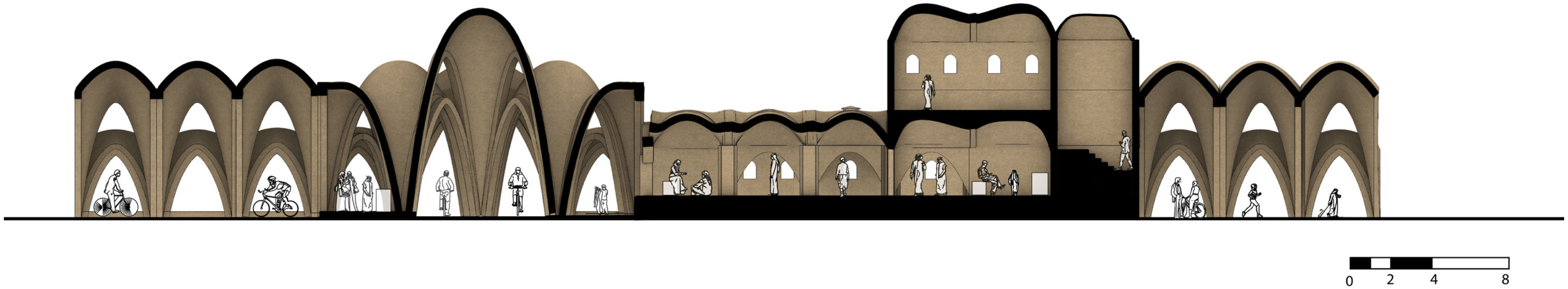


Figure 168: Section A

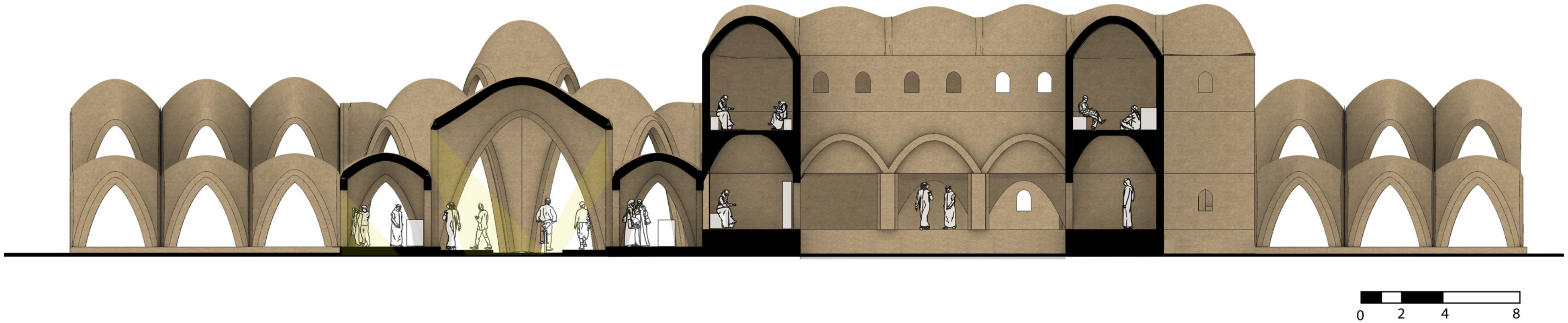


Figure 169: Section B

6.3 IMPRESSIONS

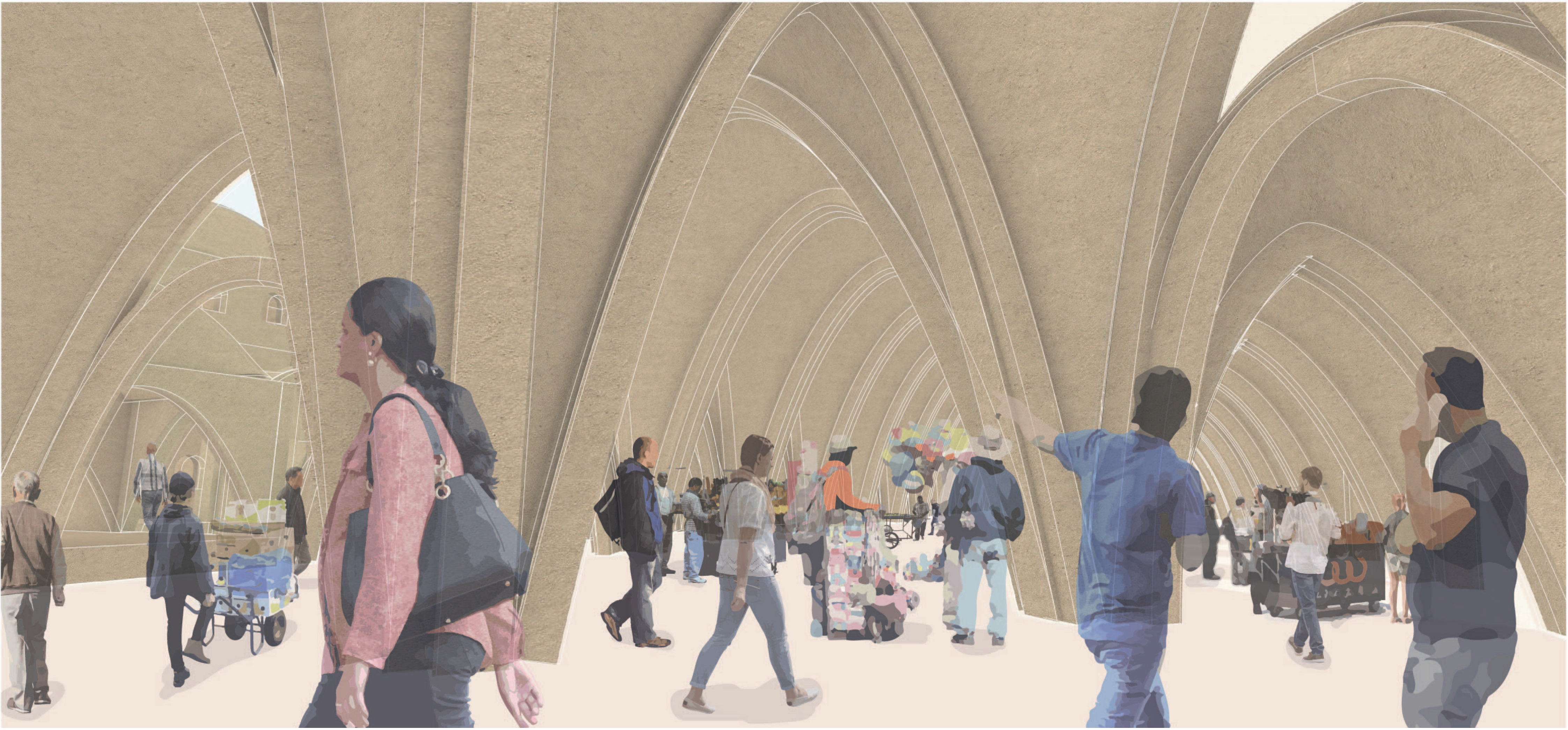


Figure 170: Impression 1

Figure 171: Impression 2

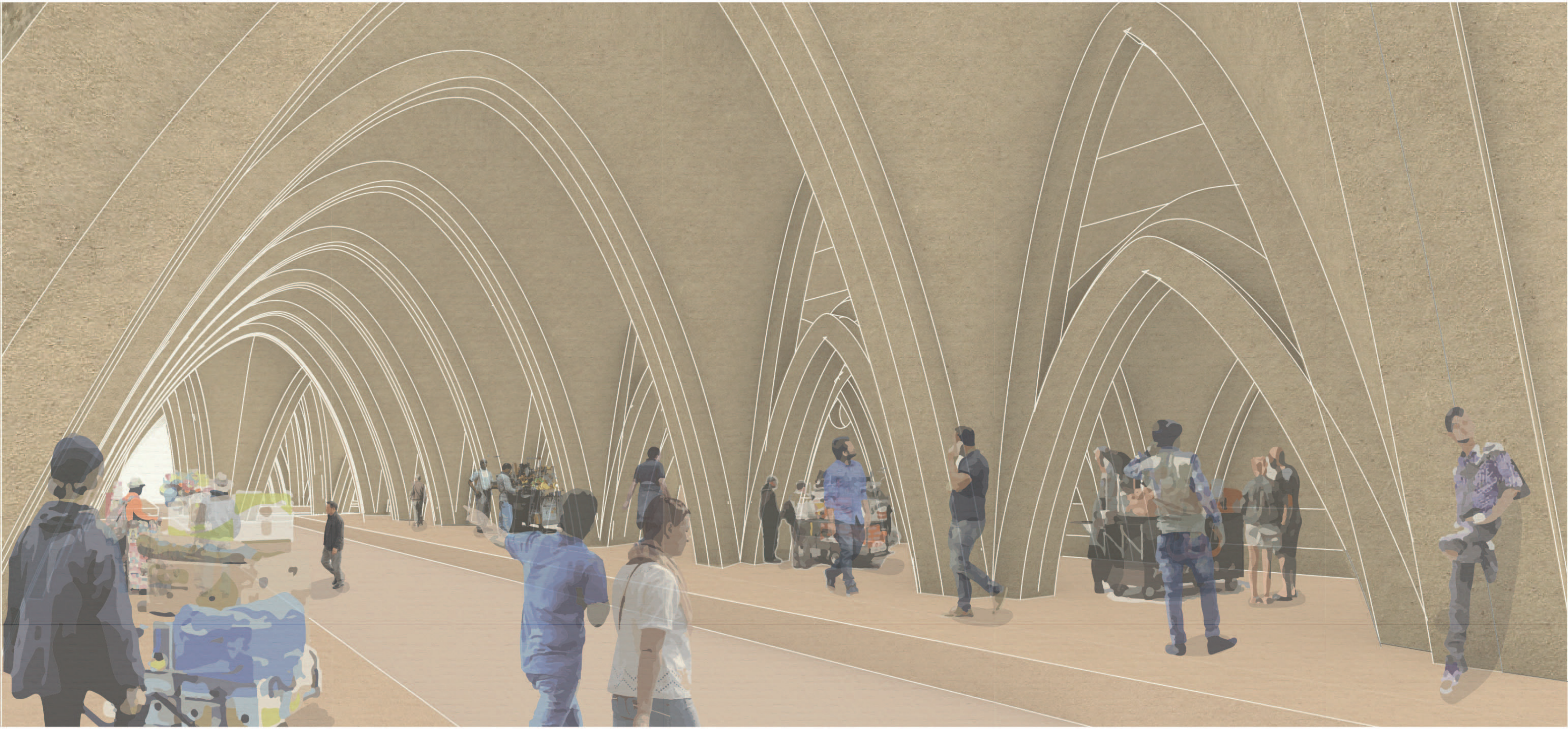


Figure 172: Impression 3

Figure 173: Impression 3

In this chapter, further points of interest to be studied and research can be found. Individual reflections on the project are also found here

REFLECTION 07

7.1 FURTHER DEVELOPMENTS

Considering the limited amount of time available to develop a complete design that ranges from configuration to detailing, it is impossible to consider it completed at this point. For this reason, in this section some of the possible directions of research we did not have the time to explore are summarized.

7.1.1 Configuration

1. Integrating the building module library with the layout tool. The final step in the configuring, placing the wall, floor/roof, and stair modules should automatically be executed as part of the script. This function would help with quickly testing the flexibility of the scripts when all working together, and can be used to evaluate different design options.
2. Further development of how the bazaar expands in the urban structure. An algorithm that grows the bazaar over time and the evaluation of how the resulting bazaar affects the urban structure.

7.1.2 Shaping and Structuring

1. More control of the dynamic relaxation process. This can be in the form of more stricter anchoring properties, possibility of defining a “range” for anchoring. This control could also help in possibly reducing the vanity in the self-standing units.
2. A seamless and automated workflow towards mesh to NURBS and vice versa, to reduce the time involved in manually simplifying the geometries as well as to reduce the amount of dilution between the relaxed mesh and the buildable re sult.
3. An additional optimization criterion for the wall supported roof modules to orient based on external weather conditions such as rain water collection, or thermal effects.
4. A workflow for creating the openings in the wall modules as needed. This would allow not only the configuration but also the general appearance of the building to be generated procedurally. When this is achieved, sun path analysis can be taken to further evaluate the building.

7.1.3 Construction

1. Improvement of the brick making script to include all types : More work can go into the brick making script so that any pattern can be generated on the surface based on a common input. Similar to the panelling tools component in grasshopper, but with more control of the brick sizes.
2. Develop a refined brick making pattern without using the boolean function. Agend based systems can be used for this to ensure each brick respects the tolerances whenever the pattern is changed, or whether the surface is rebuilt, or even bricks can be cut short based on its proximity to the neighbouring brick. Especially useful in generating patterns for complex curver shapes(eg, the arched nubian vault)
3. Explore further the manufacturing processes involved in making gypsum templates, or if too heavy look for alternative materials to do the same.
4. Develop more details of the fabricated JIG modules for the self standing unit.

7.1.4 Detailing

1. All roof geometries need to be detailed with consideration to surface hydrology and management of rainwater.
2. The foundation needs to be detailed with the custom bricks used at the base.
3. Detailing of how doors and windows can be installed.
4. Connections between the self standing roof modules need to be detailed.

7.2 INDIVIDUAL REFLECTIONS

7.2.1 Abhishek Holla

The course felt extremely intense and overwhelming and the beginning, at the same time an eye opener to the depth of the concepts it addresses. All the concepts explained in the course were extremely interesting to me, especially introduced me to a whole new way of interpreting computer graphics and design, and a peek inside into what goes on behind the screen when such graphics is being generated. The concepts of linear algebra were also a bit overwhelming for me to comprehend and apply in the short span of time, nonetheless it gave a good insight as to how these concepts are interrelated in generation of complex geometries. Finally, all the work workshops were fun and engaging, and thoroughly I enjoyed the introduction to python and the potential it offers to the field of architecture. Although it was too short for me to use it within the premise of the course, I hope to use it for future projects.
Personally since I was mostly involved in the shaping, structuring and construability aspect I have a few suggestions to improve the course for the coming period :

1. To distribute workshops and lectures through the course so that the theoretical aspects and the application part goes hand in hand.
2. Introduction to mesh modelling processes and strategies and how data can be transferred between meshes and NURBS in a more applied manner.
3. Workshop on influence of tessellation patterns and experimenting with them. The compass workshop was definitely useful for this purpose, but needless to say the level was a bit advanced and since the recorded version was not available to use, we were not able to use this application.
4. Distributing consult sessions over 2 days, so that there is enough time for people to work between consults.

7.2.2 Anastasia Florou

The course was extremely interesting and intense at the same time. It is really focused on the fields that were already at the top of my interests but it introduced me to many new concepts that at first felt too much to comprehend. As the project evolved, all the theory introduced during the first weeks started taking shape.

The first days the group work seemed more intuitive and exploratory but we gradually found our own rhythm and organization that we then kept until the end of the course. Earthy was the perfect opportunity for me to investigate the mathematical background of computational design and reach a better level of understanding its role in architecture. It was also my first opportunity to actually use python for any application and it greatly helped me develop my coding skills.

As I was mostly involved in the configuration and layout part I can reflect more on this. I am really satisfied with the result we managed to achieve but I would really like to have some more time so we could integrate the building elements library into the tool as well. That is also to teach us how to prioritize tasks for such big projects that span only one quarter.

The teamwork was beyond great and a learning experience on its own. Collaborating with fellow classmates with unique personalities and capabilities created a spontaneous balance and a really creative environment in order to push forward.

All in all, this course sealed my decision to follow the computational specialization in my graduation topic and triggered me to explore more the potential of integrating mathematics and programming into architectural applications to improve the build environment.

7.2.3 Daniel Simon

For me the corona crisis had a big impact on the course and the way I would normally study. Being busy with a lot of things at the same time is not a problem when I had the possibility to go to the university because it was easier to focus on courses. Working from home makes it difficult to fully focus on one thing only. Not being able to sit together as a group and communicate face to face has been a challenge for me in this course. I always liked spending time at the faculty working on a project and sharing ideas as well as understating what everyone is working on. When having a meeting from home, once the meeting ended you end up alone and you don't have the possibility to go ask for help, advice or even to sit next to each other working on the project. Despite the difficulties the communication in this group has been really good and clear. Working with grasshopper and rhino as main tools has been interesting and educative. The lectures in have been really interesting as well and have given me a better overview of what can be done when programming and architecture work together. My fellow groupmates are all really inspiring, talented and hardworking people and I am glad that I had the chance to work with them.
This course has shown me the possibilities lying within this field and made me eager to learn how to combine design and optimization. I have to work on my Python skills witch is what I will do for the coming year to be able to choose a graduation topic having a good bag of knowledge with me.

7.2.4 Leonardo Caldoni

As the course ends, it is possible for me to reflect on it and on what I have learnt. The first thing to mention is the online teaching and learning environment, which have highly influenced the experience. The effort from all the professors and tutors in keeping high the quality of education and at the same time in trying to break the ice and get to know us has been incredible. Lectures and workshops have resulted to be easier to follow in this situation, while as predictable group work and consults have been slightly more complicated. Online meetings cannot yet replace the efficiency of working together in the real world but we made it work. For what it concerns the contents I have to admit that it has been one of the more intense courses I have ever attended. The workload in such a limited amount of time sometimes feel too much to allow everybody to focus on developing new computational skills. Work has to be splitted and it becomes difficult to follow other people progress. However, I am really satisfied of our group, of the way we took all the main decisions together and of how we communicated them first among us and then with tutors. What I will take with me from Earthy is a new way of approaching design and a deeper understanding of computational de sign processes: thinking computationally and defining rules for each choice, perceiving space as a grid and building elements as modular components of a game has challenged my ideas about design and given me a new perspective on it.

7.2.5 Max Ketelaar

Starting it with the course I already had some preconceptions on what it was going to be about, having previously done the Spatial Computing minor. Looking back, there was a nice mix of the familiar and the foreign.
There were some novel or unknown topics to be explored during the course. The workshops were interesting for getting an up-close look at the application of the theory. Some topics I already had seen before such as the linear algebra and the voxelization, but here the repetition helped refresh the memory and gain a deeper understanding of the topics.
For me, the structure of the course was already familiar so it was easier to imagine what the progress should be at certain

stages of the project when this was not immediately apparent tive and never stops, but this has taught me that it is especially important to limit the scope and depth of such a big project in order not to get lost in the possibilities.
All in all, even when I did not get the chance to do everything I wanted to explore, the results are still satisfying to see. It is always amazing how much can be achieved within a group context, especially when the groupmates are as hard-working, bright, and pleasant as they were these past weeks.

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APPENDICES 08

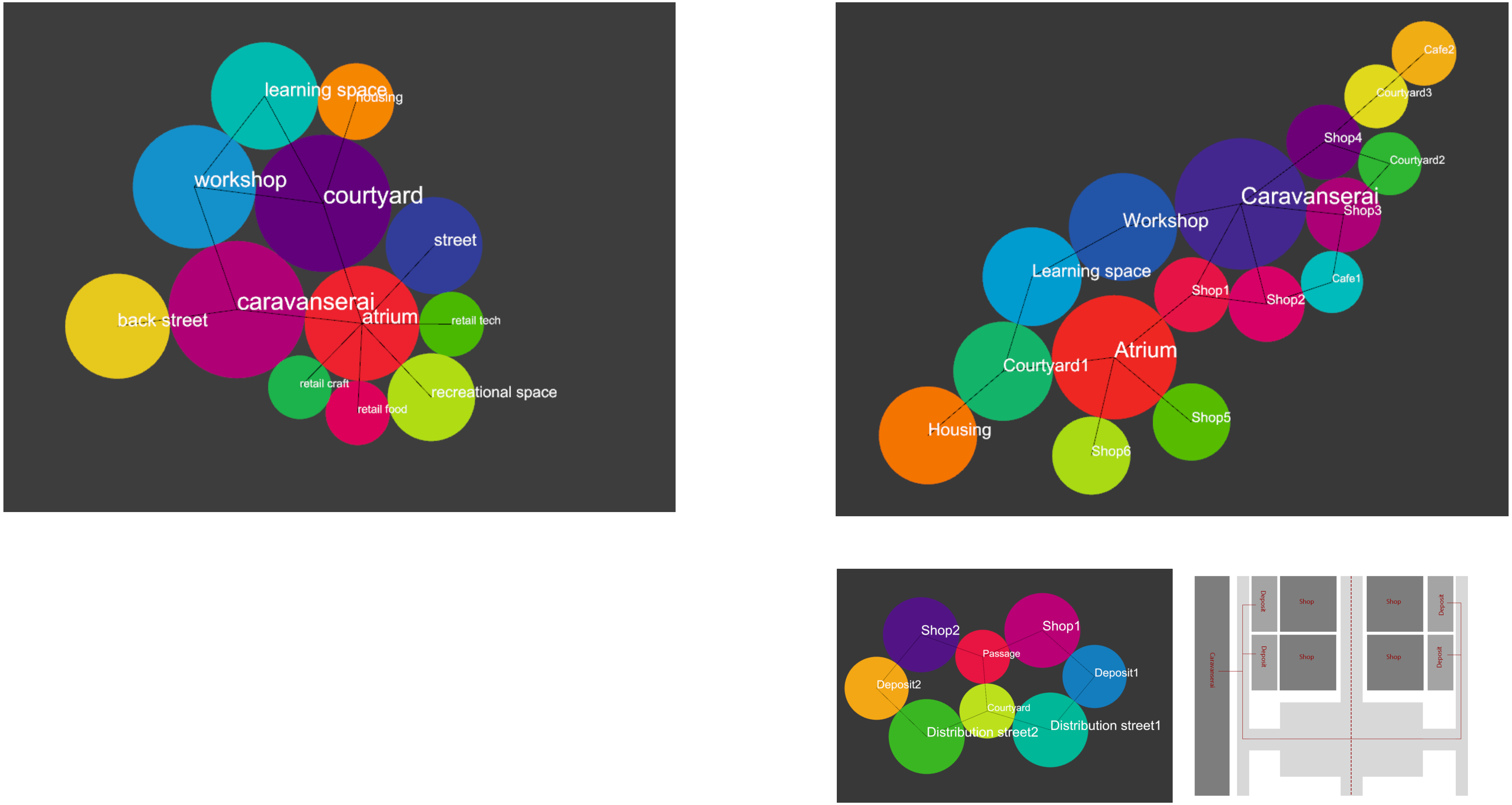


Figure 174: Bubble diagrams evolution

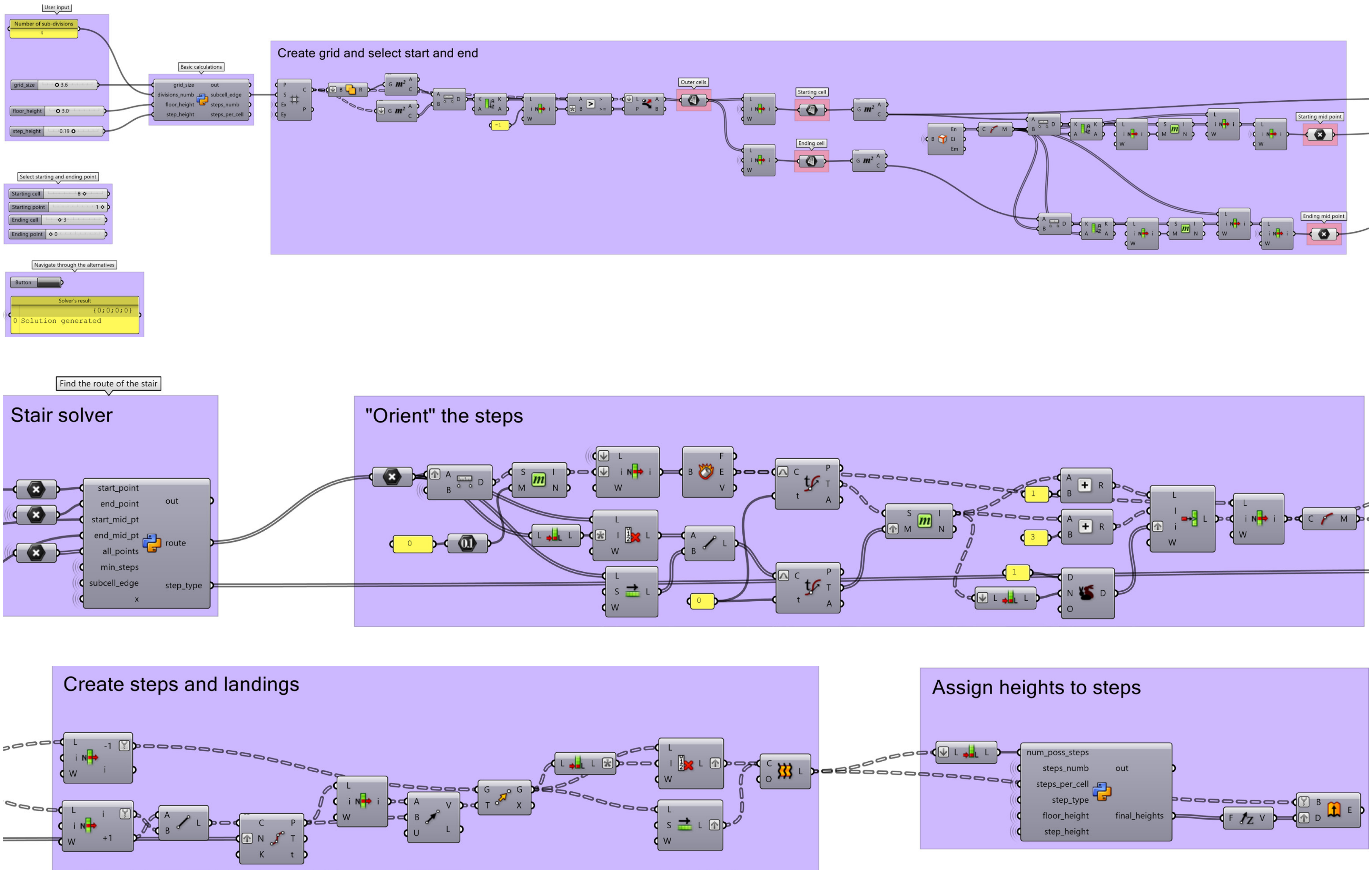


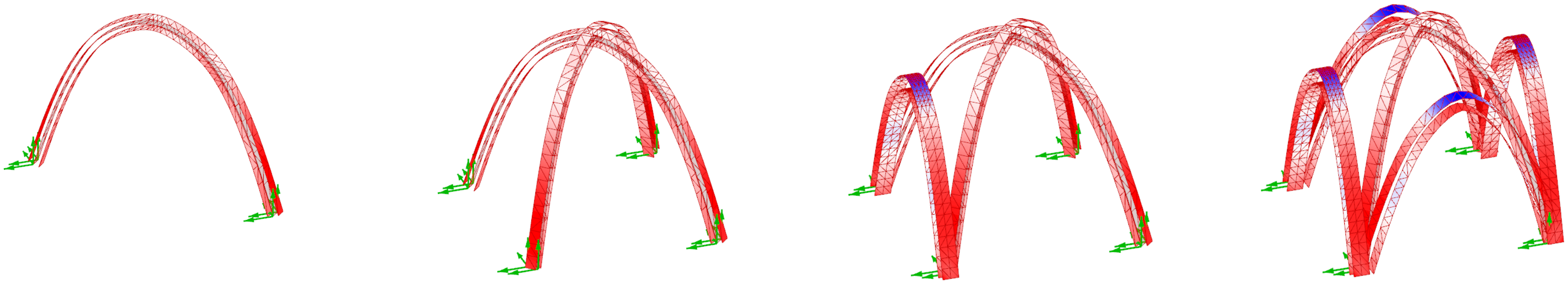
Figure 175: Stairs generator grasshopper definition

Grasshopper Python Script Editor

File Edit Tools Mode Help

```python
import rhinoscriptsyntax as rs
import random
import Grasshopper as gh
import sys
import copy

# definition to find the closest points to a particular point
def closest_points(check_point, points_cloud):
    clos_points = []
    for point in points_cloud:
        if (round(point.X, 2) == round(check_point.X, 2)) and (round(abs(point.Y - check_point.Y), 2) == subcell_edge):
            clos_points.append(point)
        if (round(point.Y, 2) == round(check_point.Y, 2)) and (round(abs(point.X - check_point.X), 2) == subcell_edge):
            clos_points.append(point)
    return clos_points


# definition to remove coincidence points
def remove_coincide(check_point, points_cloud):
    for point in points_cloud:
        if (round(point.X, 2) == round(check_point.X, 2)) and (round(point.Y, 2) == round(check_point.Y, 2)):
            points_cloud.remove(point)
    return points_cloud


# check for coincidence of points
def check_coinc(pointA, pointB):
    coincidence = False
    if (round(pointA.X, 2) == round(pointB.X, 2)) and (round(pointA.Y, 2) == round(pointB.Y, 2)):
        coincidence = True
    return coincidence


# remove start point from the "availability list"
default_avail_points = remove_coincide(start_point, all_points)

steps_count = 0

attempts = 0
limit = 10000  # limit of attempts to find a "route"

test = []
while steps_count < min_steps and attempts < limit:

    seed = random.randrange(sys.maxsize)
    rnd = random.Random(seed)
    #print("Seed was:", seed)
    current_point = start_point
    
    # make a deep copy of the avilable points
    avail_points = copy.deepcopy(default_avail_points)
    # initiate a list for the sequencial points as the "route" of the stairs
    route = []
    # set the start of the route on our starting point
    route.append(current_point)

    last_met = False  # check if we have reached the last cell

    zero_route = False  # check if we reached a point that the route cannot continue

    while not last_met:

        poss_points = closest_points(current_point, avail_points)

        while len(poss_points) == 0:
            route.remove(current_point)
            if len(route) == 0:
                zero_route = True
                attempts += 1
                break
            current_point = route[-1]
            poss_points = closest_points(current_point, avail_points)

        if zero_route:
            if attempts == limit:
                print(
                    "No solution found! Press the button to generate an alternative solution.")
            break

        else:
            # selected_point = poss_points[rnd.randint(0, len(poss_points) - 1)]
            # selected_point = rnd.choice(poss_points)
            # current_point = selected_point
            current_point = rnd.choice(poss_points)
            route.append(current_point)
            avail_points.remove(current_point)
            last_met = check_coinc(current_point, end_point)

    if not zero_route:

        step_type = []  # step type = 3 for cells that can have steps and 1 for landings

        for i in range(0, len(route)):

            # check if the first cell can have steps
            if i == 0:
                if (round(route[i+1].X, 2) == round(start_mid_pt.X, 2)) or (round(route[i+1].Y, 2) == round(start_mid_pt.Y, 2)):
                    step_type.append(3)
                else:
                    step_type.append(1)

            # check if the last cell can have steps
            elif i == int(len(route)-1):
                if (round(route[i-1].X, 2) == round(end_mid_pt.X, 2)) or (round(route[i-1].Y, 2) == round(end_mid_pt.Y, 2)):
                    step_type.append(3)
                else:
                    step_type.append(1)

            # check if the rest of the cells can have steps
            else:
                if round(route[i].X, 2) == round(route[i-1].X, 2) and round(route[i].X, 2) == round(route[i+1].X, 2):
                    # small_steps_ind.append(i)
                    step_type.append(3)
                elif round(route[i].Y, 2) == round(route[i-1].Y, 2) and round(route[i].Y, 2) == round(route[i+1].Y, 2):
                    # small_steps_ind.append(i)
                    step_type.append(3)
                else:
                    # landings_ind.append(i)
                    step_type.append(1)

        steps_count = sum(step_type)
        test.append(steps_count)

if attempts < limit:
    print("Solution generated")
```

Figure 176: Stairs' solver python algorithm



for t = 25 cm
Compressive strength = 3MPa
Tensile strength = 0,3 MPa
Arch1 (small)
Compressive princ. stresses:
0,016 MPa (0,5%)
0,098 MPa (3,2%)
Tensile princ. stresses:
0,0018 Mpa (0,6%)
0 Mpa (0%)
Arch2 (big)
Compressive princ. stresses:
0,023 MPa (0,7%)
0,14 MPa (4,6%)
Tensile princ. stresses:
0,051 Mpa (17%)
0,0029 Mpa (0,9%)

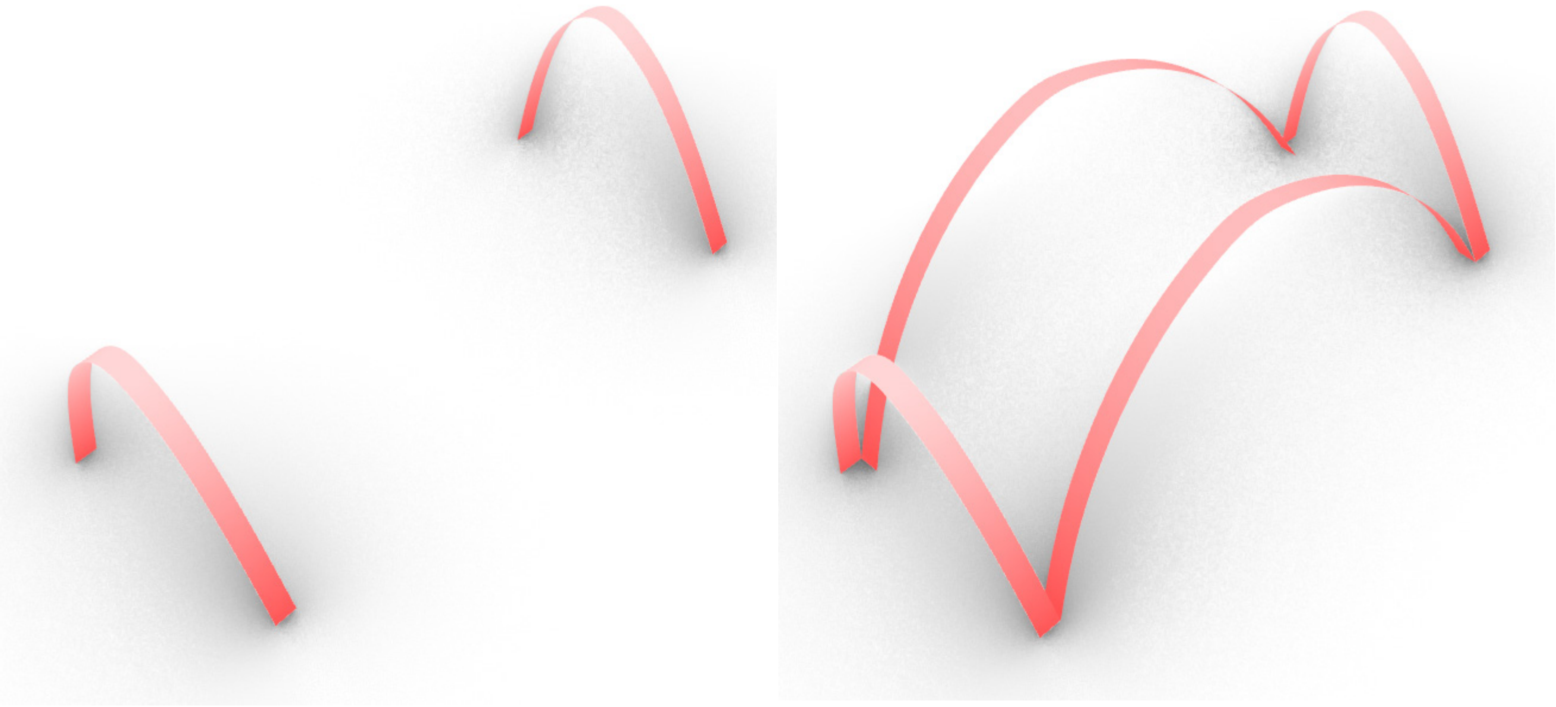


Figure 177: Structural tests of intermediate construction steps