A Prototype: a Methodology for Funicular Structural Morphologies

Berend Vos

TU Delft: Faculty of Architecture
AE: 1 Million Homes
Design: Roel van de Pas
Research: Pirouz Nourian
4432045

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Abstract: Through a literature study and experimentation on a 'toy-problem' a design methodology was formulated for the design of complex funicular structural morphologies. Important design choices regarding form finding methods, material and construction methods, pattern design and on dealing with loads were made explicit in this research. For the developed prototype the choice was made for a CNC-ed CLT masonry vaults using a solid spandrel created with a centroidal Voronoi pattern and the force density method.

H1 Introduction

Contemporary buildings almost exclusively rely on one structural system: the stacking of horizontal, bending-resistant, elements: the floors or beams, on top of vertical elements: walls or columns. (Haller & Lenart, 1986) (Weston, 2011) This system is sometimes called the orthogonal building system. This structural system that has been around since ancient times in for example the Greek temples and was further popularized in modern architecture by notably Le Corbusier with his Dom-Ino House. (Vittorio Aureli & Weaver, 2014).

The stacking based orthogonal system has its downsides. The funicular system might offer a better alternative. A funicular system is where the structure acts only in tension or compression, not in bending (Block et al, 2006). Examples of funicular systems are masonry vaults and arches.

The first advantage the funicular system has over the orthogonal system is that structural elements that have to resist bending are materially much less efficient (Schlaich, 2005). The orthogonal system based on stacking is therefore more materially intensive than a funicular system. This factor is relevant for building costs and the climate crisis. To help reduce societies material usage more efficient building forms like the funicular can play an important role. (Adiels, 2021)

The second advantage over the orthogonal system that the funicular has is more architectural in nature and needs proper explanation. Simply put the orthogonal system limits the architectural freedom. The orthogonal or stacking system often limits a building to 2.5 dimensions. The term 2.5-dimensional, sometimes also called pseudo-3D, in this case refers to something 3-dimensional built up of approximately 2-dimensional layers. The z-axis does not really play a role and the object is simply an extrusion upwards (Gosselin et al, 2016). In 3D printing the term 2.5-dimension is fairly commonplace. Most multi-story buildings can be described as a stack of floors/floor plans with a perforation for elevators and stairs. They are 2.5-dimensional architecture; the result of the stacking based structural system.

However architects like for example Adolf Loos, have long had the desire for more 3-dimensional spatial configurations for a multitude of reasons like variety, efficiency and experience. (Risselada, 1988, p27) But their ideas have not really taken off on a large scale. 3-dimensional spatial configurations that have been proposed are for example: the Raumplan by Adolph Loos, the Promenade Architecturale by Le Corbusier and more recently the Typology Puzzle by MVRDV.

Figure 1. The Typology Puzzle. *(W)ego. MVRDV (2017).*

One of the reasons these 3-dimensional spatial configurations have not been adopted on a large scale most likely has to do with the constructional difficulties associated with them. These difficulties stem from the needs of the orthogonal building system. The bending moments that inevitably occur in the orthogonal system are expensive and need to be kept as small as possible. This means columns should be placed directly above other columns and free spans must be kept as short as possible. (Schlaich, 2005) This need is what limits compositional freedom and makes a truly 3-dimensional spatial configuration unfeasible. The orthogonal structural system limits the possibilities for architectural expression, spatial diversity and complexity. The funicular system that does not rely so heavily on structural grids, consistency and the stacking of floors could offer a way around this problem.

The funicular allows for larger spans because it avoids bending moments. (Schlaich, 2005) Furthermore the funicular takes it form from the forces which are on it. It therefore also deals more efficiently with forces that don't align, like when columns are not placed directly above each other. In a funicular system there is for these reason more freedom in spatial configurations.

The funicular is not a new system but is not as of now in widespread use. Most contemporary research related to and prototypes of the funicular systems focus mostly on the material savings aspect of the funicular and don't look at the entirety of a building. Usually aiming to design very thin shells (Armadillo Vault) or large roofs (Great Court of the British Museum). But you cannot live in shells and roofs. For the funicular to be able to make a splash it has to be implementable for all kinds of architecture. Experimentation and a design methodology aimed at achieving this are lacking.

The funicular potential as a structural system for an entire (multi-story) building has not been researched except for in the SUDU project by the Block Research Group (Hebel et al, 2016). Research in how to implement a funicular system in slightly less simple spatial configurations do not seem to exist. Exploration in funicular structural morphologies potential for multi-story buildings, in particular for more 3-dimensional spatial configurations is needed. This is the gap in our knowledge this research will attempt to help fill.

Figure 2. Funicular inspired roof. *Great Court at the British Museum. Foster + Partners. (2000)*

Figure 3. Thin Funicular Shell. *Armadillo Vault. Block Research Group (2016).*

The perceived knowledge gap will be addressed through a study of existing literature. Taking a broad look at the relevant fields. The second pillar of this research is experimentation. Using a prototype or toy-problem to experiment on, new insights on how a funicular building system can be implemented in complex building can be gathered. The experimentation attempts to lead to a first step in the development of a methodology for designing funicular multi-story buildings. For this prototype an existing multi-story building was chosen as a starting point so all irrelevant design considerations could be ignored. To attempt to show the potential of the funicular system a building was chosen which departs from the typical 2,5-dimensional mentality and struggles with its structure because of this. Simply put a building was chosen which is an extreme, with the mentality that if the funicular can work there it an work anywhere. The choice was also made to focus on 'normal' housing, because it makes up the large percentage of our built environment.

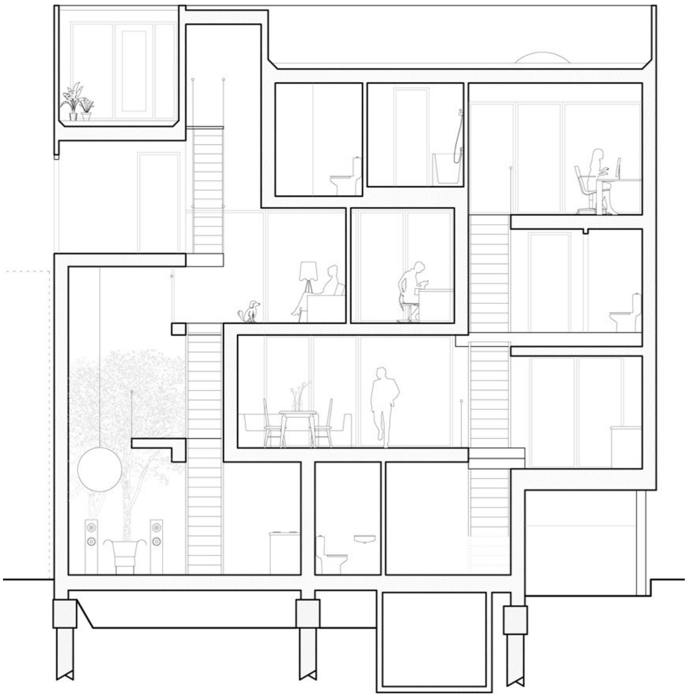


Figure 3, 4. Picture and Section of the Double House. *Double House. MVRDV. (1997)*

The starting point or toy-problem chosen is the Double House by Winy Maas from MVRDV and Bjarne Mastenbroek. The Double House consists of two semi-detached family homes in Utrecht constructed in 1997. It is one of the only examples of a truly 3-dimensional spatial configuration in housing, excluding very expensive villas. The Double House is an example of the architectural concept: the typology puzzle. A concept where different typologies lock into each other to create a diverse and dynamic whole. The typology puzzle sometimes reminds of the game Tetris. The typology puzzle is probably more relevant in large scale housing projects than other 3d concepts mentioned. This is because the typology puzzle can be scaled up and also used for low-cost housing. For this reason it is the preferred 3-dimension configuration principle for this research. The Tetris-like configuration of the Double House causes several structural difficulties as was expected. Load bearing walls could because of the spatial concept not be placed on top of other walls. The floor plan is also quite complex with its many layers and because it is not orthogonal or regular. The 3D configuration of spaces, its structural challenges and complexity makes that the Double House offers the challenge that make this digital prototype as relevant as possible.

The Double House has been distilled to its essence for this research. The first thing needed is the configuration of spaces. The configuration of spaces can be looked at as a connected walkable manifold, which can further be subdivided into standing, sitting and walking surfaces. The extrusion of these surfaces upwards can be defined as the walkable space. The space that is free of obstacles.(Nourian, 2016). The other starting point are the maximum dimensions of the house. The assumption has been made that its current plot and height are the maximum dimensions allowed and therefore are the maximal amount of space. A diagram of the spatial configuration and the maximum space is shown in figure 5. Standing spaces are annotated with the yellow pyramid, sitting with the blue sphere and walking with the red cube.

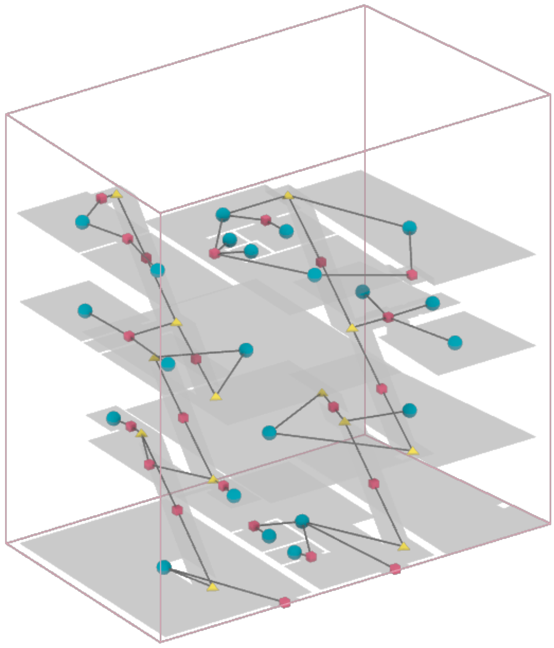


Figure 5. Configuration of Spaces Diagram of the Double House.

The research question of this research is: How can a funicular structural morphology be designed/ generated for the spatial configuration of the Double House? There are several relevant sub-questions:
1. What method for getting the funicular form should be used?
2. What material and production method should be used in the vaults?
3. What should the topology of the vaults be?
4. How should one deal with the different forces in a funicular system?

The result of the research will be a diagram showing a methodology of how a funicular system can be implemented on the configuration of space of the Double House. This methodology can hopefully serve as a prototype for a methodology for developing funicular structural morphologies in general. The subquestions and their related chapters will make all the important considerations for developing a funicular structural morphology explicit. The eventual choices made in these first chapters should considered as well informed design decisions.

H2 Methods for Funicular Forms

There are many methods that can be used to find the funicular form. The oldest method of getting a funicular shape which was used by the Gothic builders is through physical model making. In workshops builders tested what forms would and would not remain standing (Adiels, 2021). This works because models of funicular systems can be scaled up. The second, more precise method, was related to Robert Hooke's (1675) famous saying which lies at the heart of the funicular: "as hangs the flexible line, so but inverted will stand the rigid arch." The hanging of weighted chains and strings was done by for example Antoni Gaudi to find the perfect forms for his masterpieces. Heinz Isler later used pieces of cloth to take the physical approach truly three dimensional. (Liem, 2011)

Figure 6. String and Weigths Model of the Sagrada Familia. Antoni Gaudi.

Nowadays in large part thanks to computers there are many more methods of finding funicular forms. These methods do not make the older methods obsolete.

All the digital methods have their advantages and applications and none of them can be considered wrong. A lot of research has been directed into finding an intuitive method. A brief description of methods that were considered and tested for this research will be given. After this it will be explained what method was chosen and for which reasons.

1. Topology optimization

The first type of funicular form finding actually goes a step beyond just shape finding. It tries to find a optimal topology and therefore probably tries to find a funicular topology. There are many methods of topology optimization but this research only looked at SIMP and BESO. This is because software using these methods is readily available. (Sanchez, 2019) Karamba was used for BESO and Topos for SIMP.

In its essence topology optimization works by dividing a structural element into voxels. Then by removing or adding voxels where they are unnecessary or necessary to deal with a specified load case you obtain the most materially/ volumetrically efficient form. (Sanchez, 2019)

The end result of topology optimization is usually a sort of porous structure. The problem is however that objects with such complex forms of a very high genus are difficult to produce on a large scale. 3D printing offers the outcome on the small-scale. But there are no successful built examples of this technology for entire structures of buildings. The results of topology optimization were therefore considered too complex for current methods and for the purposes of this research and therefore not chosen.

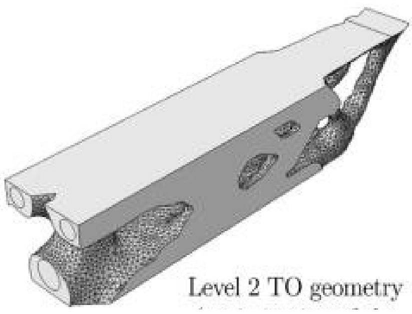


Figure 7. Topology Optimization of a Beam. Tyflopoulos et al (2018)

2. Thrust Network Analysis and 3D Graphic Statics.

Both TNA and 3d graphic statics rely on reciprocal diagrams to asses a shapes static equilibrium. (Liem, 2011) Thrust Network Analysis (Block & Ochsendorf, 2007) uses planar line diagrams while 3D Graphic Statics uses 3-dimensional polyhedrons (D'Acunto et al, 2017). Both have readily available software and are well suited for masonry in particular

However in the opinion of this researcher both methods are not as intuitive as intended by their developers. Especially when the surface that needs to be generated becomes complex. The complexity of the reciprocal diagram then increases as well. It thereby losing its readability and understandability. For the 3D Graphic Statics method this was found to be an even larger problem than with Thrust Network Analysis. Because the manifolds of the Double House are quite complex these two methods were not chosen.

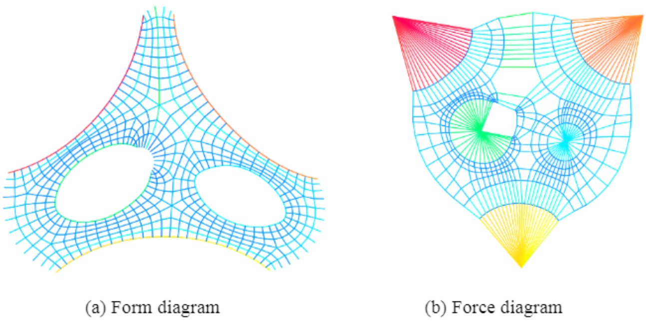


Figure 8. Thrust Network Analysis of the Armadillo Vault. Oval et al (2017)

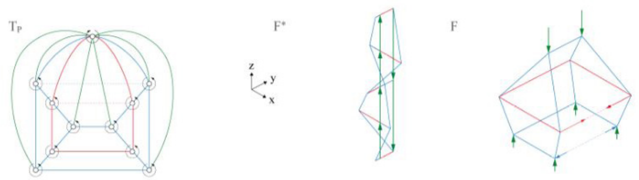


Figure 9. Example of 3D Graphic Statics. D'Acunto et al (2017)

3. Large Deformation Method

Large Deformation Method is another method for funicular form finding that was experimented with. This relatively unknown method for funicular form finding was developed in the Karamba FEM solver. Under specific load cases it deforms a structure. The deformations are done in a specified number of iterations. Each iteration does a deformation of a predetermined magnitude. The advantage is that this method gives a large amount of control on the magnitude of the deformation rather then rely on arbitrary values like the other methods (Liem, 2011). According to Karamba this method works well to simulate a hanging model to find the optimal shape with specific stresses (Karamba, n.d.).

The problem is however that this method has hardly been researched. The method also relies on the Finite Element Method. FEM is not suitable for structures which are made up of separate elements like masonry structures. The discrete element method should be used for this.

Because there is currently no scientific research into the workings and validity of this approach it was not chosen as a method for this research.

4. Force Density Method / Dynamic Relaxation

The Force Density Method is probably the most commonly used method for funicular form finding (Liem, 2011). It describes a surface as a net of lines. The net has nodes (points) and branches (lines). There are fixed nodes for which the coordinates are known and free nodes which are allowed to move. The loads for each nodes are also known. The branches are approximated as springs. The whole system is then deformed until each branch has the same predetermined force density. The tension network has then found its equilibrium shape. (Liem, 2011)

This method is simple to use and there is a lot of available software to utilize. The methods widespread usage is also an advantage for the reproducibility and understandability of this research. One downside of the method is that the value of the force densities are quite arbitrary but do affect the shape. It is therefore hard to predict which values will lead to the desired amount of deformation. This is similar in other methods however so it is not grounds for exclusion. Because of the aforementioned reasons the Force Density Method was selected for this research.

5. Conclusion

Force Density Method is the preferred method. During the experimentation with the method it was found that the topology of the net has a large impact on the outcome. The pattern has to be carefully chosen for this reason.

There are a lot of software packages that use the force density method for form finding. The choice was made to use Kangaroo. Kangaroo is a physics solver operated from within Grasshopper. An advantage of Kangaroo is that a lot of people are familiar with it. Kangaroo was selected because of this and because of prior experience with Kangaroo by the author. Other programs that offer Force Density Methods would also be good options. Open source options would be most preferable.

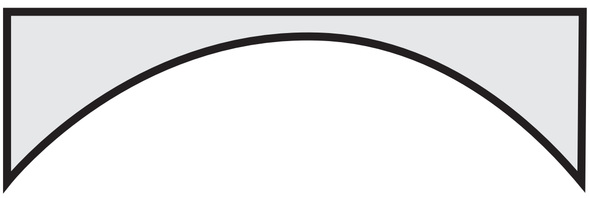
H3 Material and Production Method

The choice in material and production method affects how the funicular system is implemented and can therefore not be ignored. There are several important aspects.

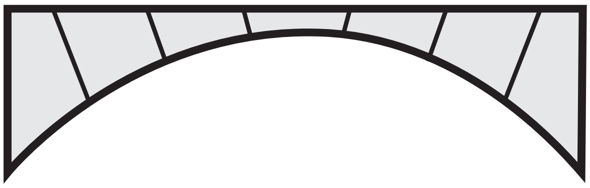
The choices made in this category should not be blindly copied. An educated guess is made in each category. The more elaborate research into material and production methods for funicular forms needed falls outside the scope of this research. The choices made should therefore be considered design choices.

1. Spandrel type

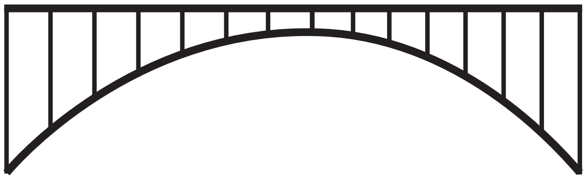
In a multi-story building each floor needs to be flat to allow it to be usable. Only the underside of the floors can be curved and can therefore take a funicular form. The need for flat surfaces is unfortunate but not a problem. The solution to the problem is what is in 2D is called a spandrel. A spandrel is what connects a flat top to the supporting curved arch. In bridge design spandrel design is well researched. There are three basic types of spandrels: the solid spandrel, the open spandrel and the braced spandrel. There is also a special version of the closed spandrel where the spandrel is made from large masonry blocks: a block spandrel if you will.



1) Solid Spandrel



2) Solid Block Spandrel



3) Open Spandrel

4) Braced Spandrel

Figure 10. Main Spandrel Types.

The block spandrel was not chosen because then the form hardly matters anymore. The forces should go through the centroids of the blocks. This means that the location of the blocks and their centroid becomes the most important. Because every change in the blocks' form changes the location of the centroid the generation process becomes quite complex. The block solution was, after experimentation, determined to be too complicated to generate for the purposes of this research. A possible advantage of this solution could be the reusability and demountability of the blocks.

The braced solution has the bracing to deal with horizontal loading. The double curved shape is most likely already quite resistant to horizontal forces (Schaich, 2005) and the bracing would therefore probably be excessive in a building.

The choice was made for an solid spandrel as opposed to an open spandrel. The solid spandrel would be filled with a different, weaker and lighter material then is used for the rest of the spandrel. The filling material should probably be something light, natural and resistant to compression.

This filled solid spandrel was chosen because it is the most simple to generate and therefore best suited for these purposes. It would also transfer the forces which are on the floor in the most continuous way which is also preferable. The effectiveness of this solution depends very much on the filling material.

2. Vault or Gridshell

Another thing that needs to be decided is whether to use the principle of a gridshell or those of a vaulted structure. A vault in this case refers to a structure made of usually one material of a single strength. The whole structure helps to carry the loads. A gridshell unlike the vault has a stronger grid to support a weaker material.

Figure 11. Example of a Gridshell. Diabatsu-Den, Japan. Frei Otto (1988).

A gridshell is useful when one wants to use glass or another weak material like in the Court of the British Museum. In some cases a grid shell can also be chosen for aide the construction process as was the case in the Mannheim Gridshell by Frei Otto (Liddell, 2015)

None of these factors are the case for this prototype. Because vault usually have only one material it is generally less complex to design. This is especially true for masonry. For these reasons a vault using only one type of material without additional grid was chosen as most suitable for this prototype.

3. Material

There are many good options for a material in funicular systems. The Block Research Group even managed to use the very brittle material limestone in their Armadillo Vault. (Block et al, 2016) It is however important that the chosen material has a high compressive strength to be self-supporting. (Vouga, 2012) The choice of material is related to the preferred production method and the choice for a gridshell or shell principle.

For this research the choice was made to use CLT. This is because it is an environmentally responsible material and easy to machine. Its strength to weight ratio is also good. (Schlaich, 2006)

4. Construction and production method

There are many types of construction and production methods for double curved forms. There are off course the traditional methods as employed by the Geodesic Domes by Buckminster Fuller or the curved concrete architecture of for example Oscar Niemeyer.

For concrete or earthy materials there are also more innovative methods for getting the correct formwork. The concrete Bini-shells with their inflatable support are an example (Bini, 2014). Other examples of innovative concrete formwork methods are the tensioned cable net and knitted formwork developed by the Block Research Group (Popescu et al, 2019). There is also the option to make complex curved molds from for example EPS using CNC-machining (Liew et al, 2017).

When using wood or stone as is the case for this prototype the curved shape most likely has to be made from smaller elements. By stacking or connecting elements like plates or blocks complex shapes can be created while keeping the elements relatively simple. In this method the elements can be produced off site and the construction can be modular. The method of constructing a form from loosely connected individual elements will be described as masonry during this research, even when not using stone.

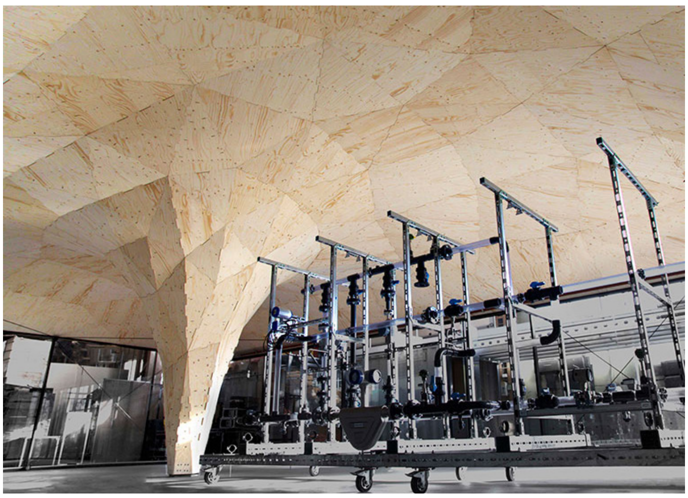


Figure 12. Example of a Wooden 'Masonry'. Skilledin Office. Studio RAP (2015)

For the prototype masonry was selected as the best option. To be precise: CLT plate masonry was chosen. The connections will be kept as simple as possible by shaping the plates as voussoirs. The plates could be CNC-ed and would, looking at references, be about 350x350mm.

Conclusion
The design decision that help guide the rest of the choices are as follows. CLT plate masonry was chosed for the ceilings, shaping them as voussoirs. The CLT elements should be about 350x350mm. The rest of the structure is more standard CLT construction where the elements can be larger in size. The complex CLT would be cut into the correct shapes using CNC technology. The floors are filled with something like gypsum, woodchips or even a type of foam and off course all technical installations to form a solid 3D spandrel.

H4 Pattern

Methods for finding funicular forms usually compute discrete meshes rather than continuous surfaces. It is important what the topology or pattern of these meshes is. Oval et al (2017) puts it well: "the topology of the patterns, which serve as input to the form-finding process, is crucial as the achievable form-found geometries, i.e. the design space, is directly related to the chosen pattern topology." In masonry a tessellation has to be done eventually anyway and it probably better to use the same tessellation or base it upon the same tessellation as is used in the form finding process (Oval et al, 2017).

This chapter will therefore look into the criteria for a good pattern and propose two new ways of generating a pattern. The second of these methods was determined to be quite successful in fulfilling the criteria. One of the ceilings of the Double House was used to experiment on.

1. Criteria for patterns

There are several important criteria for the patterns of masonry vaults identified by Oval et al (2017) and Oval et al (2018). Production seems to be the bottleneck of funicular forms not the structural efficiency. It therefore seems more important to focus on production and construction criteria rather than the structural efficiency. There is often a trade off between the criteria (Oval et al, 2017).
For production the first important criterium is the sameness in size of the elements. This can be measured using the edge lengths. Secondly the skewness of the parts should be minimized. This helps reduce the material loss when cutting the elements. Because of this criterium triangular patterns are usually more expensive to produce (Potmann et al, 2007). Thirdly: the planarity of the elements. They should be as planar as possible. This makes them much easier to produce in a bending or CNC production process (Oval et al, 2018) For the construction there is another criterium: the valencies of the pattern should not be higher than three. Otherwise the assembly proces becomes more difficult (Oval et al, 2017)

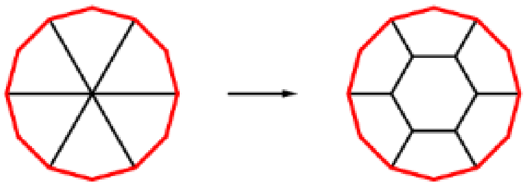


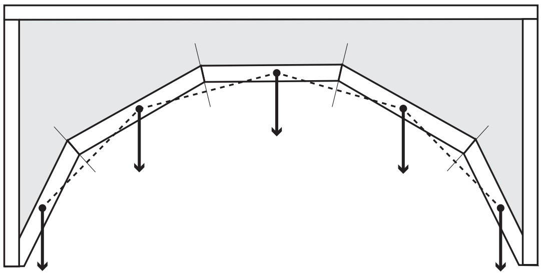
Figure 13. Example of reducing the nodal valency from six down to three. Oval et al (2017)

2. Placement of nodes

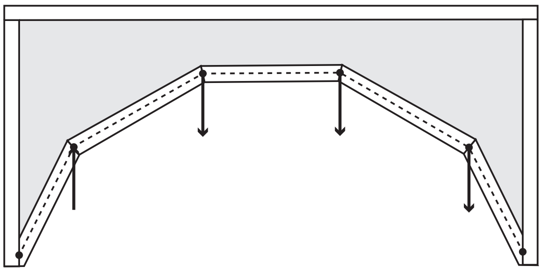
It has been established that the tessellation for masonry should be based on the pattern used in the form finding. (Oval et al, 2017) There is however a choice to be made whether the pattern for the blocks should be the exact same or the inverse. The choice is whether the nodes should represent the connections between the elements or of they should represent the centroids.

The structure follows the force line more precisely when using the connections as the nodes. This ensures that the force line is always within the structure which is important for static stability (Block et al, 2006). Using the centroids as the nodes has the advantage that the interface normals are aligned. This helps prevent sliding failure (Heyman, 1997). Both methods have their up- and downside as is visualized in figure 14.

The choice for this project was made to place the nodes at the connections and therefore use the same pattern for blocks as in the form-finding process. This simplifies the design and because of the large size of the elements it was determined to be more important to follow the force line closely. Because of the horizontal loads some form of sliding resistant connection will most likely have to be designed anyway. This mitigates the advantage of having the nodes at the centroids.



1) Nodes at Centroids



2) Nodes at Connection

Figure 14: Illustration of consequences of the nodal placement.

3. Method 1: Subdividing into quadrilaterals

The first method developed through experimentation has as a goal to establish a regular quad pattern. This would be simple if the boundary was a quadrilateral itself. A quad can be divided into a regular quad pattern by dividing the length of the edges by the desired grid size. An array of lines can then be created which will constitute the pattern.

The method therefore chose the following workflow: 1. divide the shape into basic quads, 2. further subdivide each quad. After experimentation the most successful method for dividing the original shape into rectangles was found. The edge lines longer than a certain threshold where extended. These lines where used to cut the original shape.

This method was determined not to be good enough to be used. Mostly because of two factors. The first is that this method would work poorly on non-orthogonal or free-form floor plan. The second reason is that the pattern has awkward intersections where two rectangles meet like at the doors. The valencies are also too high but this could be fixed using the method proposed by Oval et al (2017).

4. Method 2: Relaxed N-gon Voronoi

The second method developed was determined to be much more useful. The aims for this method where to keep the valency under 4 and establish a pattern capable of tiling all types of boundaries.

An addition advantage of this method is that the resulting grid is mostly hexagonal. This is an advantage because a hexagonal grid has the minimal amount of edges and therefore minimal cutting and connections length. This was proven with the honeycomb conjecture (Hales, 1999). Another advantage is that hexagons lock together better then quads because the face normals are more varied in direction.

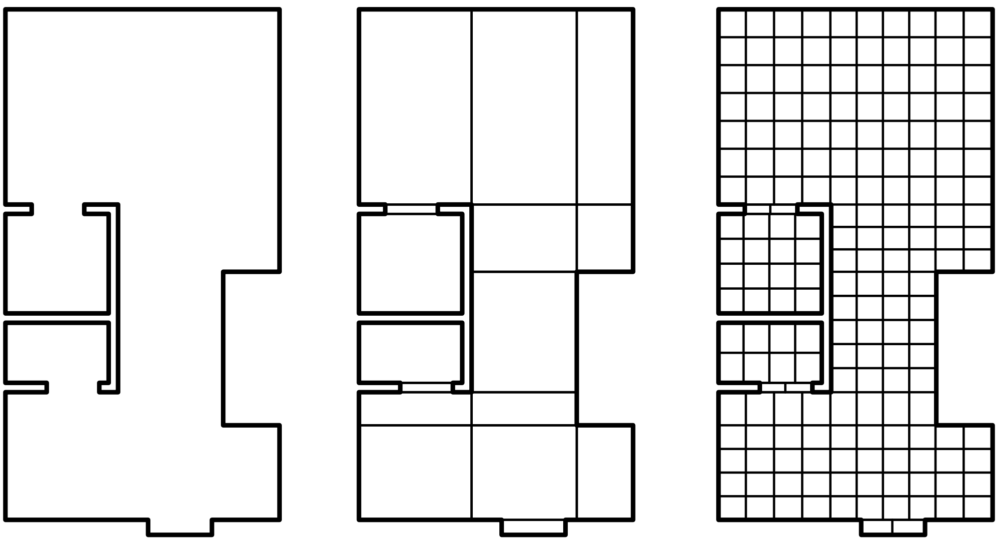


Figure 15: Pattern generation using method 1.

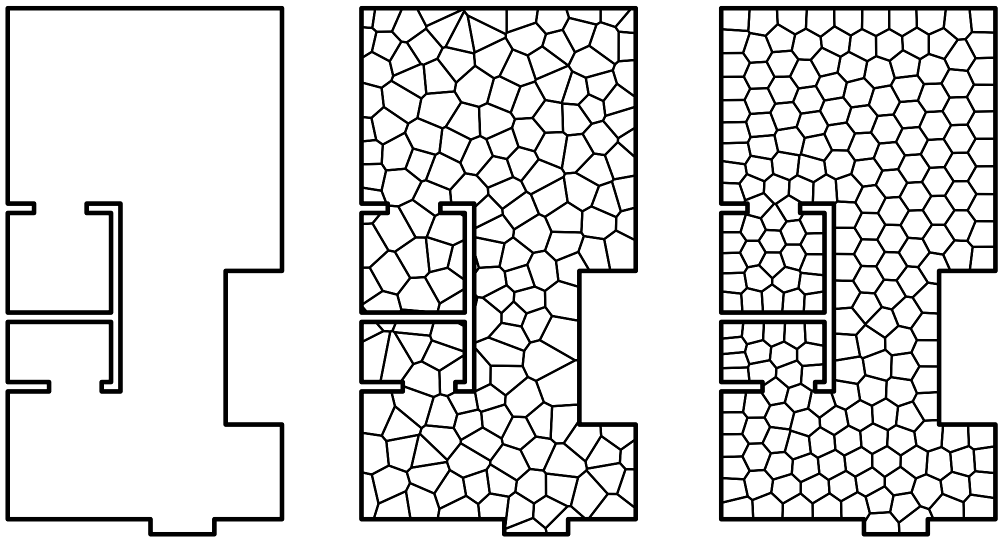


Figure 16: Centroidal Voronoi pattern generation.

A downside is the method is that the resulting mesh will be a so called n-gon mesh. Most computer software do not work well with n-gon meshes Additional software was needed during this project because of this (NGon).

The method creates a pattern using centroidal Voronoi-tiling. An initial Voronoi patterns is generated inside the boundary. The Voronoi is based on randomly distributed points. The amount of points is based on the desired average cell size. Lloyd's algorithm (Lloyd, 1982) is then applied to find a relaxed or centroidal Voronoi pattern. This is done though iterations where the centroids of the previous pattern's cells are used to construct a new Voronoi pattern. After enough iterations the algorithm converges and the result is a relatively regular Voronoi pattern. Edges tend to have pentagons while in the centre very regular hexagons appear.

This generated patterns seem to satisfy the criteria of skewness, sameness in size and valency very well. Planarity will be a challenge after the dynamic relaxation. This would also be the case with quad-patterns and is therefore not a big problem.

Most likely this is the first use of the Lloyd's algorithm for finding a pattern for funicular form finding. The true potential of the centroidal Voronoi-pattern therefore needs further research. The first signs are promising and this research will therefore use this new method. Lloyd's algorithm is already quite widely used in other fields.

H5 Loads and forces

Form follows force in funicular structures. Knowing what the forces are and how they should be dealt with is therefore important for the finding the correct funicular form.

1. Regarding the calculations of loads

Many funicular forms are designed with solely self-weight in mind. This approach will not suffice when working with floors. In normal constructions the self-weight only makes up a relatively small percentage of the total load. In normal concrete structures the load composition tends to be:
1. self-weight: 3kN/m², 2. installations and finishing: 2 kN/m² and 3. live load: 3 kN/m².
In wood and steel constructions the relevance of self-weight is even less (Arends, 2017). In BRG's concrete funicular floor for example the self-weight only accounted for 21% of the total load relevant to the design process (López López et al, 2014). This is not to say self-weight is irrelevant but it designers should not neglect to take the other loads into account. The relevance of self-weight is also heavily influenced by design choices like material and spandrel type.

Determining what loads to use for the funicular shape is not necessarily straight forward. There are two complicating factors. The first problem is the fictional nature of the imposed or live load. For this research it was chosen to find a form for the most extreme loading and thus ignore the fictional nature in the live load. To determine the best approach additional research is needed.

One approach that can alternatively be taken is to increase the self-weight so the other forces, like the imposed load, become irrelevant and can be ignored. This option is not scalable and not very elegant. This strategy can not be used as a strategy for high-rise because the compressive forces in the walls would eventually become too large and the load on the foundation as well. The strategy of embracing heaviness was therefore not chosen for this research.

The second complicating factor regarding load is that self-weight is not static during the design process. It creates a loop in the design process. Every change in the form affects the dimensions of the elements which leads to a change in load distribution and height of the load by self-weight. The loop is than restarted because the form will have to change to follow the new self-weight forces. The Block Research Group has also observed the aforementioned loop (López López et al, 2014). Iterative optimization algorithms can deal with this loop but are computationally heavy. Approximating the self-weight in a planar will probably suffice in many instances and will be done in this research.

In a multi-story structure loads from the structure above should not be forgotten.

2. Variable loads

Contemporary funicular systems focus on rigid loads. However a structure must also deal with variable loads. The most relevant variable load is probably the wind load but for example earthquakes can also play a role. To deal with these types of loads funicular structures have a few options.

The structure can be over-dimensioned to deal with variable loading. The Block Research Group for example uses FE analysis to decide how to change the dimensions to account for variable loads (López López et al, 2014).

The other option is to simply give the structure a lot of mass. This way the system can be insured to always stay in compression. The downsides of this solution have been previously mentioned.

The ultimate solution would be that structures become form active. Meaning that they change their form depending on the load conditions. A structure would for example lean into the wind like a person would. This is too complex for now.

3. Horizontal forces

Horizontal resultant forces are a challenge for all funicular forms and are a common cause of their collapse (Block et al, 2006). Other than orthogonal beams and floors a funicular system will always need some form of horizontal bracing. Making the funicular form more vertical decreases the relative magnitude of the horizontal forces and vice versa.

Solutions dealing with these horizontal forces can be quite complex as can be observed in the buttress solutions used in Gothic churches. The use of tension elements as done in the Funicular Floor Slab by BRG might offer a relatively simple solution (López López et al, 2014). Especially for floors far away from the foundation tension ties will be needed. The alternative is very heavy and strong walls to enclose the vaults.

H6 Workflow for multi-story funicular structure

Oval at al (2017) said the workflow of the funicular form finding processes is as follows: “1. defining the boundaries, 2. designing a planar mesh, 3. setting the constraints, and 4. form finding.” This research would like to much expand on these steps to get a more precise overview of the workflow when developing funicular multi-story housing or funicular structural morphologies is general.

The proposed methodology is not fixed and static and needs additional research and experimentation to be confirmed. The methodology attempts to make the design choices and processes explicit. The methodology has been made so it can be applicable to a wide variety of projects. Variations on the methodology can be made depending on the projects specifics. This methodology for creating a structural morphology is off course only a small aspect of the entire design process when creating a building.

The methodology was established through experimentation on the Double House’s spatial configuration. The design choice previously discussed affected the methodology. The methodology is related to the algorithm created for the Double House prototype.

The methodology has been visualized in a self-explanatory flowchart, shown in figure 17. The four basic steps are 1. find max structure, 2. tessellate ceilings. 3. find funicular form through FDM and 4. create the masonry blocks.

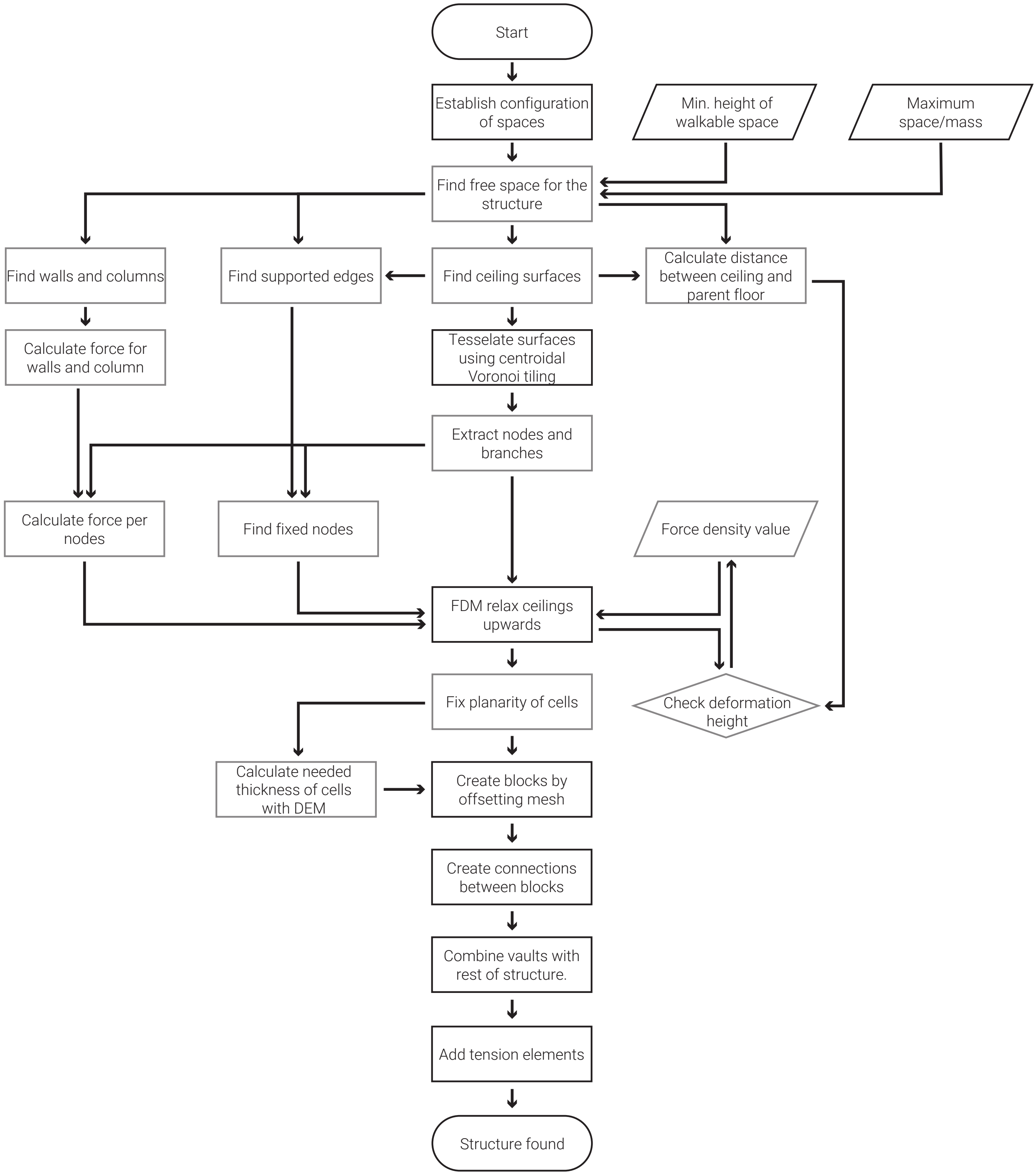


Figure 17: Proposed methodology for funicular structural morphologies

H7 Results

The methodology led to a prototype and vice versa. The prototype developed serves as the proof of the effectiveness and validity of the methodology. The prototype should not be considered as the goal or main outcome of the research. It is without the rest of this research not very relevant in its own right.

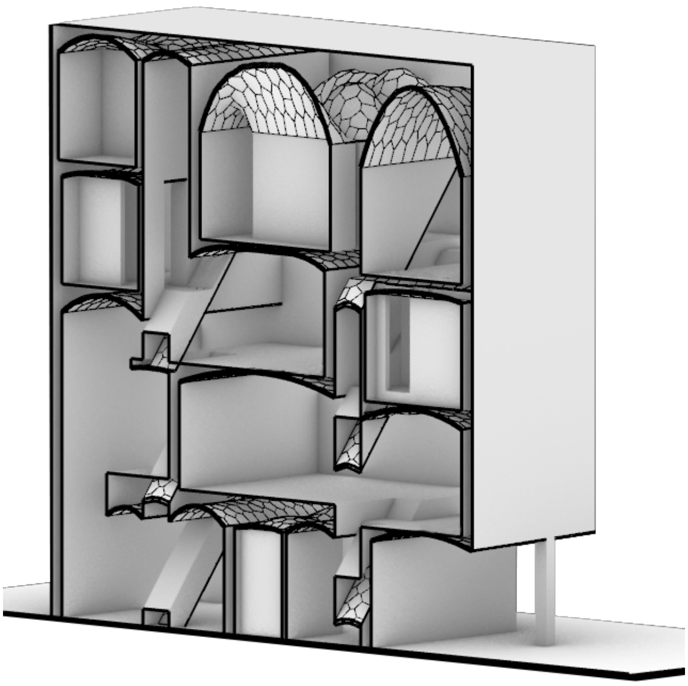


Figure 18: Section of developed prototype

All spaces and stairs where given a funicular vault. The walls where kept orthogonal so normal furniture can be placed in it. A further iteration would include facade openings and the tension bracing. The Grasshopper script developed and used is available upon request.

H8 Conclusion and Discussion

The research question was: how can a funicular structural morphology be designed/generated for the spatial configuration of the Double House? The answer to this question is the combinations of the proposed methodology and the design choices made explicit regarding form finding method, construction and material and pattern design. The findings are the result of experimentation on the Double House and a literature study.

The main choices for form finding are: topology optimization, reciprocal diagram form finding (TNA and graphic statics), large deformation method and force density method. Considering the current state of the technologies force density method was selected to be the most suitable. Large deformation method deserves additional research into its potential however.

The design consideration regarding material and construction are numerous. The considerations made explicit are the 3D spandrel type, the choice between a gridshell or vault principle, the material choice and the choice for a construction and production method. A CNC-ed CLT masonry vault using a solid spandrel was chosen by this research. Additional research is needed to validate these design choices.

Thirdly the considerations regarding pattern design for the vaults were made explicit. Firstly planarity, sameness, valency and planarity of the cells were identified as important criteria. The choice between centroidal of connection nodal placement was then elaborated on, choosing the latter as best. Lastly two types of patterns were proposed. Especially method two where Lloyd’s algorithm was used to create a centroidal Voronoi n-gon mesh was determined to be quite successful and hold a lot of potential. Further research is needed into this method.

The last design consideration discussed regarded how to deal with loads. The design loop and challenge created by the load from self-weight was made explicit, proposing several solutions. Variable loads and the resultant horizontal forces of funicular vaults were also identified as important design challenges. Both require additional bracing to be solved.

The proposed methodology is the end result of this research. It is best summarized in the diagram shown in figure 17. Further research is needed to confirm the validity and helpfulness of the methodology. This research could be done by letting multiple people design multiple prototypes of funicular structural morphologies. The potential of a multi-story funicular building needs further research as well. Physical prototypes and Discrete Element Analysis should form the basis of this research.

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Figure 15: Original work

Figure 16: Original work

Figure 17: Original work

Figure 18: Original work