GRADED**STRUCTURES**

DENISE JONKER

The design of a grid shell that uses gradual densification to enhance the performance of the overall structure.

PROBLEM

STATEMENT

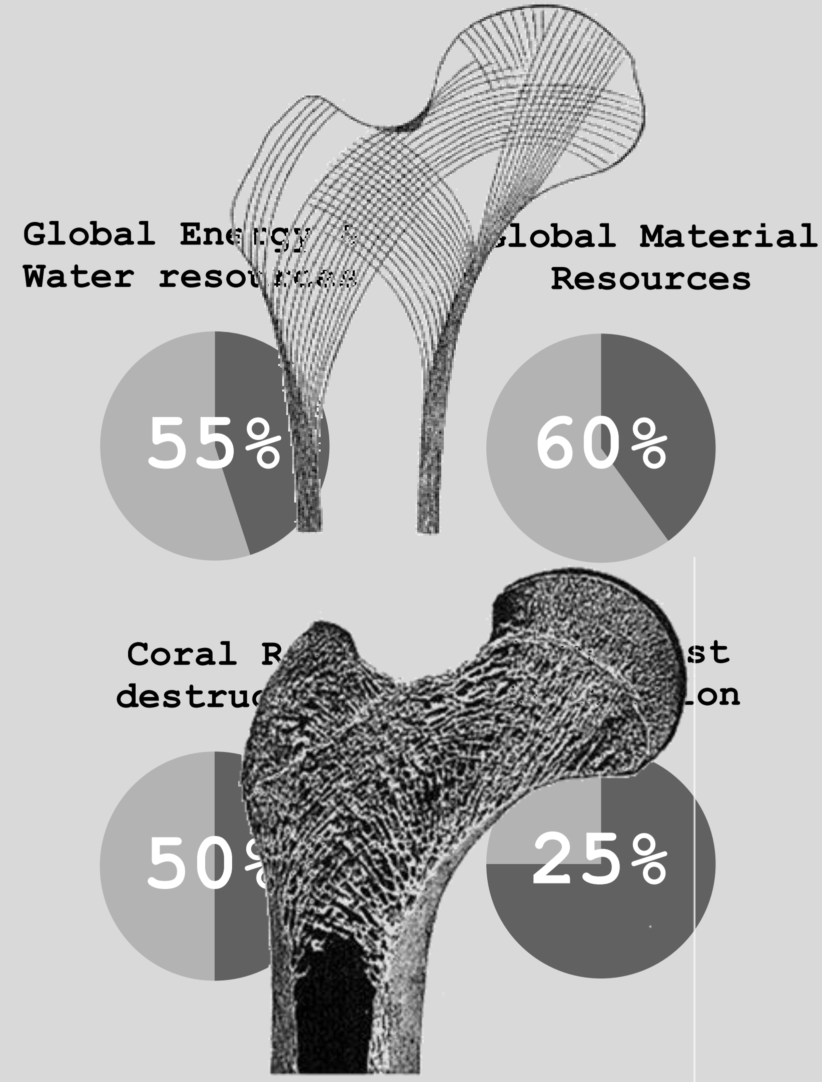
» CONSTRUCTION

Is one of the least sustainable industries in the world

» SMARTEST STRUCTURE?

» BONE STRUCTURE

A bone adds material where needed and removes material where it is not needed



GRADED

STRUCTURE

» FROM BONE TO BUILDING

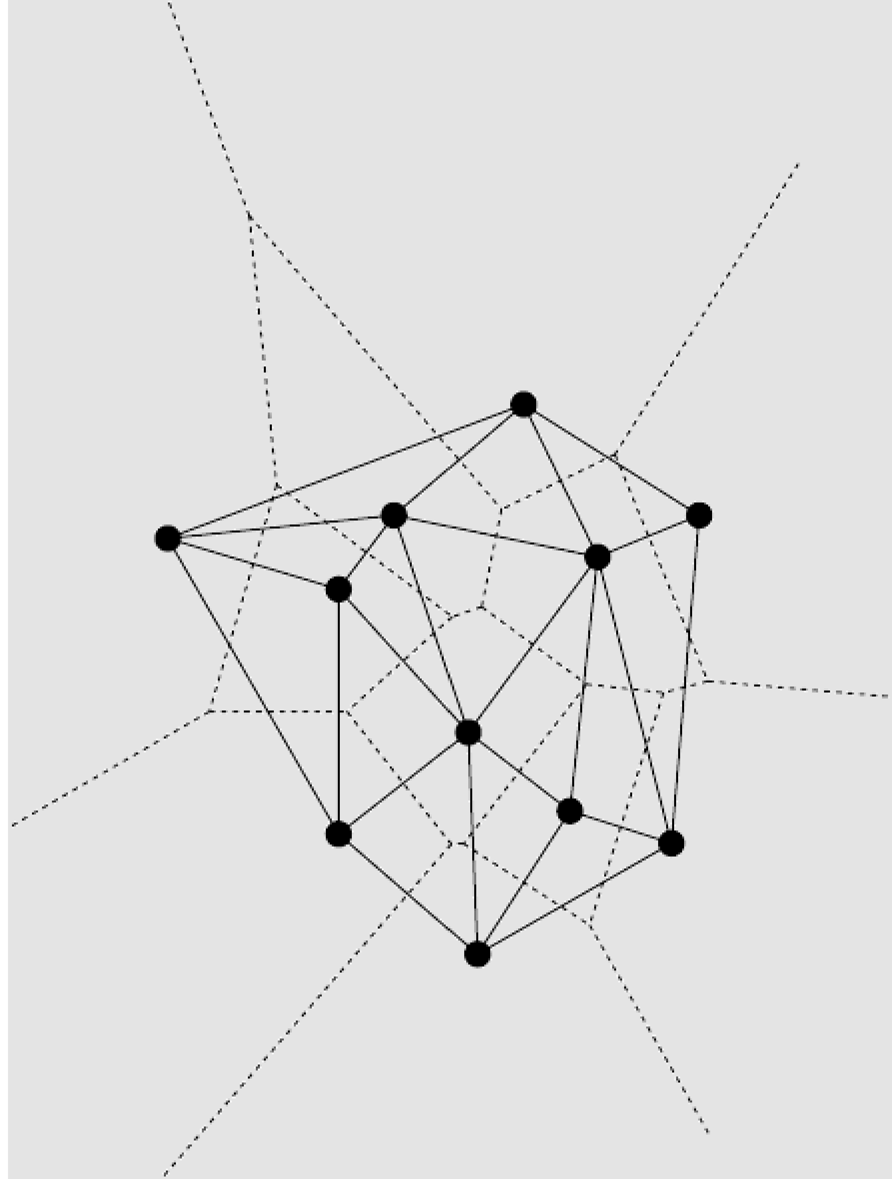
Graded structures

» TRADITIONAL STRUCTURES

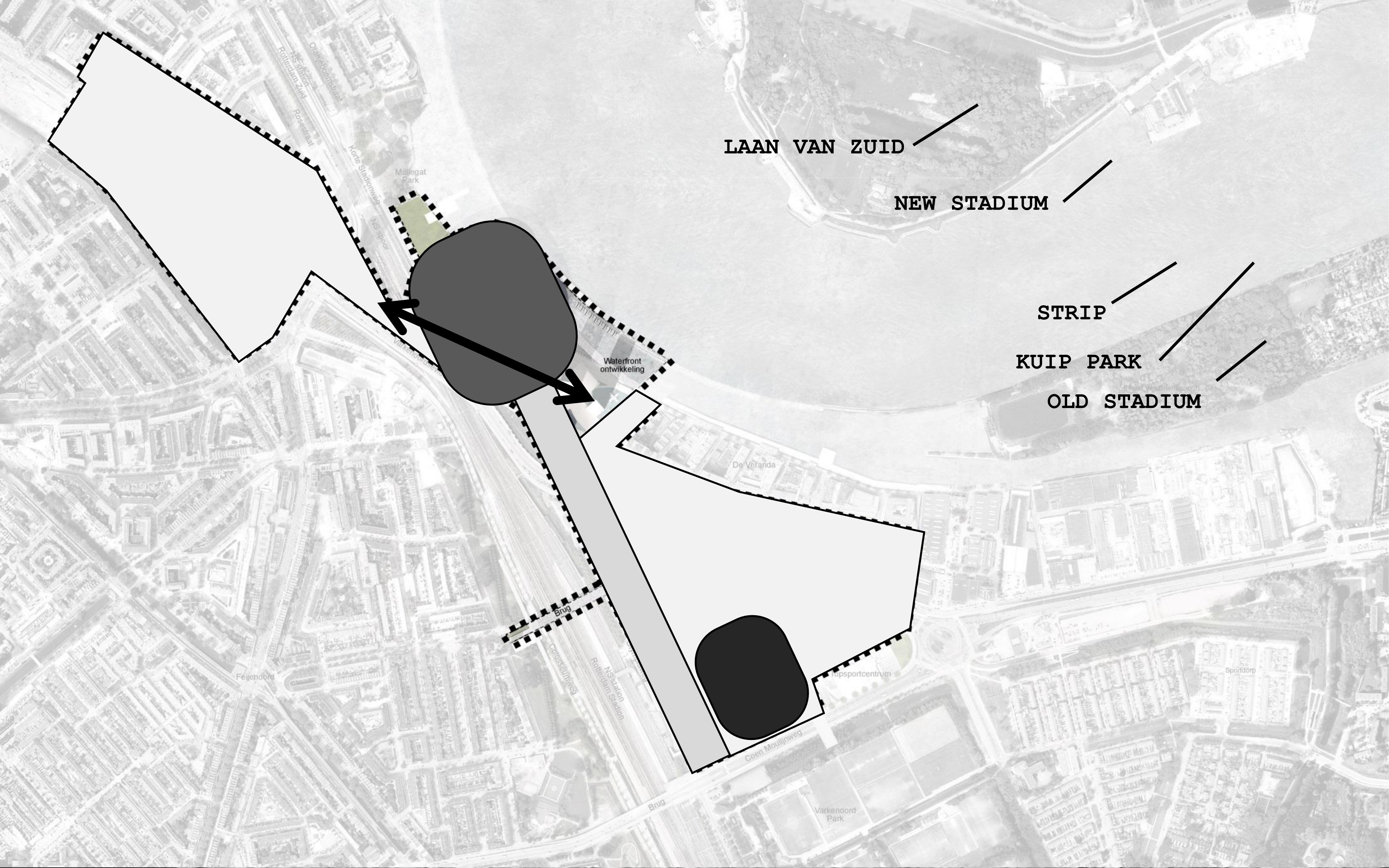
The densification of these structures happens not gradually, but incrementally

» GRADED STRUCTURES

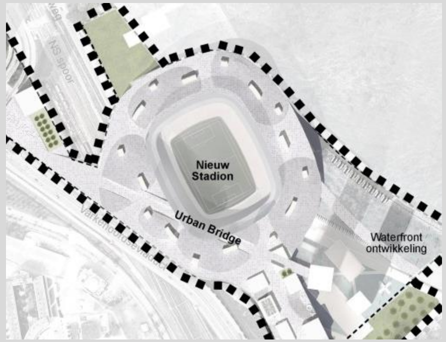
Voronoi and Delaunay

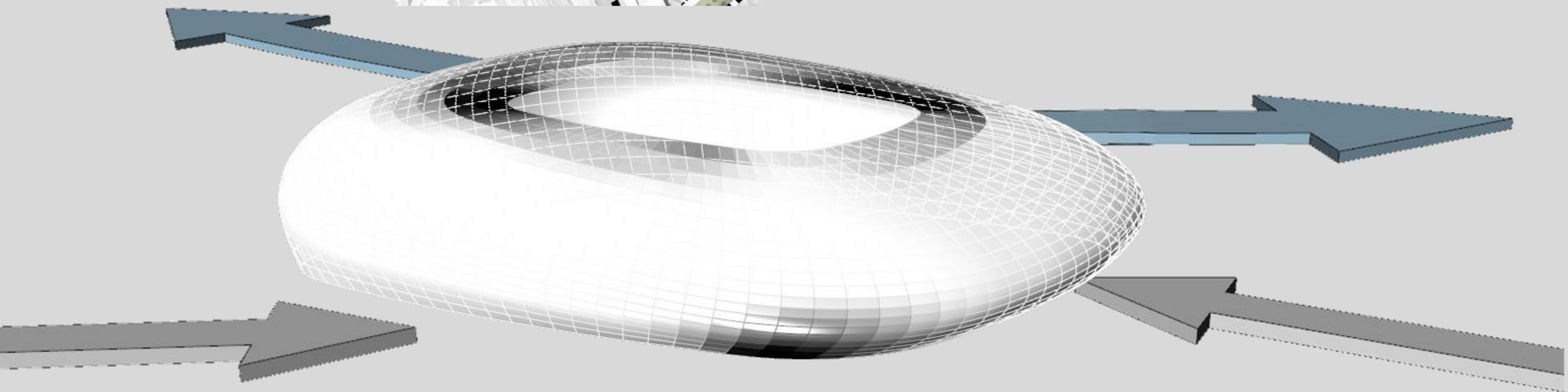


CASE**STUDY**

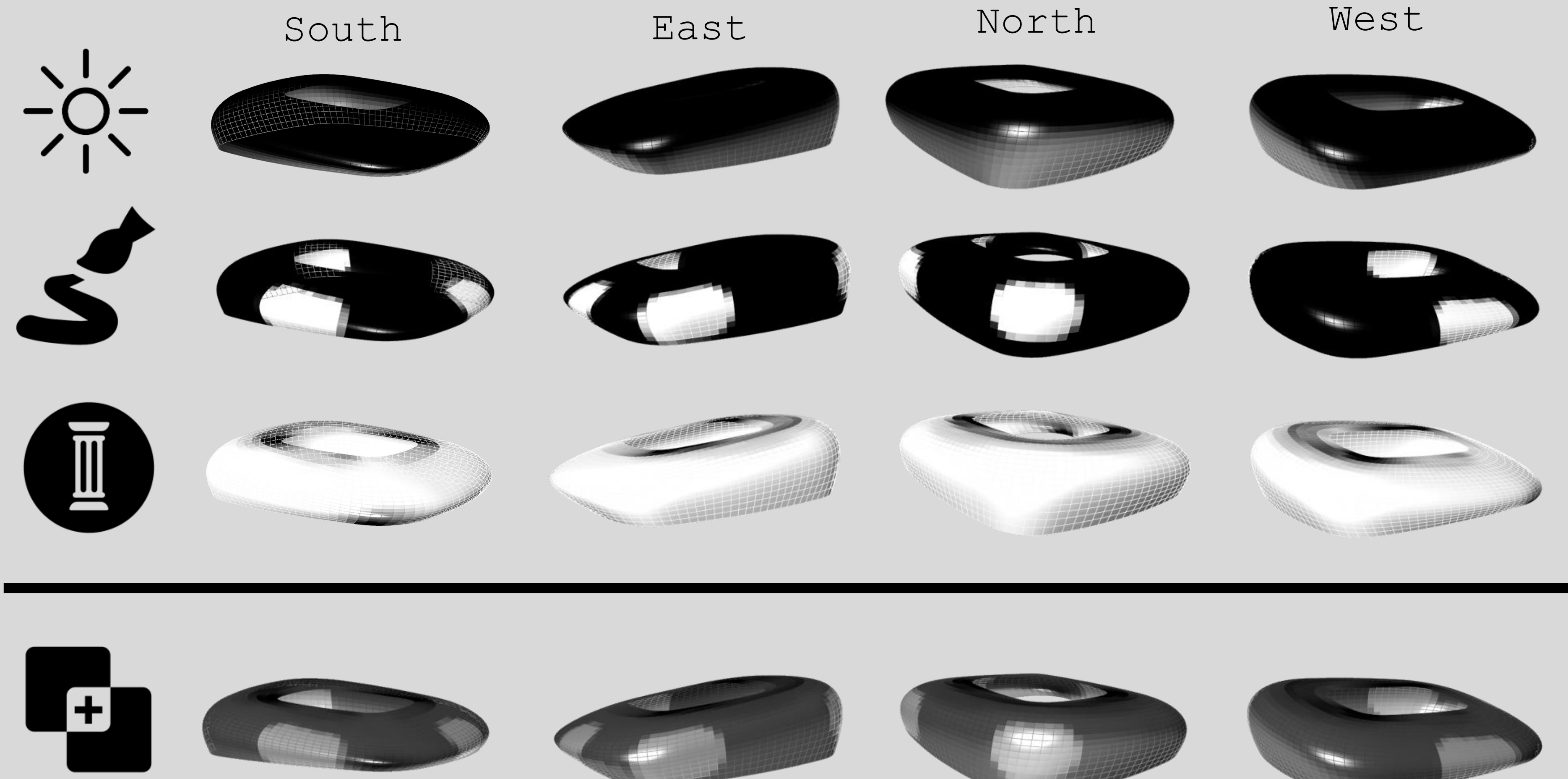

LAAN VAN ZUID
NEW STADIUM
STRIP
KUIP PARK
OLD STADIUM
Mallegat Park
Waterfront ontwikkeling
De Veranda
Brug
Topsportcentrum
Coen Moulijnweg
Varkenoord Park
Brug
Sportdorp
Feijenoord
NS-station Rotterdam Stadion

CASE**STUDY**

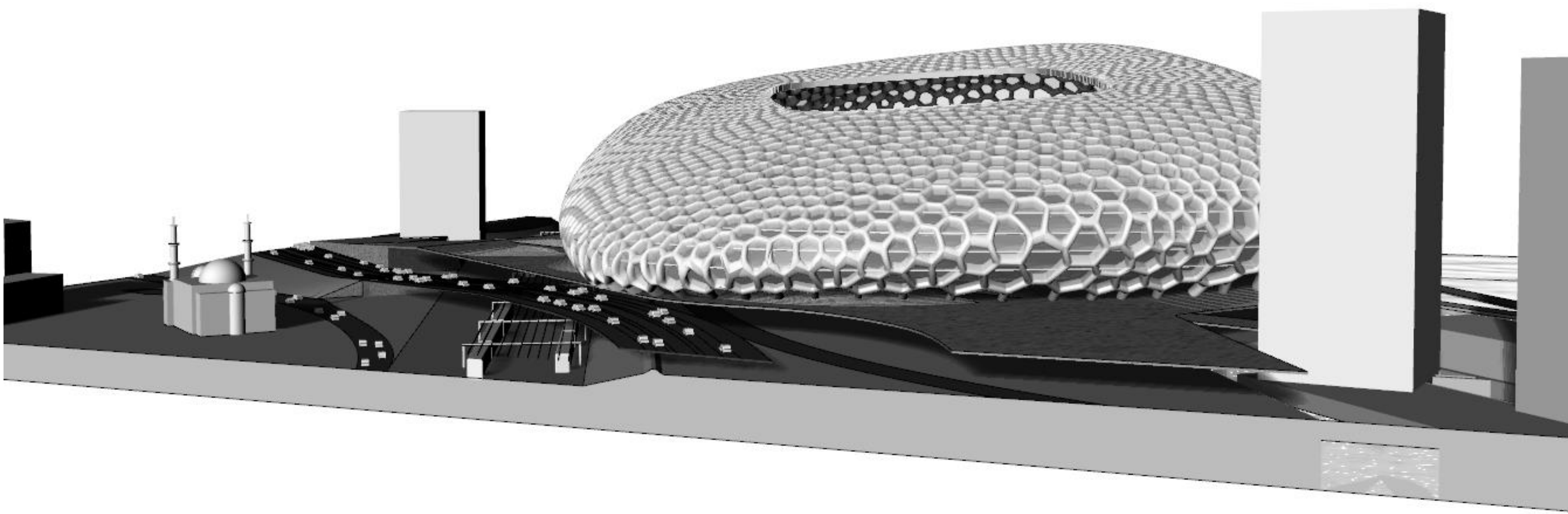




CASE**STUDY**



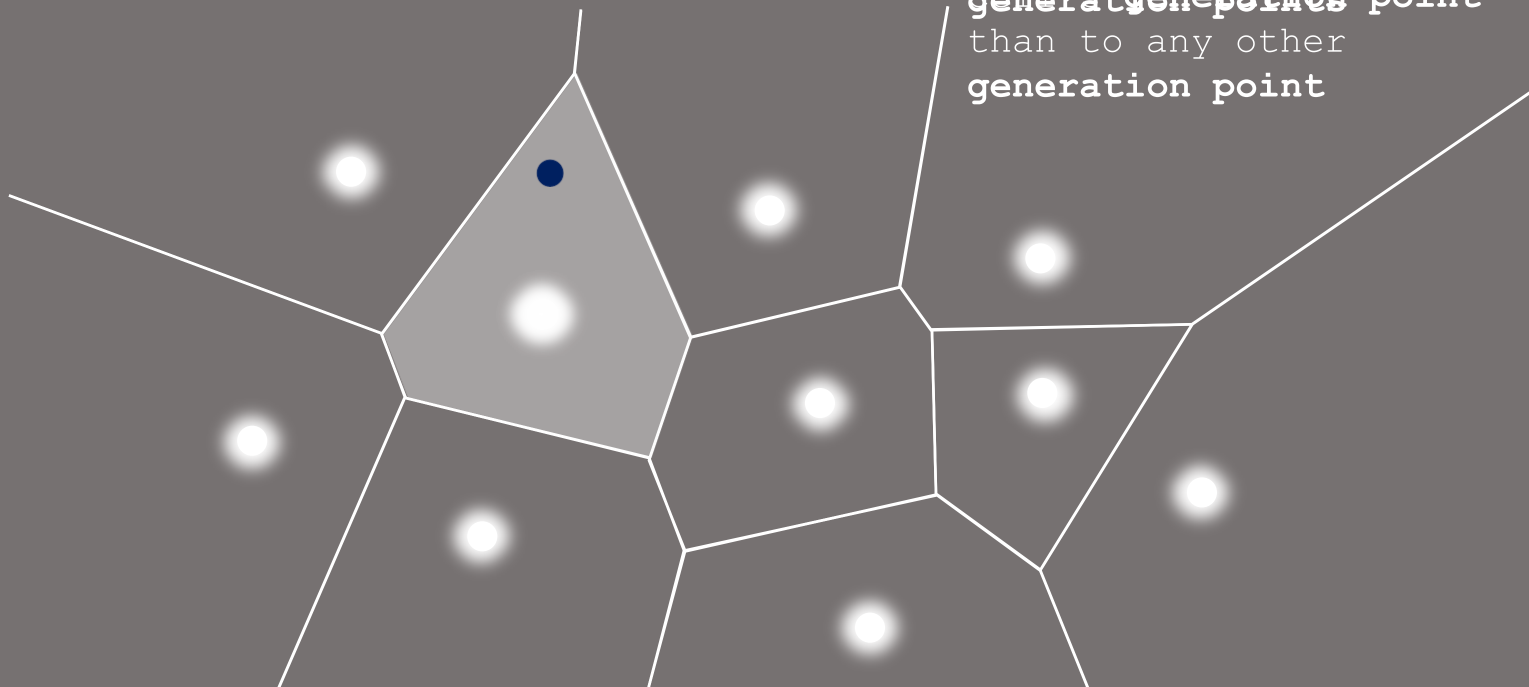
IMPRESSION



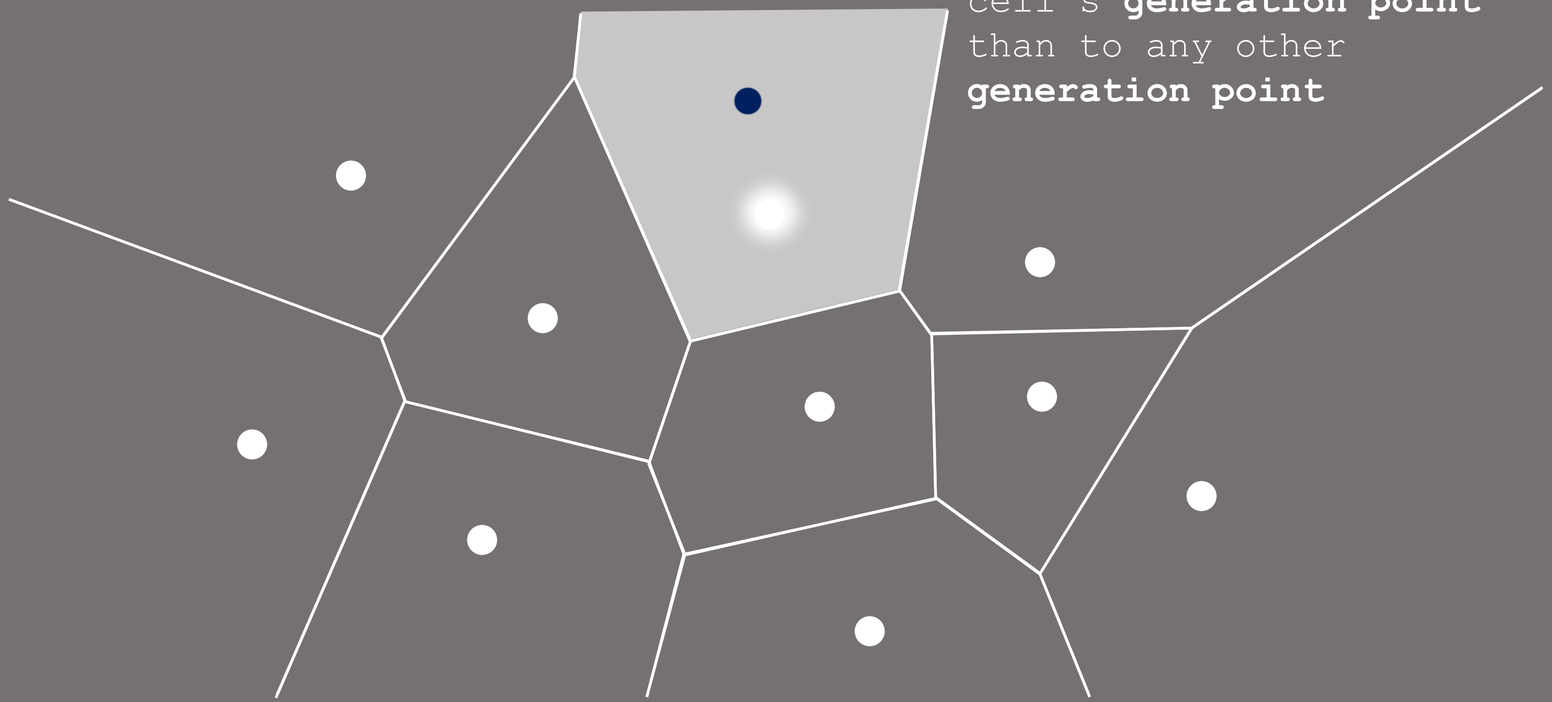
VORONOI **EXPLANATION**

A Voronoi diagram
consists out of and **cells**
generation points

Every point within this
cell lies closer to this
cell's **generation point**
than to any other
generation point



VORONOI **EXPLANATION**

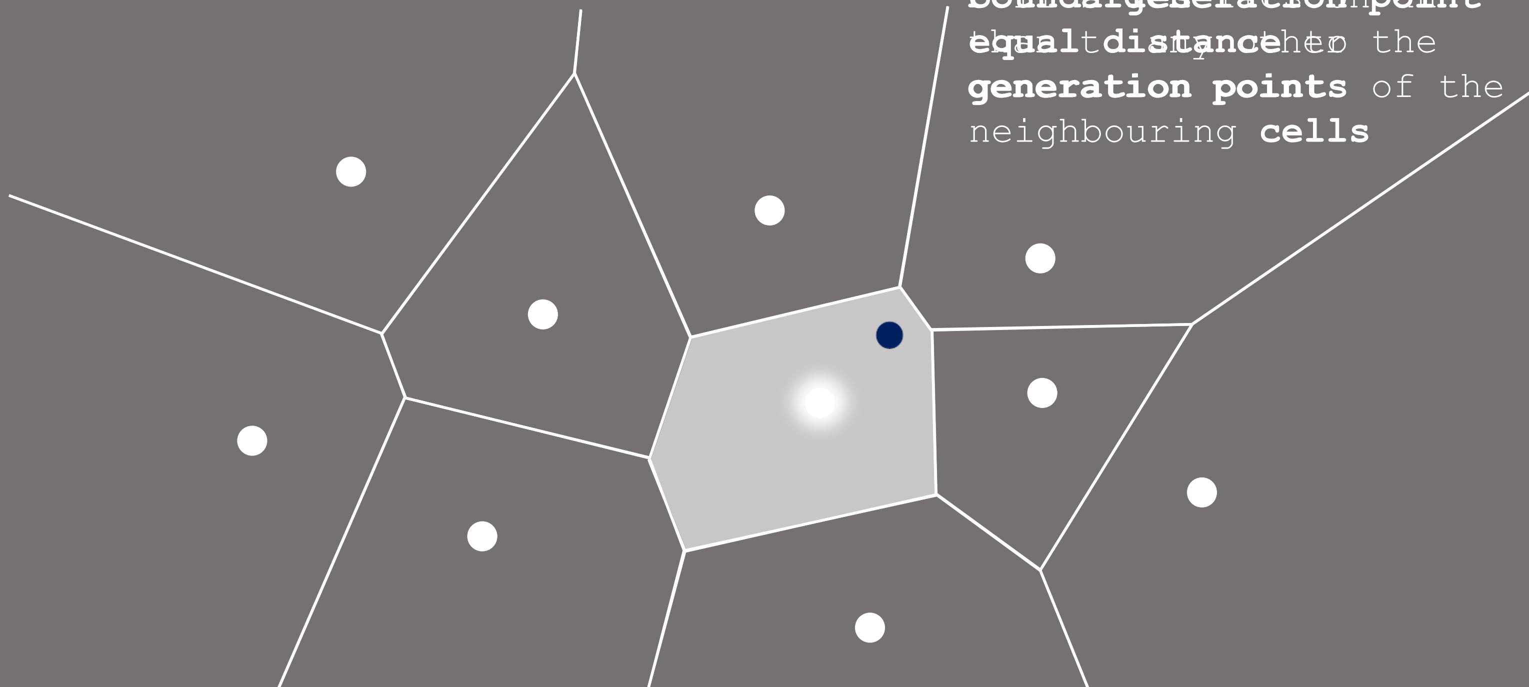


Every point within this **cell** lies closer to this cell’s **generation point** than to any other **generation point**

VORONOI **EXPLANATION**

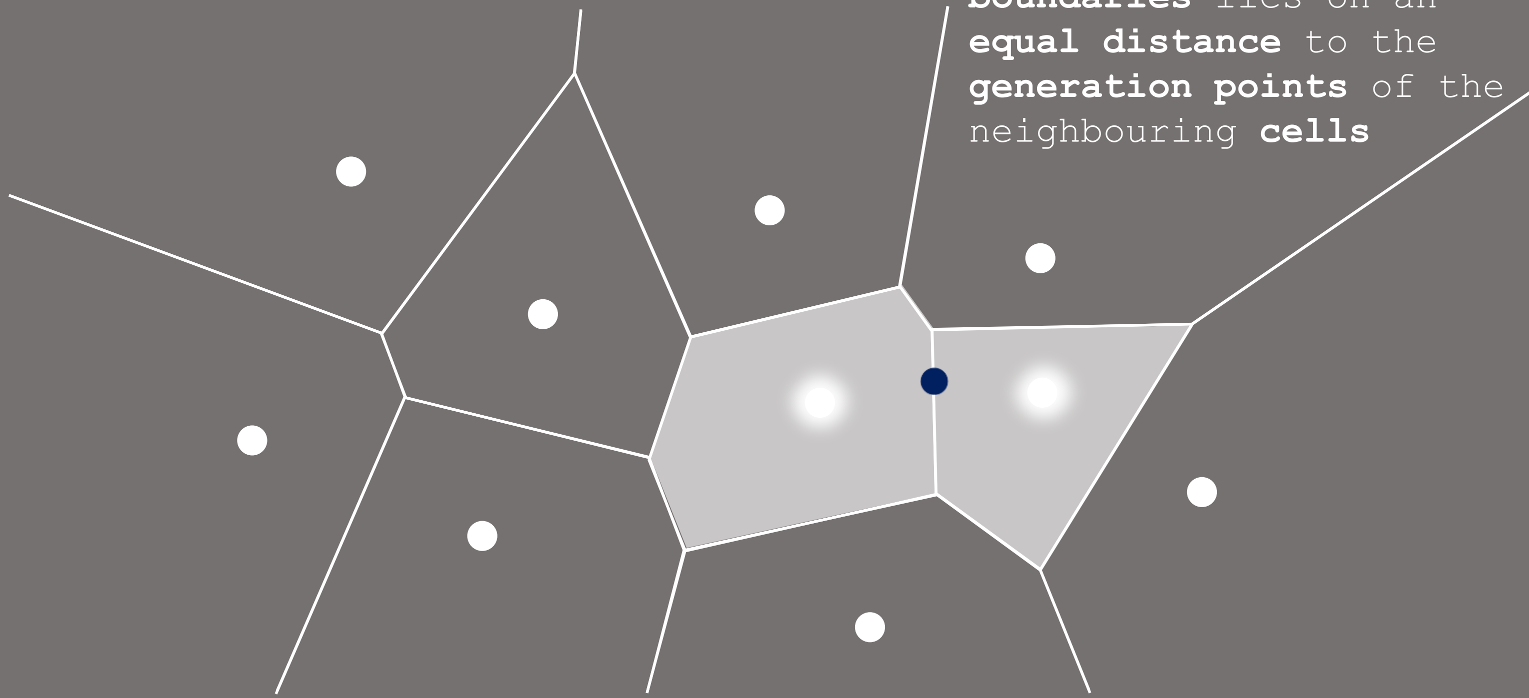
Every point within this **cell** is closer to this cell's **generation point** than to any other

Every point that lies on of the **cell** **boundary** is at an **equal distance** to the **generation points** of the neighbouring **cells**



VORONOI **EXPLANATION**

Every point that lies on one of the **cell boundaries** lies on an **equal distance** to the **generation points** of the neighbouring **cells**



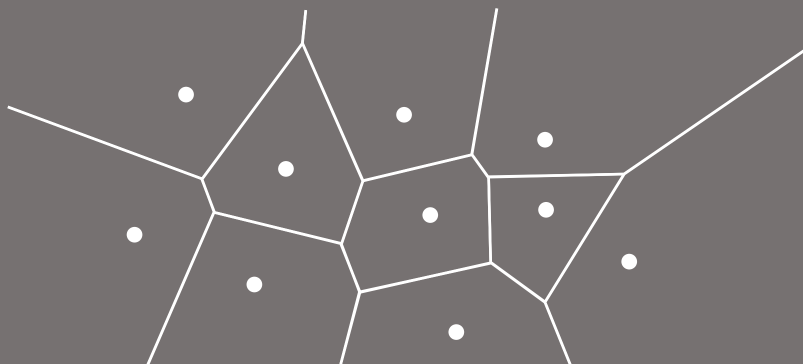
VORONOI **EXPLANATION**

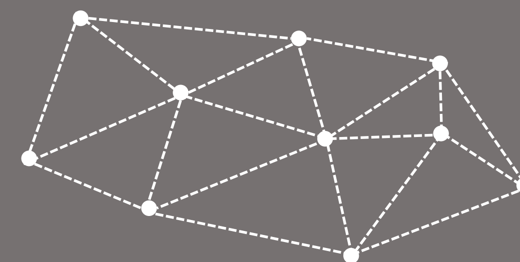
Every point that lies on one of the **cell boundaries** lies at an **equal distance** to the **generation points** of the neighbouring **cells**

The Delaunay diagram can be drawn by connecting the **generation points** of neighbouring **cells** with a straight line

VORONOI VS

DELAUNAY





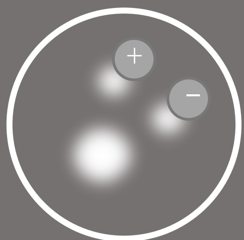
+ Simple connections
 Complies to optical rules
 Suits the desired bonestructure look
 Polygons are not the strongest shape

Additional notes:
1. Needs stiff connections

+ Triangles are the strongest structural shape
– Does not comply to optical rules
 More complex connections

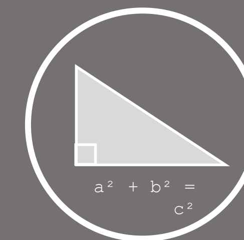
HOW TO GENERATE

A GRADED VORONOI



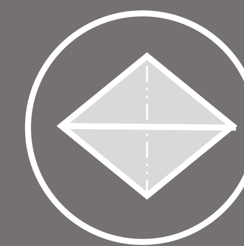
Adding or Subtracting Points

Circle Packing based on Mathematical Theorems



Relaxation techniques

Remeshing Techniques

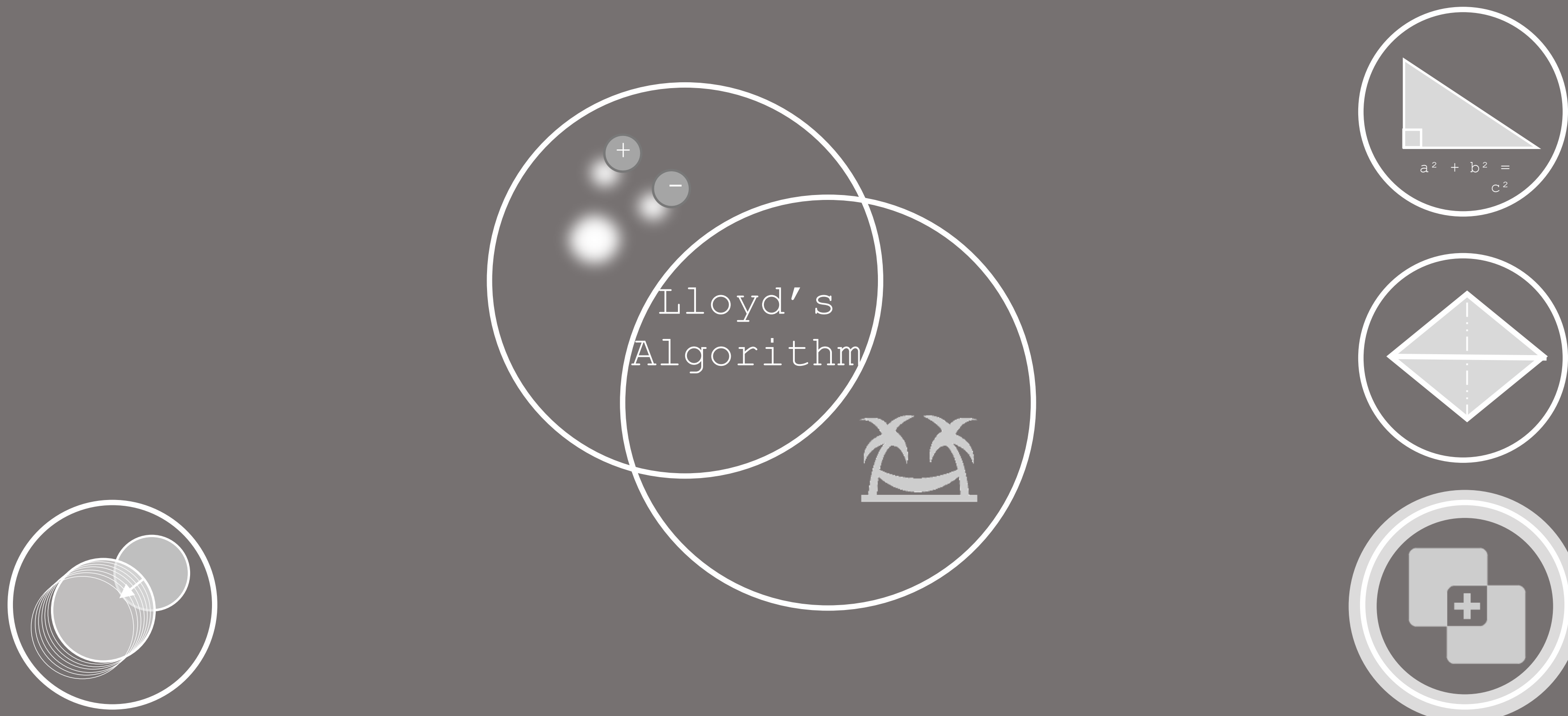


Force-driven Circle Packing

Combination of Techniques

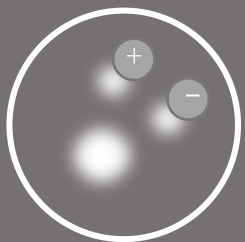
HOW TO GENERATE

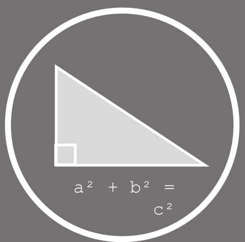
A GRADED VORONOI

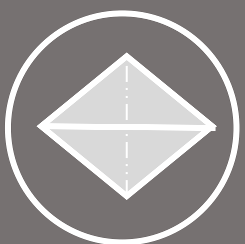


HOW TO GENERATE

A GRADED VORONOI







HOW TO GENERATE
A GRADED VORONOI

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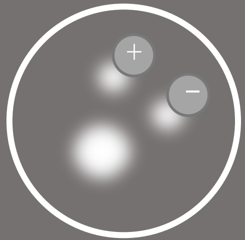

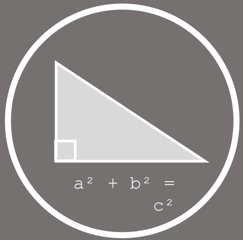

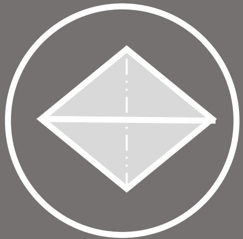

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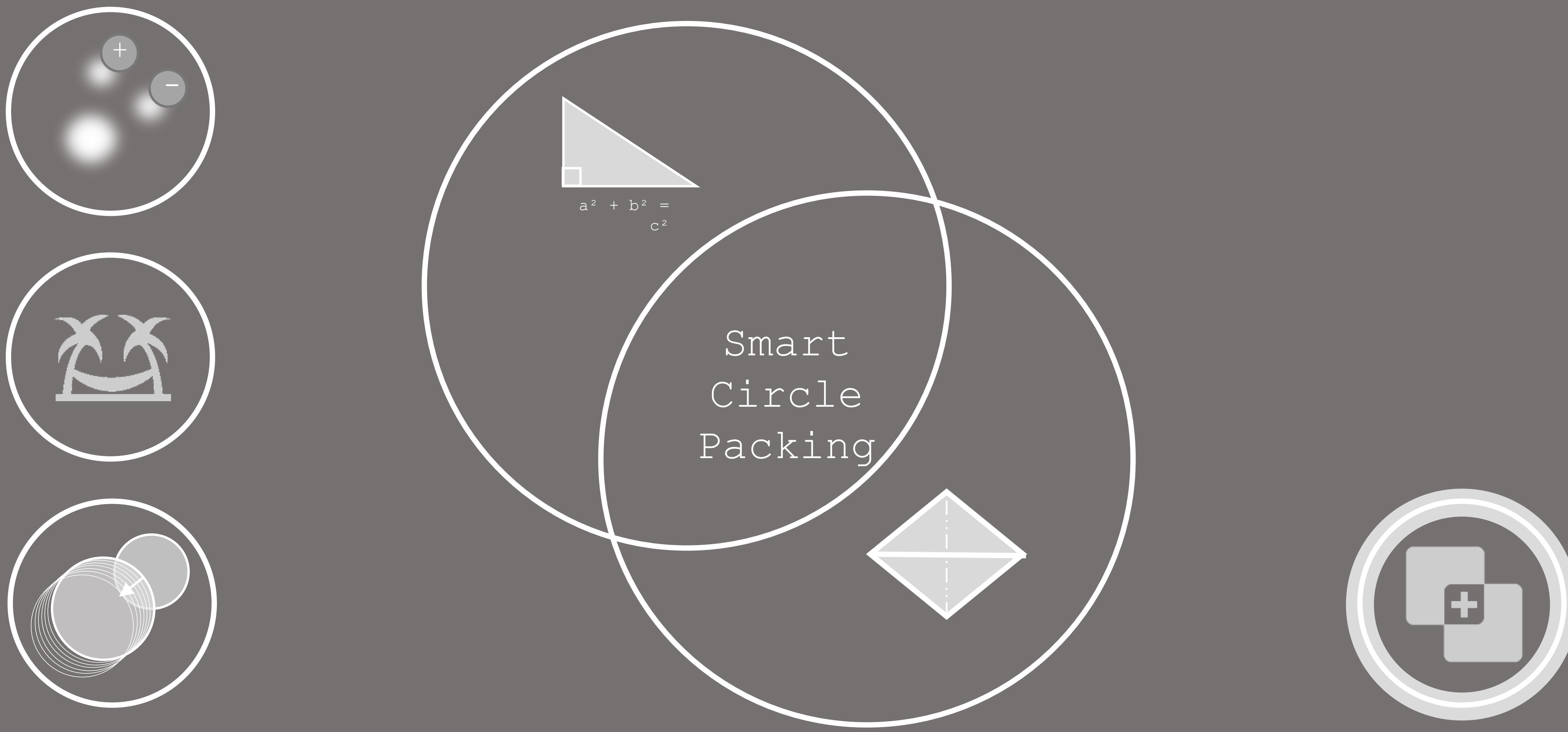
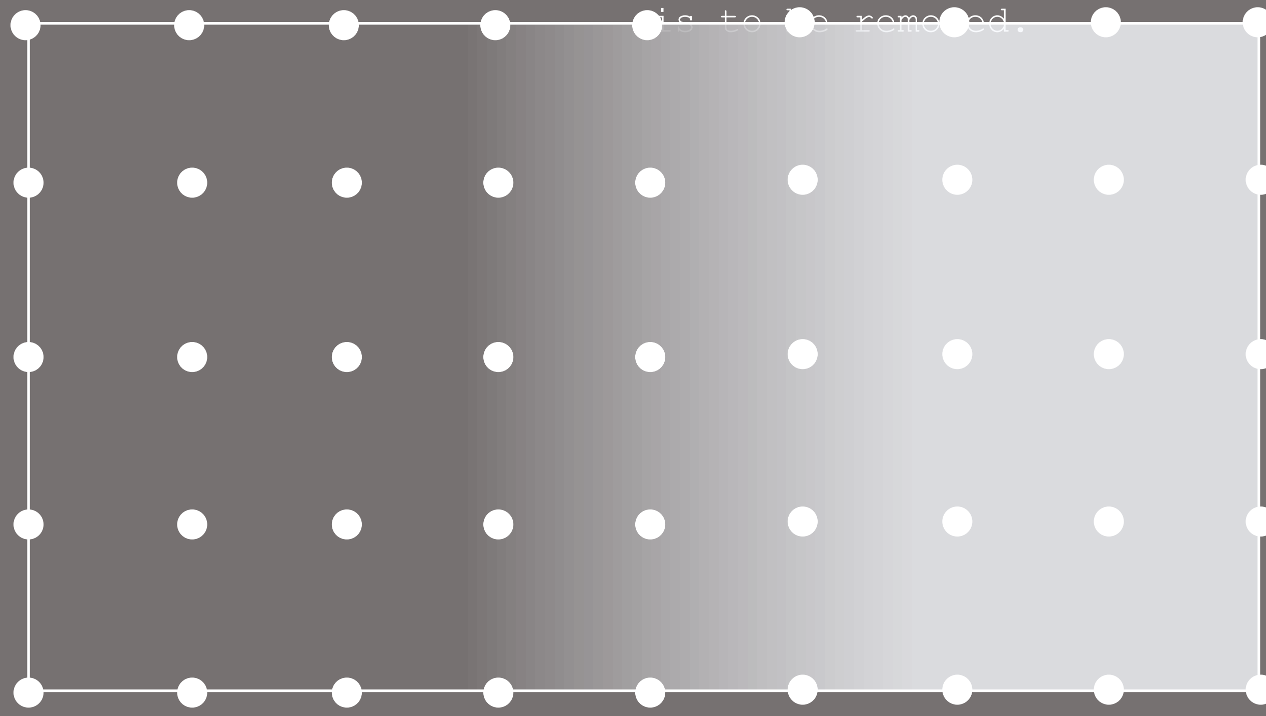


LLOYDS'S

ALGORITHM

Points on the lighter parts of the image map are removed. The lighter the area the more likely a point is to be removed.

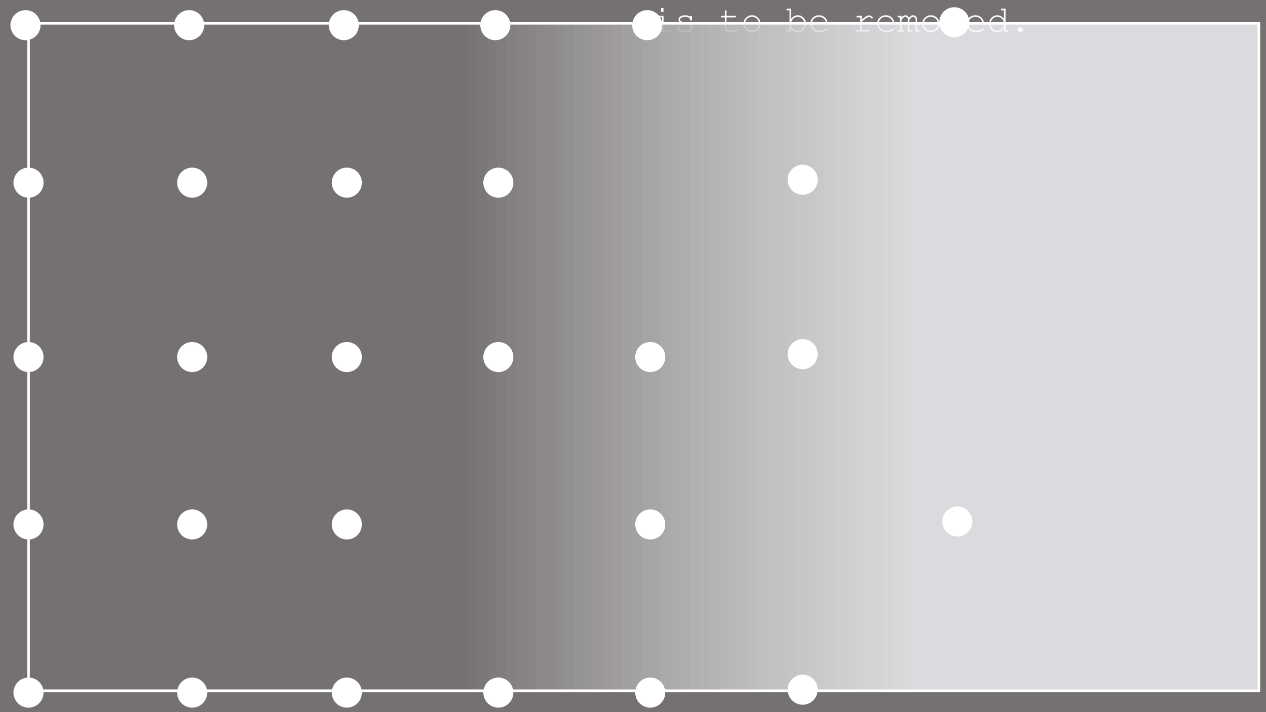


LLOYDS'S

ALGORITHM

Points on the lighter parts of the image map are removed. The lighter the area the more likely a point is to be removed.

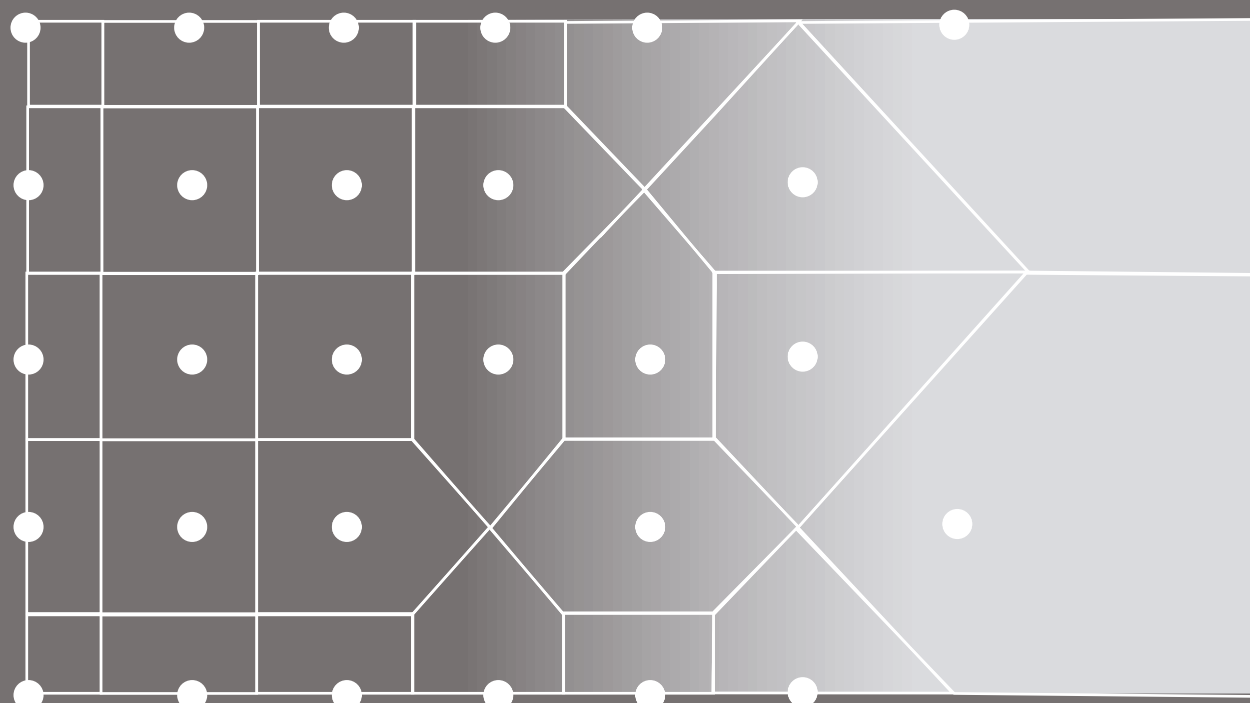
Then, a Voronoi is generated based on the remaining points.



LLOYDS'S

ALGORITHM

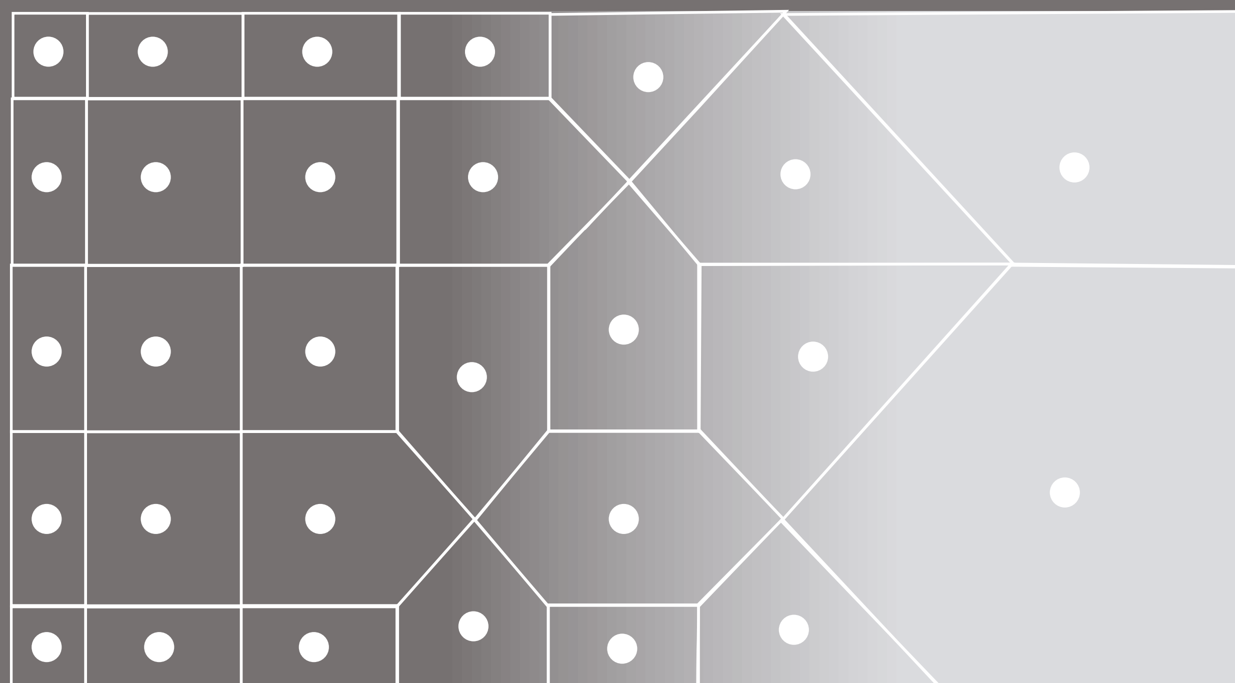
Then, every Voronoi cell is generated based on the remaining points.



LLOYDS'S

ALGORITHM

For every cell the center of mass is calculated.



ITERATION 1

LLOYDS'S

ALGORITHM

With these points a new Voronoi is generated. This can be repeated multiple times.

ITERATION 1

LLOYDS'S

ALGORITHM

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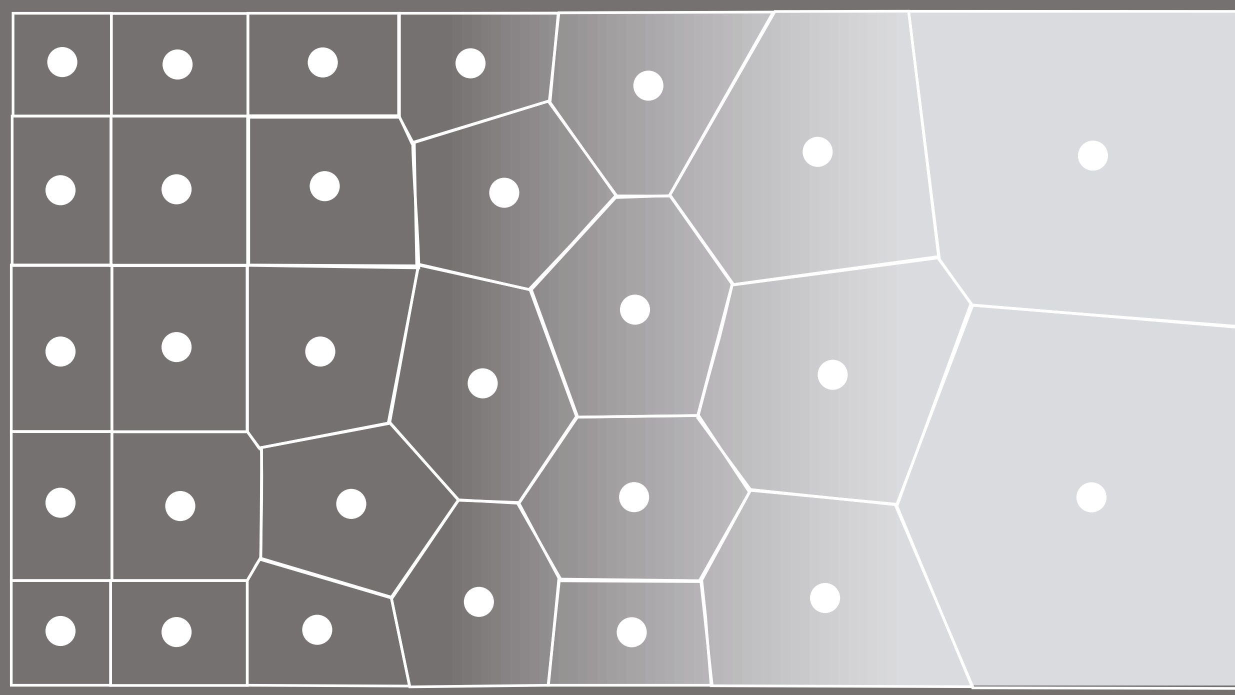


ITERATION 2

LLOYDS'S

ALGORITHM

With these points a new Voronoi is generated. This can be repeated multiple times.

ITERATION 2

LLOYDS'S

ALGORITHM

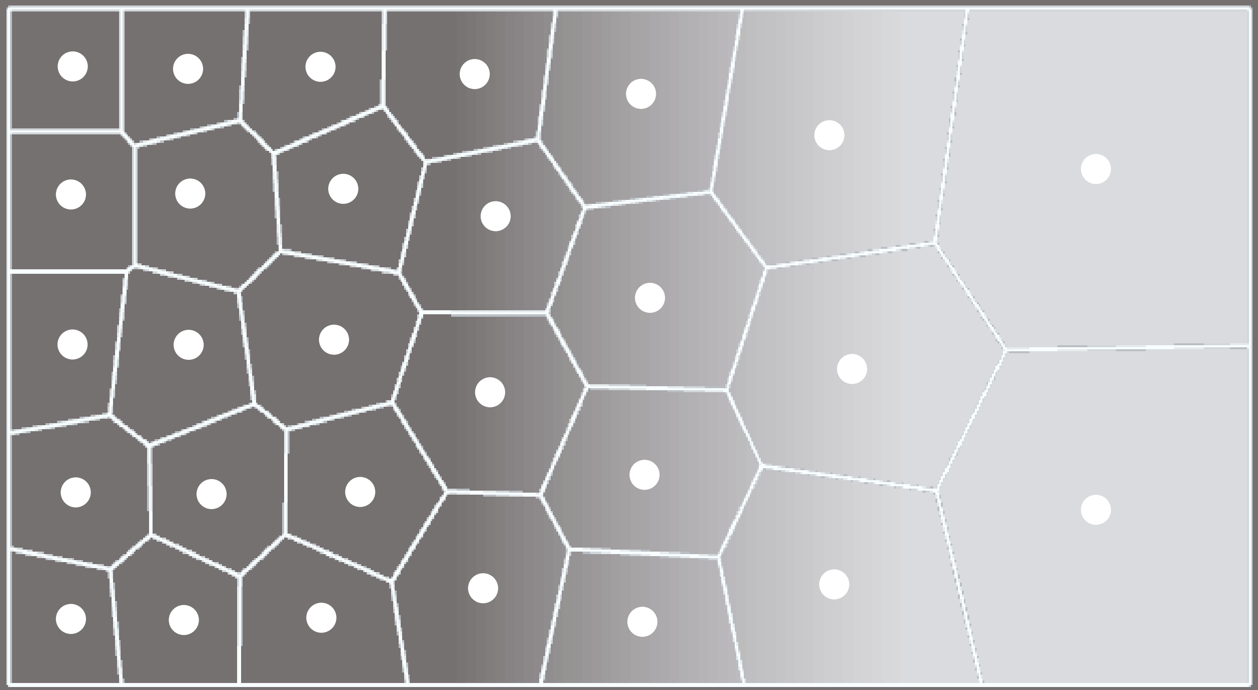
With these points a new Voronoi is generated. This can be repeated multiple times.

ITERATION 3

LLOYDS'S

ALGORITHM

With these points a new Voronoi is generated. This can be repeated multiple times.

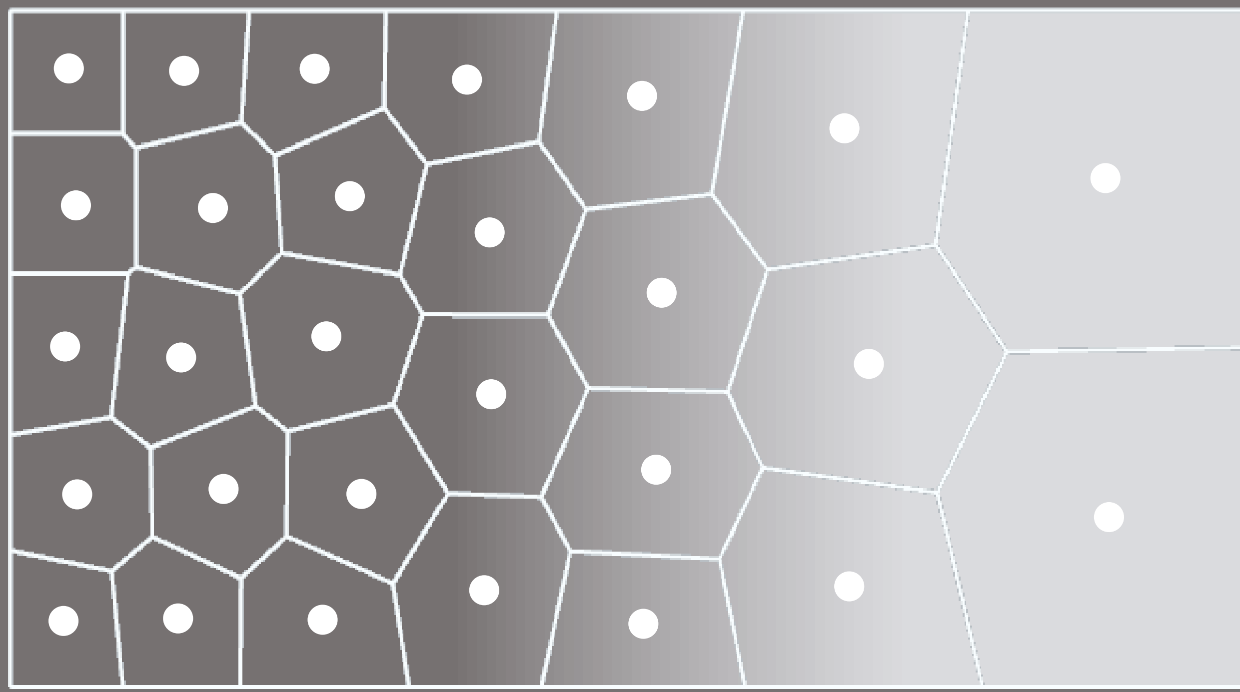


ITERATION 3

LLOYDS'S

ALGORITHM

With these points a new Voronoi is generated. This can be repeated multiple times.

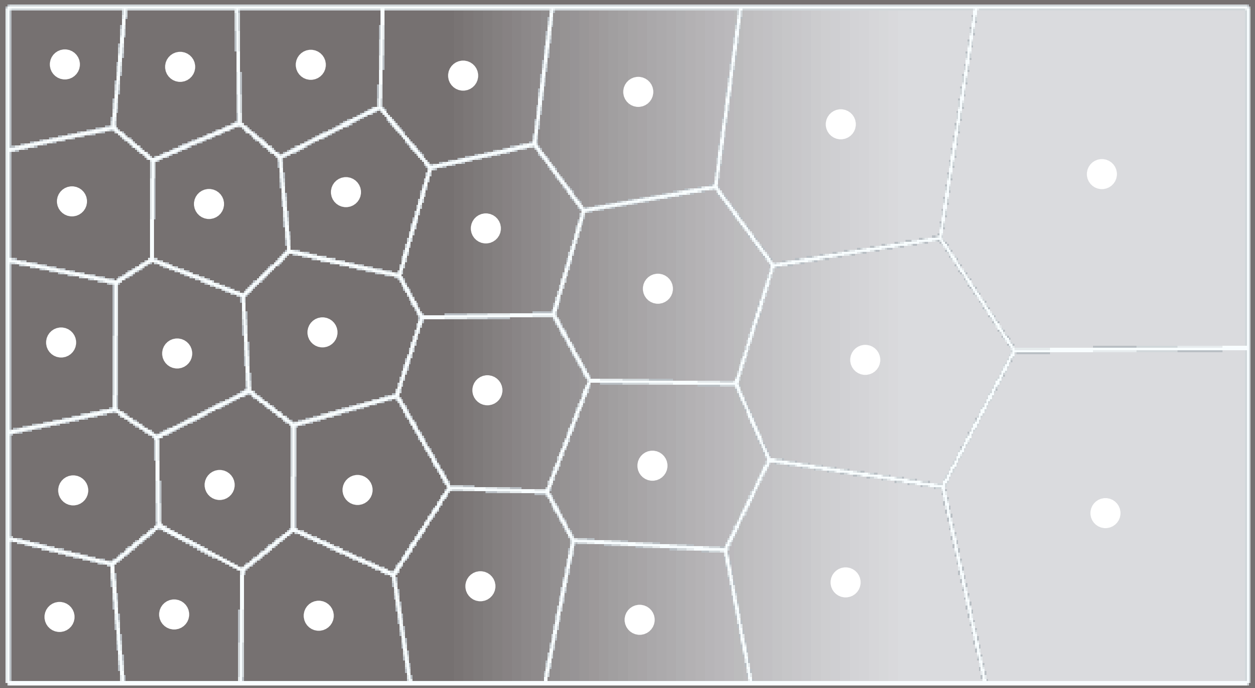


ITERATION 4

LLOYDS'S

ALGORITHM

With these points a new Voronoi is generated. This can be repeated multiple times.



ITERATION 4

LLOYDS'S

ALGORITHM

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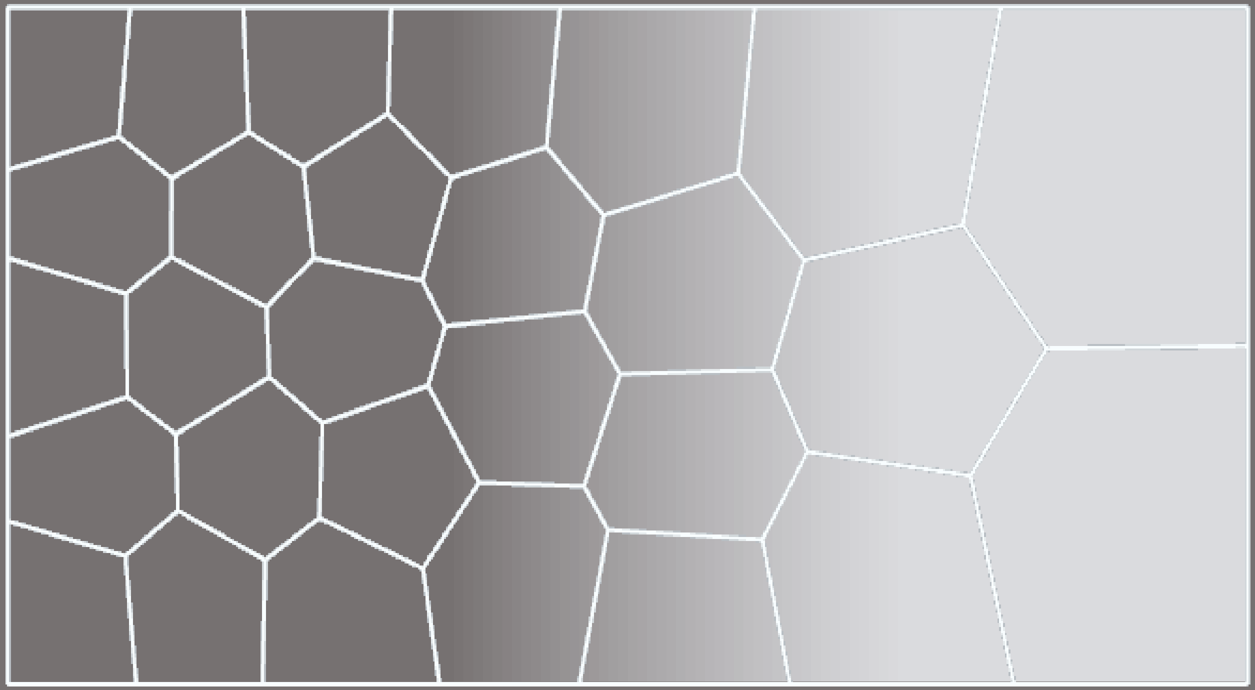
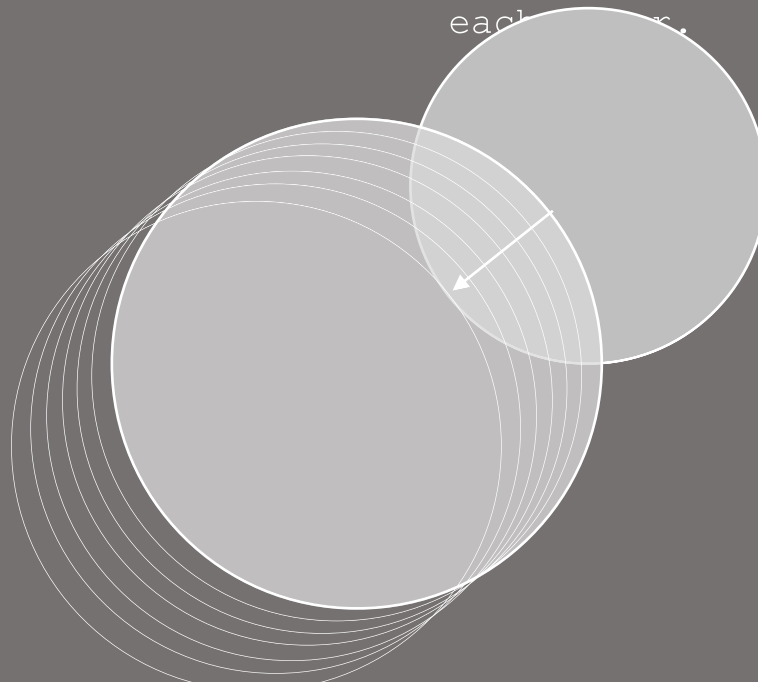


ITERATION 10

SPRING FORCE

SYSTEM

When circles overlap they push each other away, when there is a distance between two circles they attract each other.

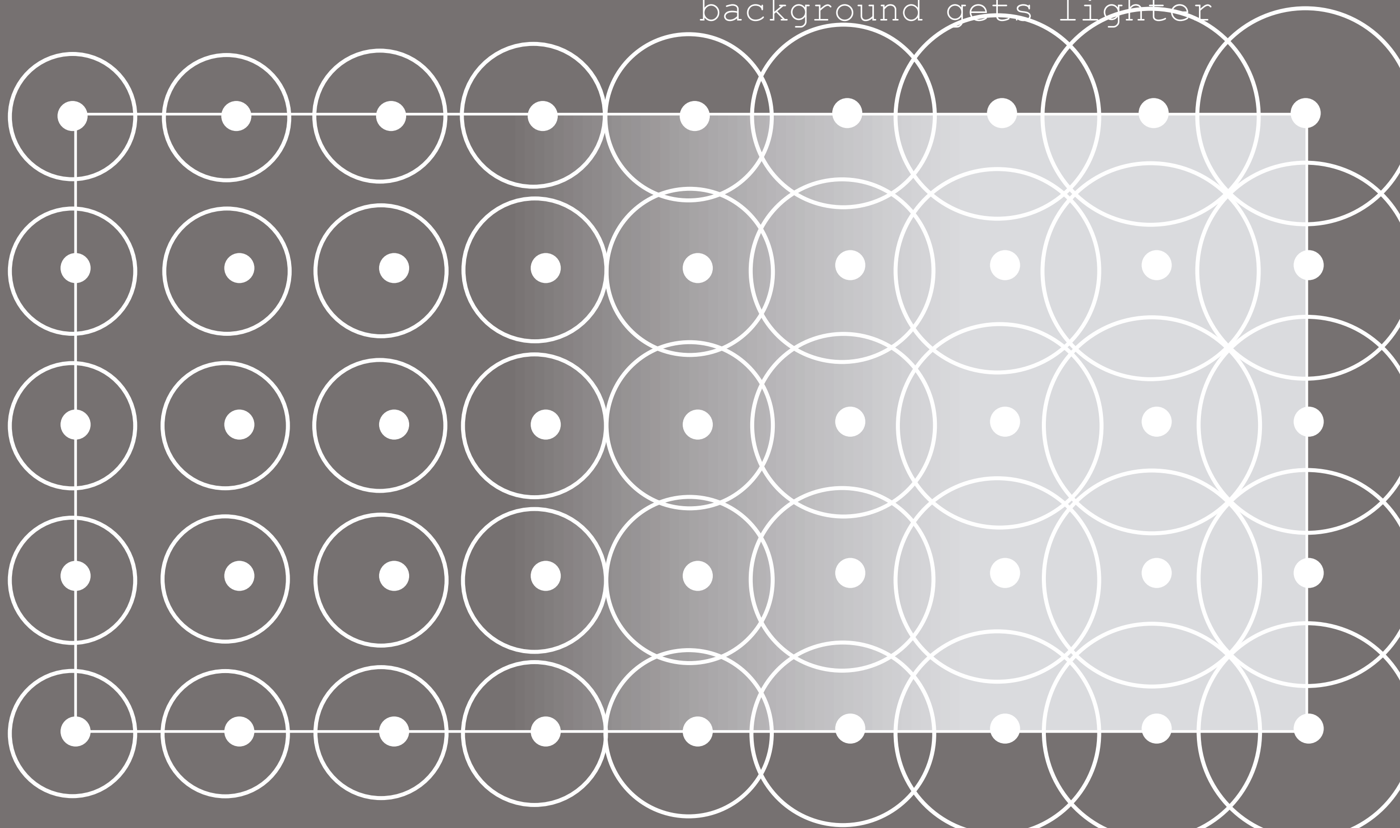


SPRING FORCE

SYSTEM

every point has a circle with a diameter that gets larger when the background gets lighter

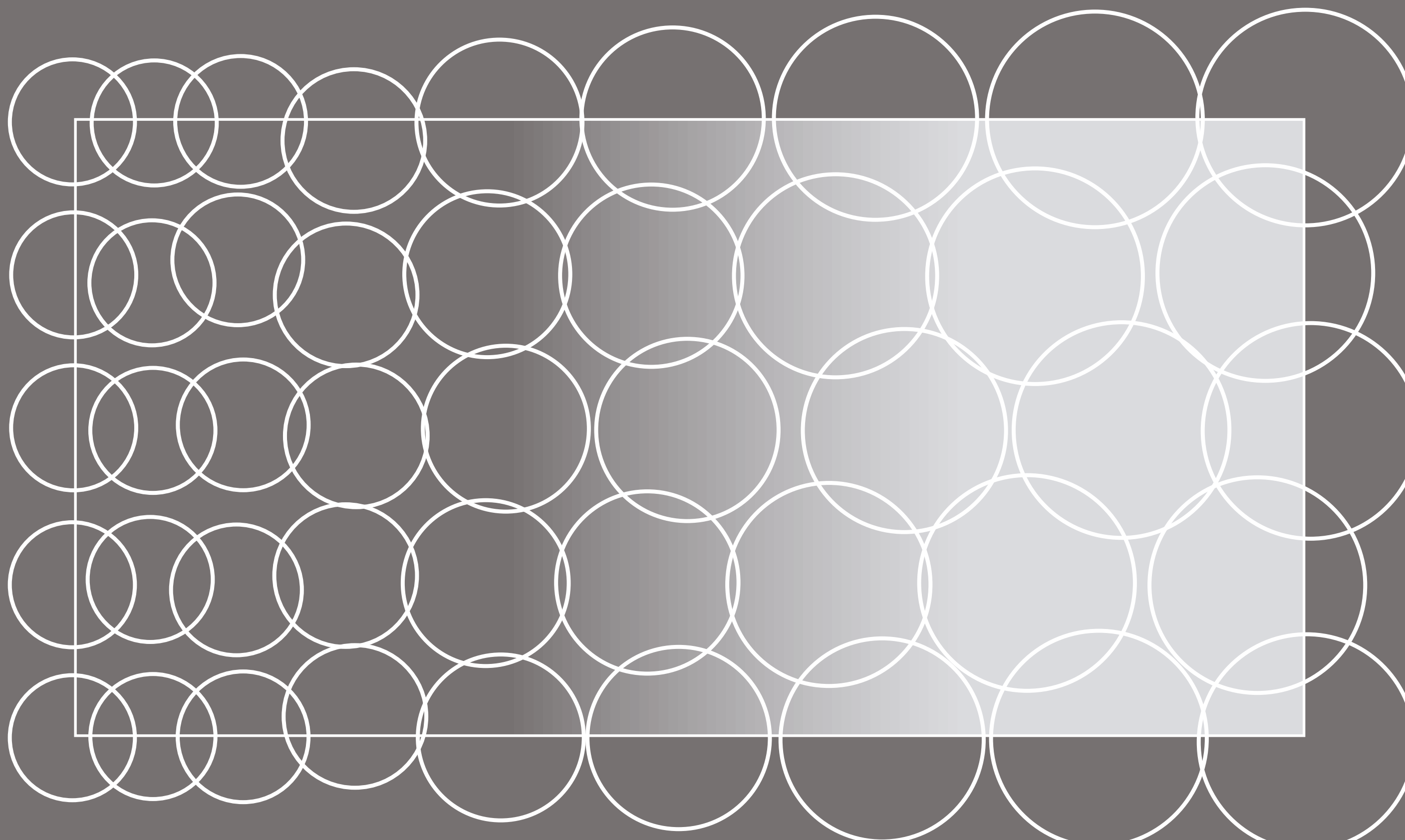
The circles will start repelling and attracting each other



SPRING FORCE

SYSTEM

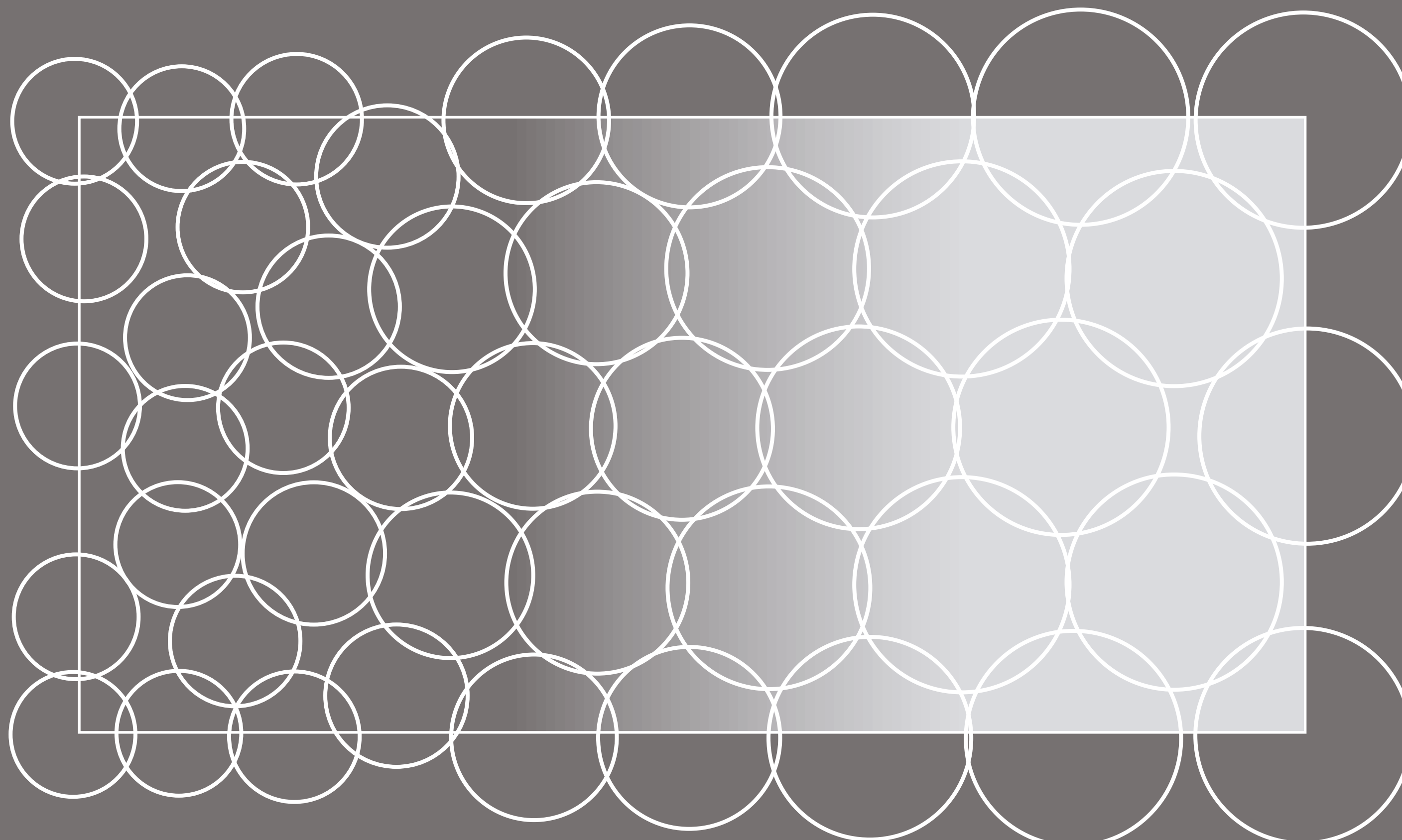
Then the circles will start repelling and attracting each other



SPRING FORCE

SYSTEM

Then the circles will start repelling and attracting each other

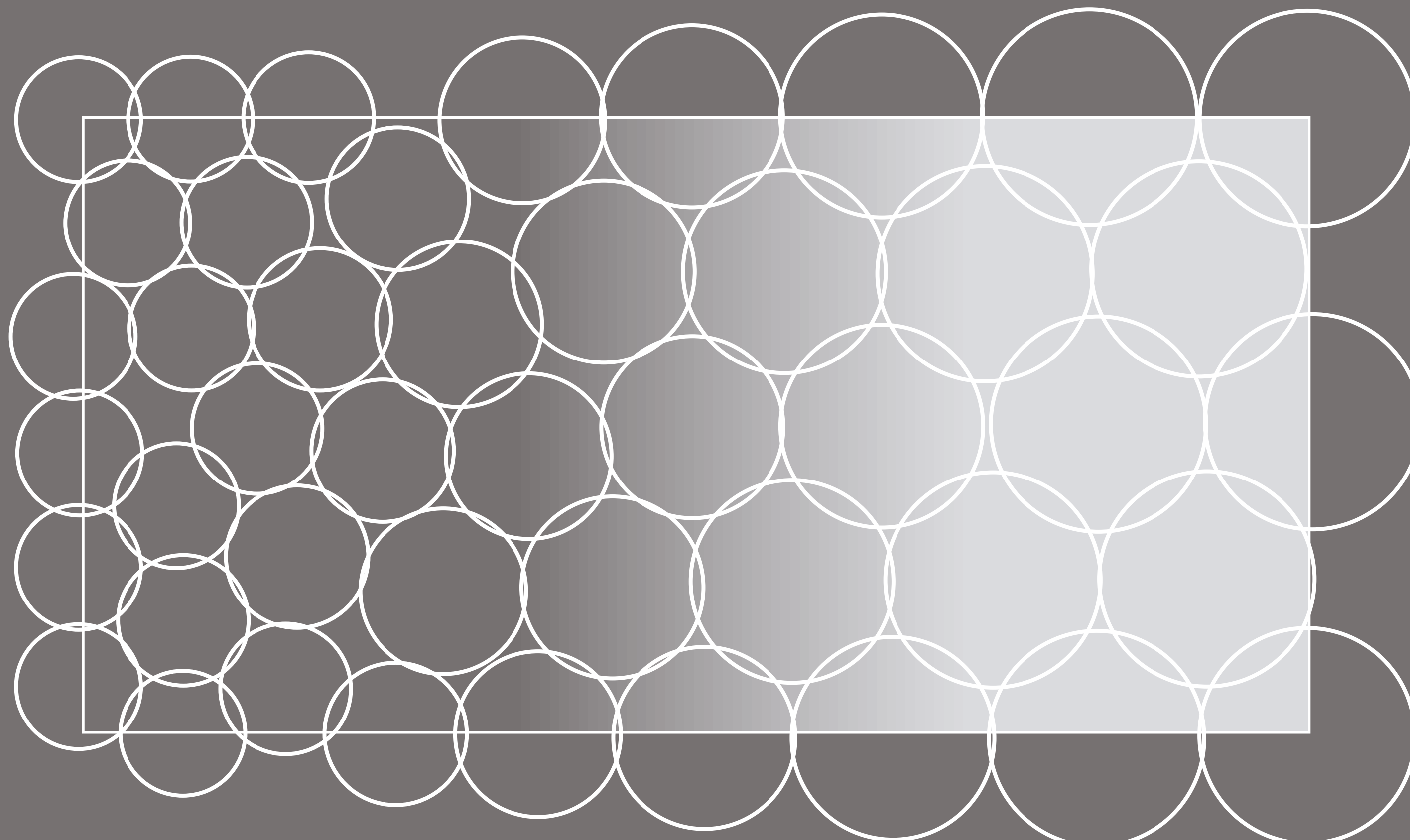


SPRING FORCE

SYSTEM

Then the centers will start repelling and attracting each other

Then the center points of the circles are used to generate a Voronoi diagram



SPRING FORCE

SYSTEM

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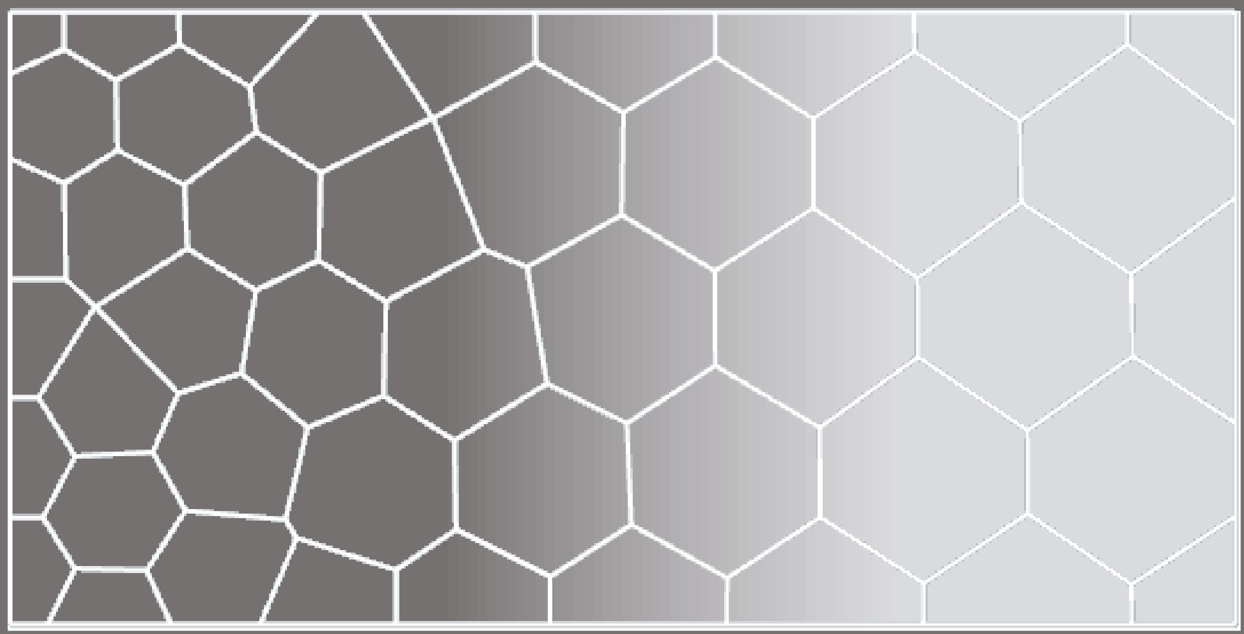


SMART CIRCLE

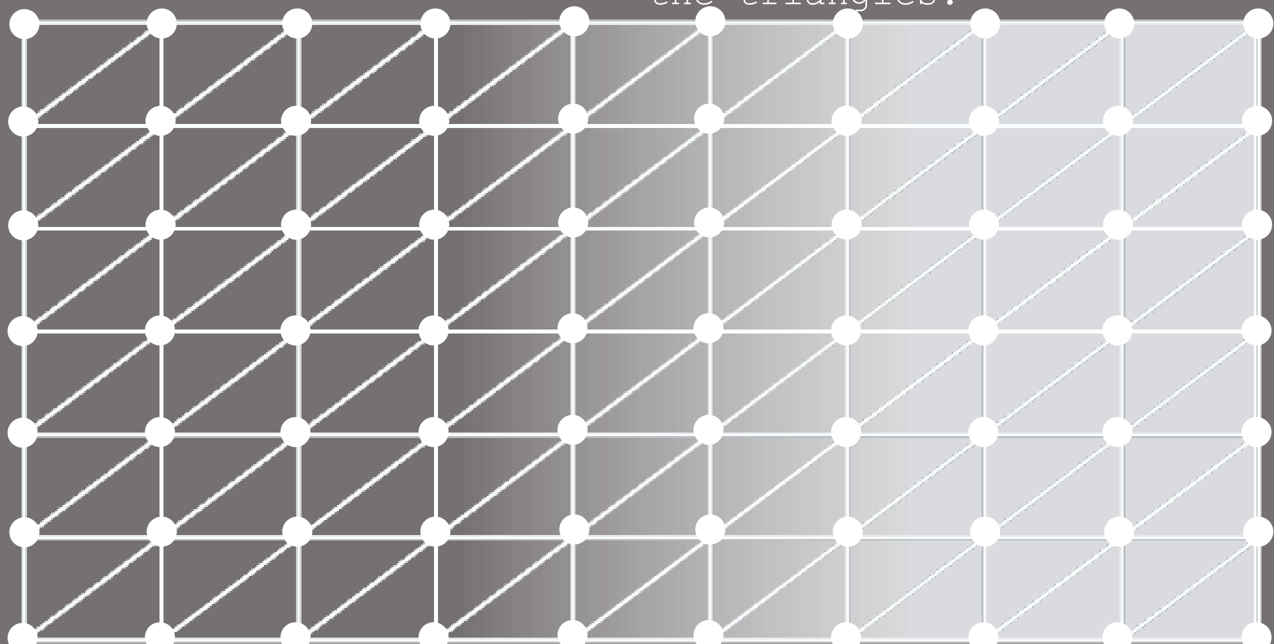
PACKING

Four methods are used to adjust the edge lengths:

- Edge Collapse
- Edge Split
- Edge Flip
- Vertex Shift.

the desired edge length is determined by the underlying image.

the triangles.



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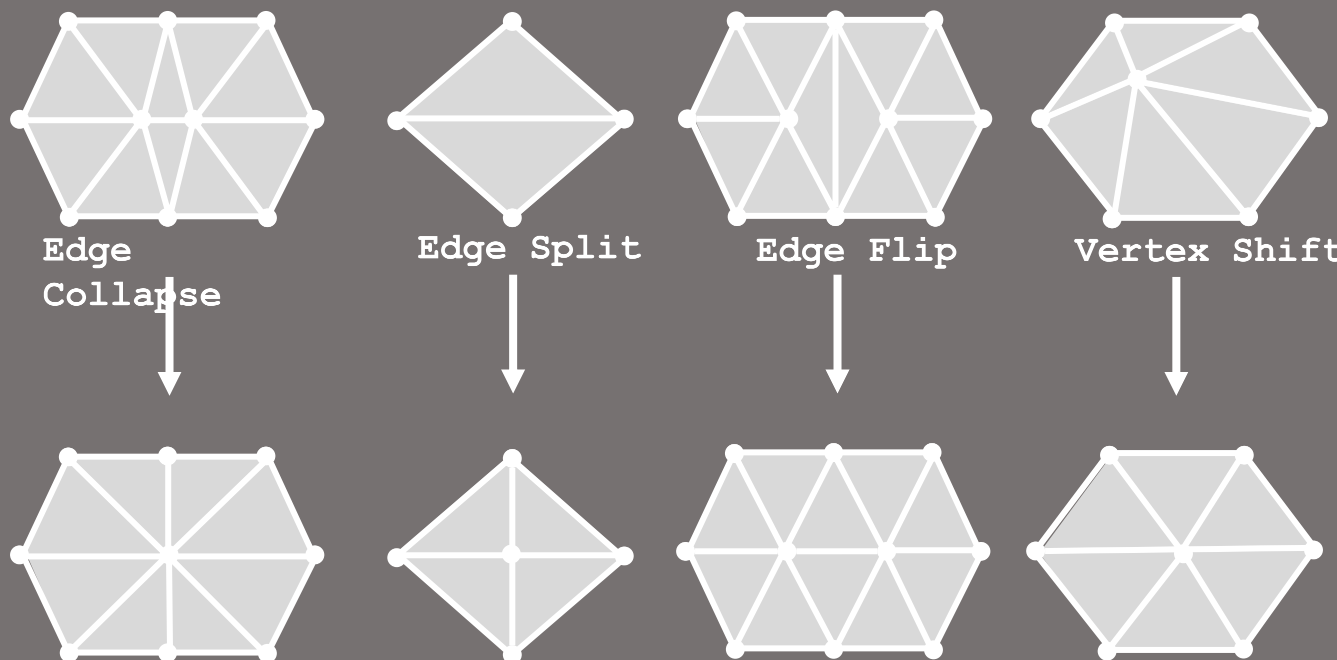
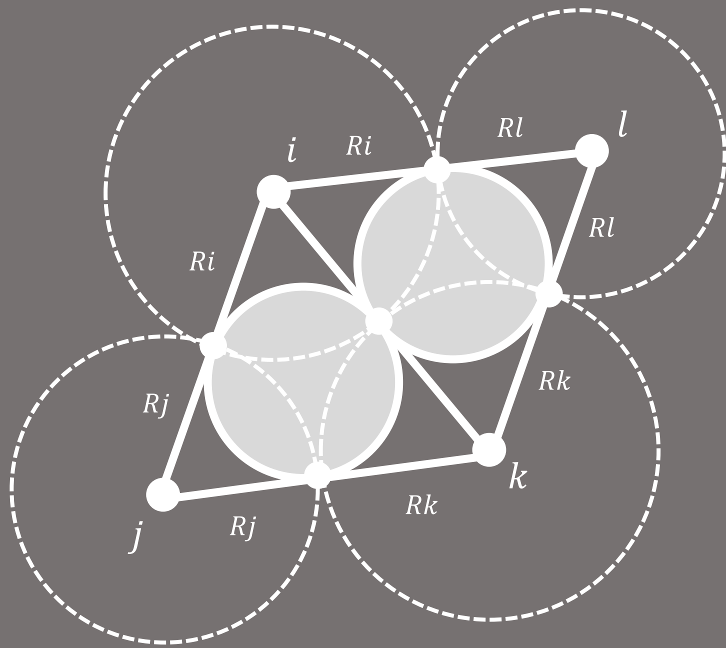


SMART CIRCLE PACKING



The vertex shift is based on a mathematical theorem that ensures the circles that have the corners of the triangles as centerpoints (white dotted circles) are touching each other.

$L_{ij} + L_{kl} = L_{jk} + L_{il}$

The condition of the edges can be derived as follows:

$L_{ij} = R_i + R_j$ and $L_{jk} = R_j + R_k$ and $L_{il} = R_i + R_l$ and $L_{kl} = R_k + R_l$

This means that:

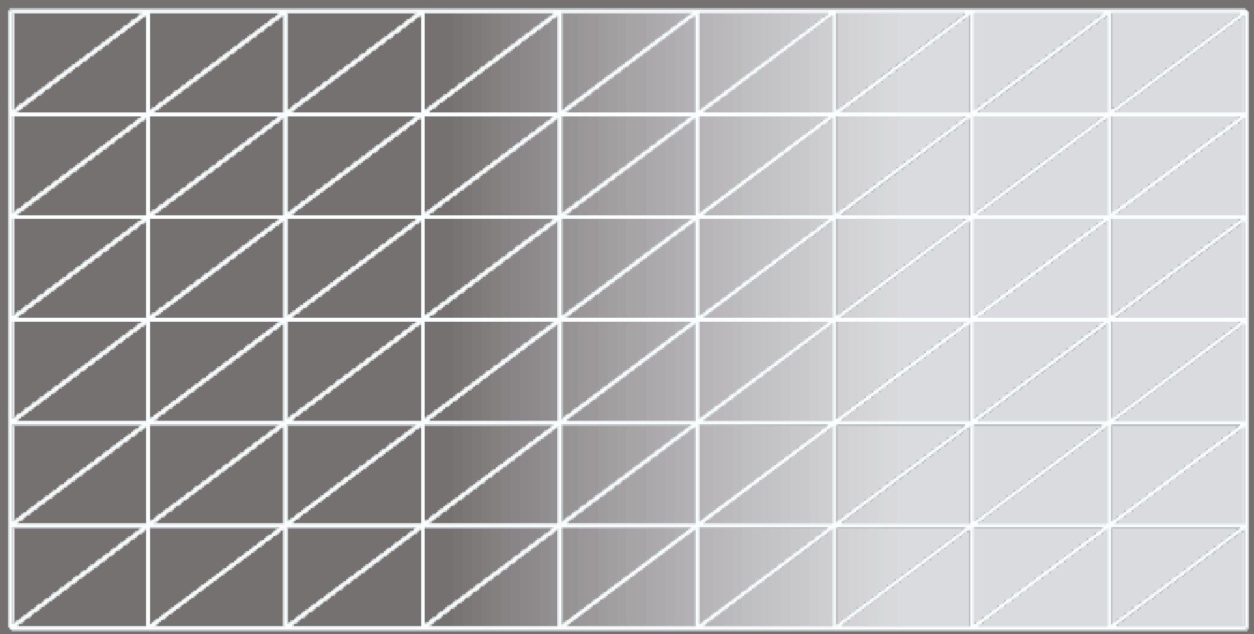
$L_{ij} + L_{kl} = R_i + R_j + R_k + R_l$ and $L_{jk} + L_{il} = R_j + R_k + R_i + R_l$

Or in other words:

$$L_{ij} + L_{kl} = L_{jk} + L_{il}$$

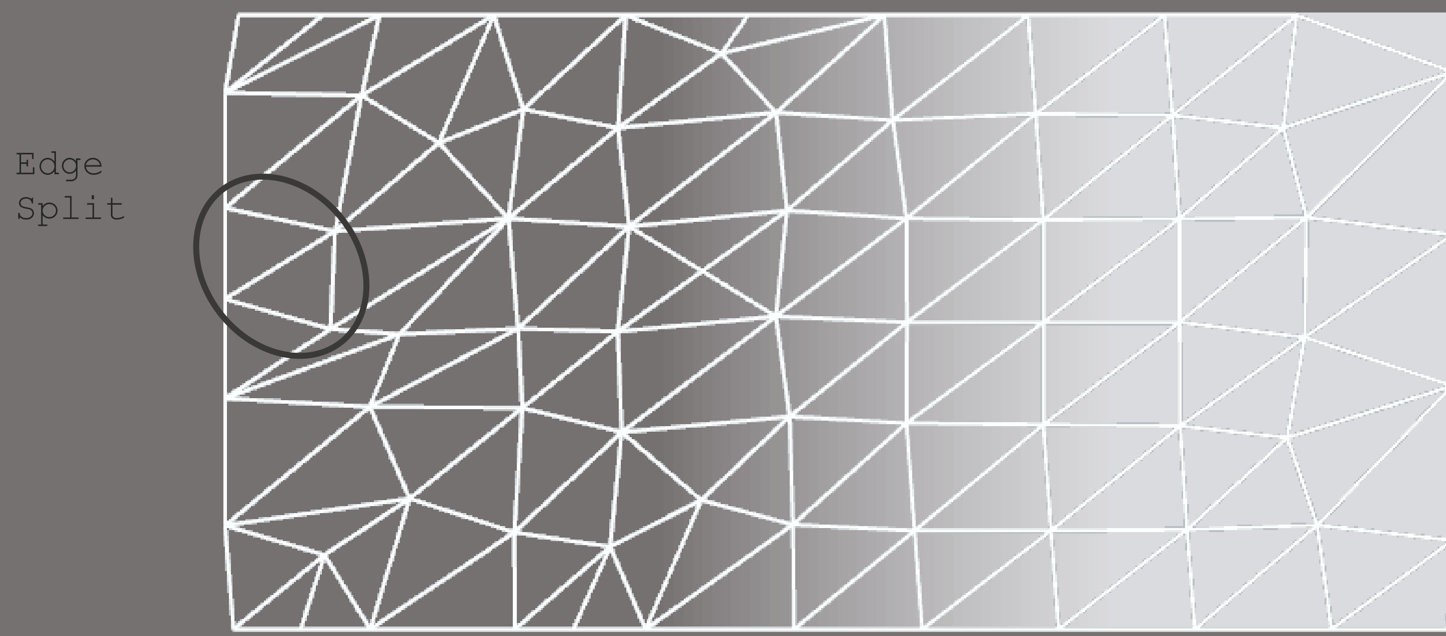
SMART CIRCLE

PACKING



SMART CIRCLE

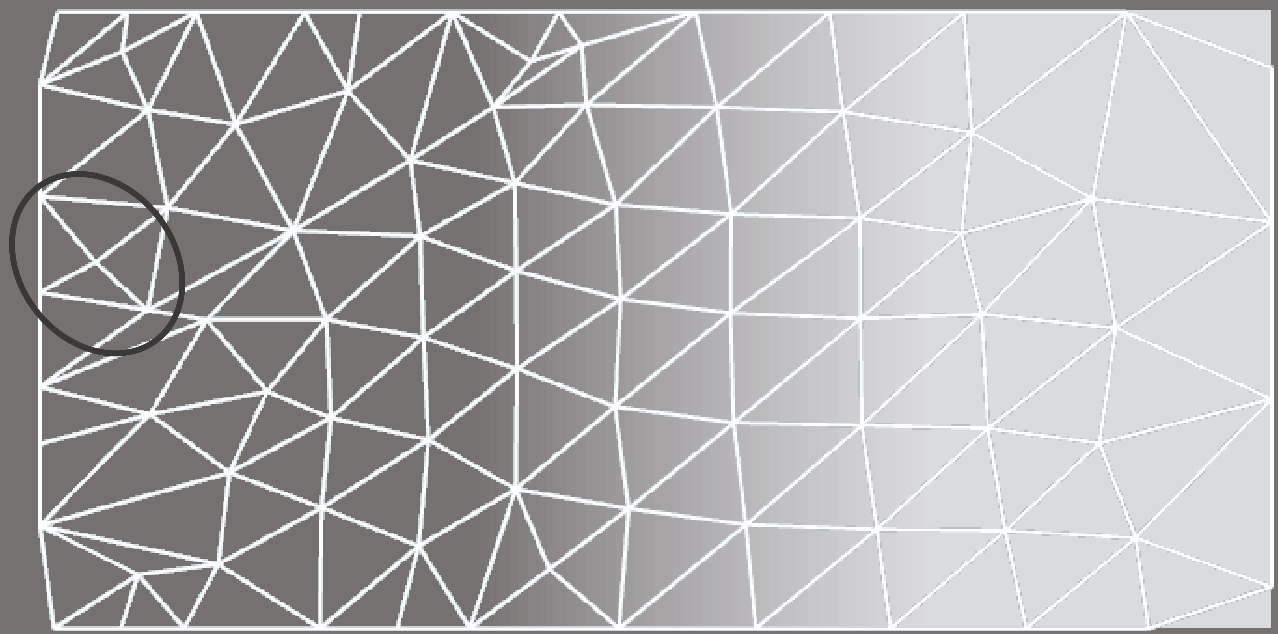
PACKING



SMART CIRCLE

PACKING

Edge
Split



SMART CIRCLE

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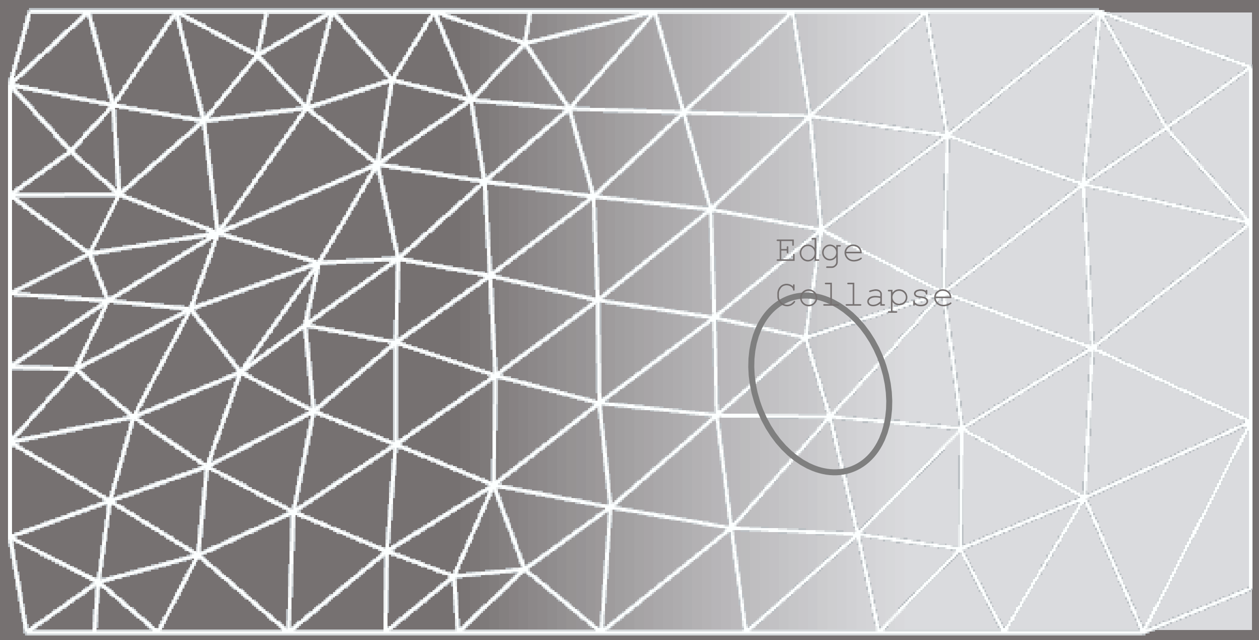

SMART CIRCLE

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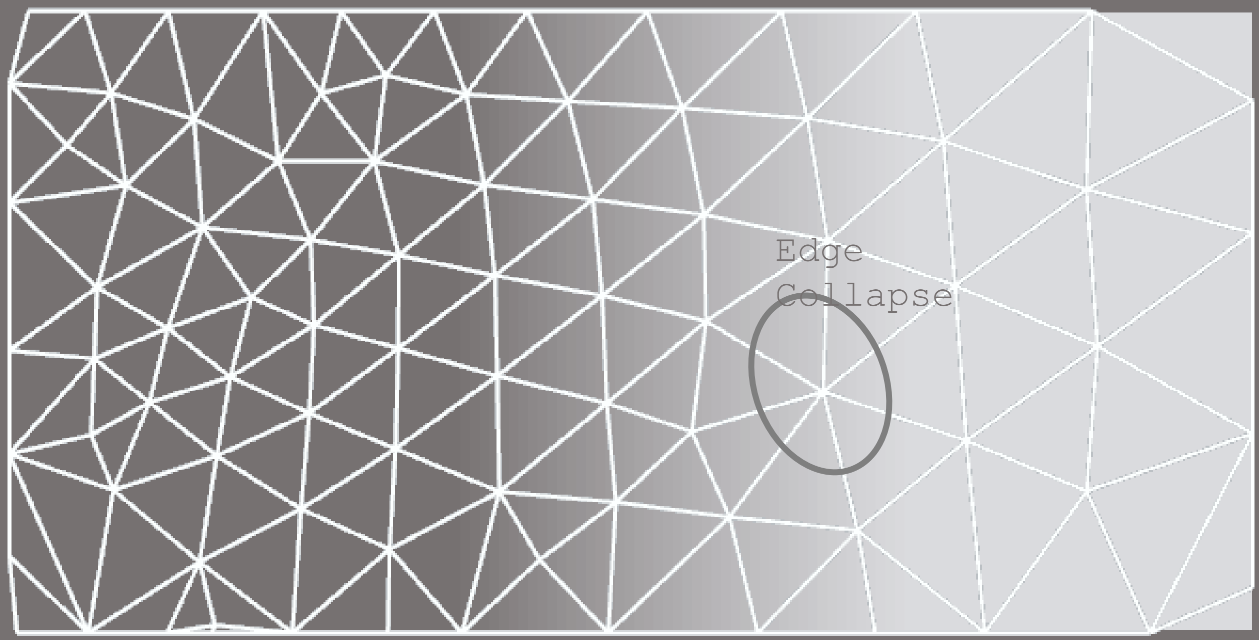

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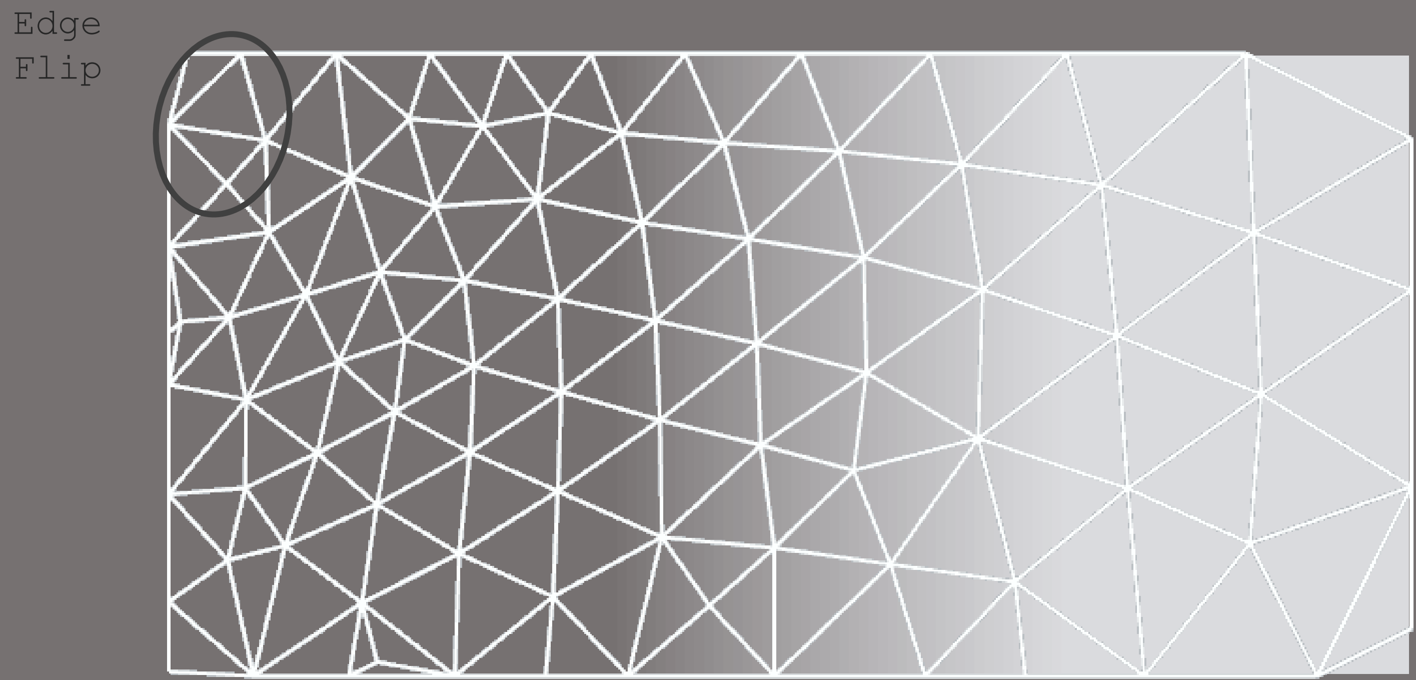

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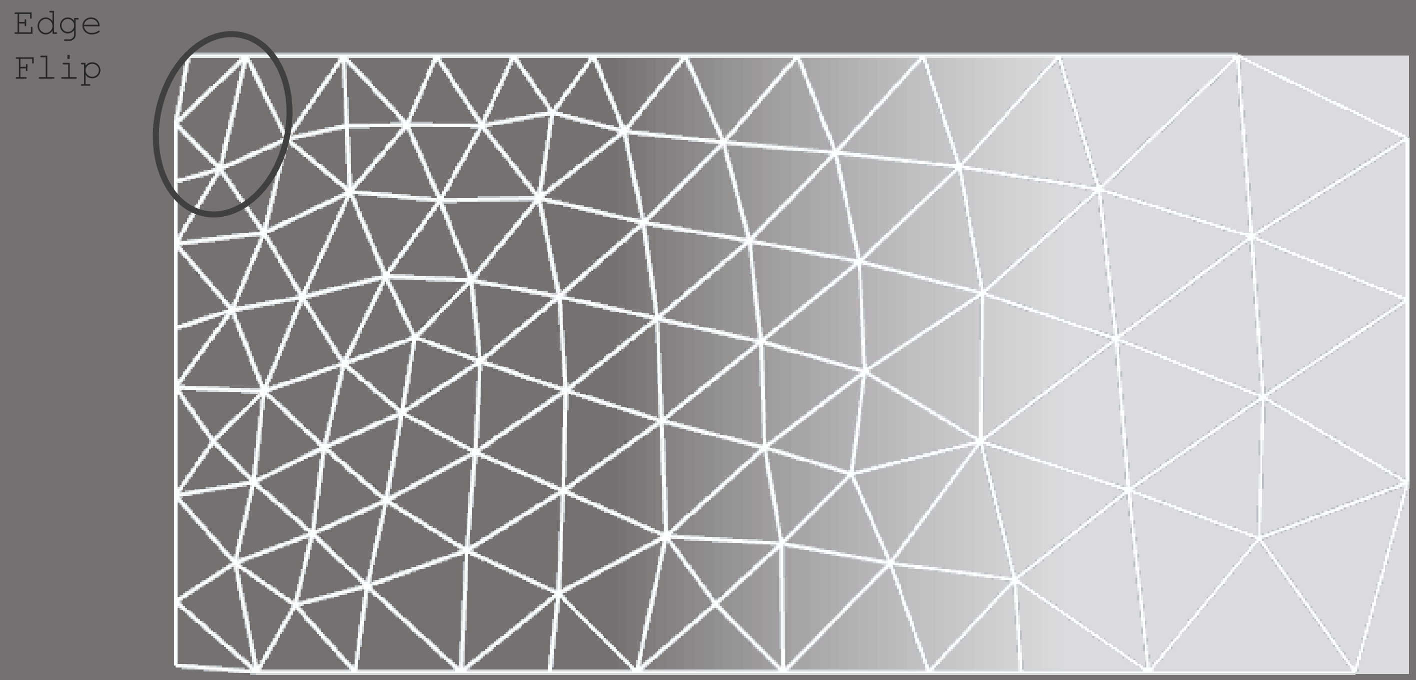

SMART CIRCLE

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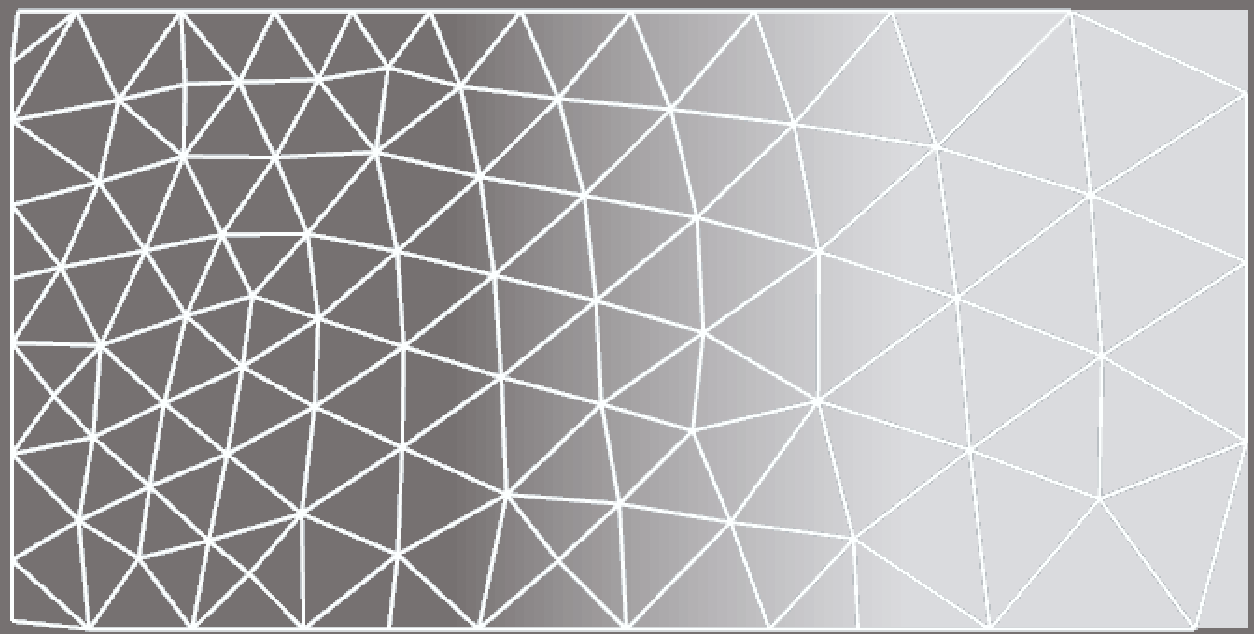

SMART CIRCLE

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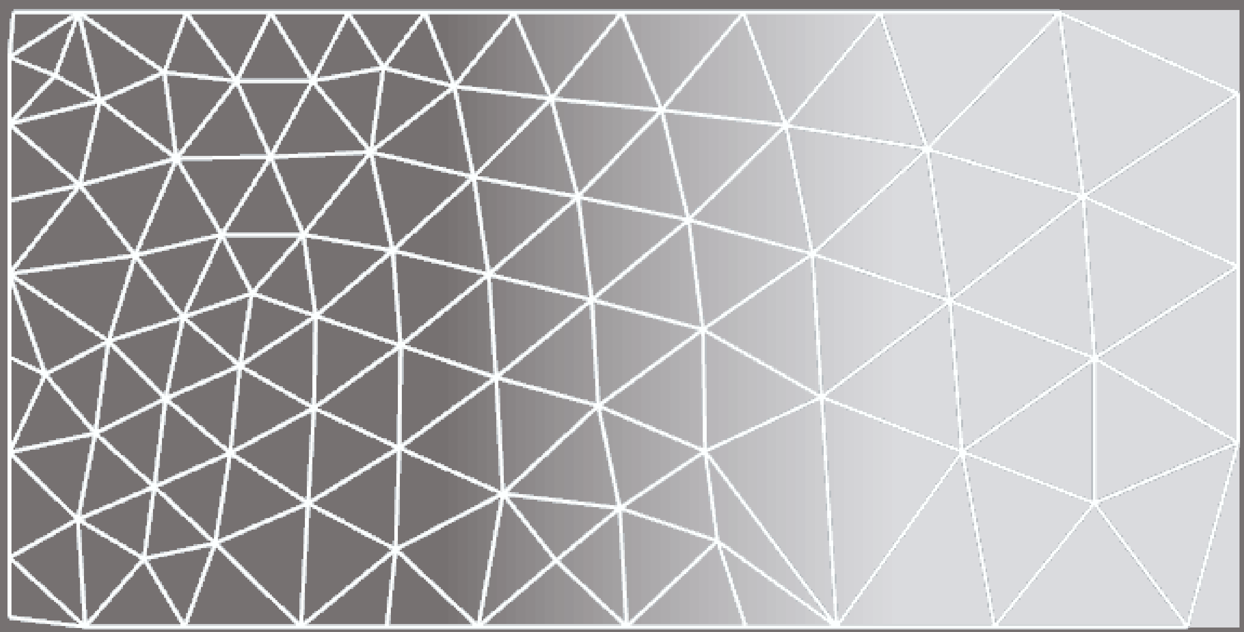

SMART CIRCLE

PACKING

Then the corner points of each triangle are used to generate the final Voronoi diagram

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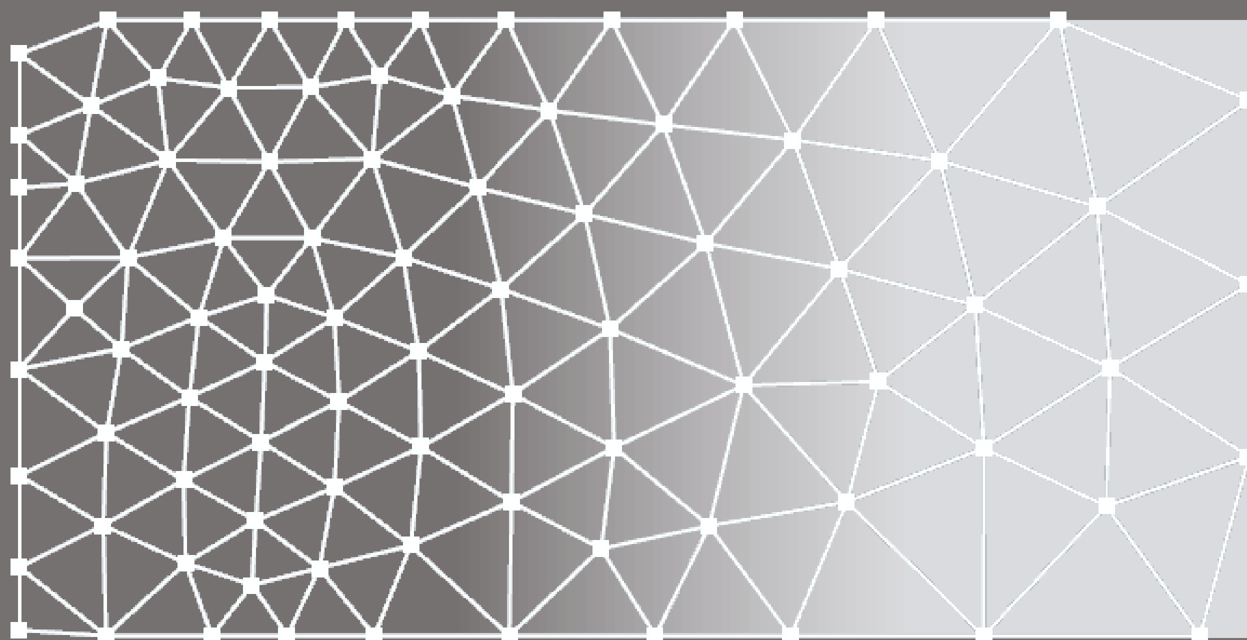

SMART CIRCLE

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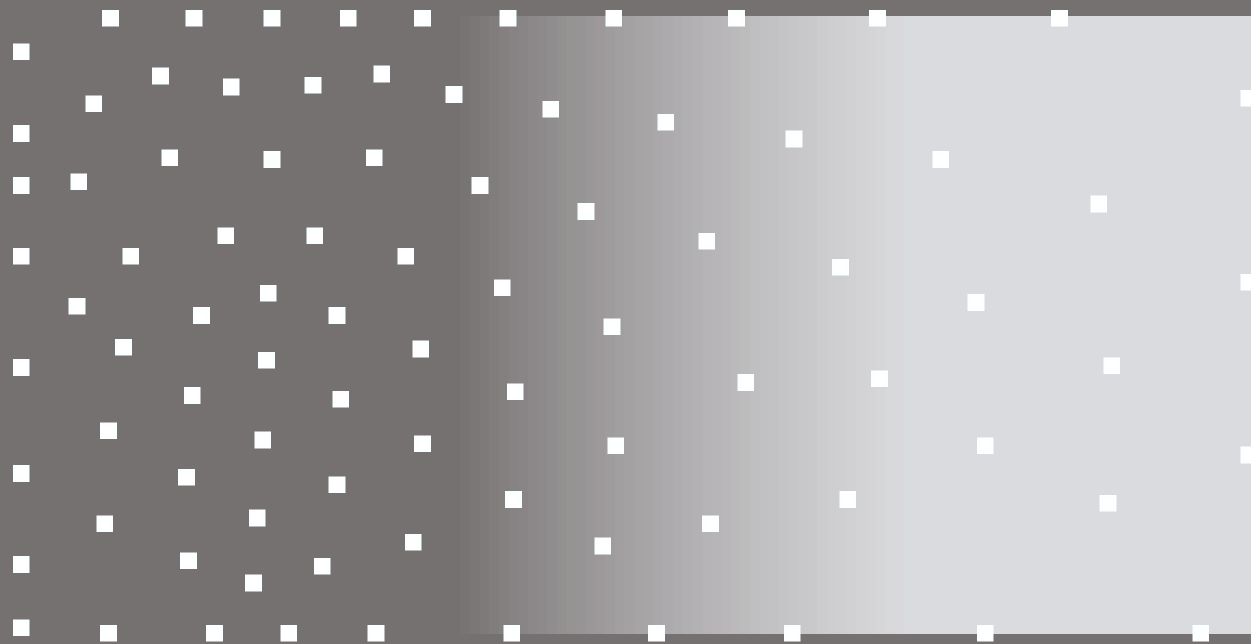

SMART CIRCLE

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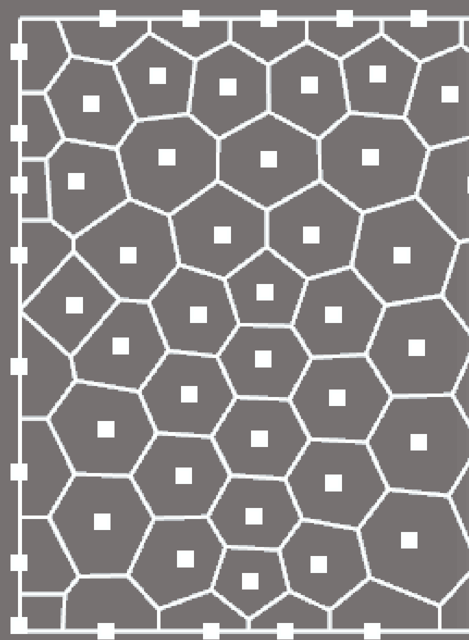
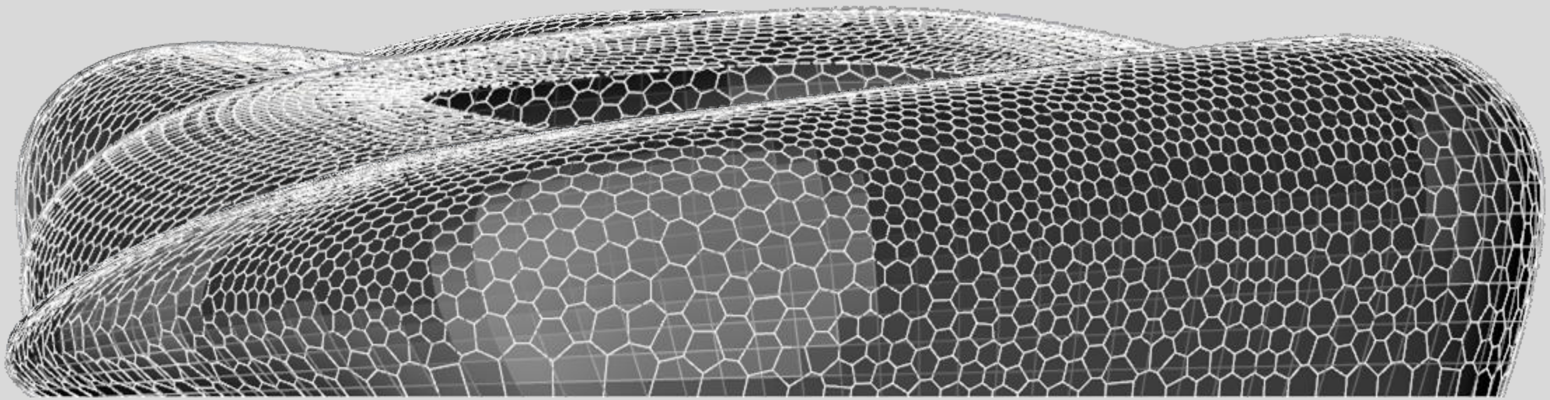


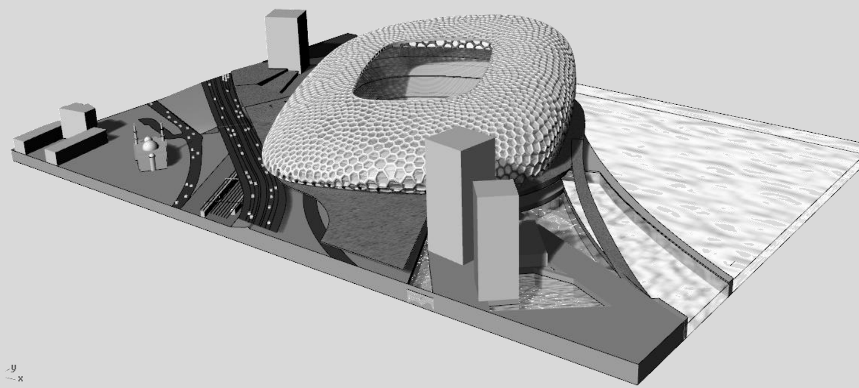
CASE**STUDY**

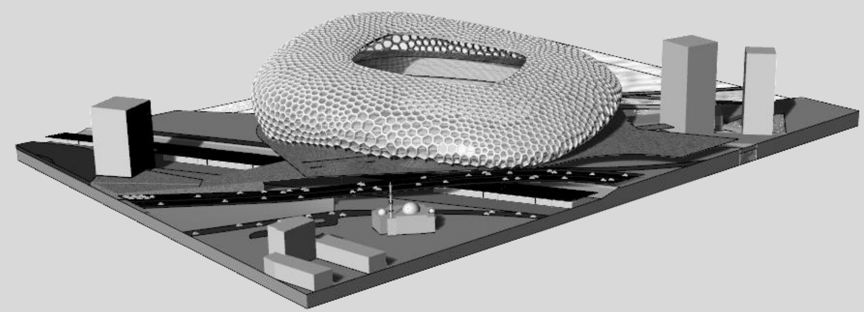


ABSTRACT
TO CONCRETE

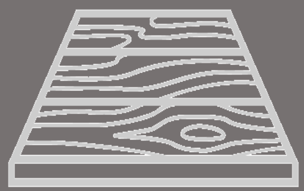
- **ABSTRACT GRID OF LINES**
  Needs to be transformed to an actual manufacturable structure
- **MATERIALS?**

- **STRUCTURAL ANALYSIS**
  Effect of opening sizes?
  Can it be built?
  Detailing?





MATERIALS &
DETAILING

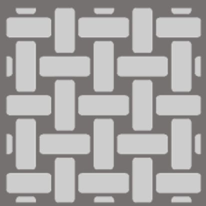


WOOD

+ Renewable
□ Lowest CO^2 emmission
□ Light Weight
□ Low Young's Modulus
□ Low Yield Strength
□ Susceptible to funghi, insects, weathering, fire and natural defects
□ High Maintenance

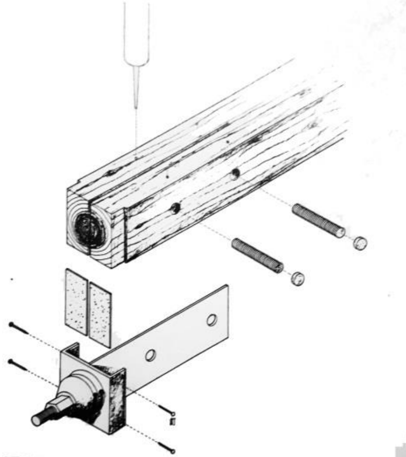
STEEL

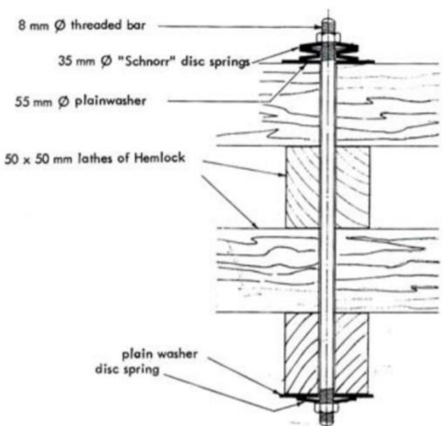
+ Low Maintenance
□ Corrosion resistant (stainless steels)
□ High Yield Strength
□ High Young's Modulus
□ Very high CO^2 emmission
□ Heavy



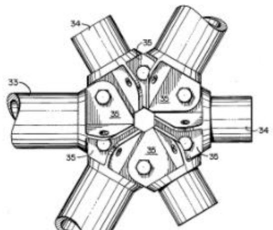
FRP

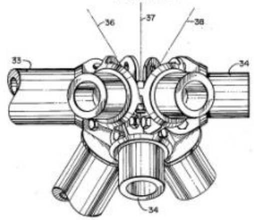
+ Very Low Maintenance
□ Corrosion resistant
□ Very High Yield Strength
□ Medium Young's Modulus
□ Very Light Weight
- Medium high CO^2 emmission
□ Expensive (especially CFRP)

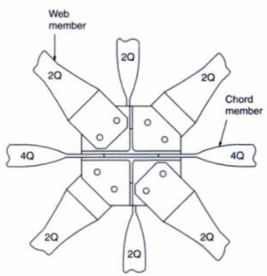


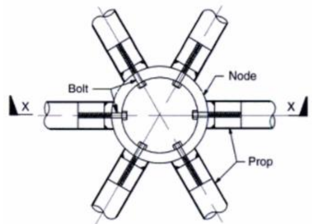


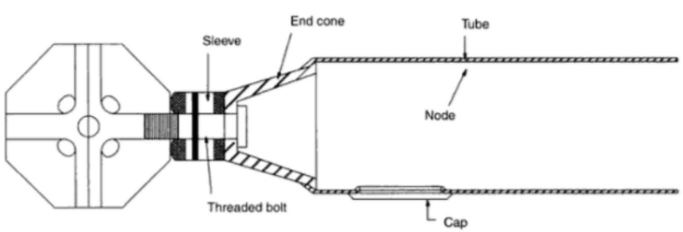
8 mm Ø threaded bar
35 mm Ø "Schnorr" disc springs
55 mm Ø plainwasher
50 x 50 mm lathes of Hemlock
plain washer
disc spring

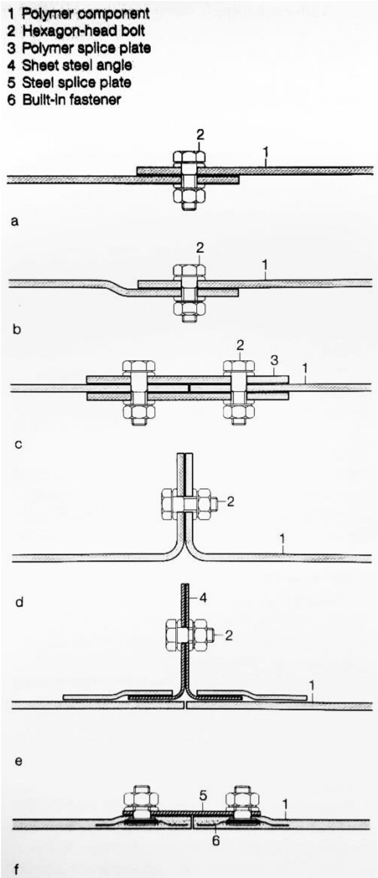

34
35
33
34
35
35
35
FIG. 12

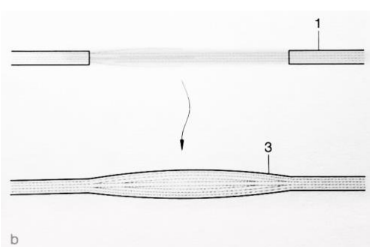

36
37
38
33
34
34

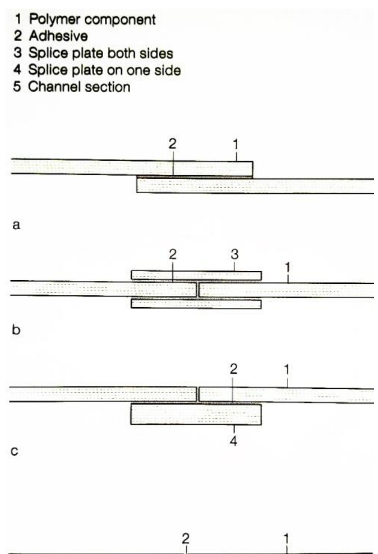

Web member
2Q
2Q
2Q
Chord member
4Q
4Q
2Q
2Q
2Q


Node
Bolt
X
X
Prop


End cone
Tube
Sleeve
Node
Threaded bolt
Cap

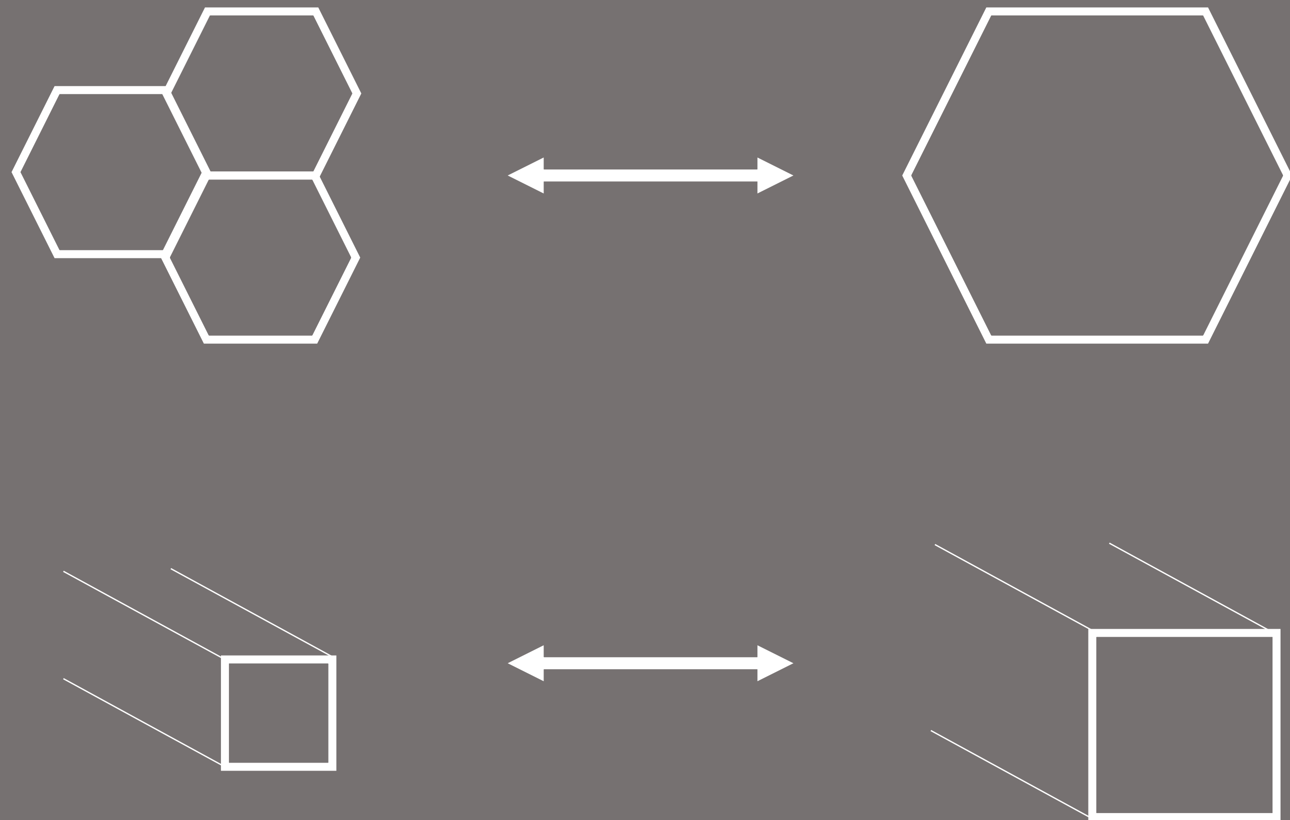

1 Polymer component
2 Hexagon-head bolt
3 Polymer splice plate
4 Sheet steel angle
5 Steel splice plate
6 Built-in fastener
a
b
c
d
e
f


b

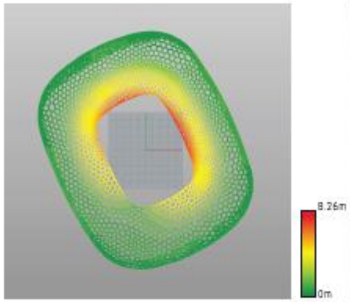

1 Polymer component
2 Adhesive
3 Splice plate both sides
4 Splice plate on one side
5 Channel section
a
b
c

ABSTRACT
TO CONCRETE

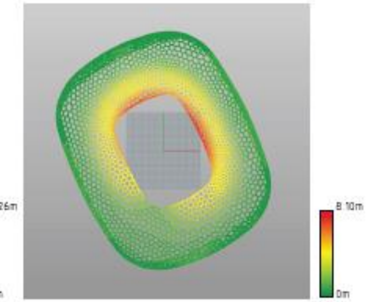
- **DESIRED LOOK**
  Looking for a bonestructure like look
- **MATERIAL?**
  Fibre Reinforced Plastic



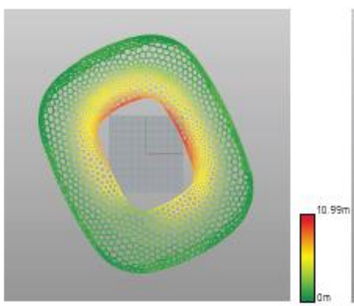
STRUCTURAL **TESTING**



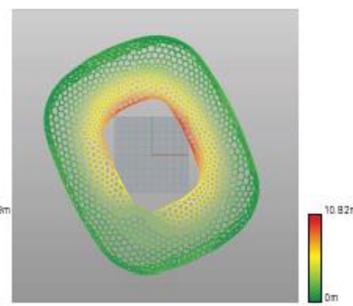
Range: 2 to 8
Max. Displacement: 8.26m
Utilization: -35.6% to 38.7%
Mass: $2.0e^8$
Nodal Displacement: 2.28cm



Range: 4 to 8
Max. Displacement: 8.10m
Utilization: -34.6% to 38.8%
Mass: $2.0e^8$
Nodal Displacement: 2.40 cm



Range: 4 to 10
Max. Displacement: 10.99m
Utilization: -47.1% to 51.6%
Mass: $2.0e^8$
Nodal Displacement: 4.33 cm

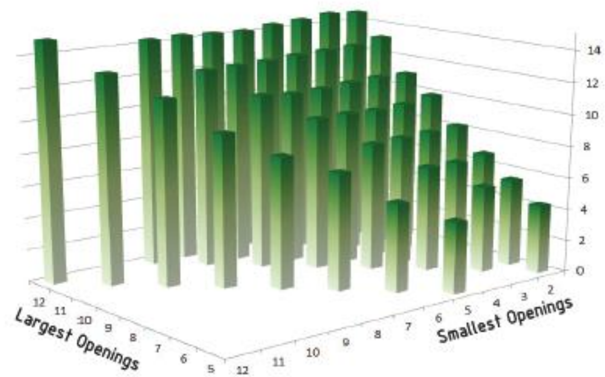


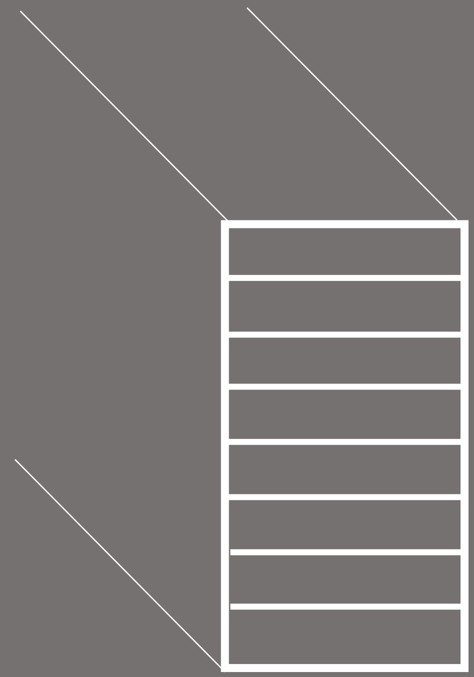
Range: 6 to 10
Max. Displacement: 10.82m
Utilization: -51.6% to 53.5%
Mass: $2.0e^8$
Nodal Displacement: 4.38 cm

Max. Displacement

Smallest Openings \ Largest Openings	5	6	7	8	9	10	11	12
2	4,32	5,50	6,78	8,26	9,92	11,04	13,21	14,66
3		5,41	6,58	8,16	9,62	11,09	12,88	14,78
4			6,61	8,10	9,53	10,99	12,80	14,57
5	4,46			8,02	9,58	10,85	12,72	14,44
6		5,54			9,58	10,82	12,58	14,24
7			7,33			10,98	12,55	14,30
8				8,26			12,50	14,38
9					9,59			14,35
10						11,62		
11							13,05	
12								15,26

Results of all options in a table and a bar graph



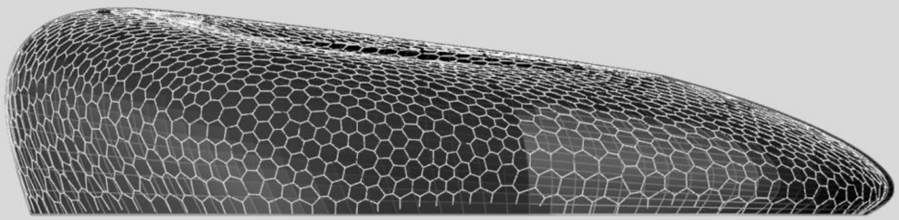


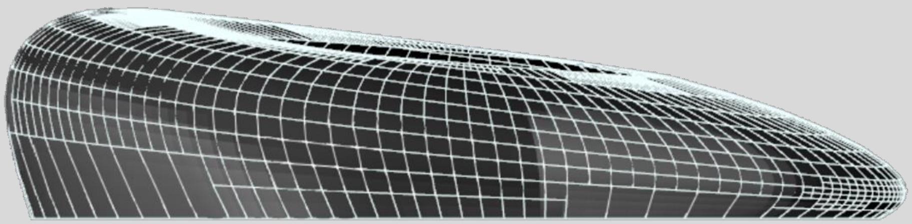
COMPARISON

TRADITIONAL

Total member length: 25.658m
Total mass: 8.6e^{7}
Loadcase 1: 7.10m
Loadcase 2: 6.76m
Loadcase 3: 6,.86m
Loadcase 4: 6.83m
Loadcase 5: 6.27m
Max. Relative Displacement: 0.83m
Utilization: -38.2% tot 36.9%

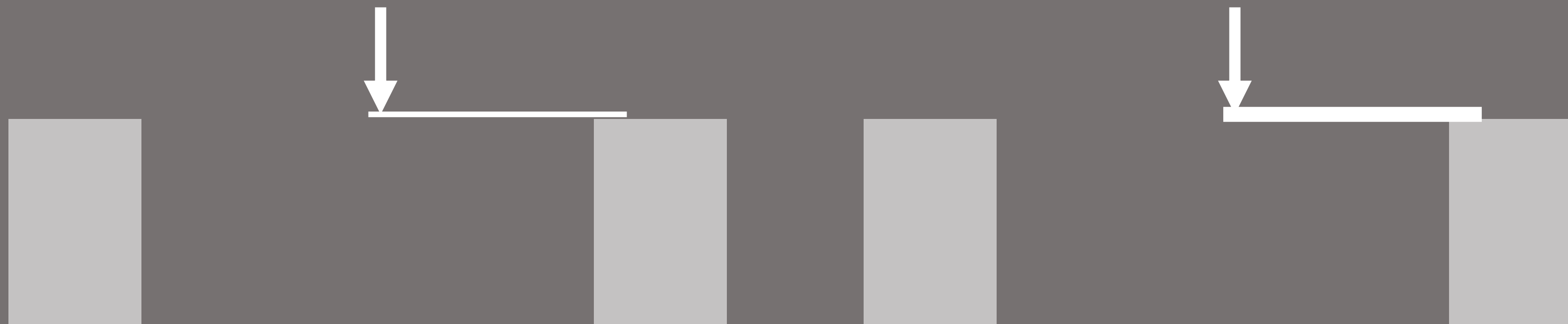
Total member length: 25.735m
Total mass: 8.6e^{7}
Loadcase 1: 3.62m
Loadcase 2: 3.49m
Loadcase 3: 3.54m
Loadcase 4: 3.48m
Loadcase 5: 3.24m
Max. Relative Displacement: 0.38m
Utilization: -28.4% tot 17.2%





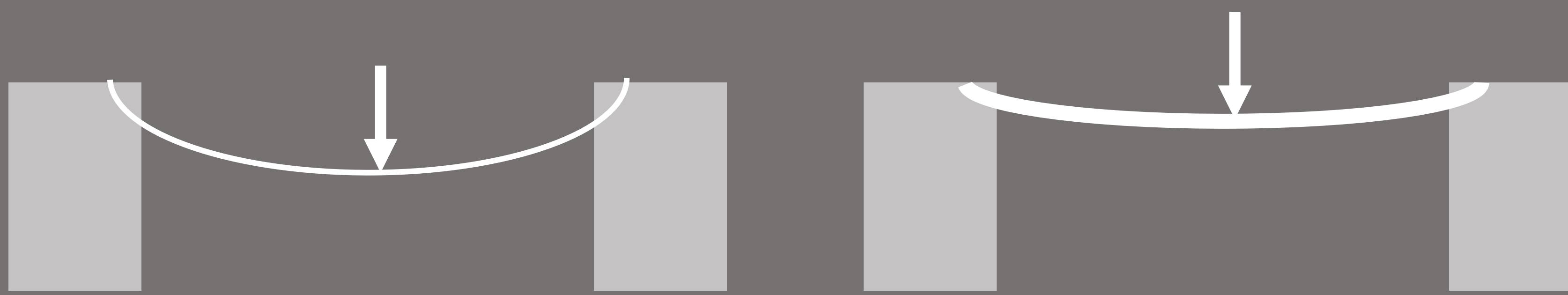
STRUCTURAL

OPTIMIZATION



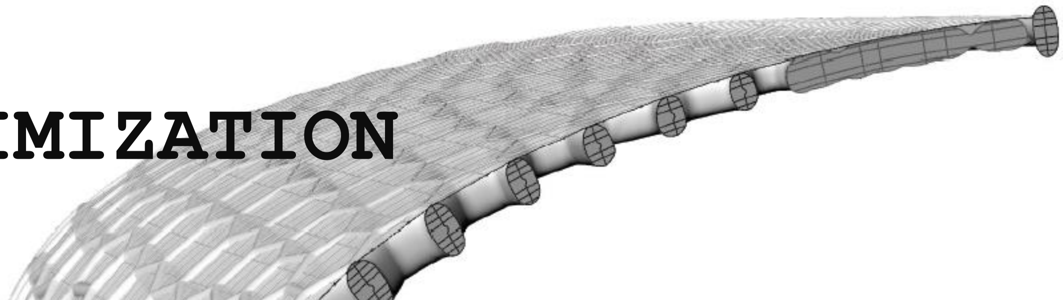
STRUCTURAL

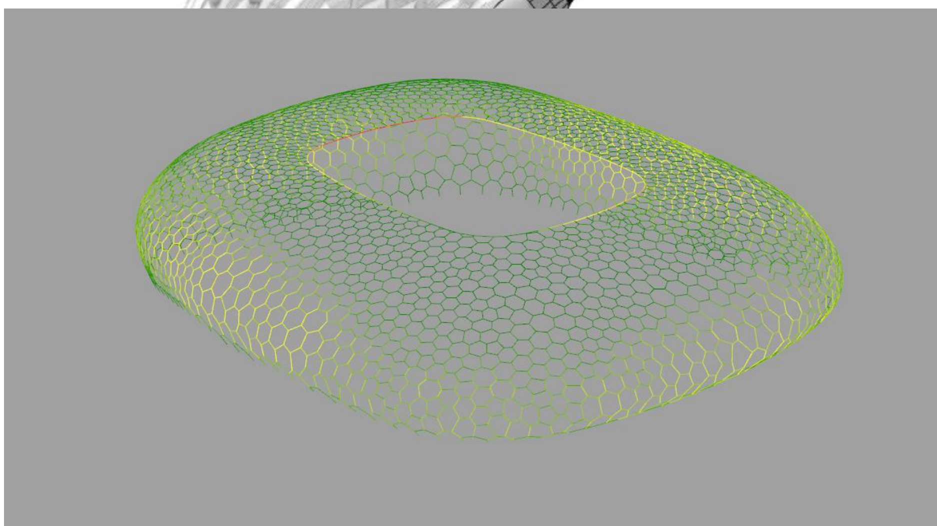
OPTIMIZATION



STRUCTURAL

OPTIMIZATION



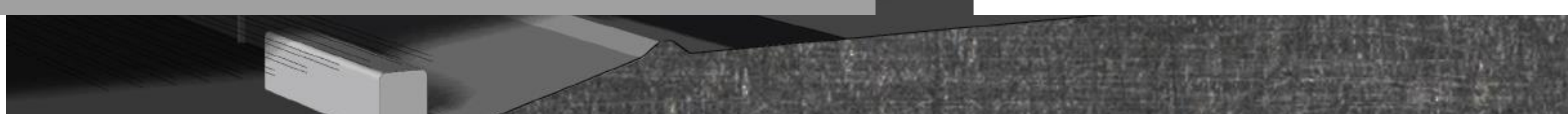


Relative Deflection : 0.82 m
Mass Polymer: $8.07e^7$ kg
Mass Foam: $1.71e^7$ kg
Cost: 325.5 million

For the optimized solution:

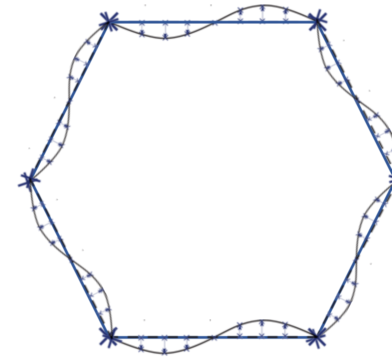
Relative Deflection : 0.75 m
Mass Polymer: $4.36e^7$ kg
Mass Foam: $9.89e^6$ kg
Cost: 180 million

The optimized solution meets the requirement of a maximum allowed relative deflection of 80cm.



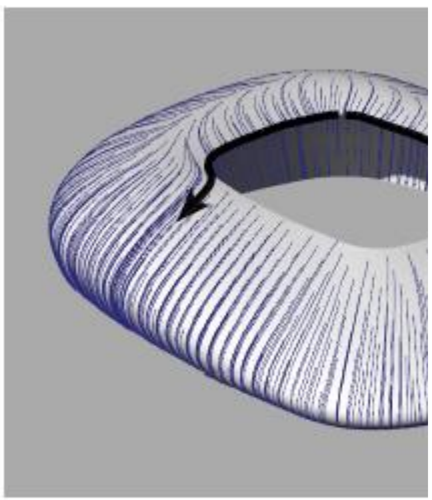
DETAILING &

PRODUCTION

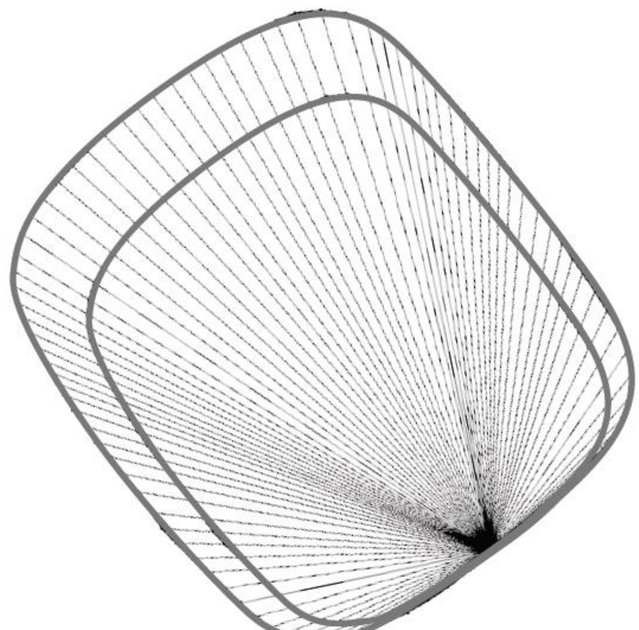


» WATERFLOW

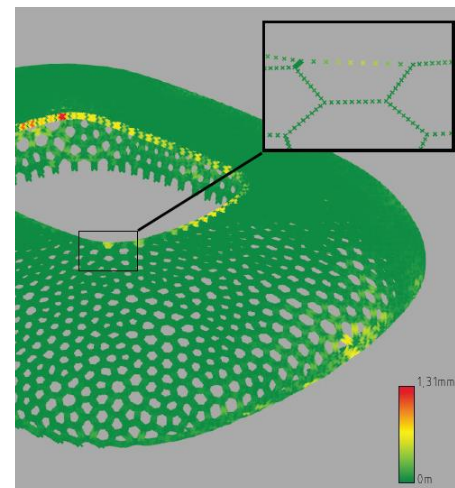
Rainwater analysis



» THERMAL EXPANSION

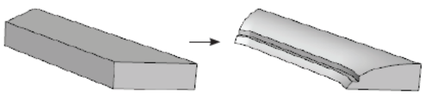


» NODAL DISPLACEMENT

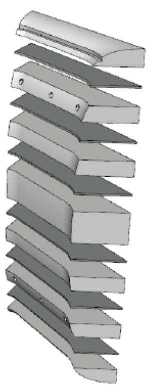


PRODUCTION OF A PANEL

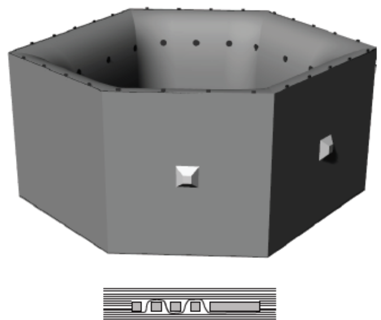
Step 1
All the foam blocks will be milled into the desired shape.



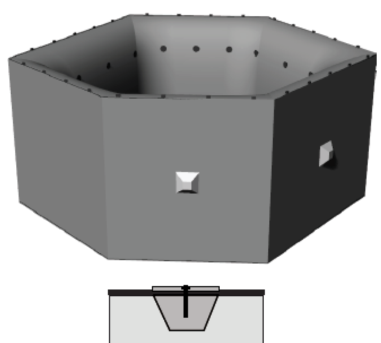
Step 2
The foam blocks of one 'member' are stacked together with layers of woven E-glass fabric in between.



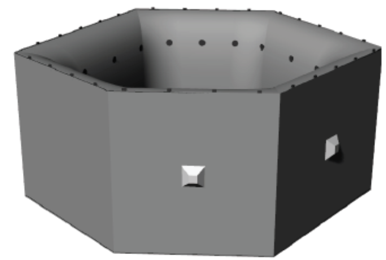
Step 7
Add final layers of woven fabric to the element.



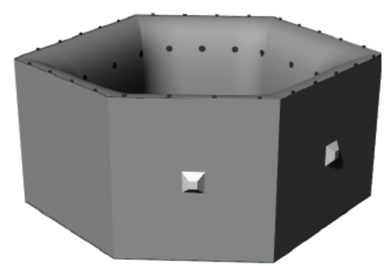
Step 8
Screw covers onto the opening covers and clench the fibers in between. To ensure they stay dry during the vacuum injection process.



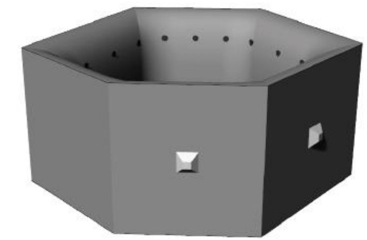
Step 9
Vacuum injection



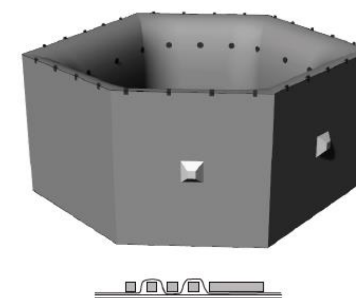
Step 10
Once the resin is cured the resulting element has to be sanded and polished to get rid of any imperfections that were created during the vacuum injection process



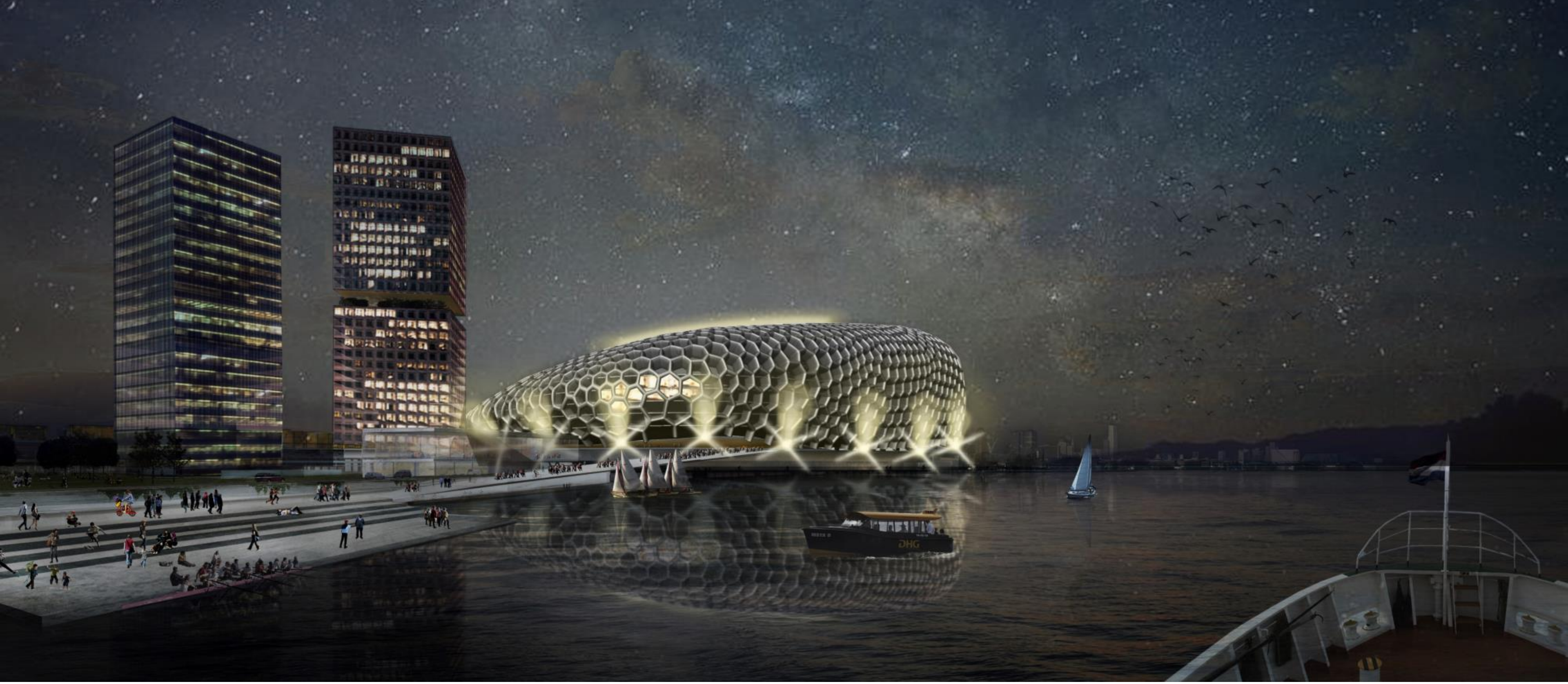
Step 5
First layers of fiber are added onto the element.



Step 6
Aluminium members are embedded into the upper layer of fibers. Fibers are pulled throught the perforates parts of the aluminium.




DHG

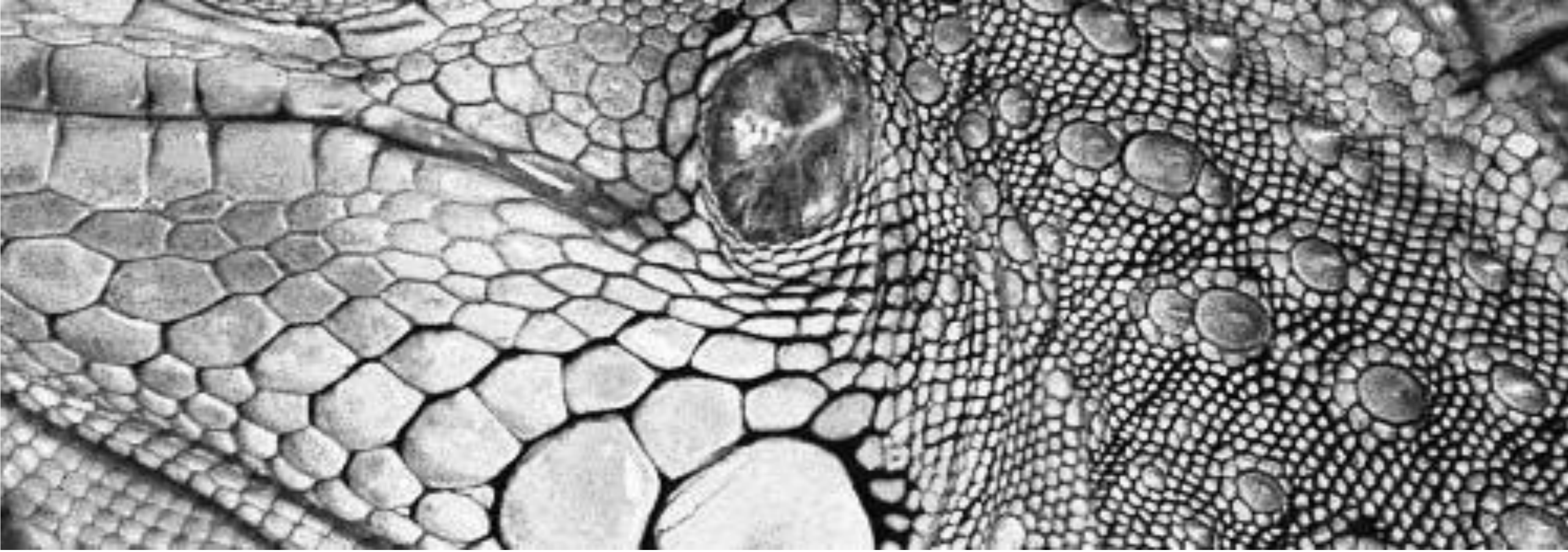


THANK YOU FOR

ANY **QUESTIONS?**

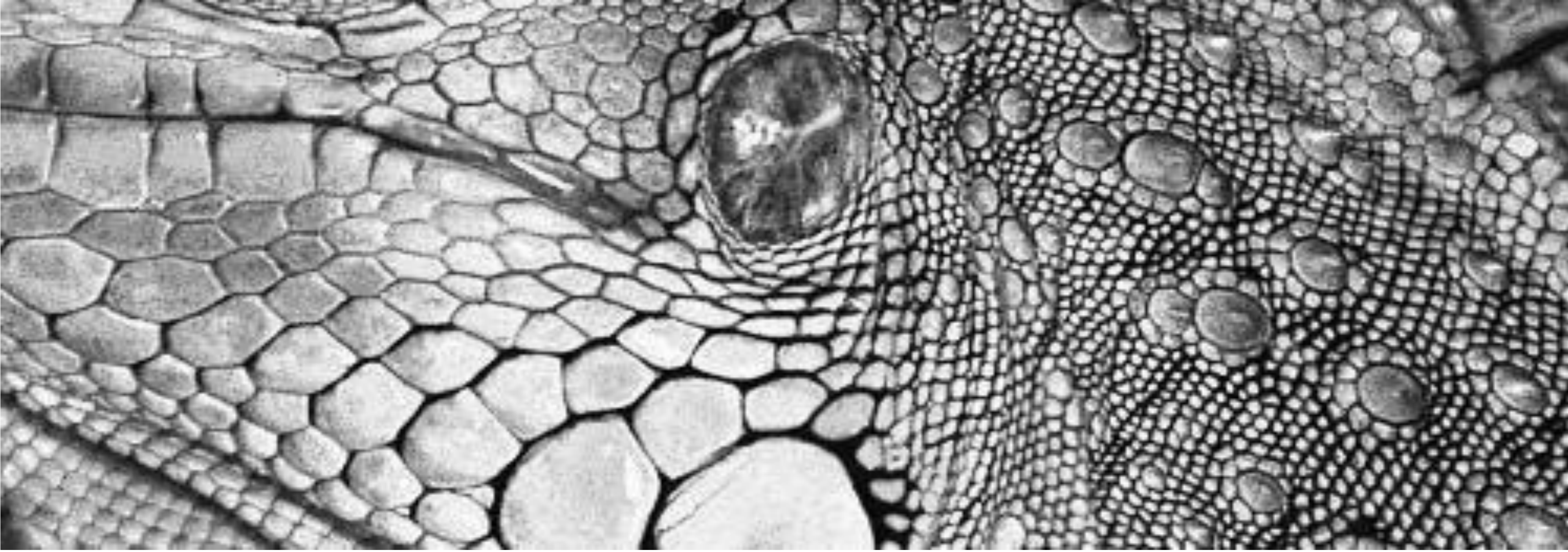
YOUR

ATTENTION



AIM OF **THE RESEARCH**

The aim of the research is to take a step forwards in limiting the impact of the construction and energy use of buildings on the global environment by developing a workflow that integrates the results from performance analyses with the structural design.



RESEARCH **QUESTIONS**

» **MAIN QUESTION**

How to design a grid shell for the canopy of a stadium that uses performance based densification to enhance the performance of the structure?

RESEARCH

DESIGN

» WHAT MATERIALS ARE USED FOR GRIDSHELLS AND GRADED STRUCTURES?

- What are the properties of these materials?
- What connection types exist for each material?
- What material and connection type is most suitable for the task?

» HOW CAN THIS METHOD BE APPLIED TO GENERATE BASED ON AN UNDERLYING PERFORMANCE MAP?

- How can a multiple performance based shape for the canopy be generated by using multi-objective optimization?
- Which of these methods is most suitable for the task?
- How can the results of different performance analyses be combined in one performance map?
- How is the abstract grid of lines of the graded structure translated to an actual structure for the canopy?

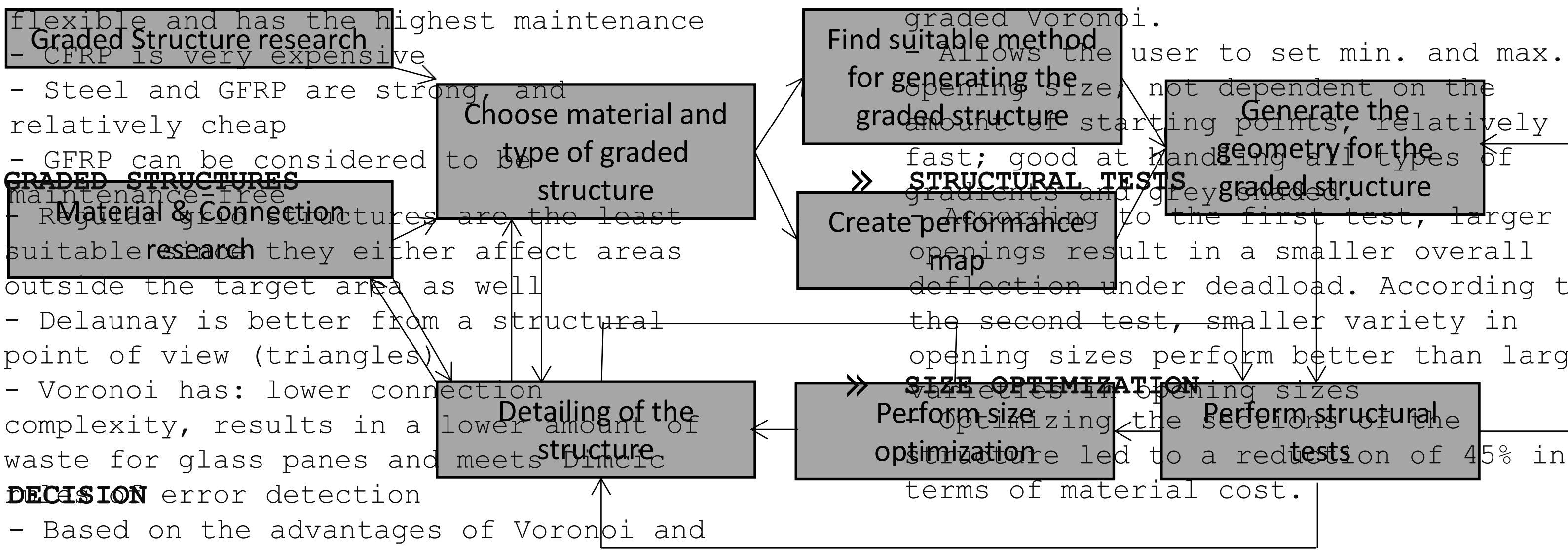
» WHAT KIND OF GRADED STRUCTURES EXIST?

- What are the advantages and disadvantages of these different kinds of graded structures?
- Which of these graded structures is most suitable

FINAL **CONCLUSIONS**

MAIN QUESTION

How to design a grid shell for the canopy of a stadium that uses performance based densification to enhance the performance of the structure?



» **MATERIALS**

- Wood is most sustainable, however structurally the weakest and most flexible and has the highest maintenance
- CFRP is very expensive
- Steel and GFRP are strong, and relatively cheap
- GFRP can be considered to be maintenance-free

» **GRADED STRUCTURES**

- Regular grid structures are the least suitable since they either affect areas outside the target area as well
- Delaunay is better from a structural point of view (triangles)
- Voronoi has: lower connection complexity, results in a lower amount of waste for glass panes and meets Dimcic rules on error detection

» **DECISION**

- Based on the advantages of Voronoi and the desired bonestructure-like look Voronoi and GFRP were chosen

» **GENERATION OF GEOMETRY**

- Smart circle packing proved to be the most suitable method of generating a graded Voronoi.
- Allows the user to set min. and max. opening size, not dependent on the amount of starting points, relatively fast; good at handling all types of gradients and grey shaded.

» **STRUCTURAL TESTS**

- According to the first test, larger openings result in a smaller overall deflection under deadload. According to the second test, smaller variety in opening sizes perform better than large varieties in opening sizes

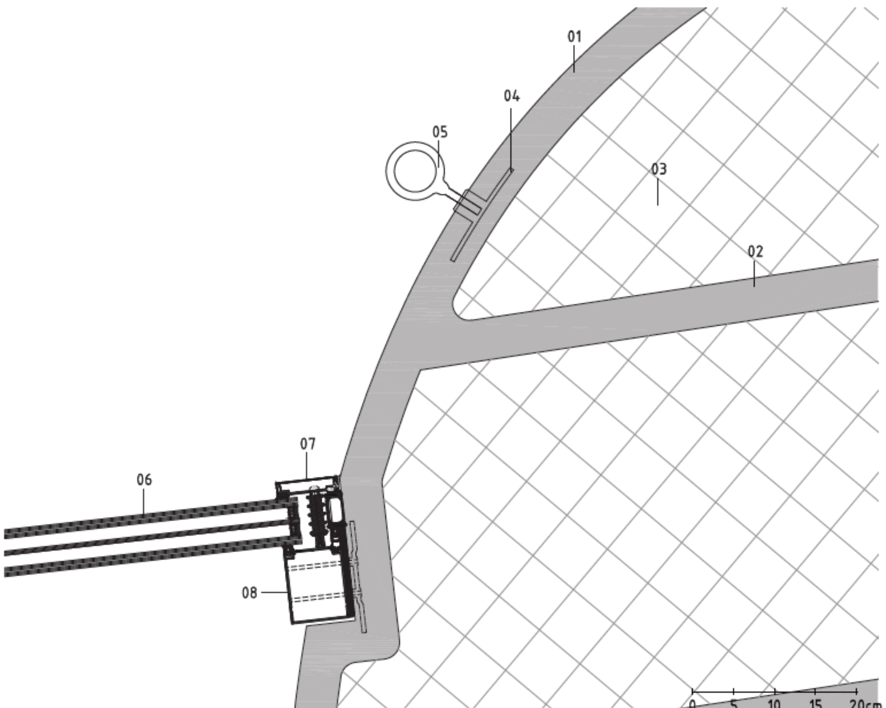
» **SIZE OPTIMIZATION**

- Optimizing the sections of the structure led to a reduction of 45% in terms of material cost.

DETAILING &

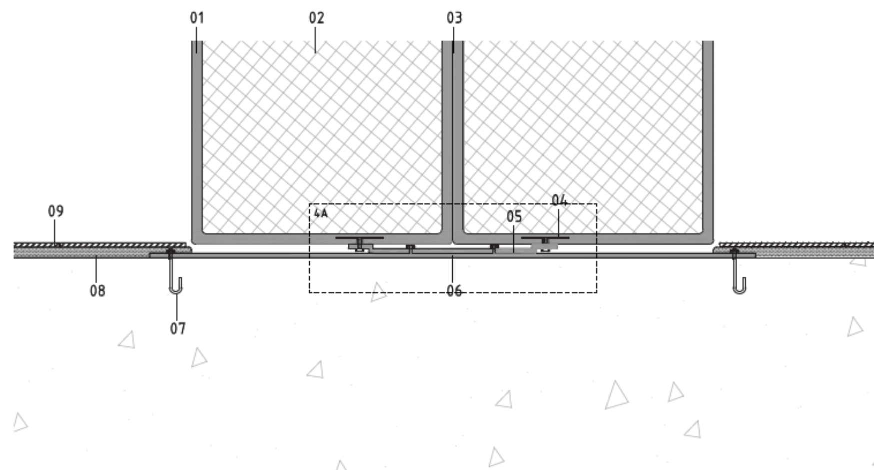
3

01 Polyester/E-glass fiber, woven fabric, 65wt% glass, biaxial lay-up, 50mm thickness
02 Web of the FRP component
03 Polyurethane foam (rigid, closed cell, 0.062)
04 Aluminium member with threaded holes, embedded in polyesther
05 Aluminium bracket with threaded end for rope access
06 Triple glazing 10-15-5-15-10
07 Cover with click system
08 Aluminium mullion



4

01 Polyesther/E-glass fiber, woven fabric, 65wt% glass, biaxial lay-up, 50mm thickness
02 Polyurethane foam (rigid, closed cell, 0.062)
03 Structural adhesive
04 Stainless steel member with threaded holes, embedded in polyesther
05 Stainless steel member with a layer of PTFE
06 Stainless steel member with two extruding pins
07 Steel reinforcement anchors with threads
08 Sand
09 Tiles



STRUCTURES

BY NATURE

MULTIFUNCTIONAL

Nature is very good at creating multifunctional structures and materials

SUSTAINABLE

Nature minimizes the amount of necessary material and energy

CONSTRUCTION

Is one of the least sustainable industries in the world

GRADED

STRUCTURES

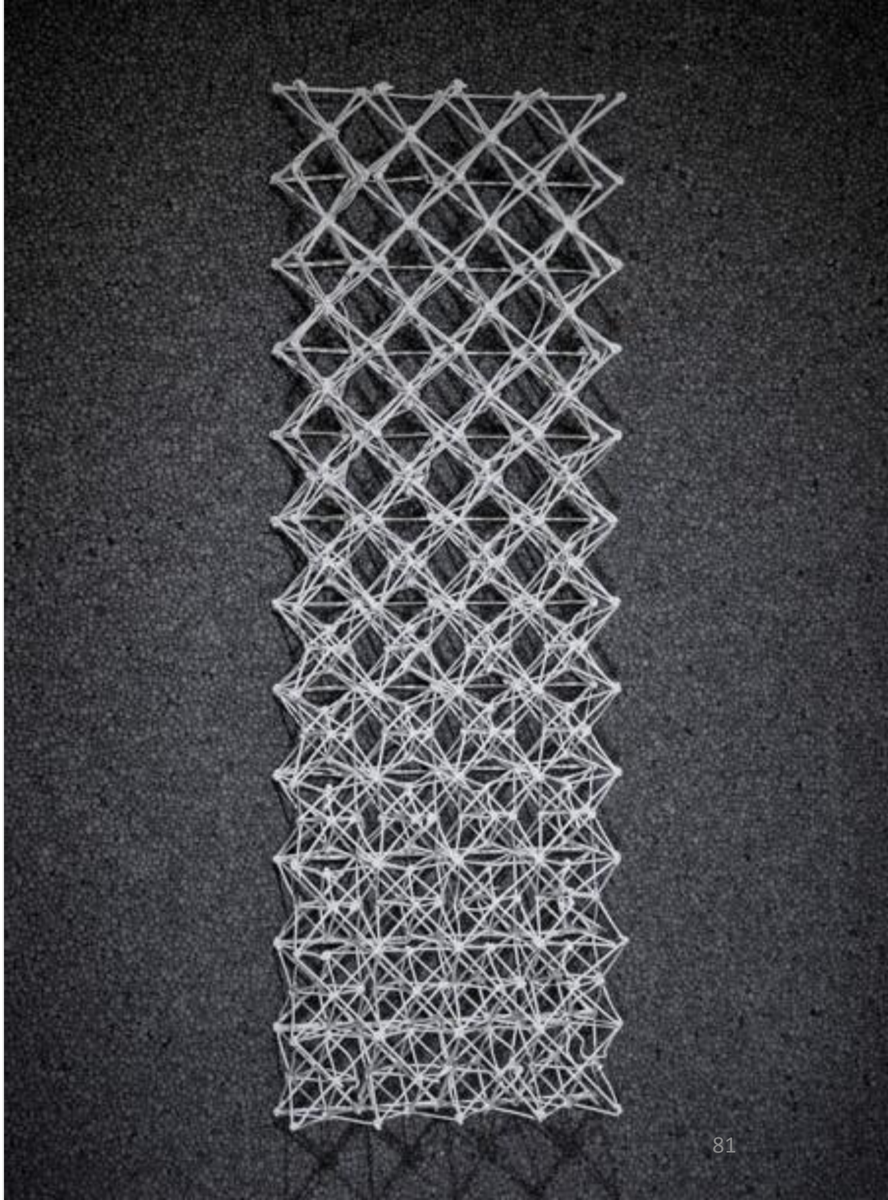
- **VORONOI**

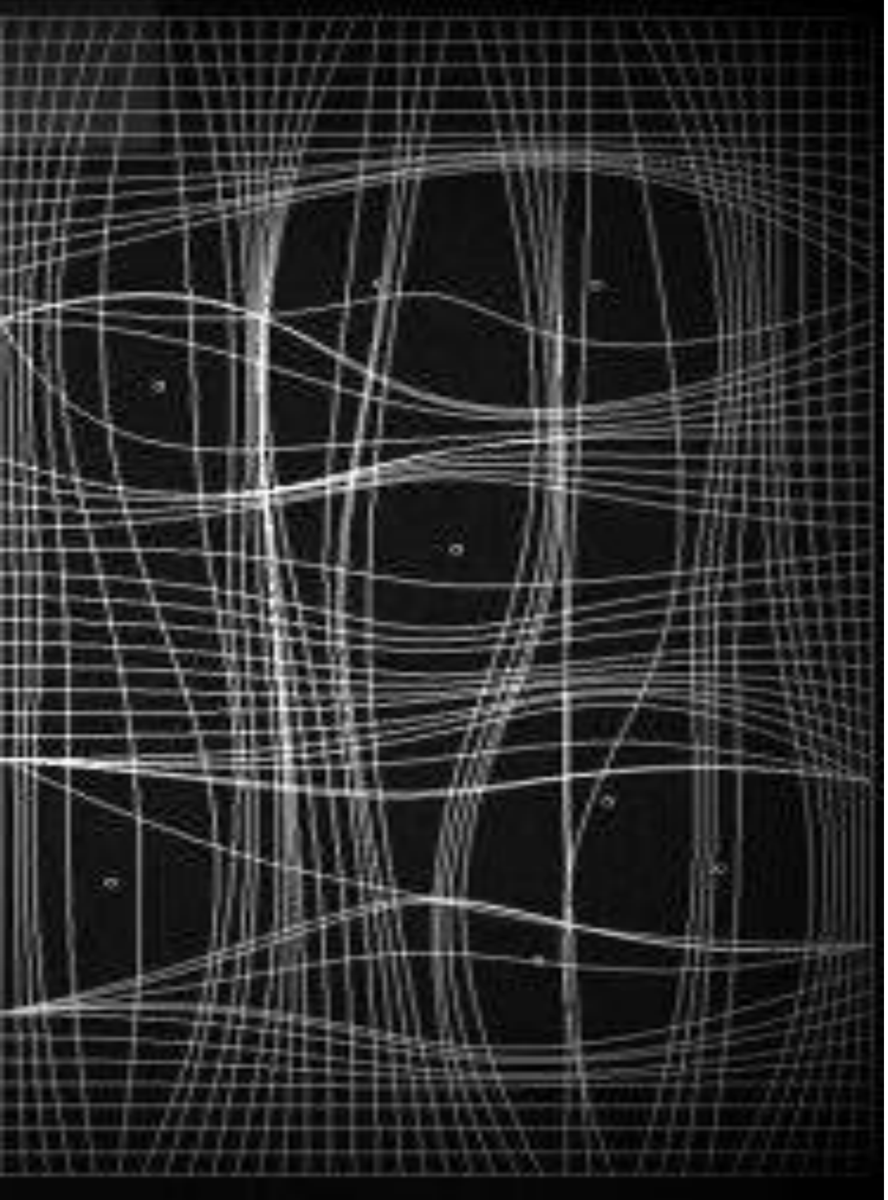
  the partitioning of a plane in regions based on a specific set of generator points

- **DELAUNAY**

  these diagrams are dual to Voronoi diagrams

- **REGULAR STRUCTURES**





REGULAR

STRUCTURES

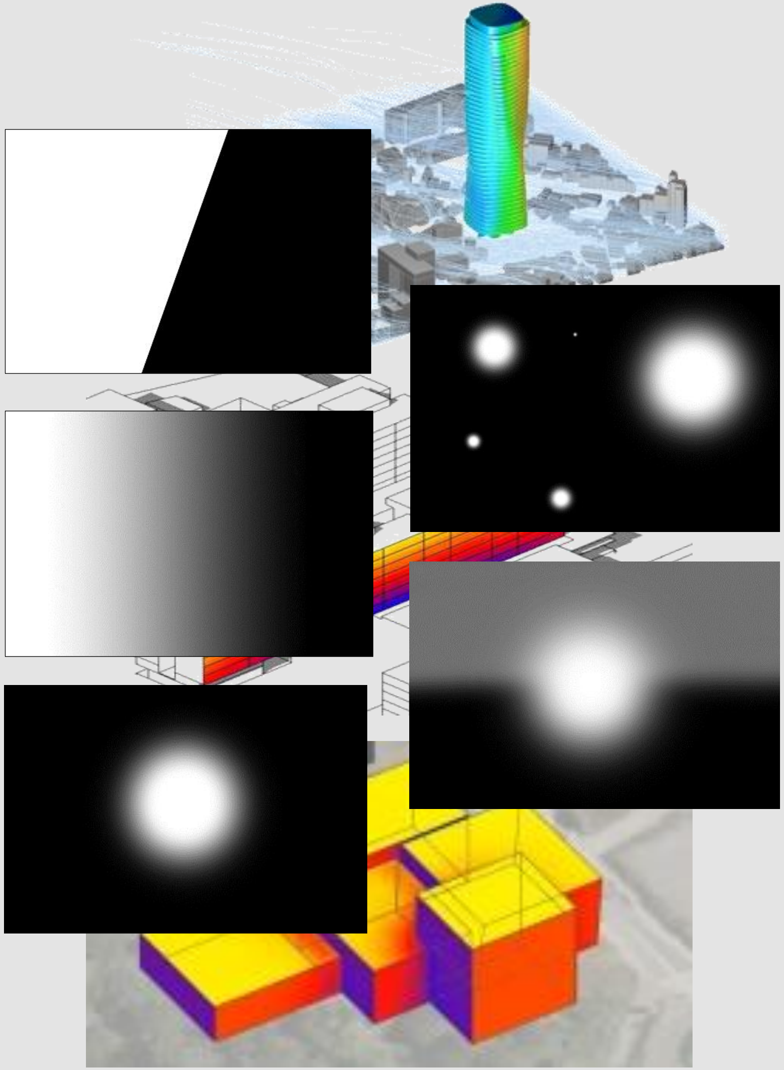
- **TRADITIONAL DENSIFICATION**

  - does not allow gradual densification but only incremental densification

  - a side effect is that when the target area is densified, other areas are effected as well

- **ATTRACTORS**

  a side effect is that when the target area is densified, other areas are effected as well

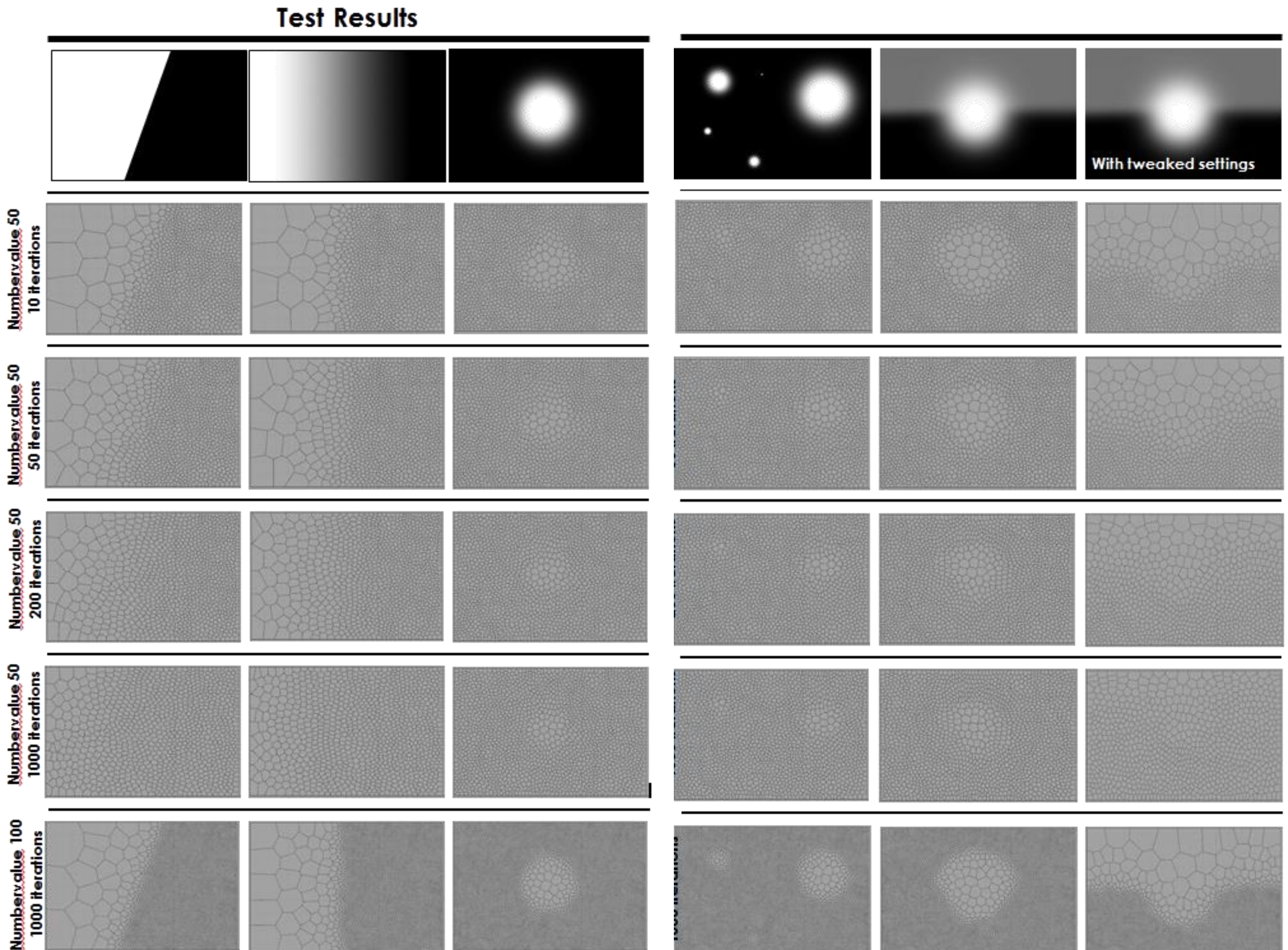


GRADED

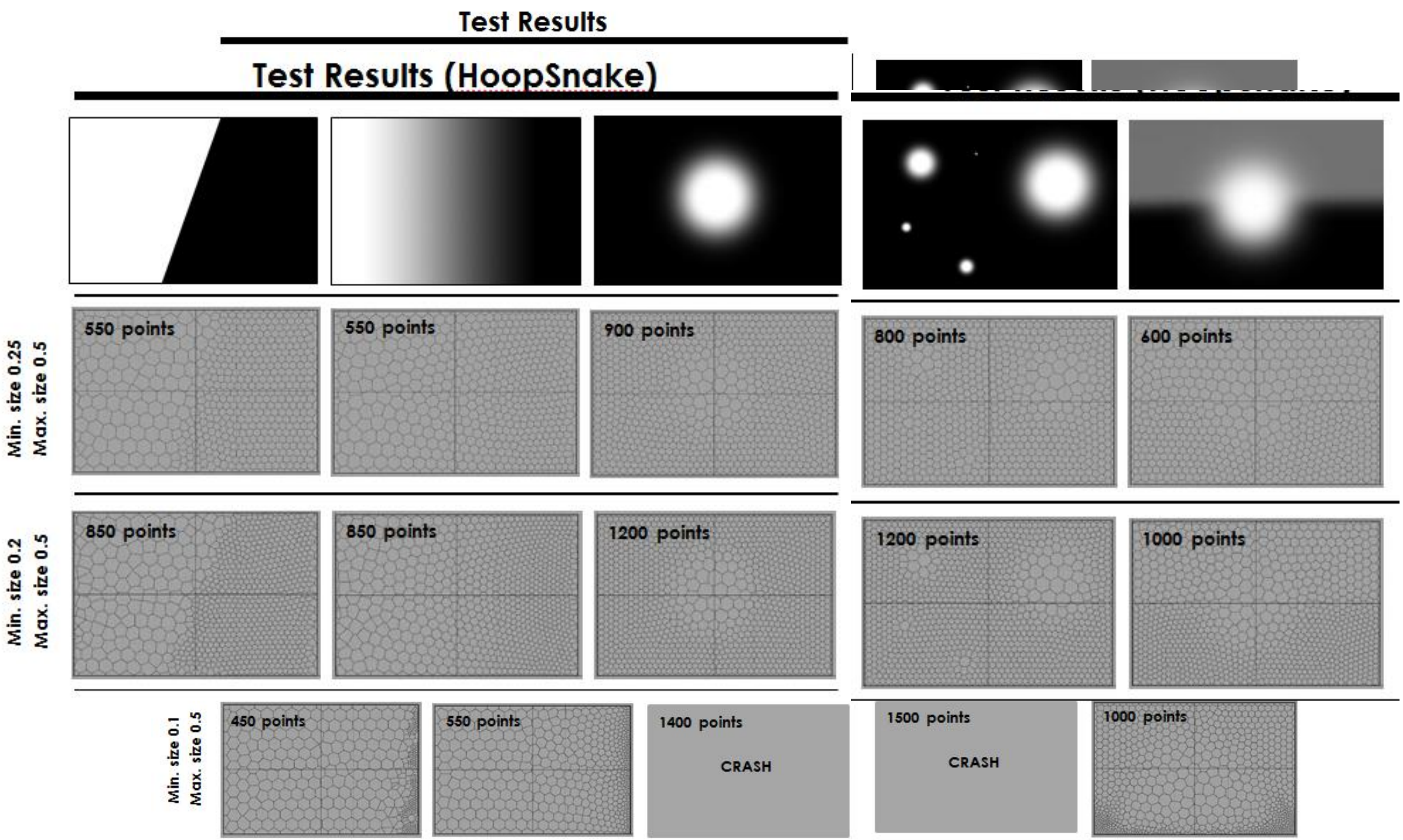
VORONOI

- **PERFORMANCE ANALYSIS**
  image maps that are projected on a complex surface
- **DIFFERENT GRADIENTS**
  Scripts needs to be sensitive to all of these gradients
- **TEST IMAGES**
  Used to test the scripts

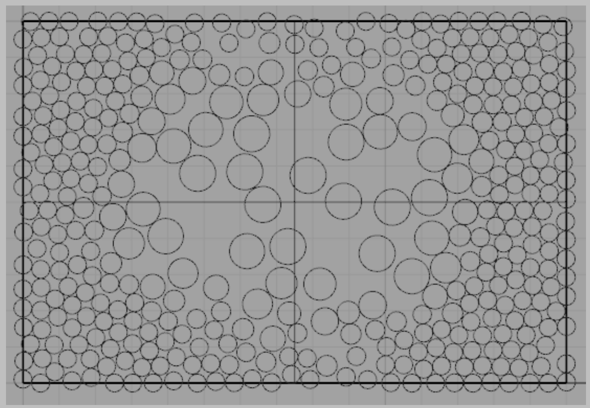
LLOYD'S **ALGORITHM**

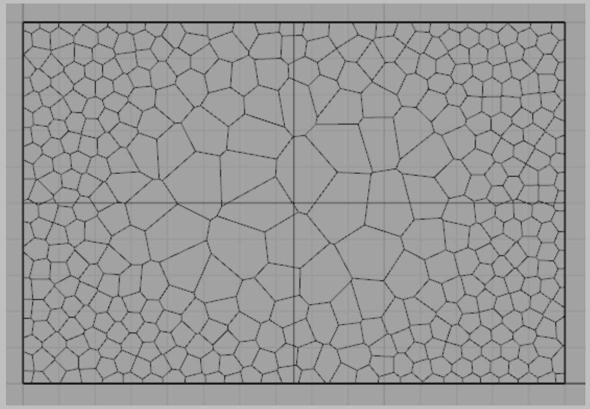


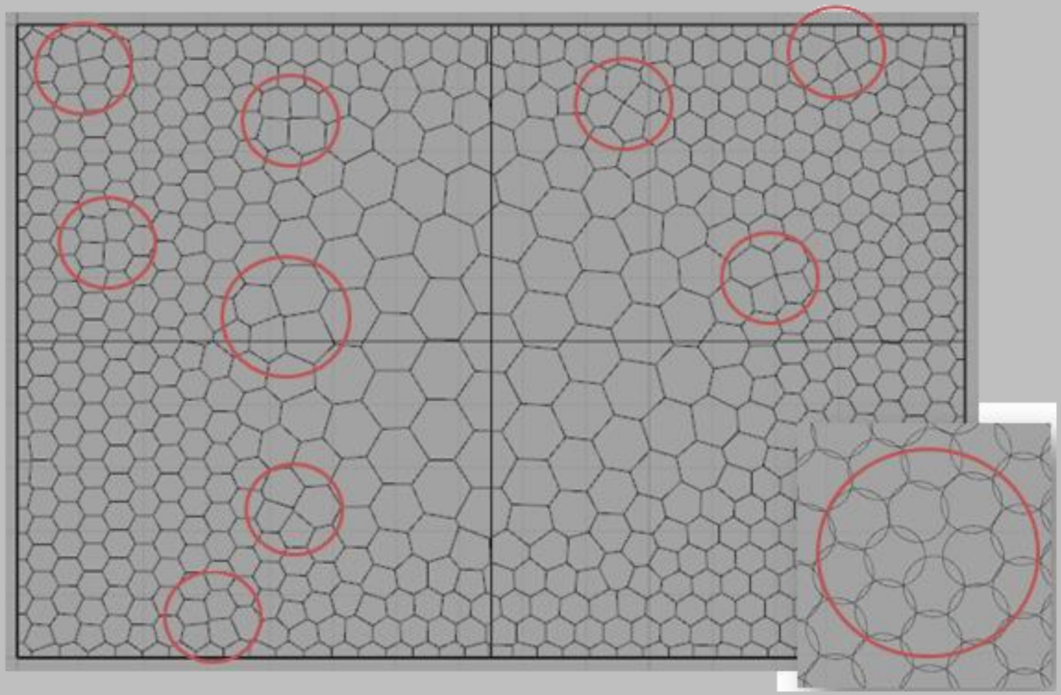
SPRING **FORCE SYSTEM**



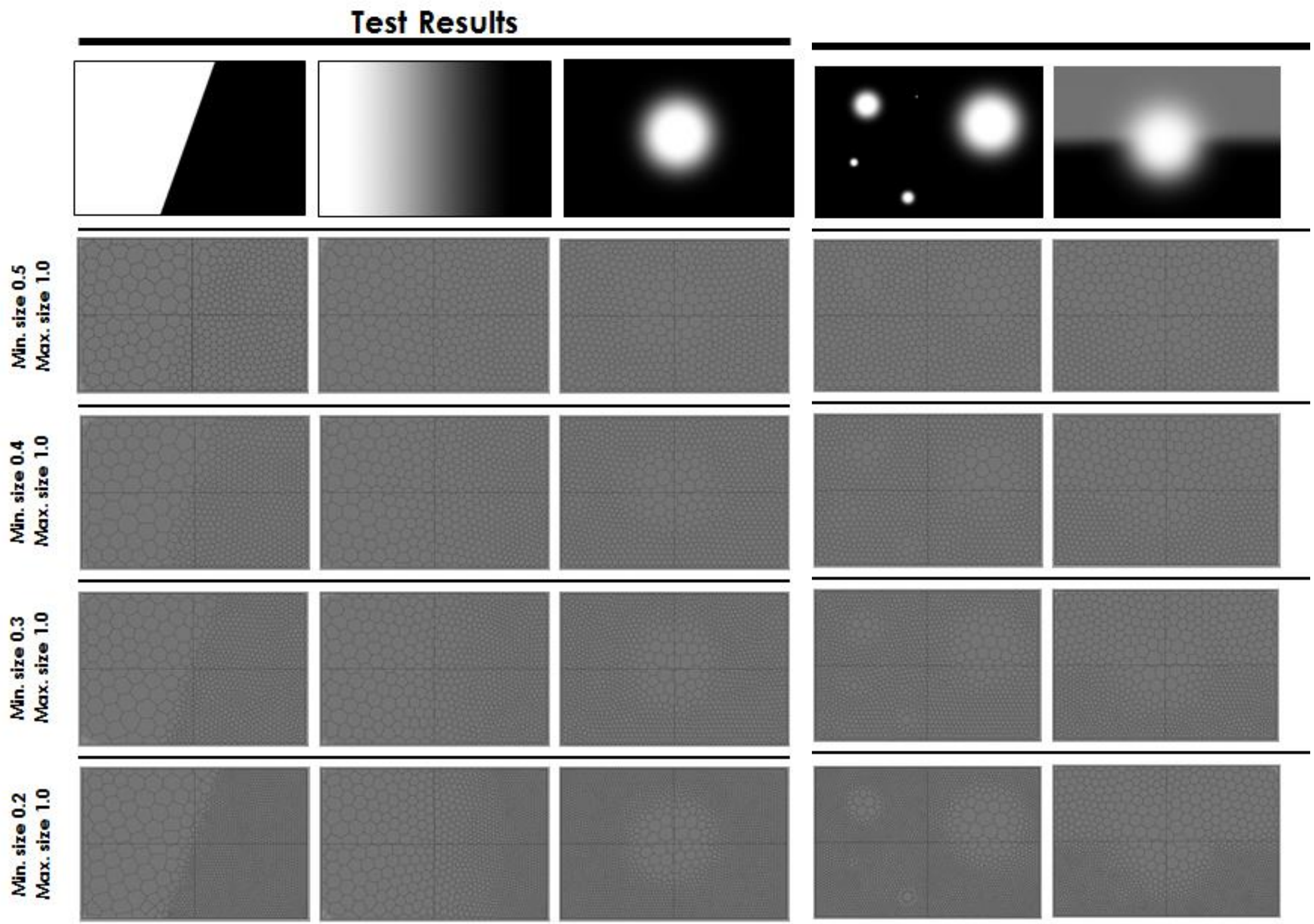
SPRING **FORCE SYSTEM**







SMART **CIRCLE PACKING**



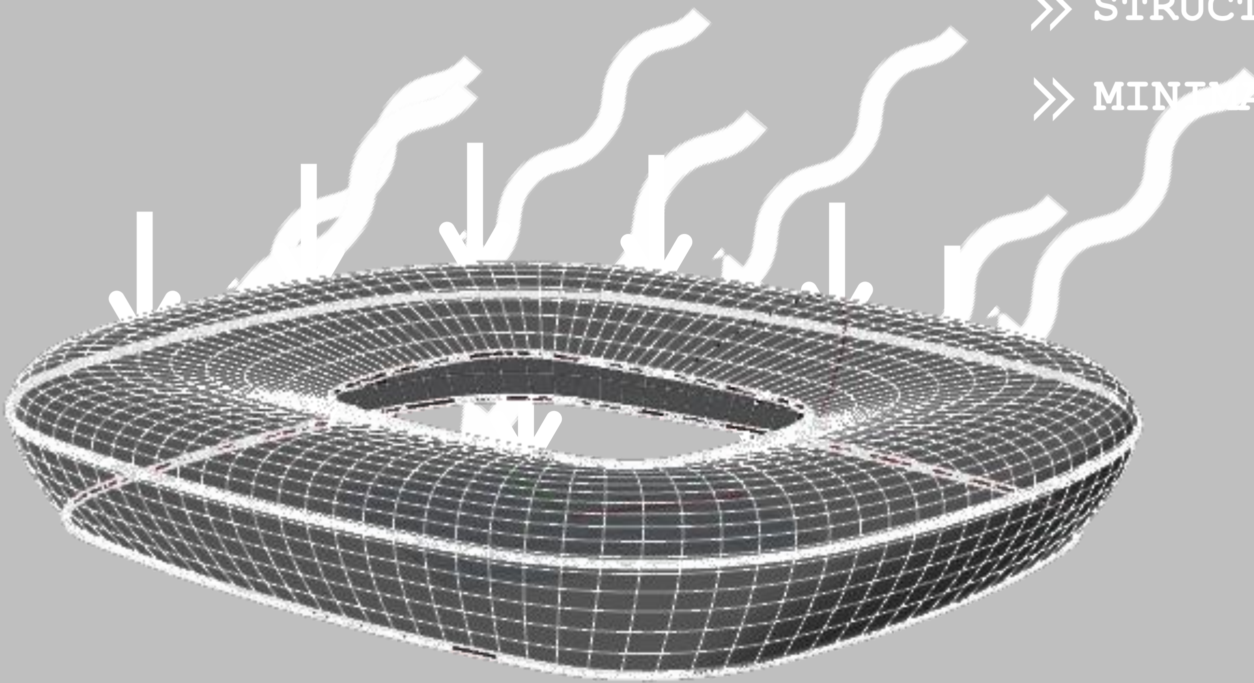
CASE **OPTIMIZATION**

The goal is to optimize the canopy design for multiple objectives in order to limit the amount of necessary materials and energy

» **SOLAR GAINS ROOF**

» **STRUCTURAL STRENGTH**

» **MINIMAL SURFACE**



12 GENES FOR GENETIC ALGORITHM

» **TOP**

Scale X
Scale Y
Angle X
Angle Y
Move Z

» **MIDDLE**

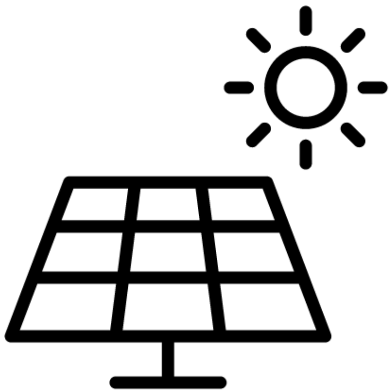
Scale X
Scale Y
Angle X
Angle Y
Move Z

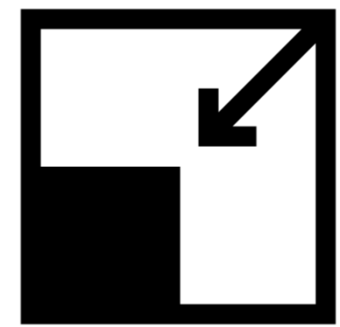
» **BOTTOM**

Scale X
Scale Y

CASE **OPTIMIZATION**

The goal is to optimize the canopy design for multiple objectives in order to limit the amount of necessary materials and energy





» SOLAR GAINS ROOF

Measured by calculating the amount of received radiation of the roof over a year

» STRUCTURAL STRENGTH

Measured by calculating the deflection of the shell from the basic shape of the canopy with a preset thickness

» MINIMAL SURFACE

Measured by calculating the area of the shape of the canopy

RESULTS OF **OPTIMIZATION**

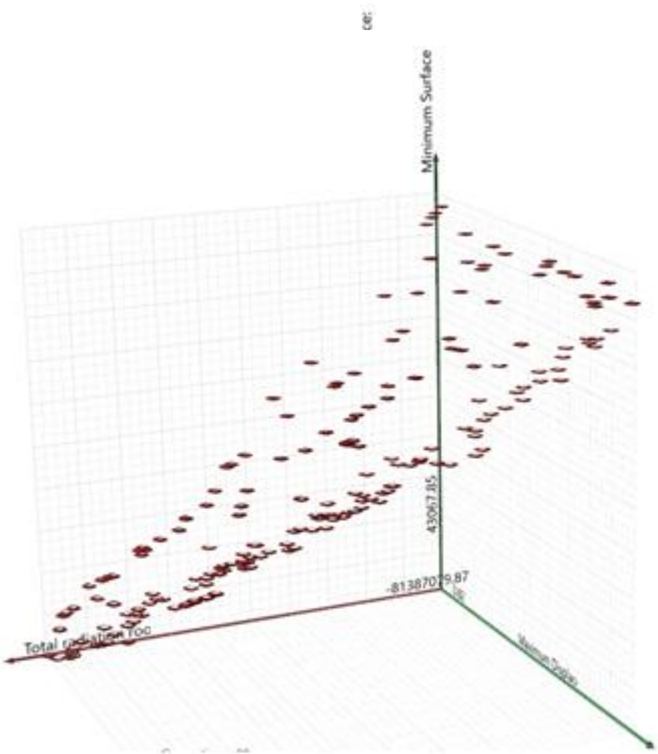


Figure 35: Display from the multi-objective optimization projected with only the pareto solutions displayed.

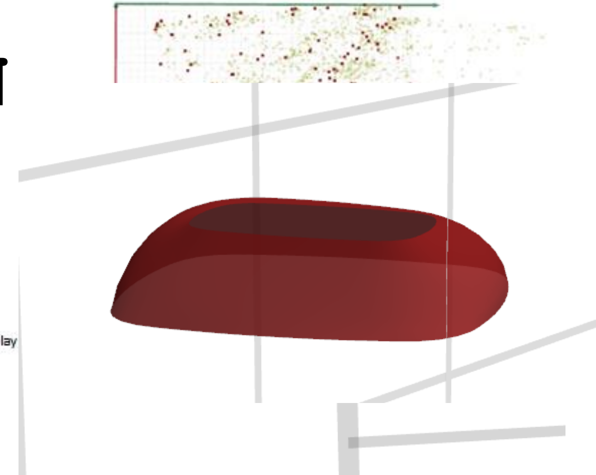


Figure 32: Display ed-axis,

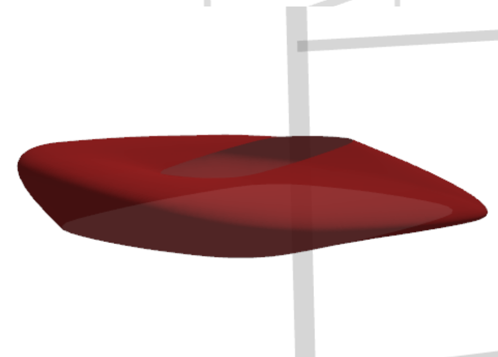


Figure 33: Display fro the red-axis,

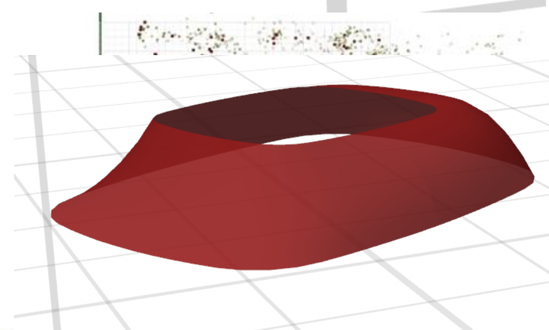
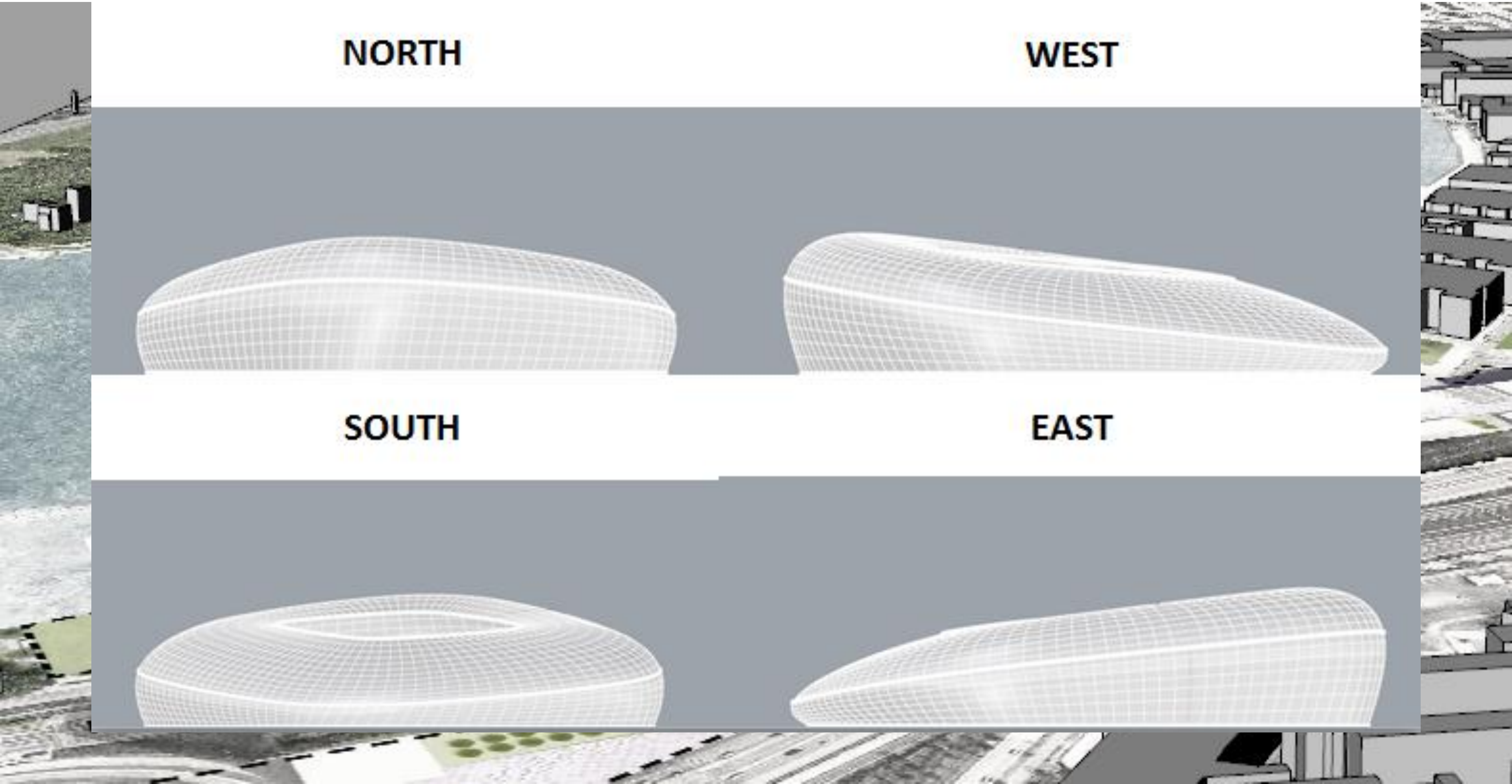
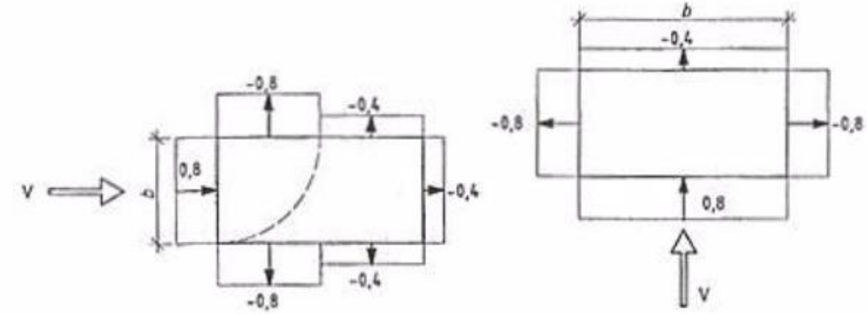


Figure 34: Displ green axis, Maximum Displacement on the light green axis.

RESULTS OF **OPTIMIZATION**

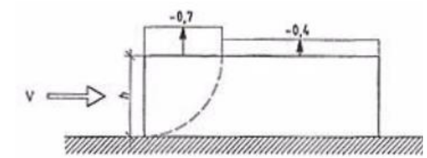


STRUCTURAL CALCULATIONS



» FIVE LOADCASES

- Load case 0: only gravity load (reference)
- Load case 1: north western wind load
- Load case 2: south western wind load
- Load case 3: south eastern wind load
- Load case 4: north eastern wind load



» MAX. DEFORMATION

0.004 x 200 = 0.80 m deflection

» LOADS

- A live load: 1.0 kN/m²
- The stadium lies within windzone II in an urban area and has a height of 75 meters:
  - 1.37 kN/m² windload