Computational design of Metamaterials: From Geometry to Mechanical Properties

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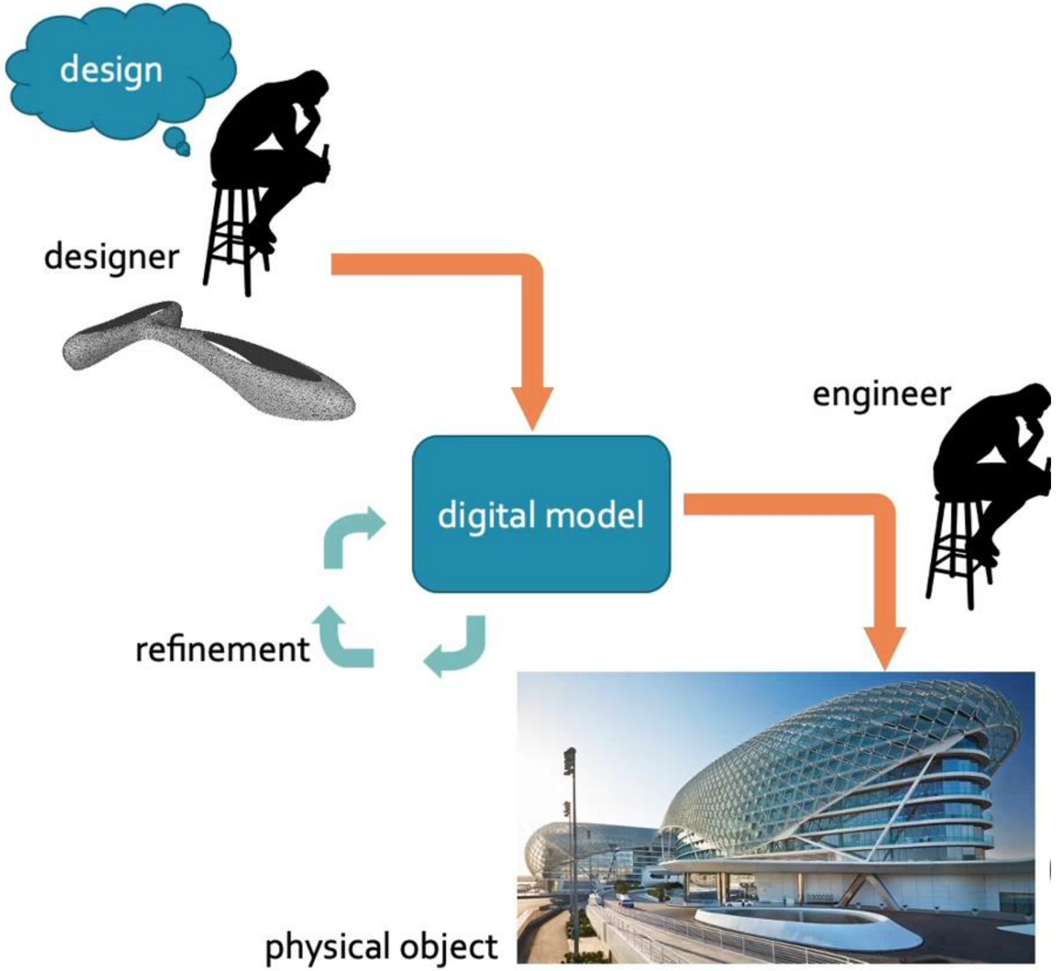
Outline

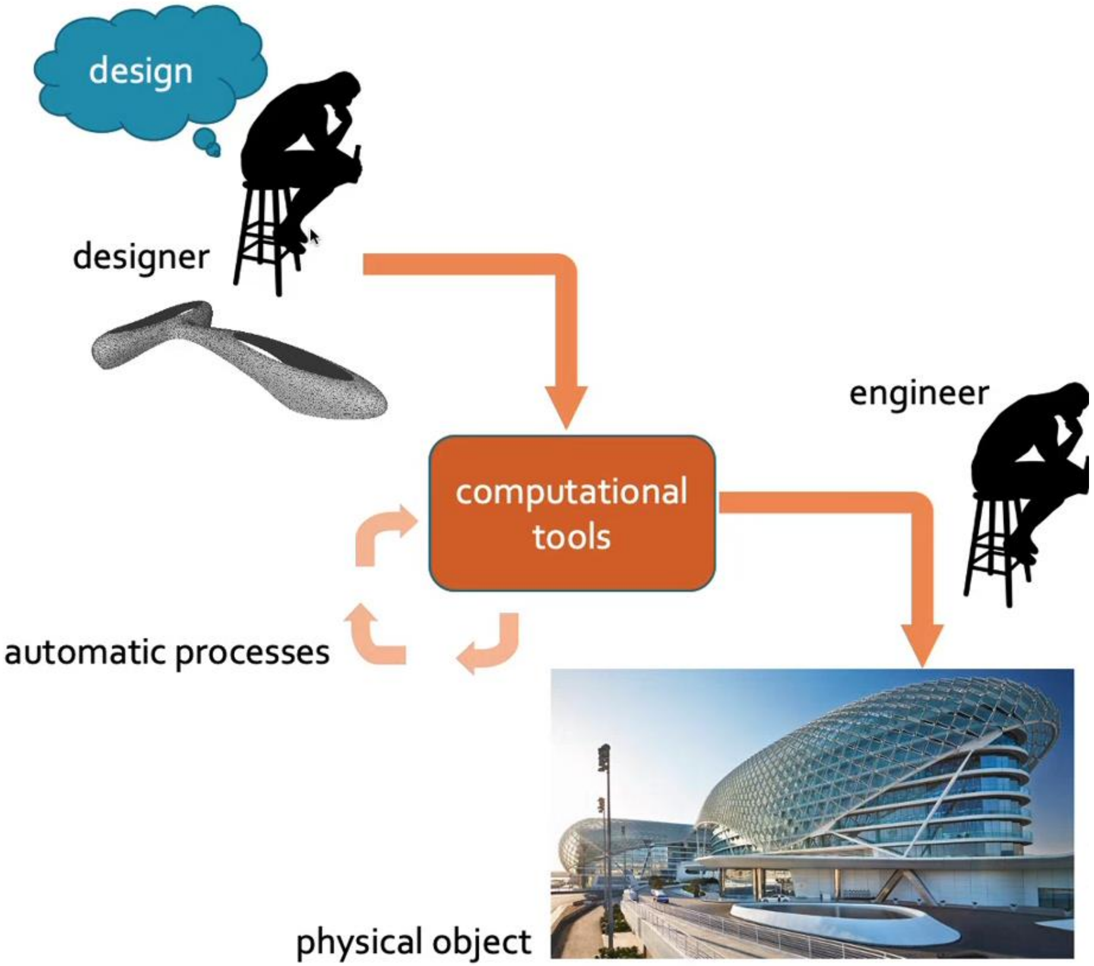
1. Introduction
2. State of the art
    a. Metamaterials
    b. Shape approximations
3. Computational design of flat patterns for approximating 3D shapes
    a. Simulation model
    b. Topology exploration of flat patterns
    c. Optimization Framework
4. Future directions

The digital fabrication pipeline



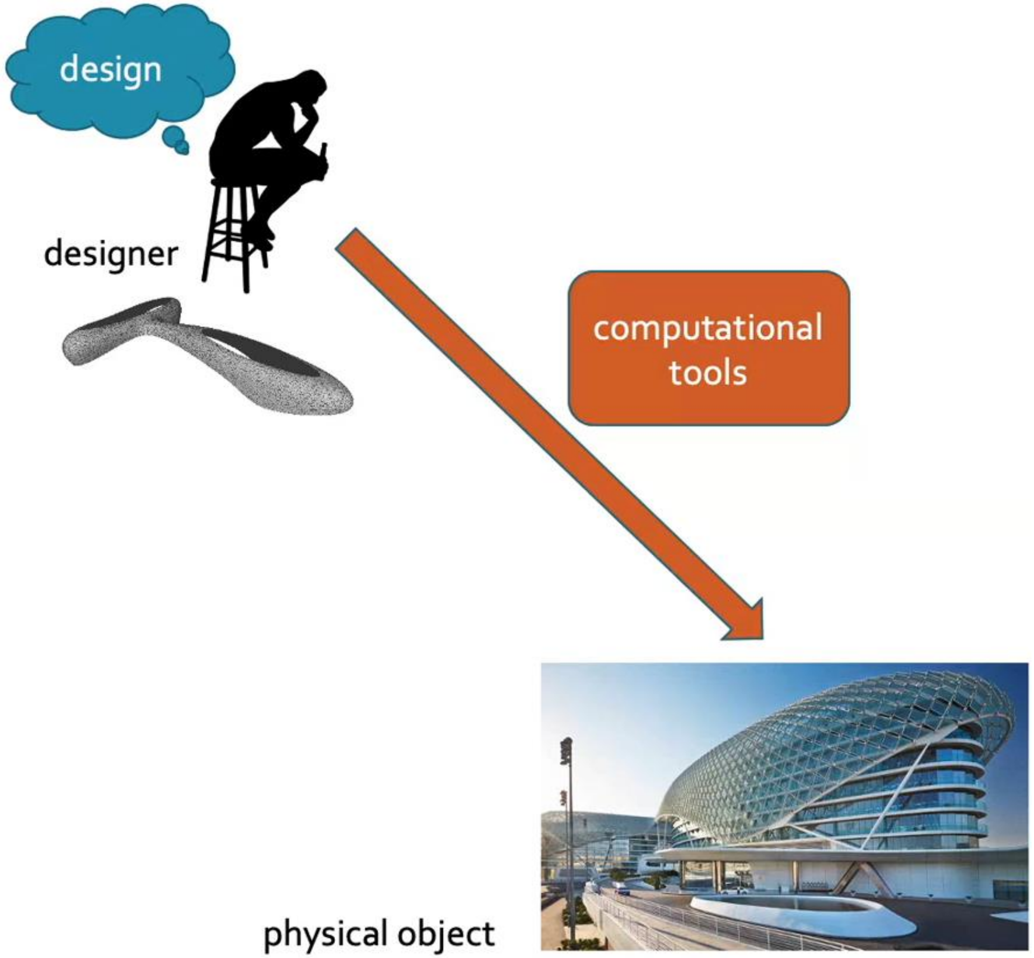
[Yas Hotel Abu Dhabi]

The digital fabrication pipeline



[Yas Hotel Abu Dhabi]

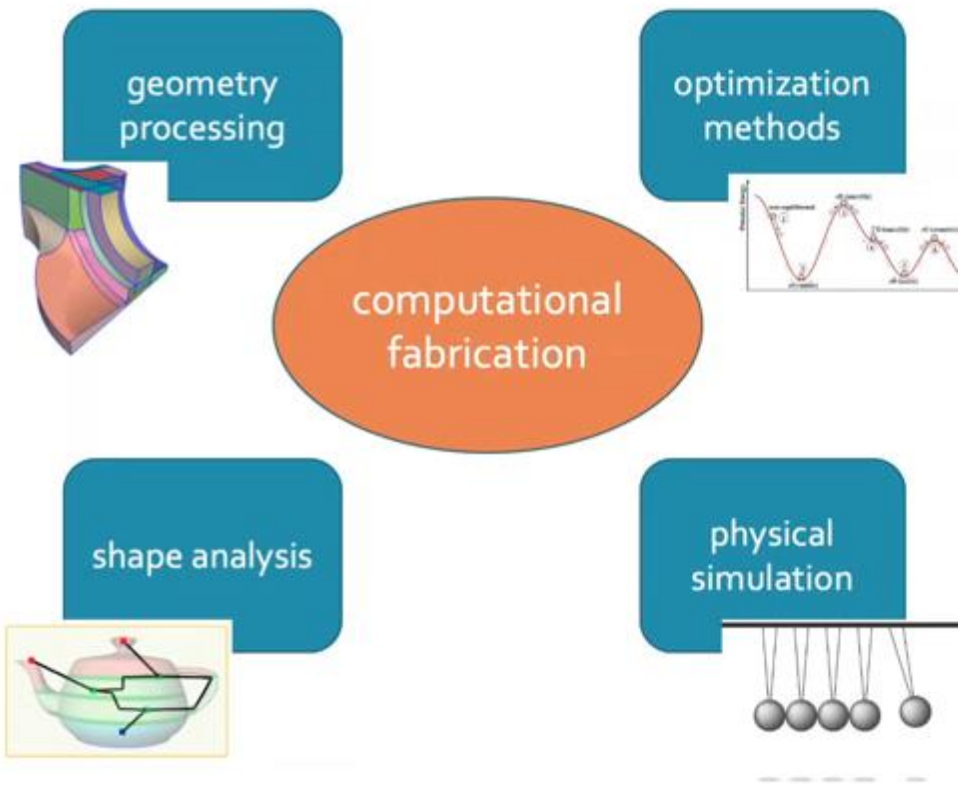
The digital fabrication pipeline



[Yas Hotel Abu Dhabi]

Computational Fabrication

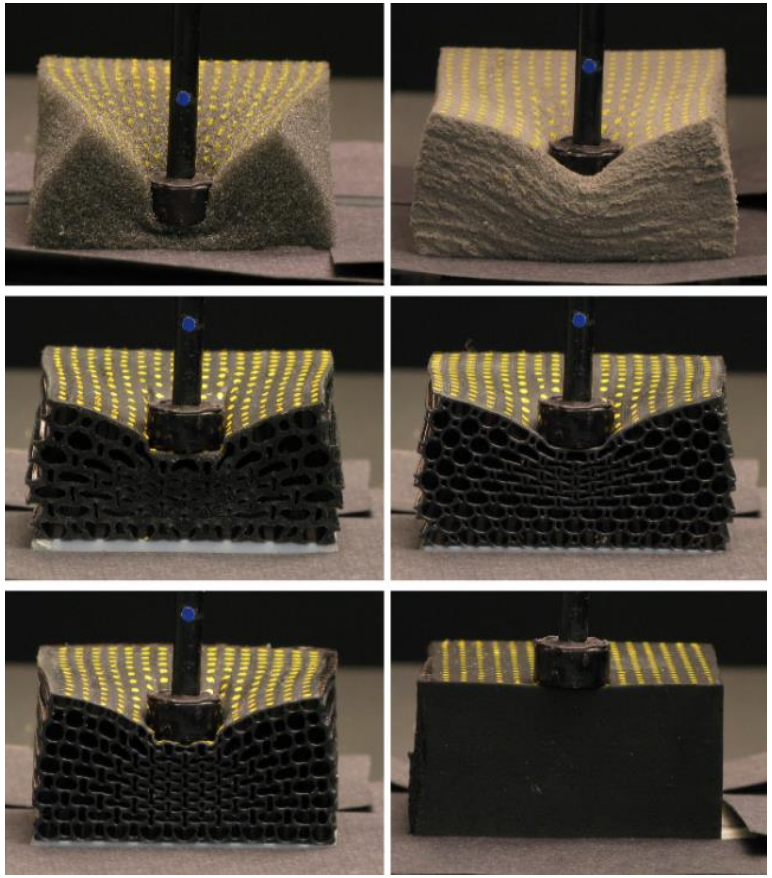
Computational Fabrication Is a field that attempts to aid digital manufacturing by developing computational tools



Achieving desired mechanical properties

[Prevost et al. 2013]

[Lu et al. 2014]

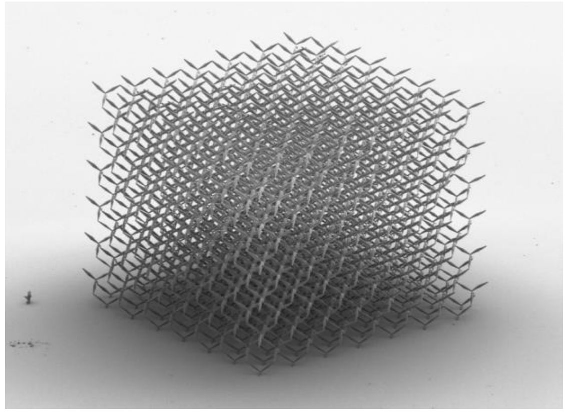


[Bickel et al. 2010]

Metamaterials

Various applications:
- Seismic metamaterials
- Acoustic metamaterials
- Metamaterial antennas
- Mechanical metamaterials

and a lot more..

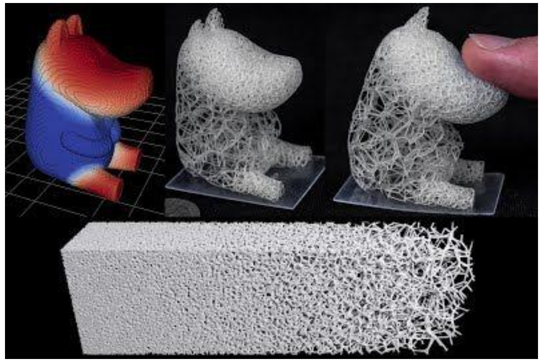
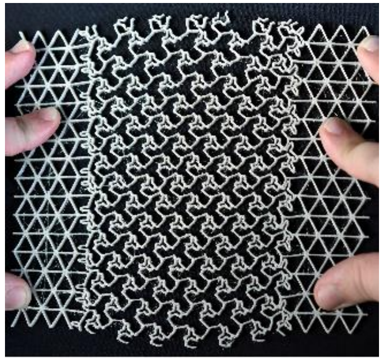


Goal

"*Computational design of flat ornamental patterns which, when tiled in a prescribed way, approximate a desired 3D shape*"

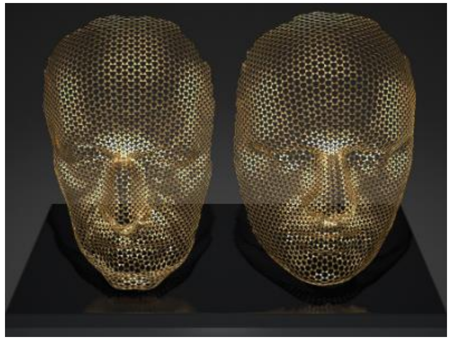
State of the art

- Metamaterials

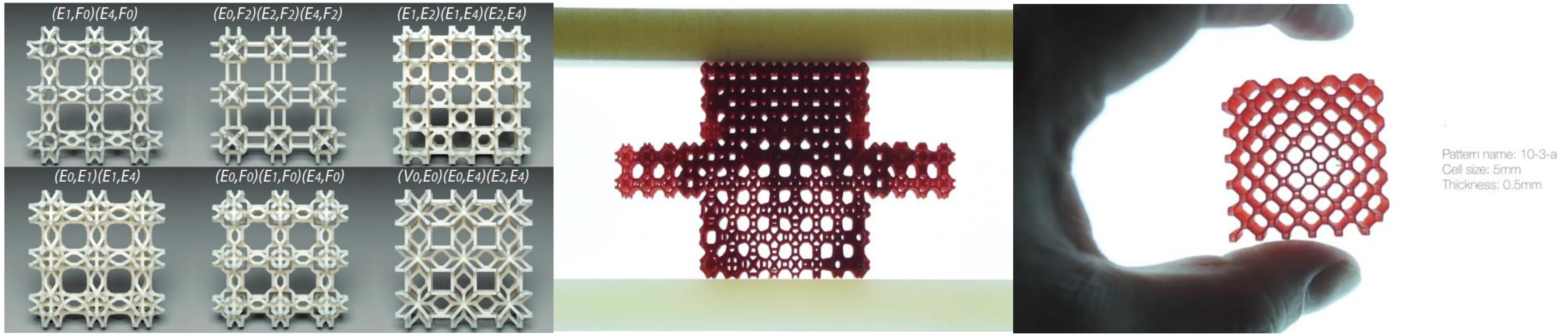

- Shape approximation




Deformations using Metamaterials

[Schumacher et al. 2015]



[Panetta et al. 2015]

Shape approximations using flat pieces

[Chen et al. 2017]

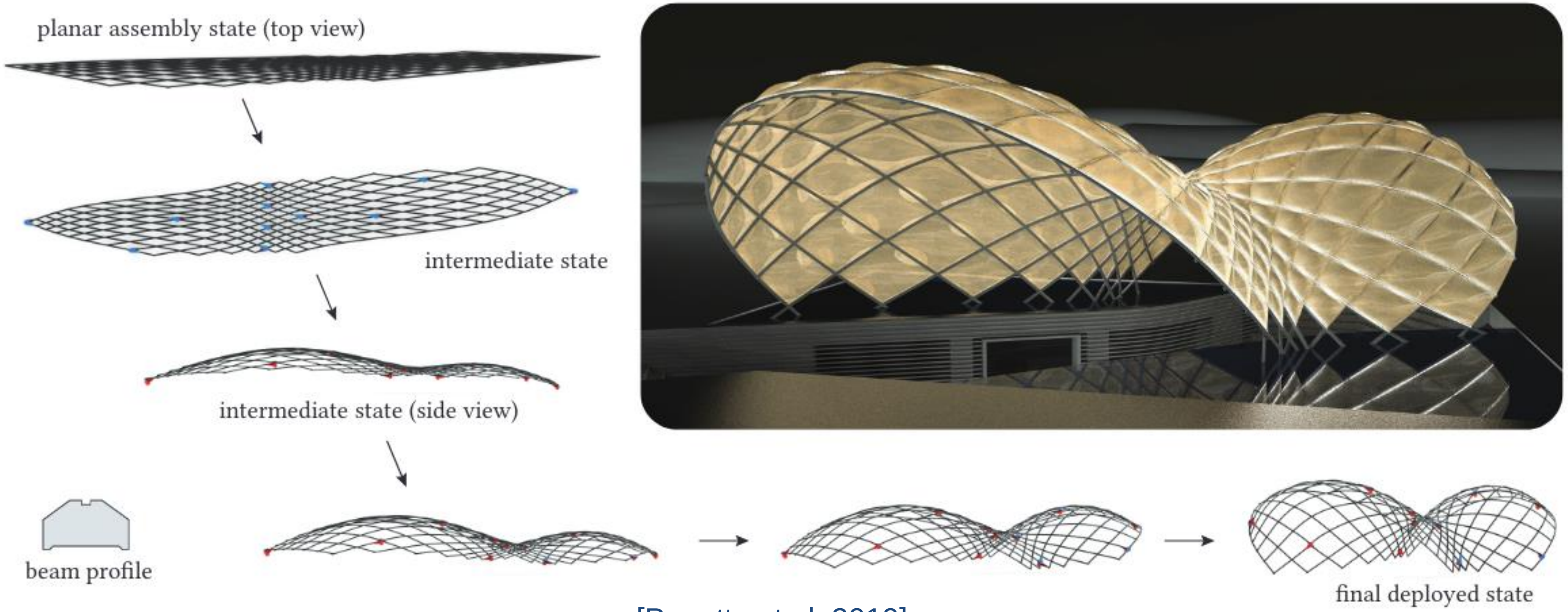
[Guseinov et al. 2017]

Shape approximations using flat pieces

[Chen et al. 2017]

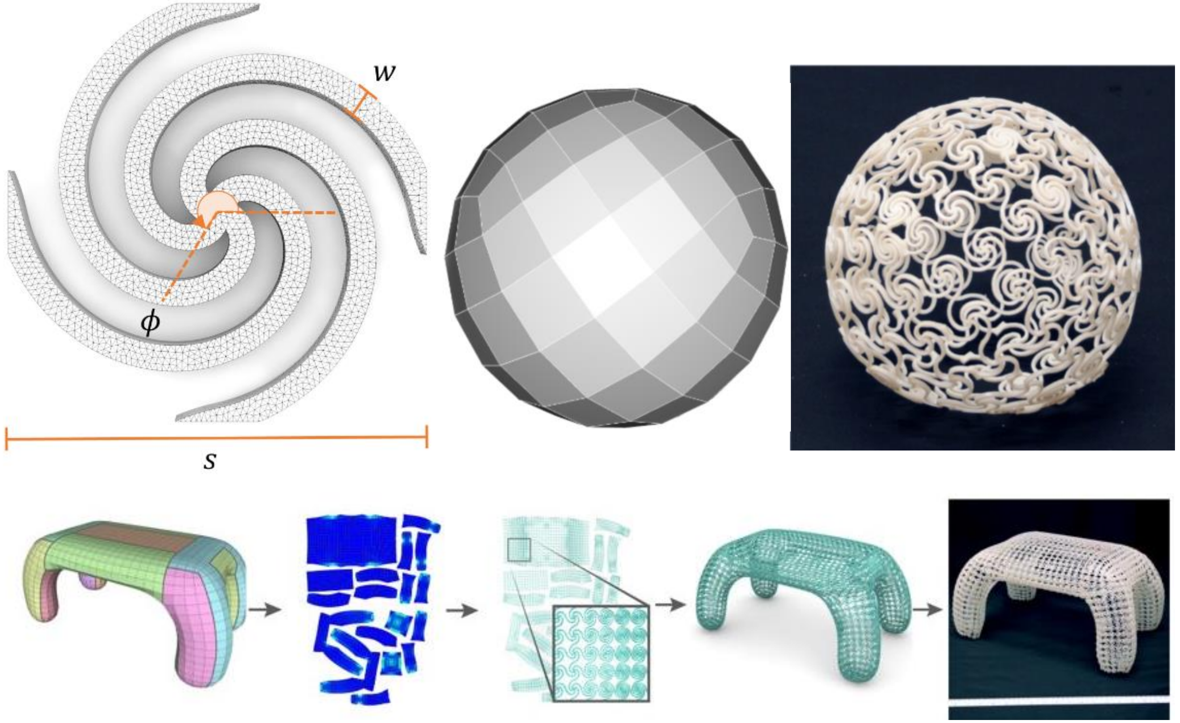
[Guseinov et al. 2017]

Bending-active structures



[Panetta et al. 2019]

Shape approximations using spiral patterns



[Malomo & Perez et al. 2018]

[Laccone et al. 2020]

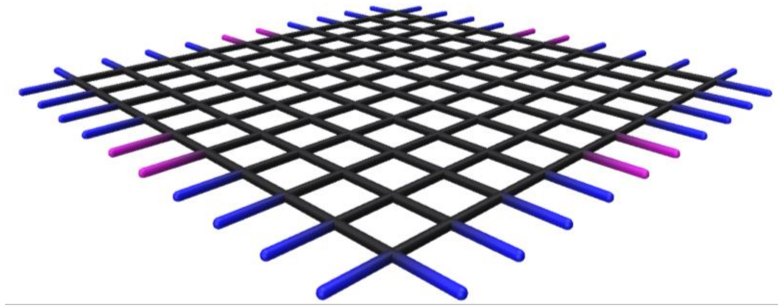
Motivation

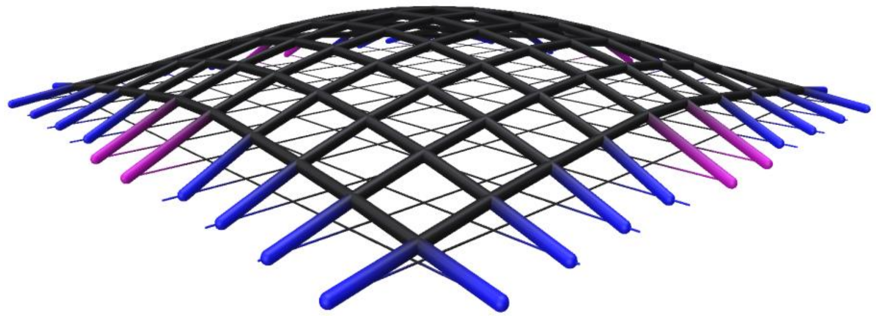
- Simulation tools are essential for assesing accuracy and for determing feasibility of deformations
- Commercial FEM packages are both computationally demanding & not open
- Scarcity of lightweight and open simulation tools

Sakai et al. 2020 - Non-linear beam simulation model

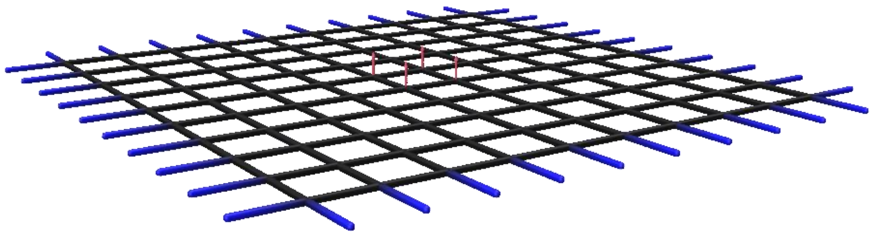
Sakai et al. 2020 : “*A computational tool for the analysis of 3D bending-active structures based on the dynamic relaxation method*”

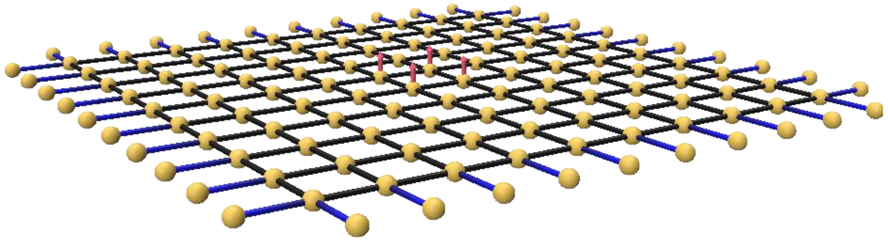
Problem: Computation of the static equilibrium state of structures



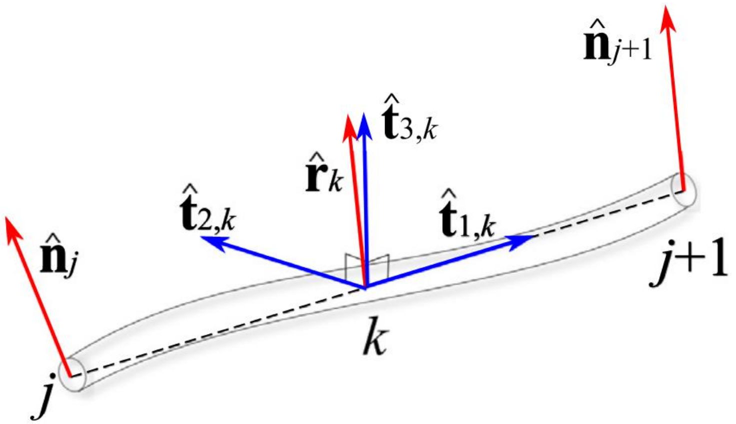


Sakai et al. 2020 - Element frame formulation





Formulation of the element frame with respect to the normal of the nodes



Sakai et al. 2020 - The dynamic relaxation method

Input: Discretized structure, Loads, Boundary conditions
Result: Structure in static equilibrium
Initialize();
while *Structure is not in static equilibrium* **do**
    UpdateResidualForces();
    UpdateCoordinates();
    $t = t + \Delta t$;
    if *Local maxima of kinetic energy reached* **then**
        DampKineticEnergy();
    end
end

Sakai et al. 2020 – Visual results

Input: Discretized structure, Loads, Boundary conditions
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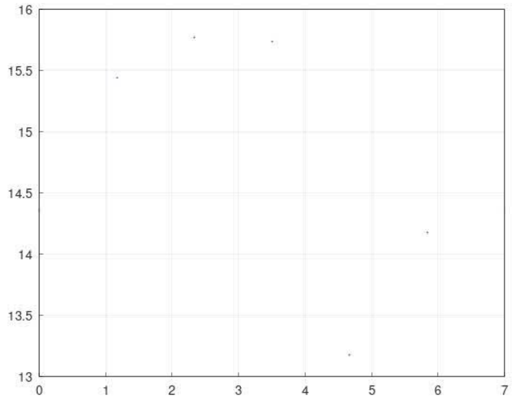
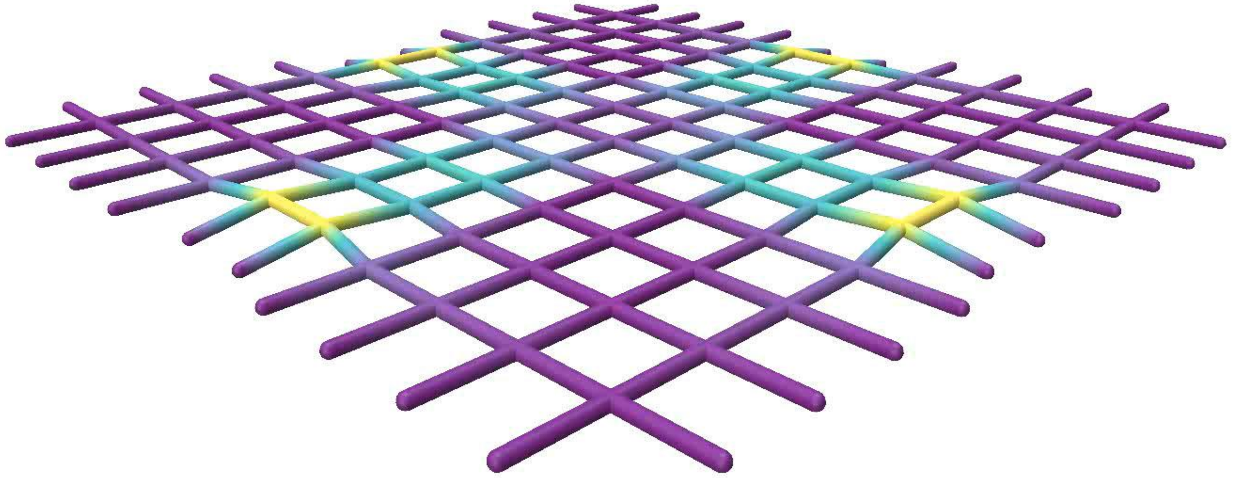
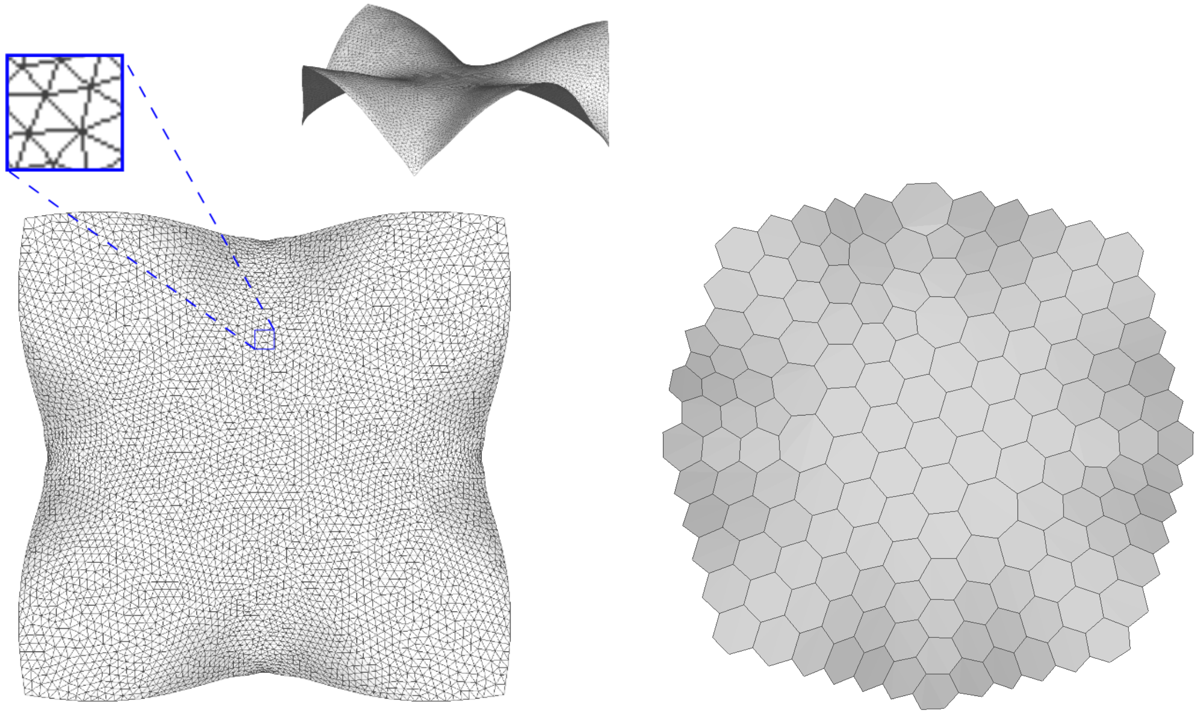




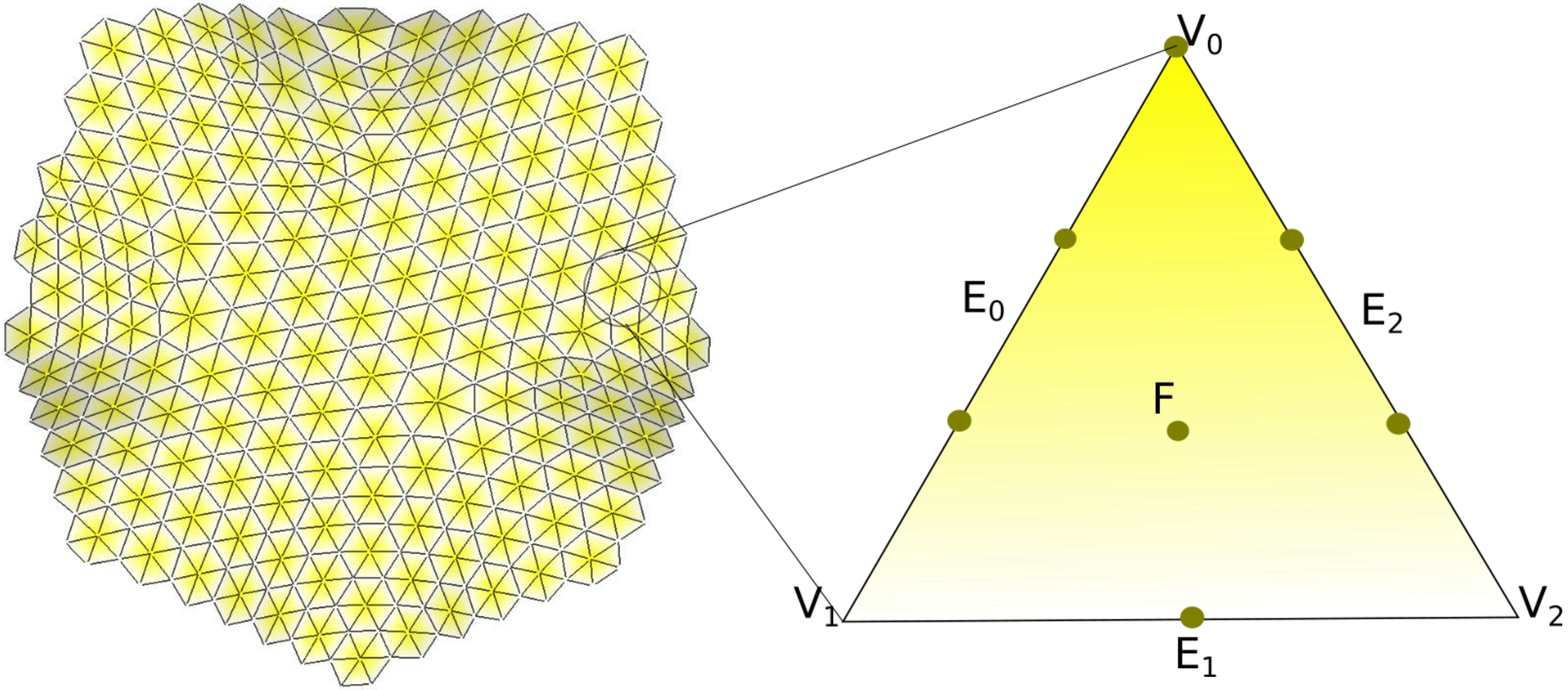
Topological exploration of flat patterns

- Goal: Tessellating a surface with a range of patterns in a consistent way
- For doing that we compute a voronoi tesselation



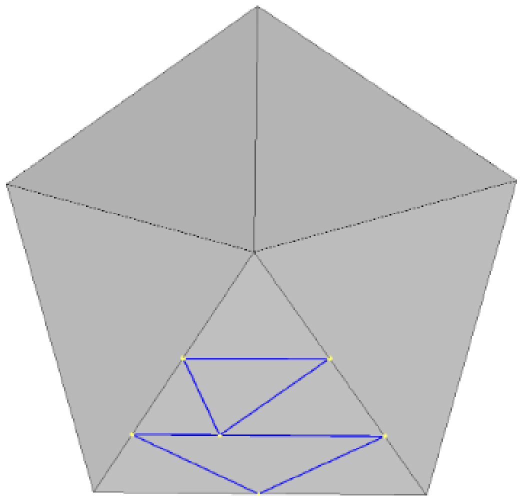
Topological exploration of flat patterns

Due to the symmetry of the tesselation, we can generate pattern topologies by studying graphs on a base triangle

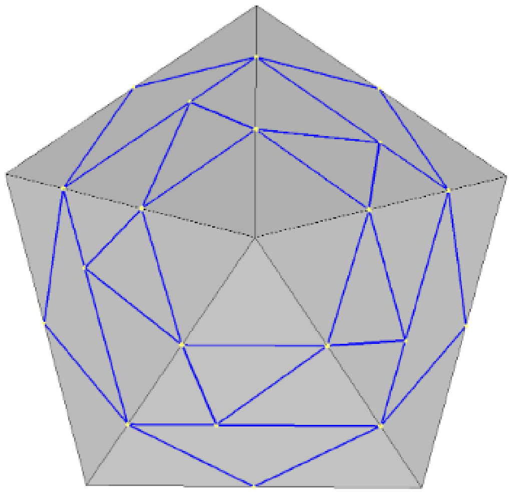


Pattern example

We generate topologies by connecting nodes on the base triangle and then tiling the result



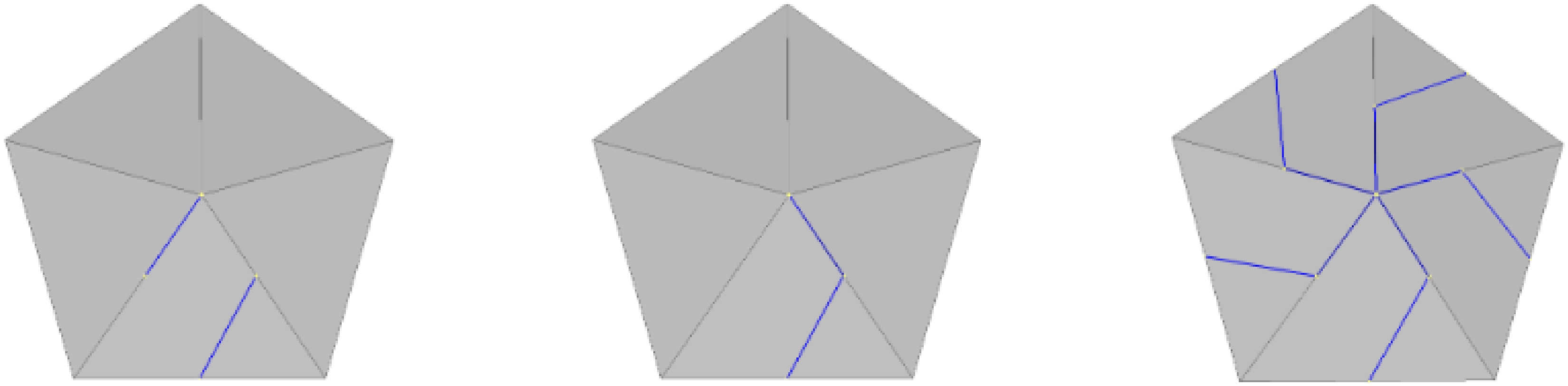
(a) Non-tiled Pattern



(b) Tiled pattern

Valid edges

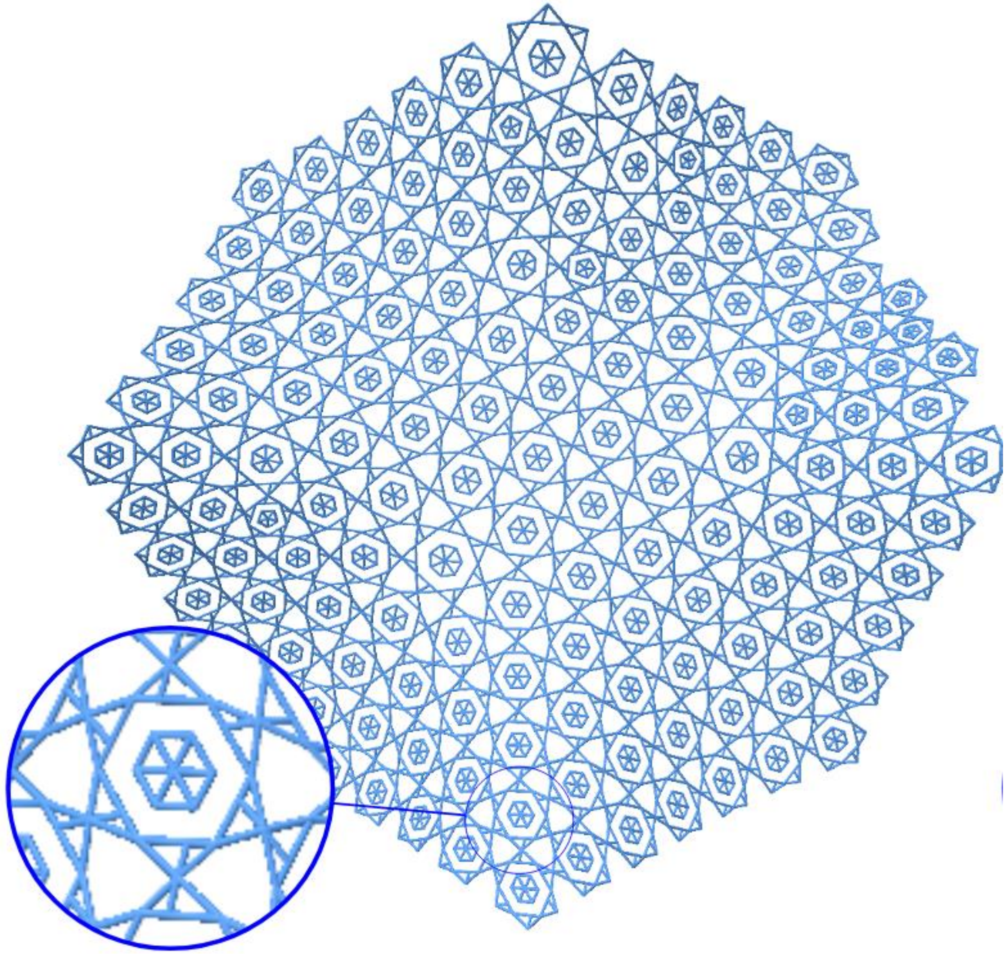
- We begin by creating a valid set of edges
- We do not allow edges that intersect with each other
- We do not allow edges that due the rotational symmetry of the tessellation are the same



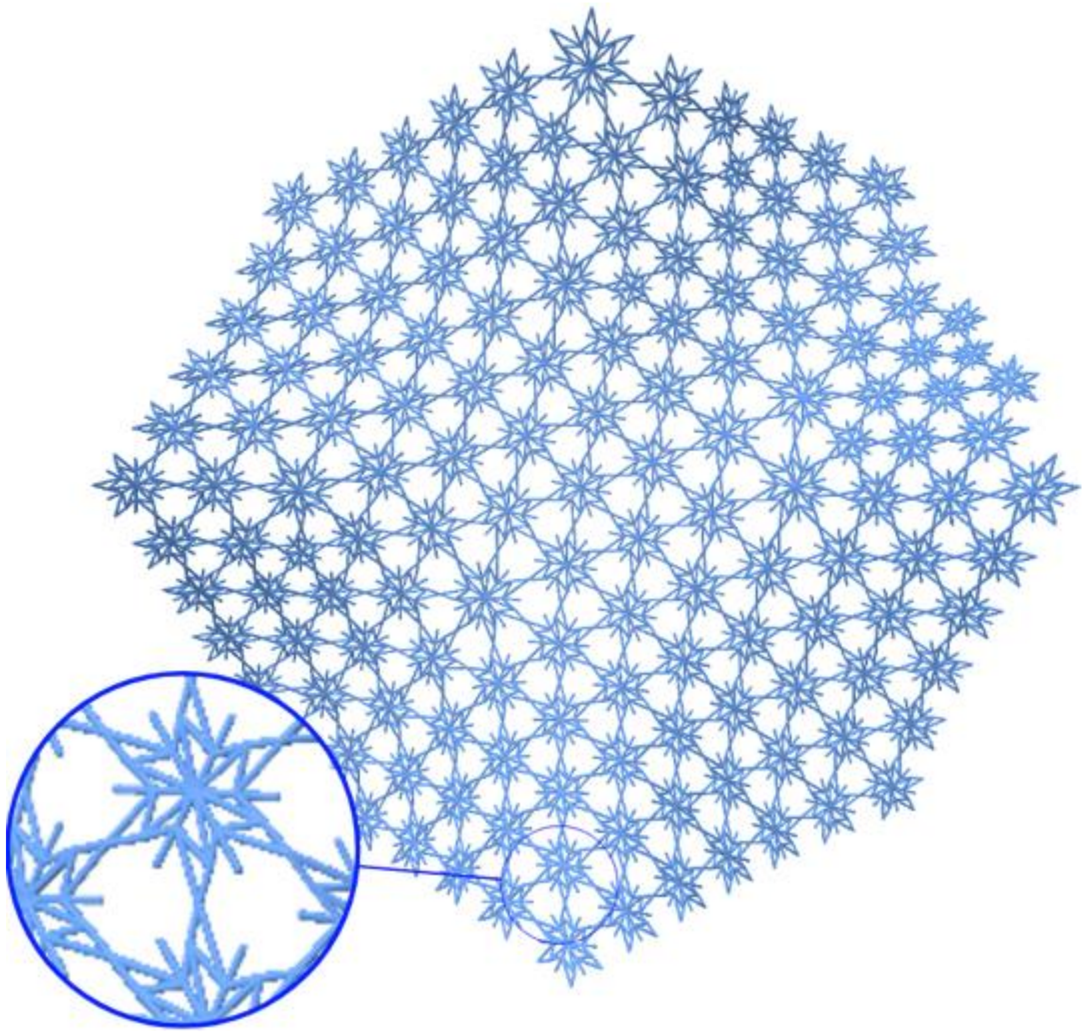
Valid topologies

- We enforce the fabricability of the topologies by making sure they meet the following criteria:
  - Single connected component
  - No Dangling edges
  - No Articulation points
- All patterns that meet these criteria form the subset of valid topologies

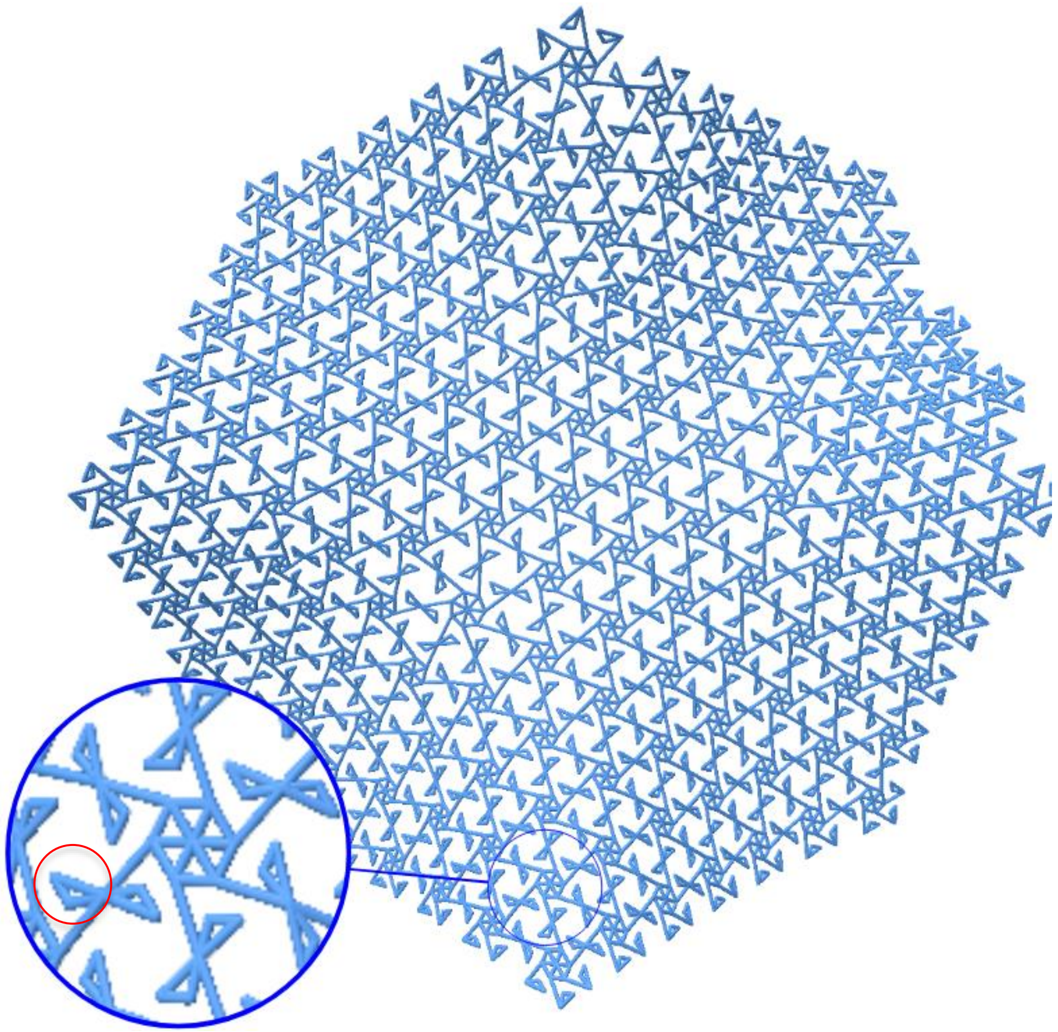
Multiple connected components



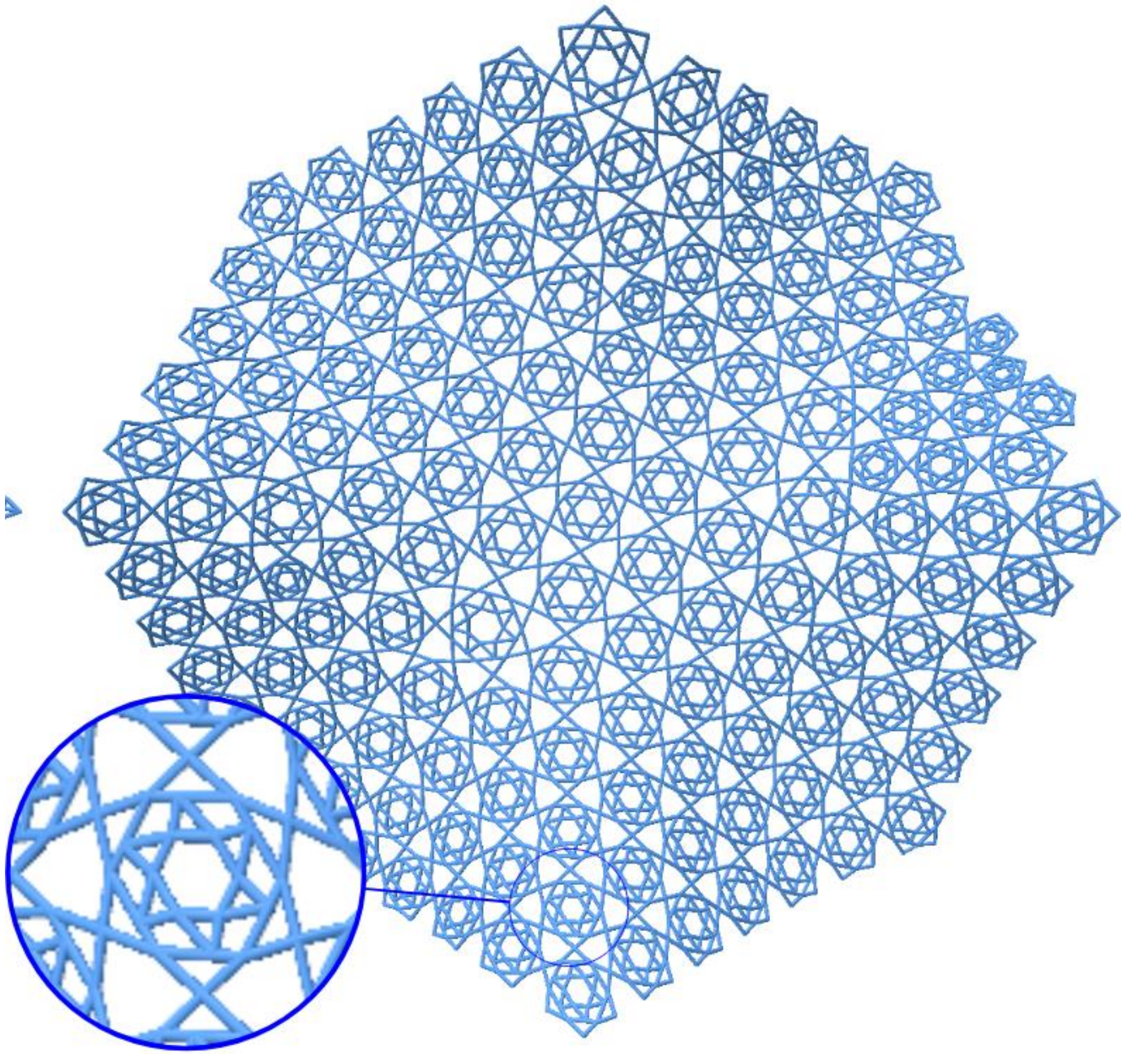
Dangling edges



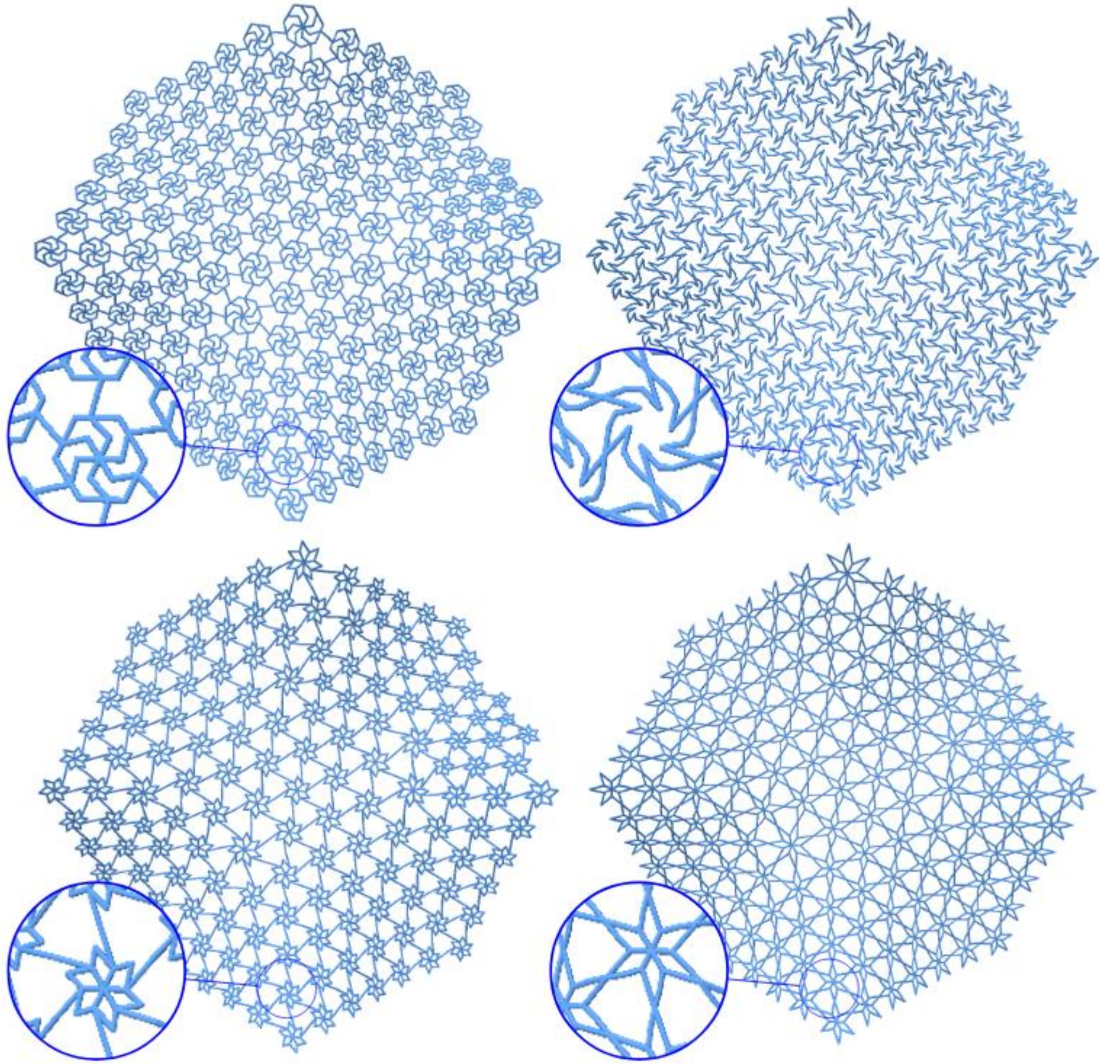
Articulation points



Valid patterns



Valid patterns

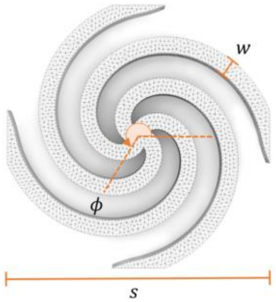


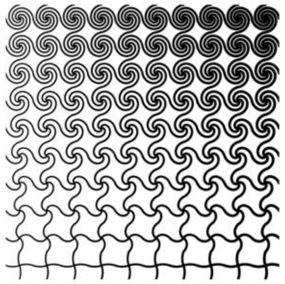
Optimization Framework

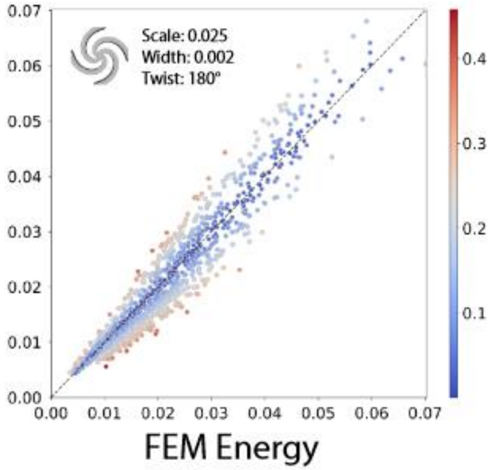
- A framework that can optimize the geometry of the patterns for minimizing the approximation error
- A straightforward approach: Running an optimization method on the full structure. But that would be computationally infeasible
- Currently exploring: Constructing a reduced model

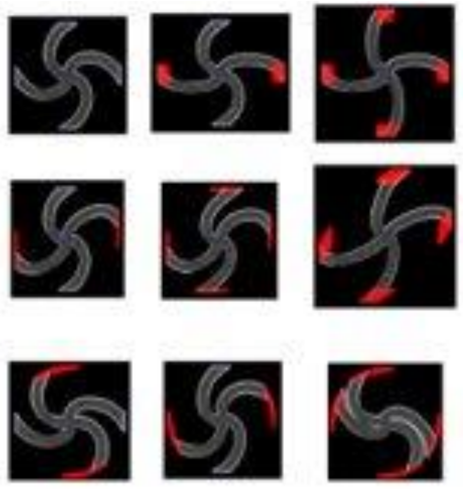
Optimization Framework

Constructing a reduced model for our patterns





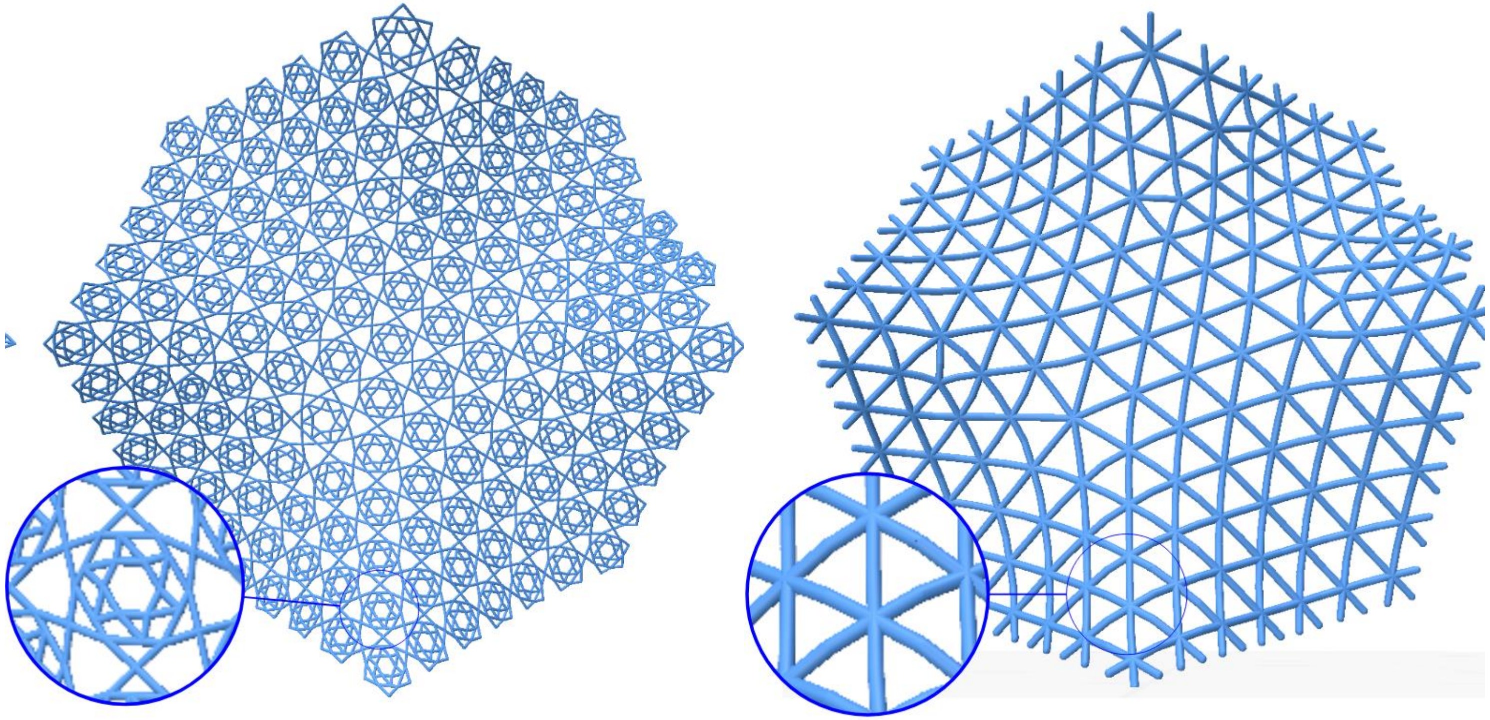




$$min_{\mathbf{p}} \sum_{i=1}^{r} \left(\frac{V(\mathbf{p}, \mathbf{q}_i)}{U_i^F} - 1 \right)^2$$

[Malomo & Perez et al. 2018]

Single bar reduced model



Future directions

- Creating families of patterns with identical stiffness, but different macro-mechanical properties such as rigidity, weight etc.
- Multiple external loads, rain actuated shapes
- Simulation tool & pattern topology exploration can benefit future computationally assisted smart design tools

Summary

- Digital fabrication lacks automatic tools that encapsulate field-specific knowledge
- We proposed a plan for computationally designing flat structures which when tilled approximate a desired 3D shape
- Future extensions of our work

Thank you for your attention!