A Biologically Inspired Methodology for Multi-Disciplinary Design Optimization

Master’s Thesis in Mechanical Engineering

Miguel Alexandre Nunes

- **Outline**

1.0 Introduction

- Traditional Engineering Design vs. Biologically Inspired Automated Design

JetTrain

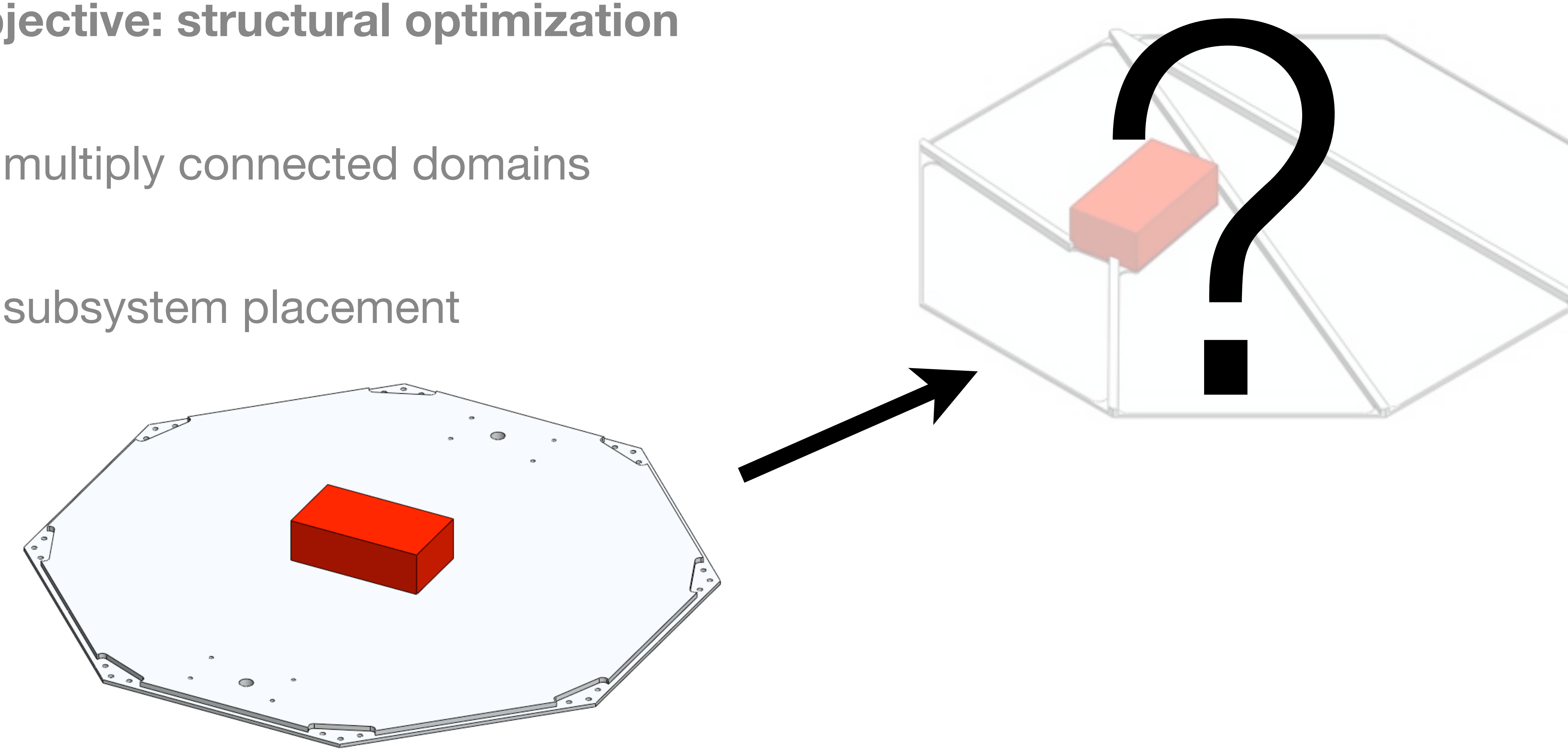
Shinkansen bullet train

kingfisher bird.

1.0 Introduction

- Traditional Engineering Design vs. Biologically Inspired Automated Design

- **Objective: structural optimization**
  - multiply connected domains
  - subsystem placement



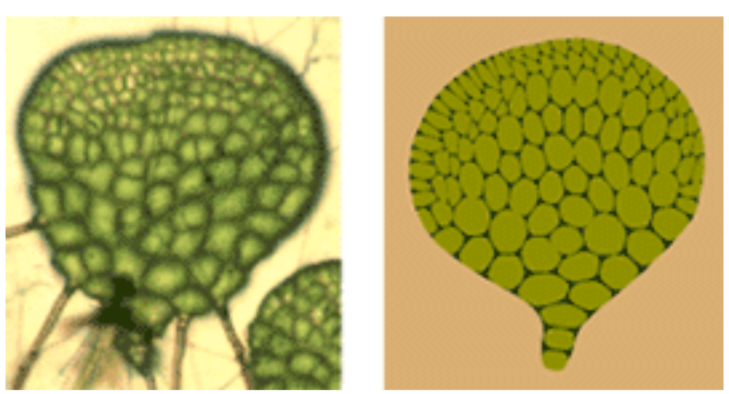
1.0 Introduction

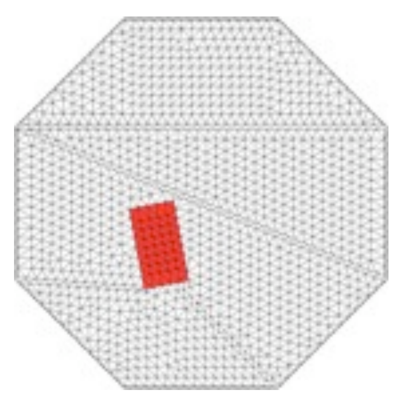
- **Biologically Inspired MDO procedure:**

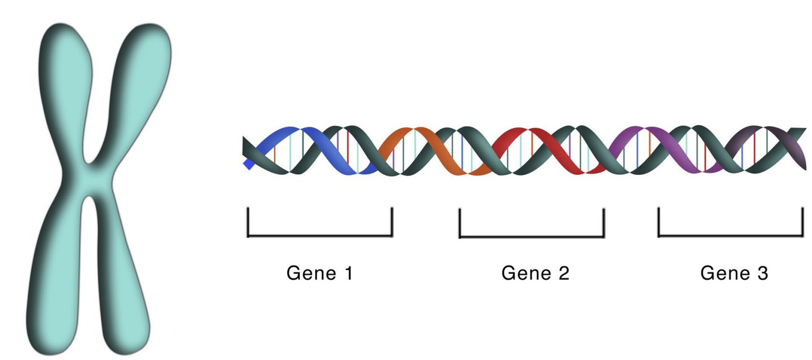
1. Map-L Systems for ***structural topology representation*** (inspired in biology)

2. Finite Element method for ***structural analysis***

3. Genetic Algorithm for ***objective topology optimization*** (inspired in biology)



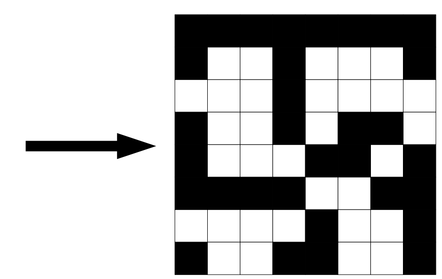




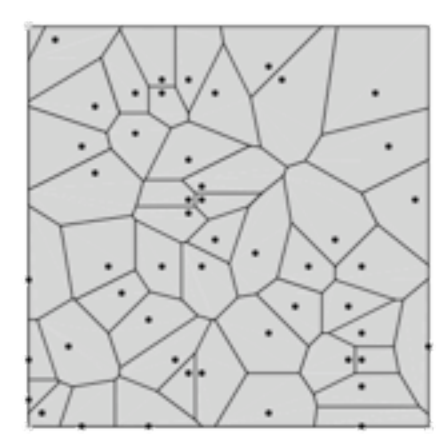
1.0 Introduction

- Why use a biologically inspired methodology for **topology representation?** (Map-L System)
  - Improve the representation for structural elements compared to traditional methods:
    - Bit-array representation - may have physical limitations or create non-viable topologies

1	1	1	1	1	1	1	1
1	0	0	1	0	0	0	1
0	0	0	1	0	0	0	0
1	0	0	1	0	1	1	0
1	0	0	0	1	1	0	1
1	1	1	1	0	0	1	1
0	0	0	0	1	0	0	1
1	0	0	1	1	0	0	1

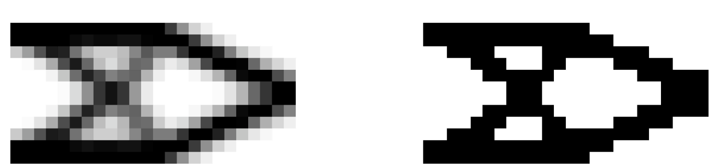


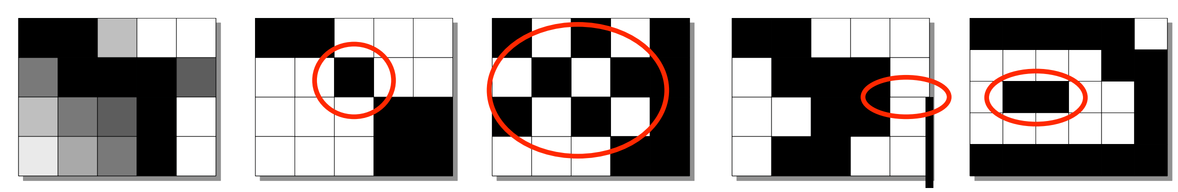
    - Voronoi-based representation - has problems of design connectivity



1.0 Introduction

- Why use a biologically inspired methodology for **topology optimization?** (Genetic Algorithm)
  - Improve the solutions for structural optimization in efficiency and robustness given by traditional methods:
    - Solid Isotropic Material with Penalization (SIMP) Methods - the solution may be represented by non-existent materials (or hard to manufacture)



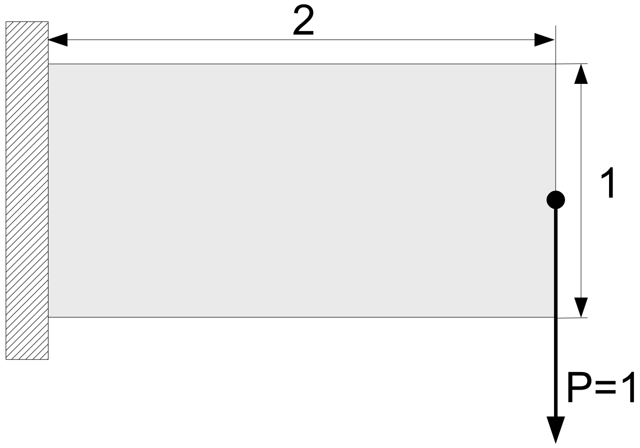


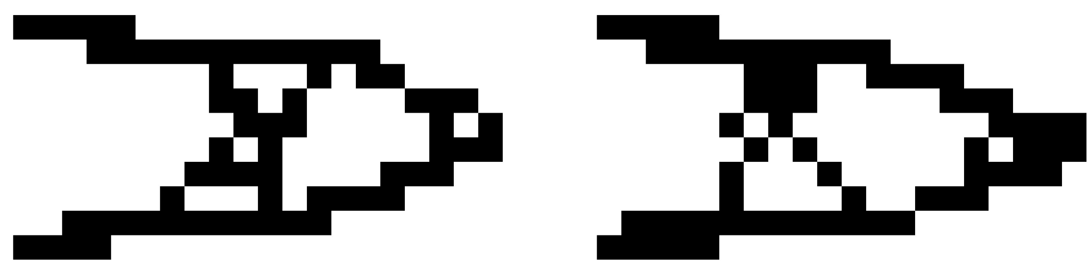
    - “Hard-kill” Methods usually determine a complex structure

1.0 Introduction

- Cantilever Benchmark Tests for weight optimization (by Dr. Hugo T. C. Pedro)

Bit Array Representation





(a) (b)

Traditional Design

m = 100 %

Wang et al. Design

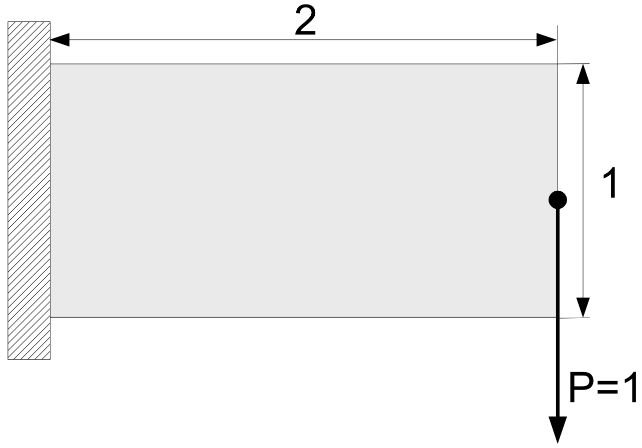
m = 32.5 %

Balamurugan et al Design

m = 34.0 %

1.0 Introduction

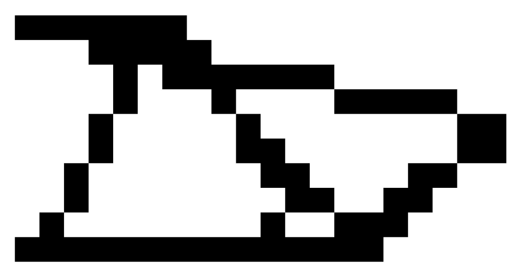
- Cantilever Benchmark Tests for weight optimization (by Dr. Hugo T. C. Pedro)



Traditional Design

m = 100 %

Voronoi-based representation

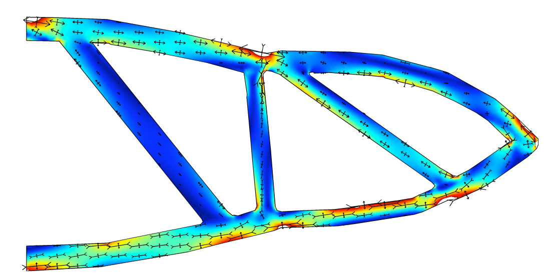


(c)

Hamda et al. Design

m = 33.0 %

Map-L System

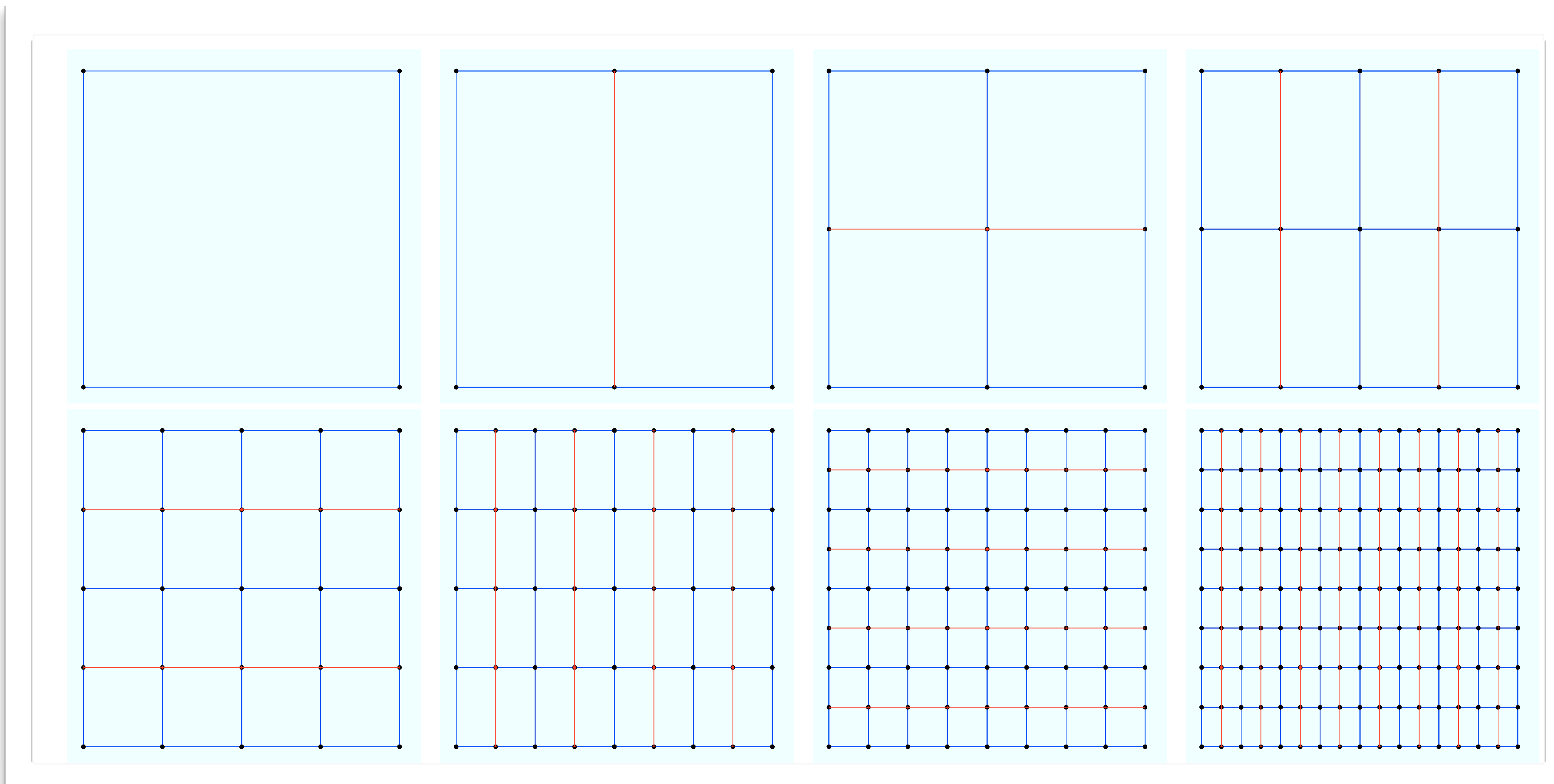


Biologically Inspired Design

m = 26.0 %

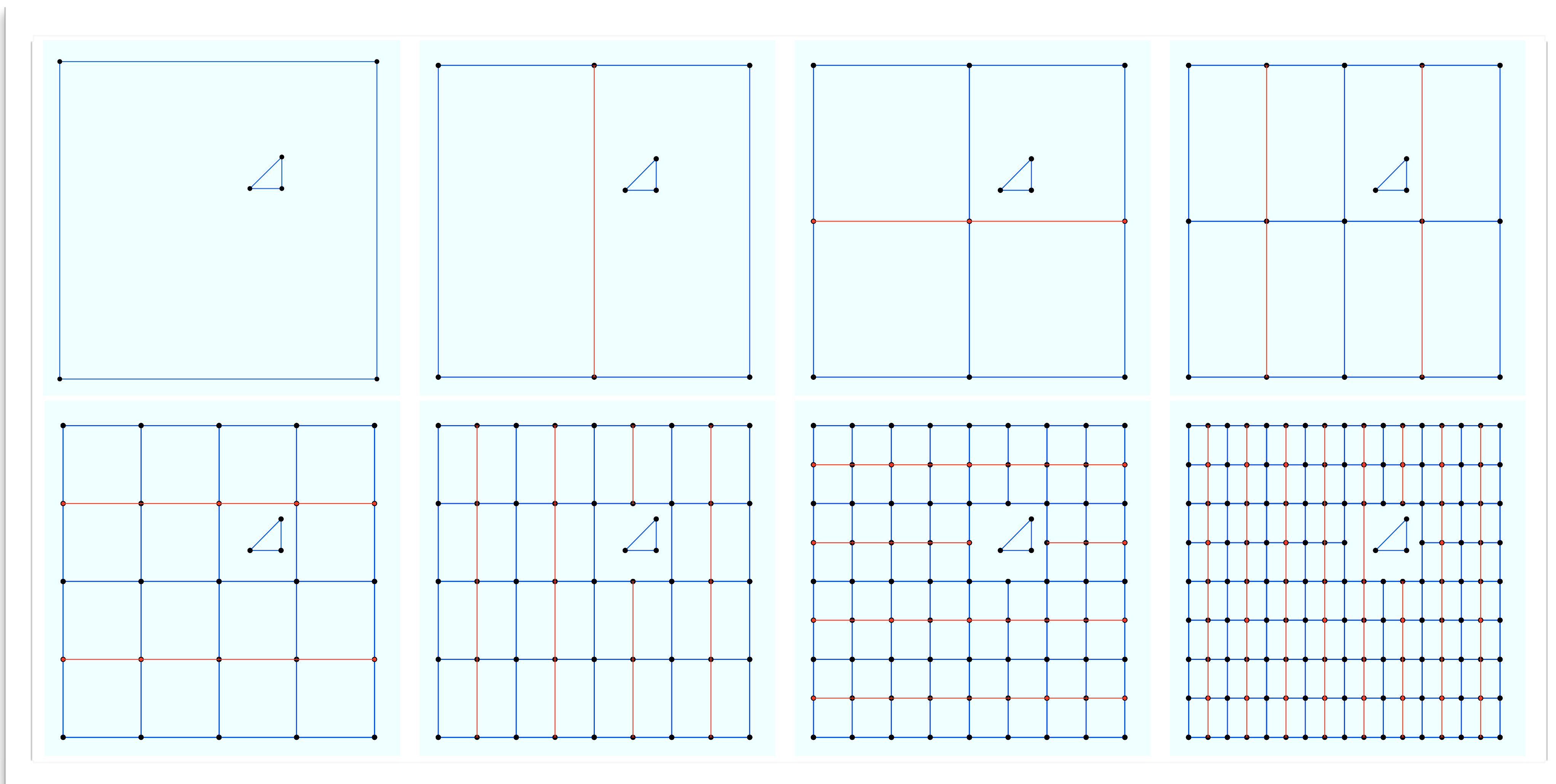
1.0 Introduction

- **Innovation**
  - Map-L Systems and Multiply Connected components



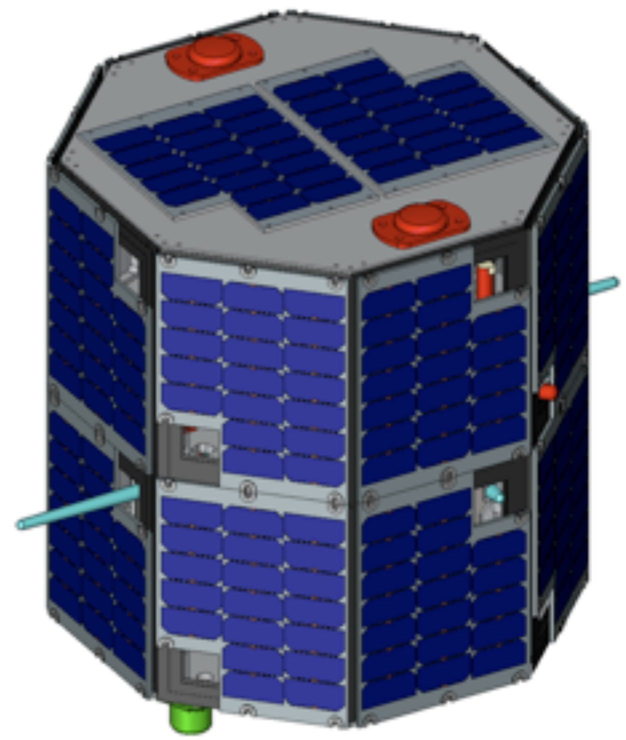
1.0 Introduction

- **Innovation**
  - Map-L Systems and Multiply Connected components



1.0 Introduction

- **Motivation**
  - Satellite Systems
  - Cost Reduction
  - Robust Design



- **Outline**

1. Introduction

2. **Methods Used**

3. Structural and Finite Element Models

4. Software Development

5. Case Study and Results

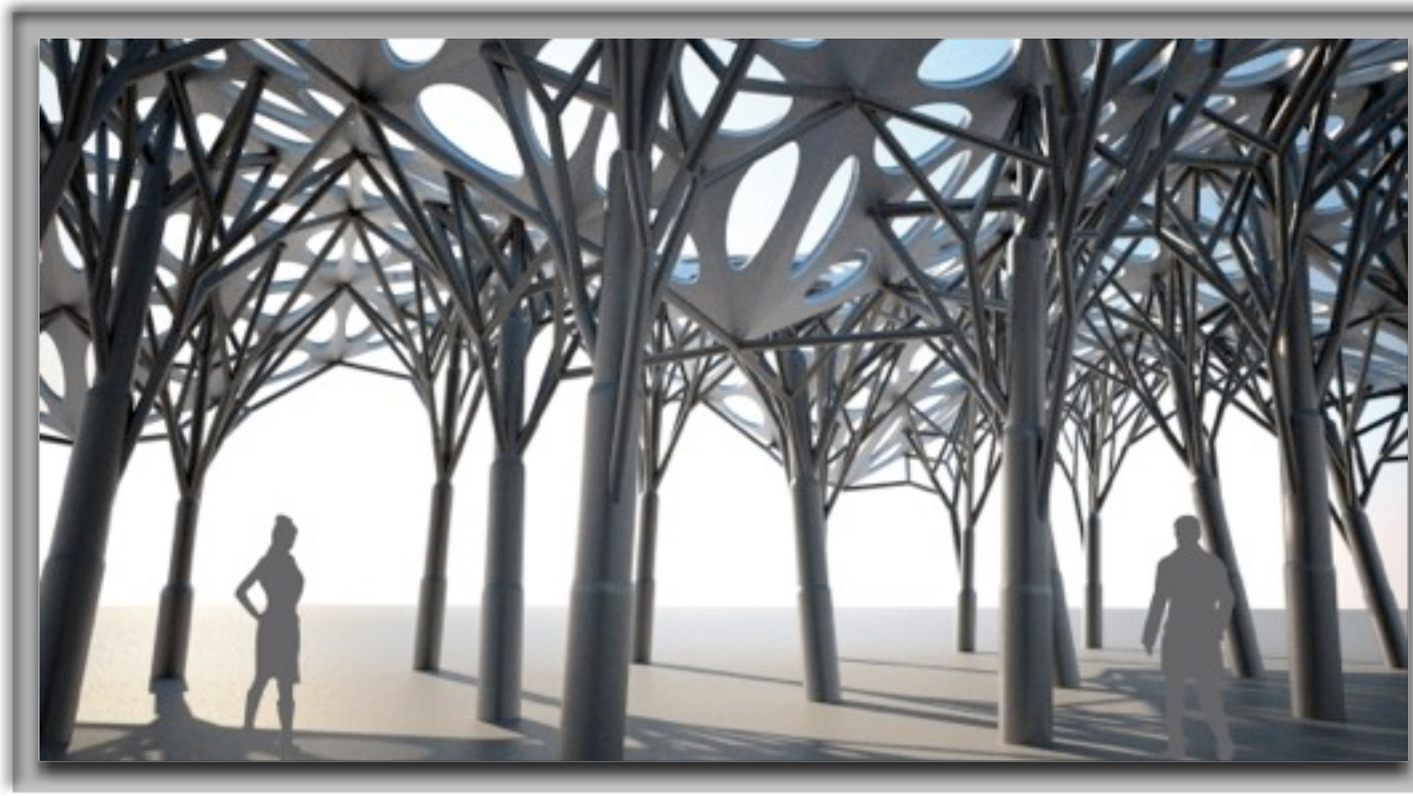
6. Conclusion and Future Work

2.0 Methods

2.1 Map L-Systems

2.2 Map L-system and Connected Components

2.3 Single Objective Optimization



2.1 Methods/Map L-Systems

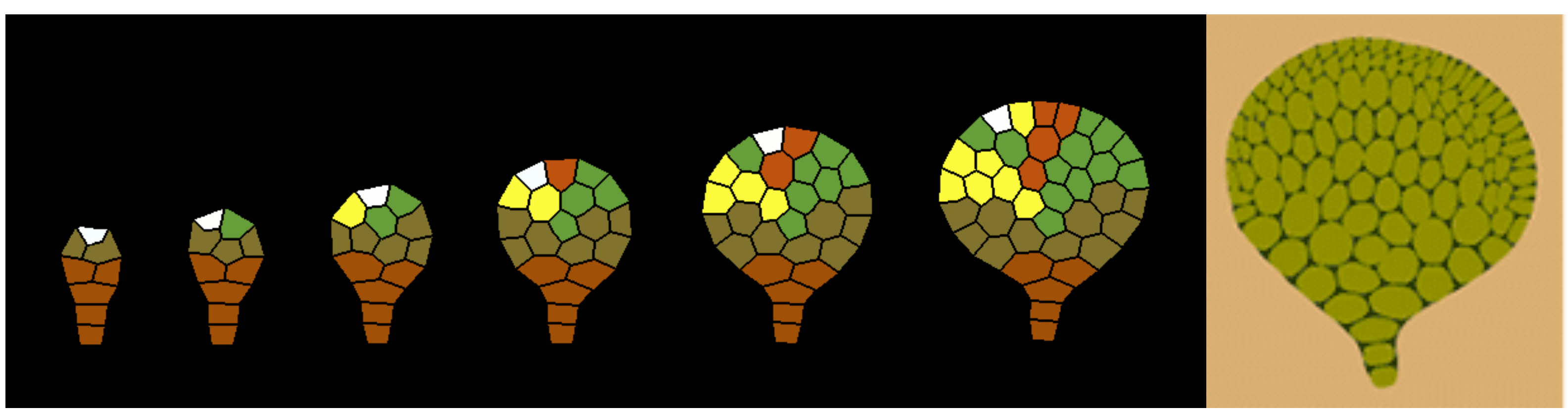
- L-Systems
  - Parallel Rewriting of Strings
  - Branching Topologies
  - Complex Organic Systems modeling
  - Used in mathematics, computer graphics, artificial intelligence, arts, etc.

variables : A B
start : A
rules : (A → AB), (B → A)

n = 0 : A
n = 1 : AB
n = 2 : ABA
n = 3 : ABAAB
n = 4 : ABAABABA
n = 5 : ABAABABAABAAB

2.1 Methods/Map L-Systems

- Map L-Systems
  - Extension of the L-Systems
  - Closed loop topologies, planar graphs
  - Complex Organic Systems modeling



Microsorium linguaeforme

2.1 Methods/Map L-Systems

- Map L-Systems formalism: **B**inary **P**ropagating **M**ap **0L**-system with markers (mBPMOL-systems):
  - **Binary**: at most in two daughter cells can be created
  - **Propagating**: cells cannot merge of disappear
  - **0L system**: context-free parallel rewriting systems where regions do not interact
  - **markers**: juncture points on the edges where the cell may divide

2.1 Methods/Map L-Systems

- Alphabet: $$\Sigma = \{A, B, C..., [,], +, -\}$$
- Axiom: $$\omega = ABAB.$$
- Rules: $$A \rightarrow B[-A]x[+A]B$$ $$B \rightarrow A$$

2.1 Methods/Map L-Systems

- Alphabet: $\Sigma = \{1, 2, x, [,], +, -\}$

- Axiom: $\omega = 1, 2, 1, 2$

- Rules:

$$1 \rightarrow 2[-1]x[+1]2$$

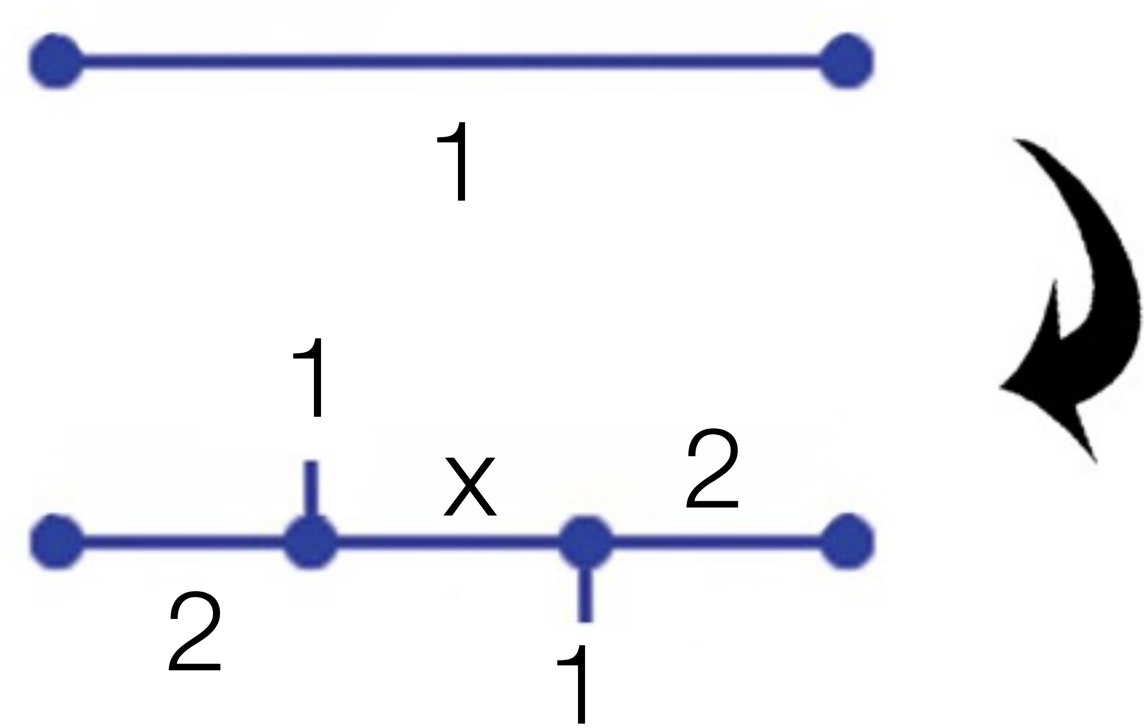
$$2 \rightarrow 1$$

2.1 Methods/Map L-Systems

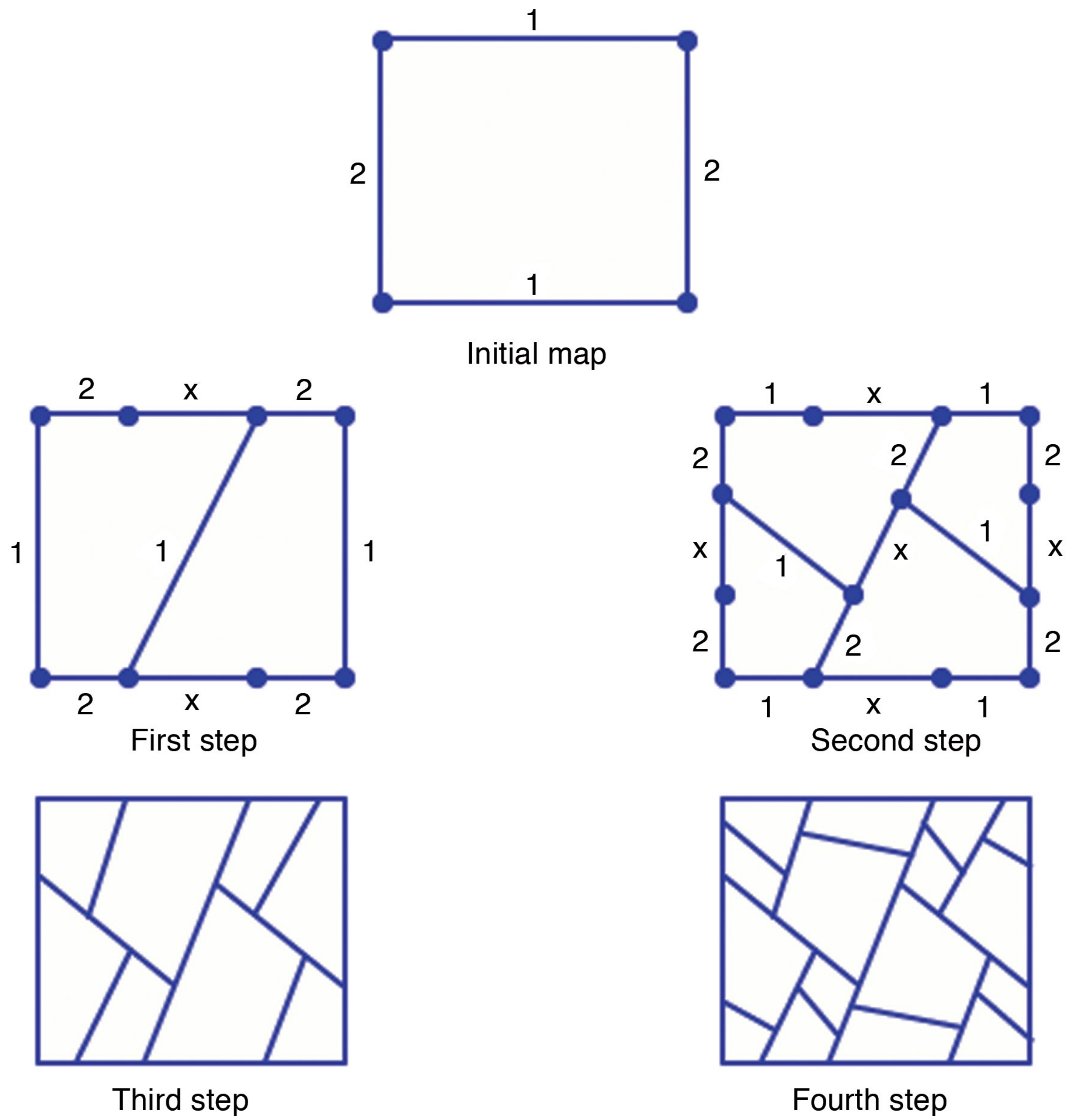
Example of Edge Rewriting

$$1 \rightarrow 2[-1]x[+1]2$$

$$2 \rightarrow 1$$



2.1 Methods/Map L-Systems



2.1 Methods/Map L-Systems

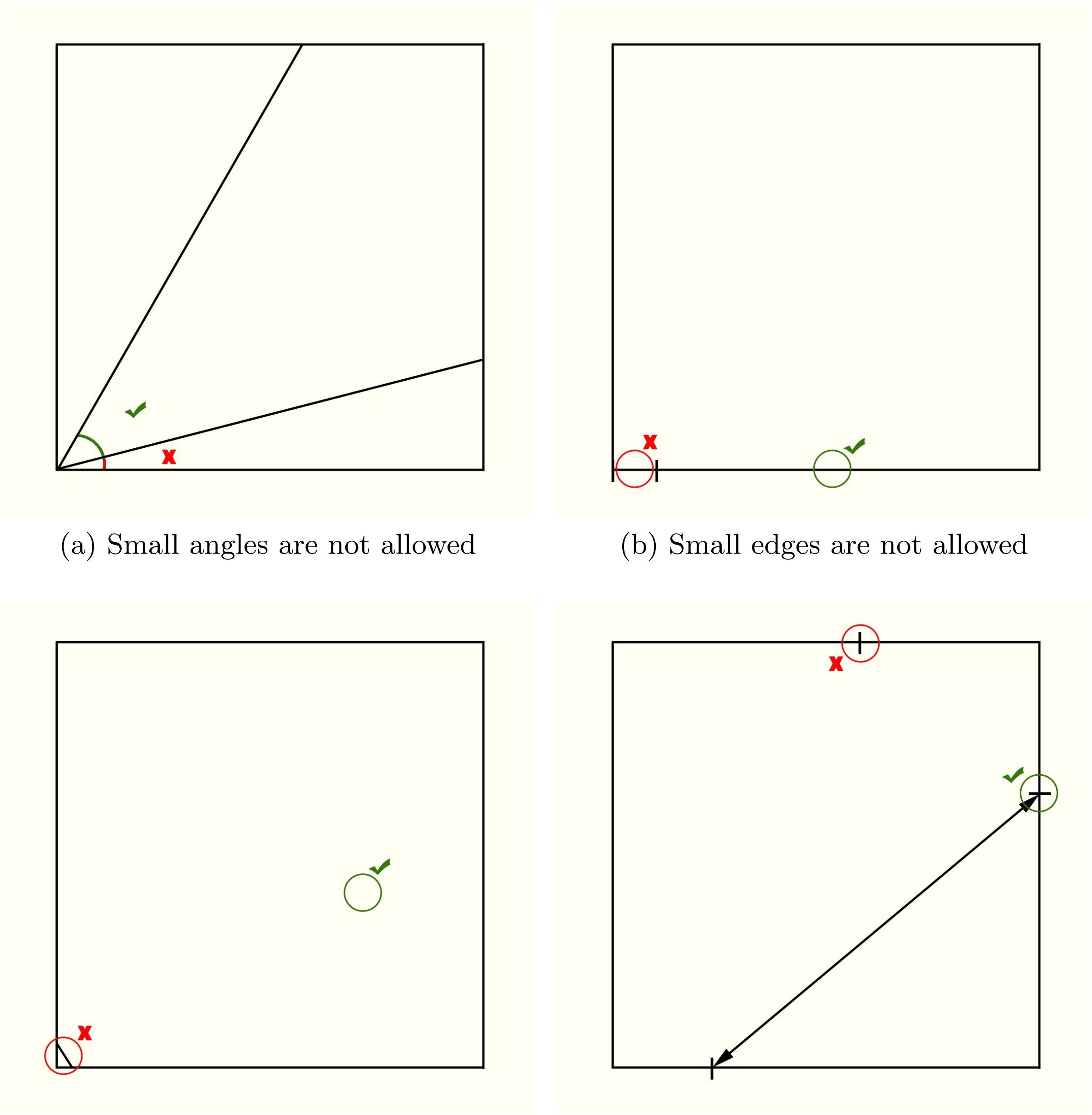
- Criteria for cellular division

  1. Small Angles

  2. Small Edges

  3. Small Areas

  4. Only two markers used



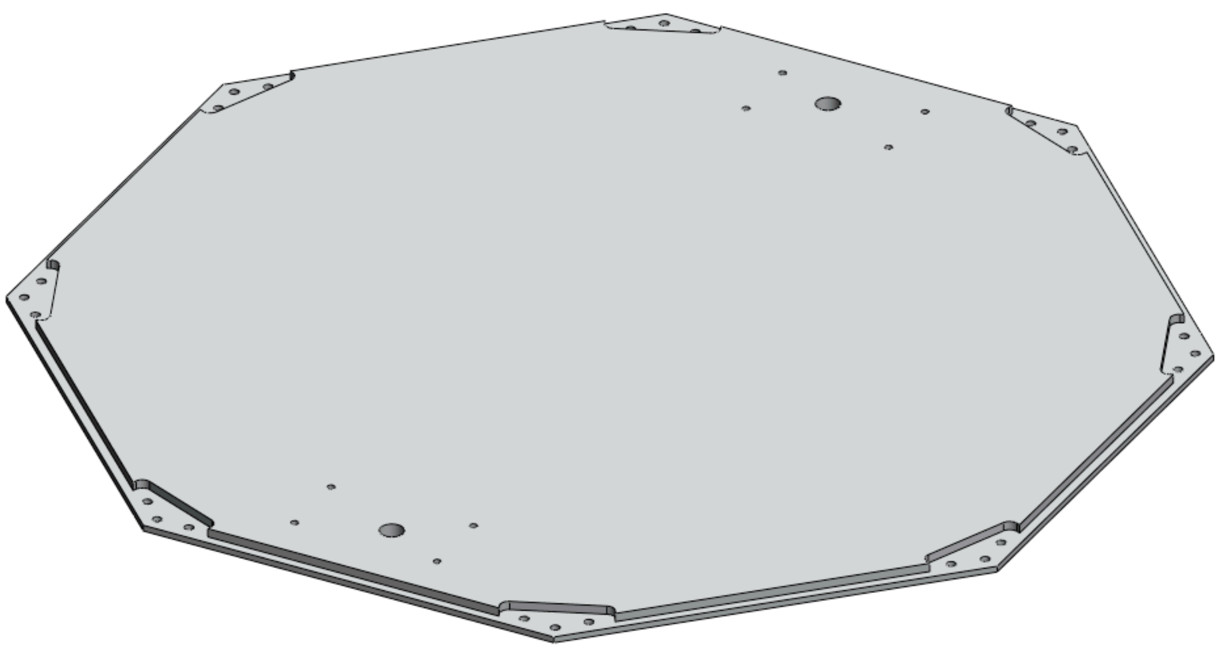
(a) Small angles are not allowed

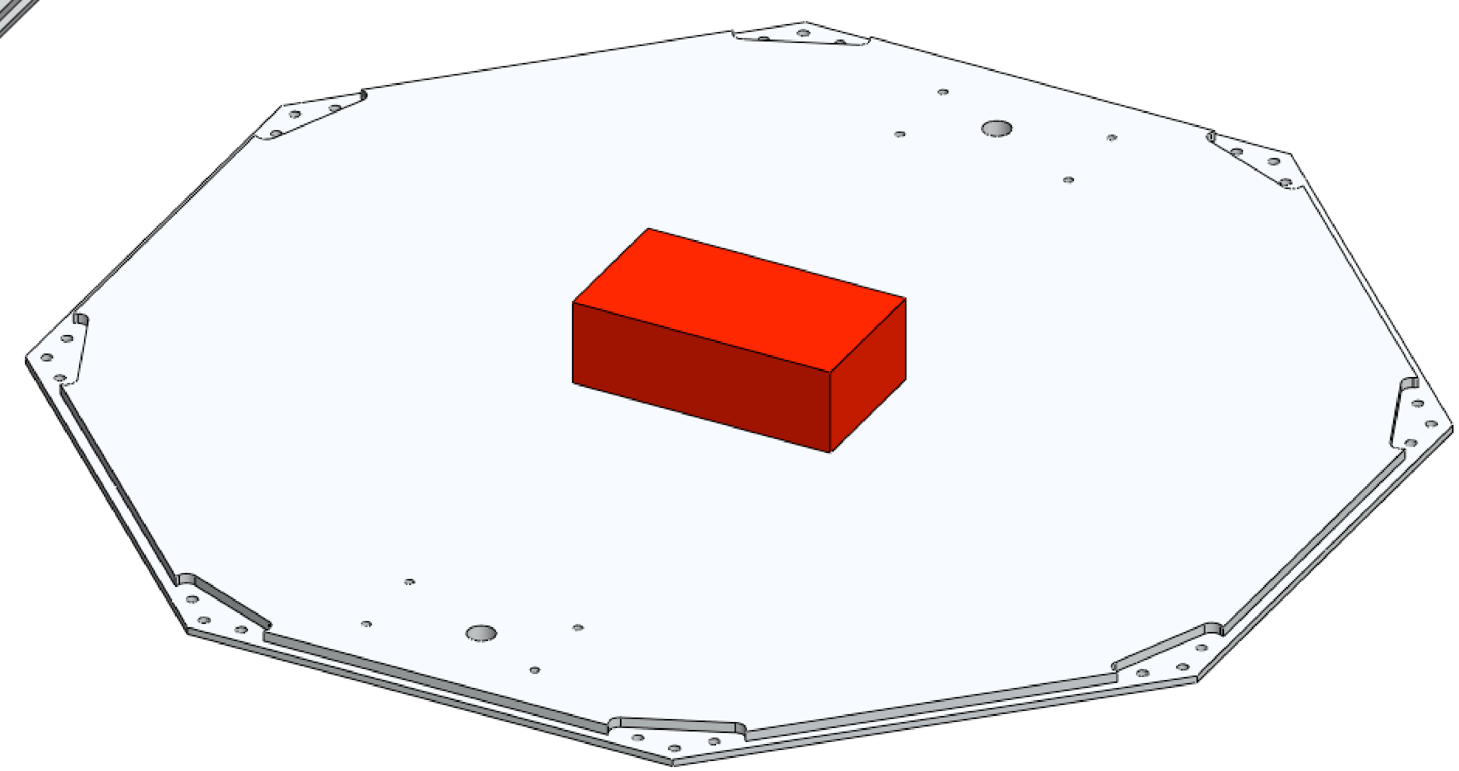
(b) Small edges are not allowed

(c) Small areas are not allowed

(d) Only the first two markers will be selected

2.2 Methods/Map L-system and Connected Components



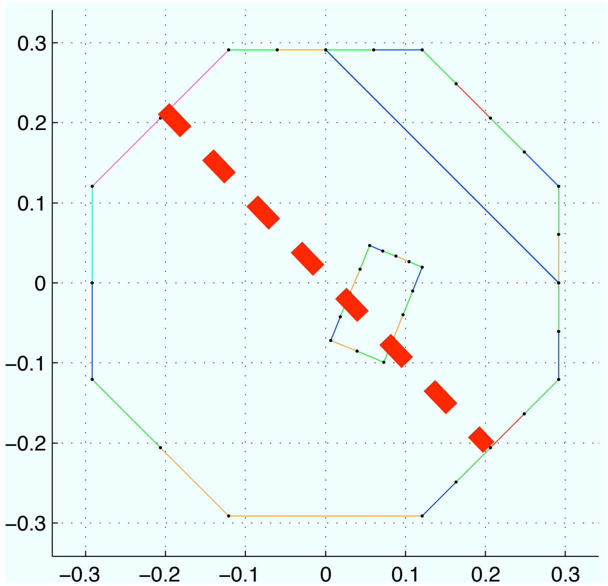


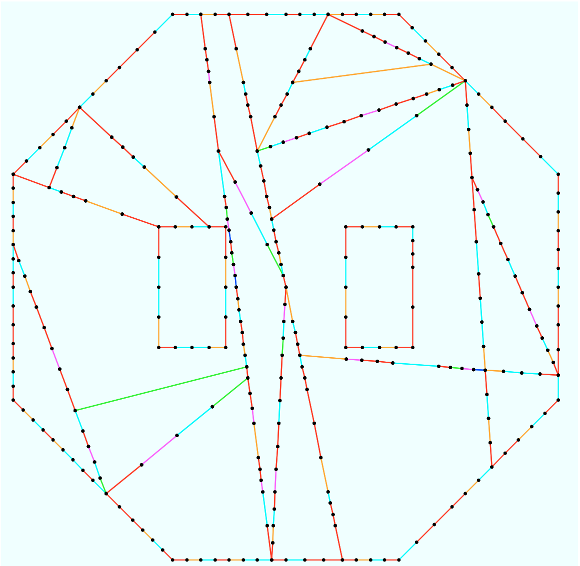
2.2 Methods/Map L-system and Connected Components

- Main Challenges

  1. Divide cells without intersecting the connected components

  2. Define the new cells properly (general approach for different topologies)



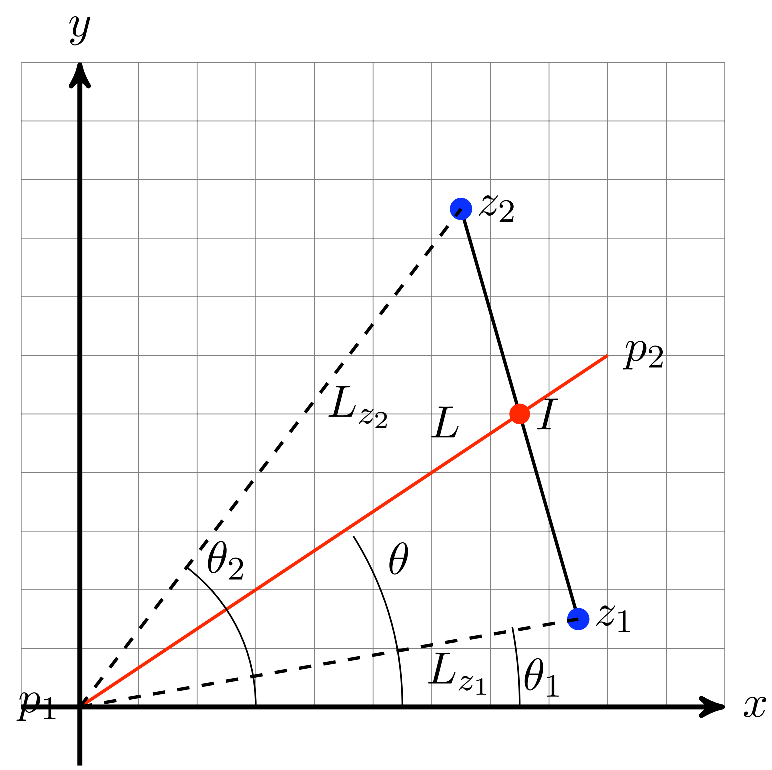


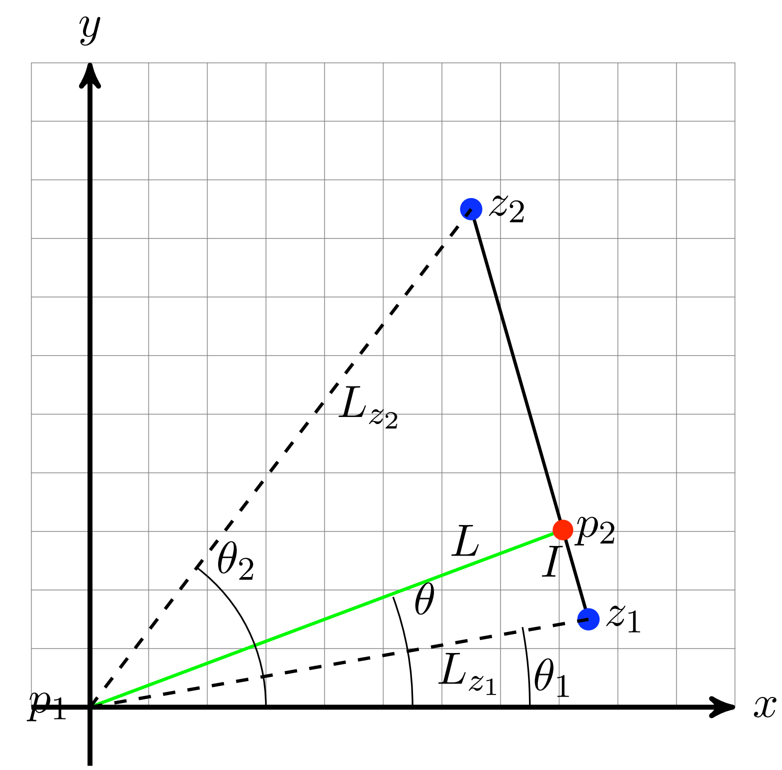
2.2 Methods/Map L-system and Connected Components

CHALLENGE #1

- The Intersection of Connected Components

  - $\theta_1 \leq \theta \leq \theta_2$
  - $|L| > |L_I|$





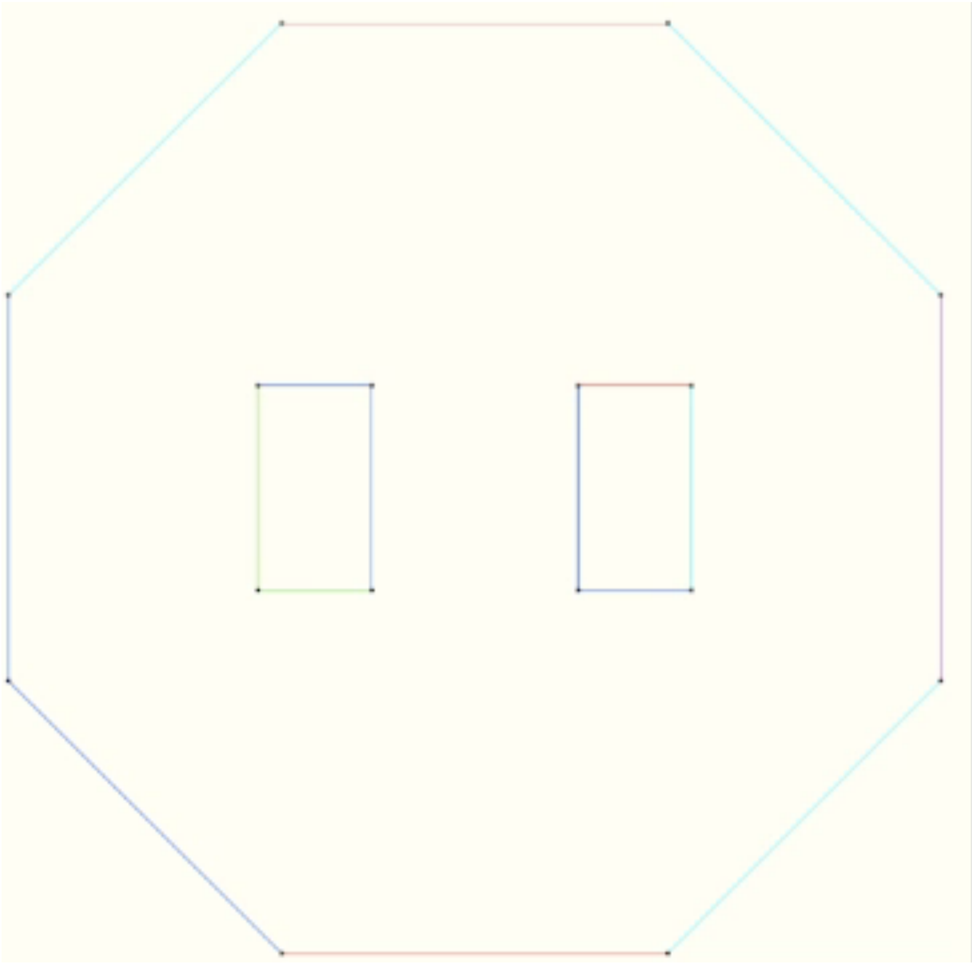
$$|L_I| = r_{L_I}(z_1, z_2, \theta) = real\{\frac{z_1 - \overline{z_1} * \alpha}{e^{i\theta} - \alpha * e^{-i\theta}}\}$$

$$\alpha = \frac{z_2 - z_1}{\overline{z_2} - \overline{z_1}}$$

2.2 Methods/Map L-system and Connected Components

CHALLENGE #1

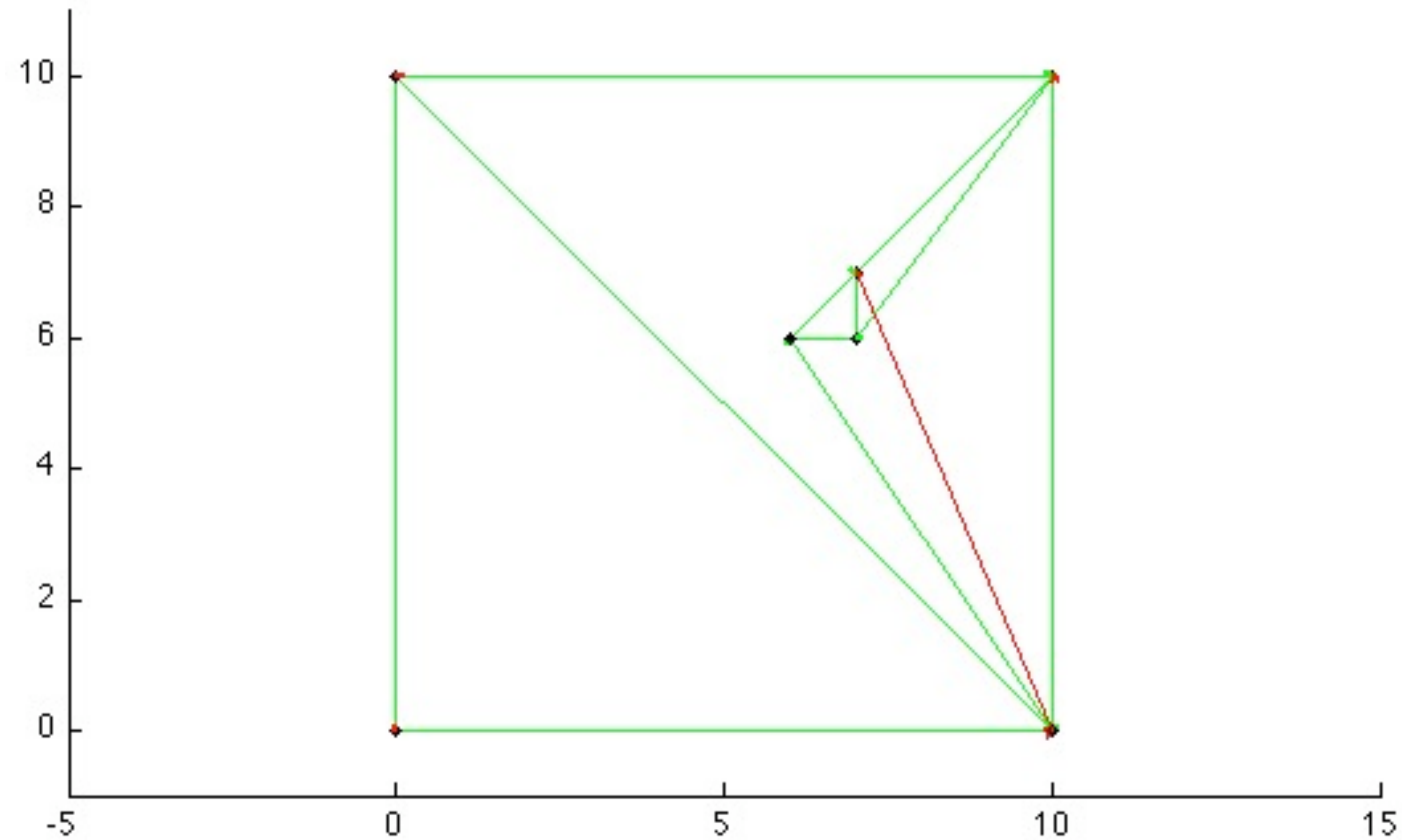
- The Intersection of Connected Components



2.2 Methods/Map L-system and Connected Components

CHALLENGE #2

- Define new cells:
  - Simple Face Search
  - Breadth First Search
  - Depth First Search
  - and more ...



2.2 Methods/Map L-system and Connected Components

CHALLENGE #2

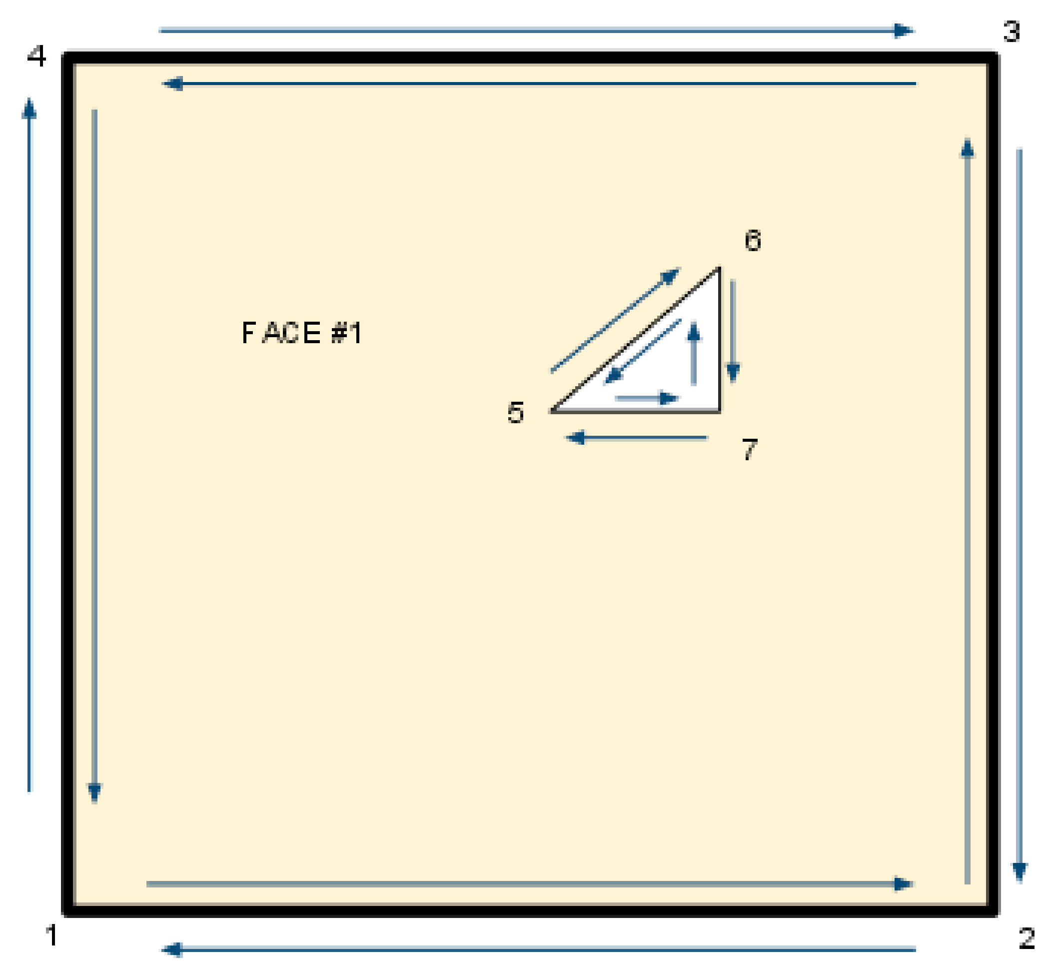
- Define new cells: **topology search based on Graph Theory**
    - “an undirected graph can be represented by a directed graph if every undirected edge a,b is represented by two directed edges < a, b > and < b, a >”
    - Every edge is composed of **two half-edges**
    - Every half-edge is attached to a different face

2.2 Methods/Map L-system and Connected Components

CHALLENGE #2

- Define new cells: cellular division process - initial map

- Face #1 vertices: [1 2 3 4 1; 5 6 7 5]
- Face #1 edges: [1 2 3 4; 5 6 7]
- Face #1 edges dir: [1 1 1 1; 1 1 1]

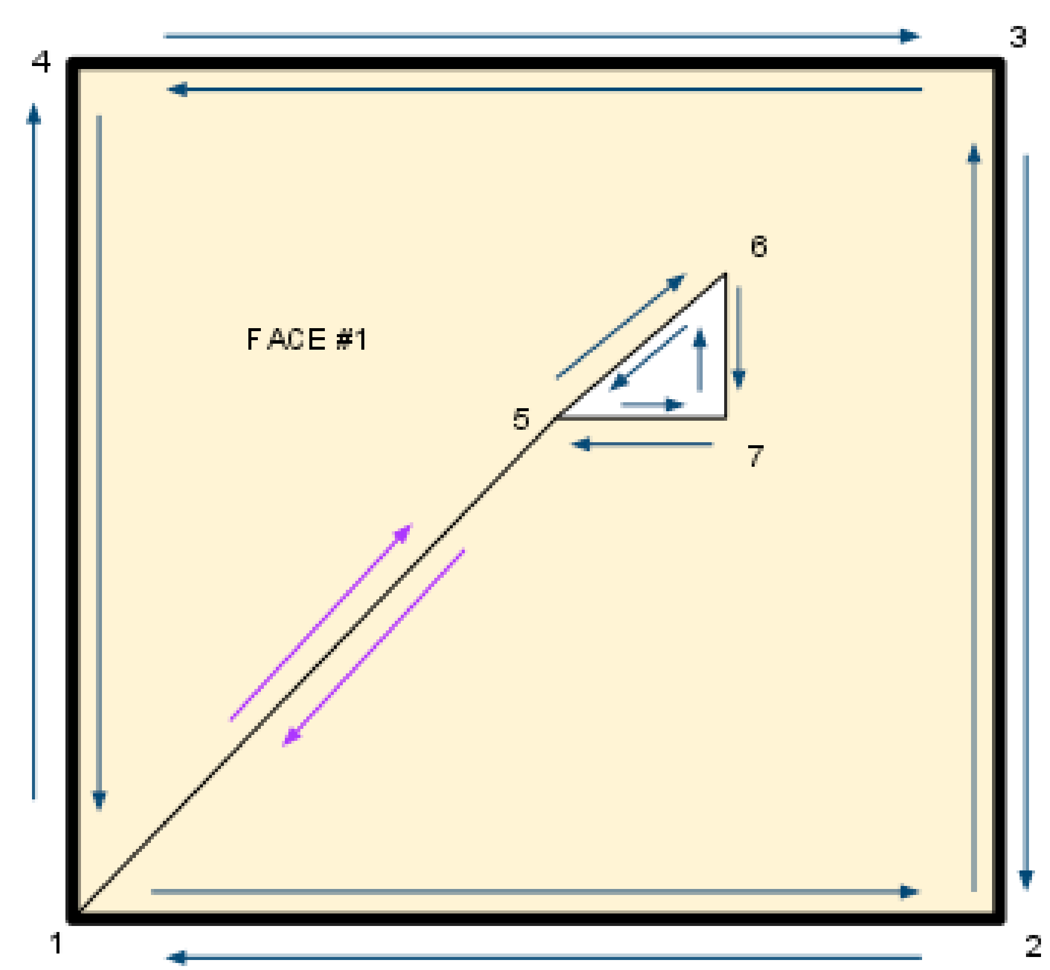


2.2 Methods/Map L-system and Connected Components

CHALLENGE #2

- Define new cells: cellular division process - first connection

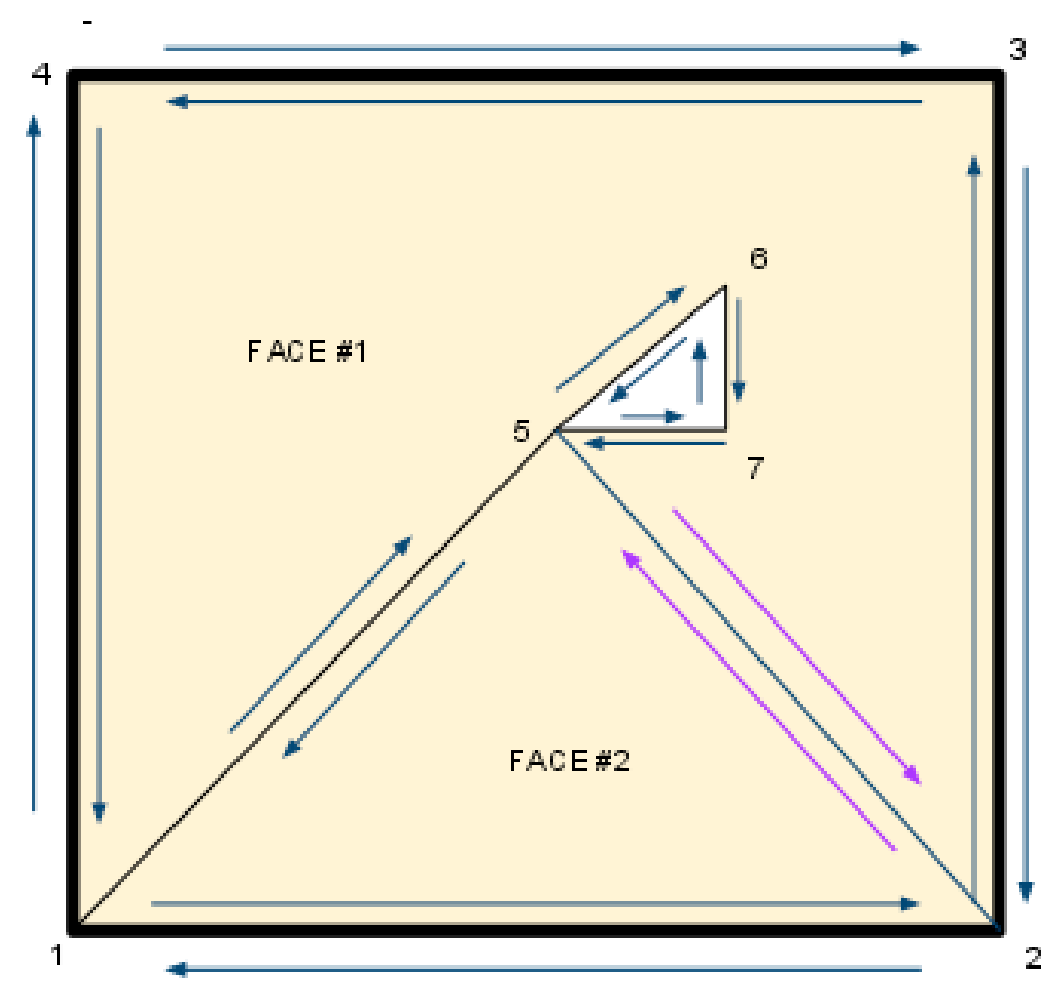
- Face #1 verts: [1 2 3 4 1 5 6 7 5 1]
- Face #1 edges: [1 2 3 4 **<u>8</u>** 5 6 7 **<u>8</u>**]
- Face #1 edges dir: [1 1 1 1 **<u>1</u>** 1 1 1 **<u>2</u>**]



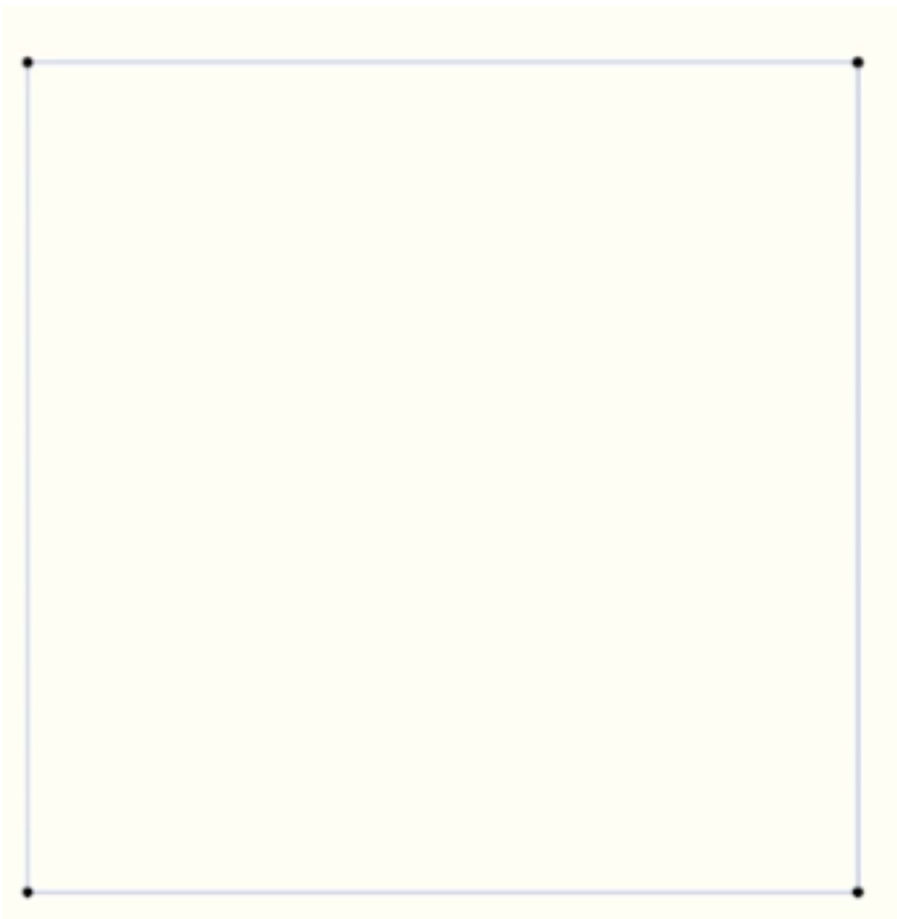
2.2 Methods/Map L-system and Connected Components

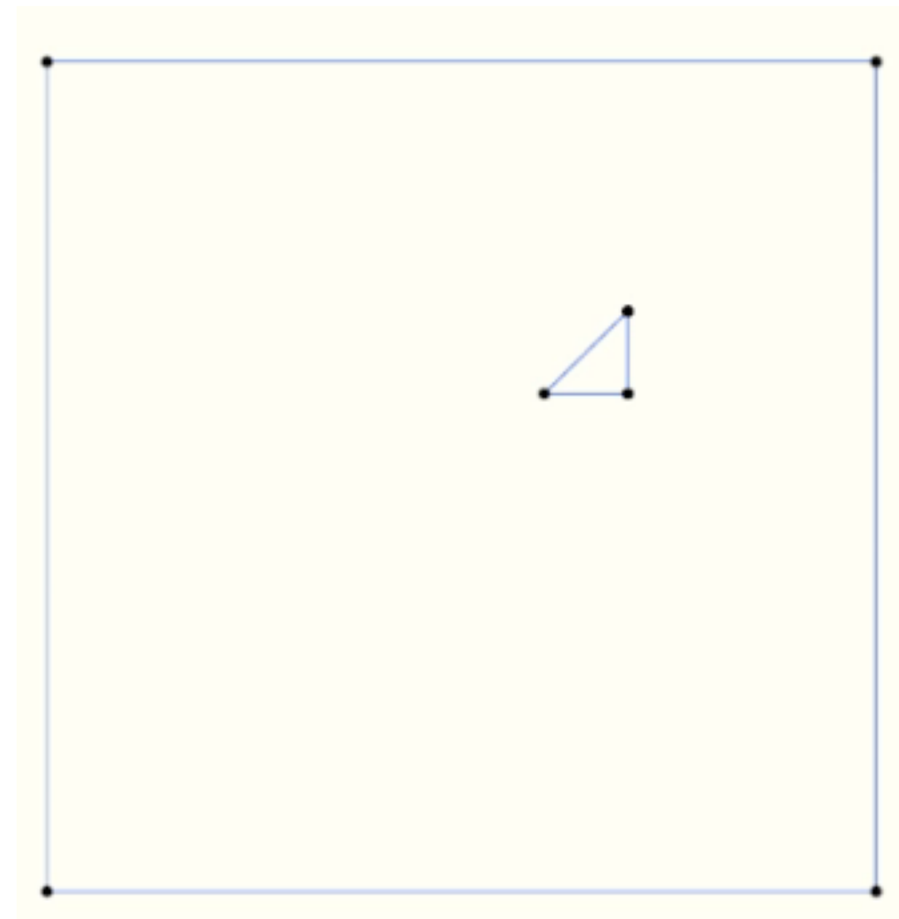
CHALLENGE #2

- Define new cells: cellular division process - second connection
  - Face #1 verts: [5 2 3 4 1 5 6 7 5 2]
  - Face #1 edges: [9 2 3 4 8 5 6 7 9]
  - Face #1 edges dir: [1 1 1 1 1 1 1 1 2]
  - Face #2 verts: [2 5 1 2]
  - Face #2 edges: [9 8 1]
  - Face #2 edges dir: [1 2 1]

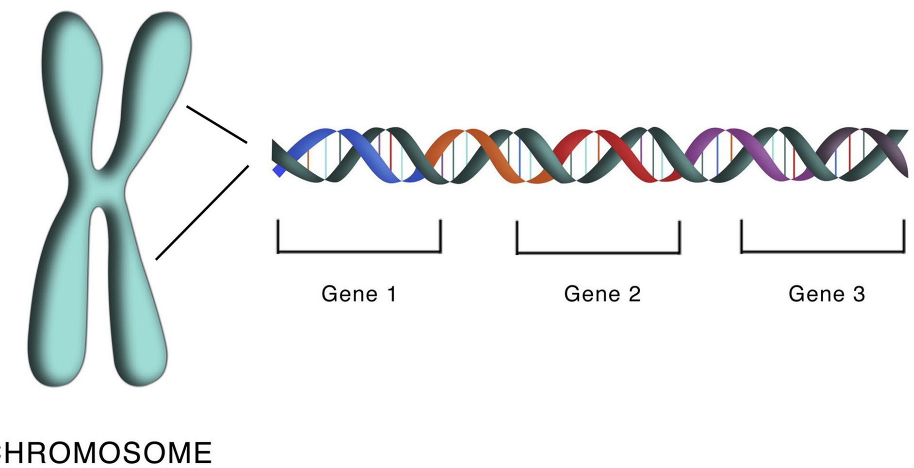


2.2 Methods/Map L-system and Connected Components





2.3 Methods/Single Objective Optimization

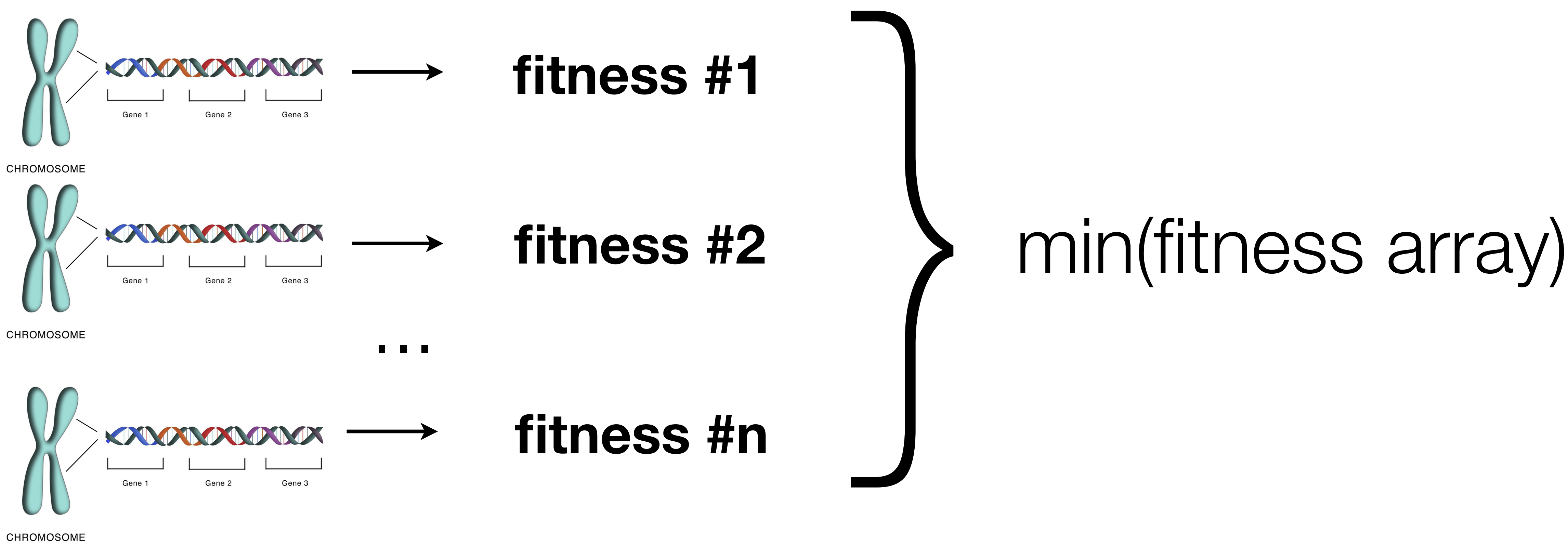


Genetic Algorithm

	Gene 1	Gene 2	Gene 3
genotype	[19.3, . . . , 53.6] Axiom	[53.6, . . . , 17.8] Rules	[39.9, . . . ,46.7] Topology input
phenotype	con. comp. 1: 2 1 2 1 2 1 4 2 con. comp. 2: 4 5 3 4	$1 \rightarrow$ [+5];[-3];[+6];5;5 $2 \rightarrow$ [+1];[-6];1;2;[+5] $3 \rightarrow$ [-5];6;[-2];[-3];[-4] $4 \rightarrow$ [-4];2;1;[-2];6 $5 \rightarrow$ 3;3;[-2];5;6 $6 \rightarrow$ 6;5;4;1;[-5]	number of iterations = 6 global shell thickness = 1.8 [mm] subsystem shell thickness = 0.5 [mm] external beam feature size = 9.4 [mm] internal beam feature size = 3.1 [mm] subsystem position x = -57.3 [mm] subsystem position y = -46.8 [mm] subsystem angle = 168.1 [deg]

2.3 Methods/Single Objective Optimization

- Minimize mass of structural element
- Optimization: $f(x_0) \leq f(x) \; \forall x \;\; in \;\; A$
- Genetic Algorithm (a biological metaphor from genetics applied to computer science)



- **Outline**

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    2. Methods Used

    3. **Structural and Finite Element Models**

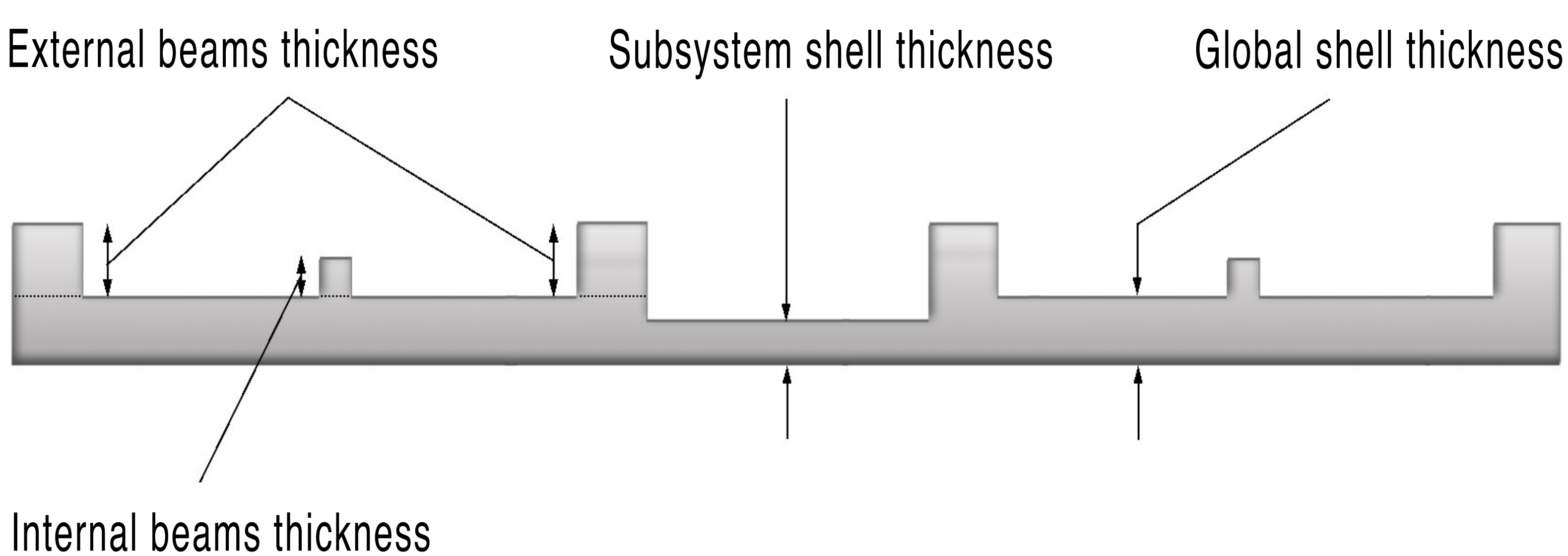
    4. Software Development

    5. Case Study and Results

    6. Conclusion and Future Work

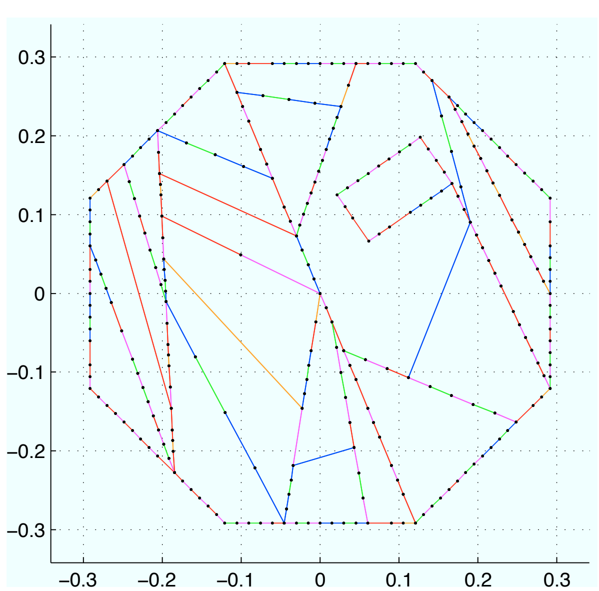
3.0 Structural and Finite Element Models

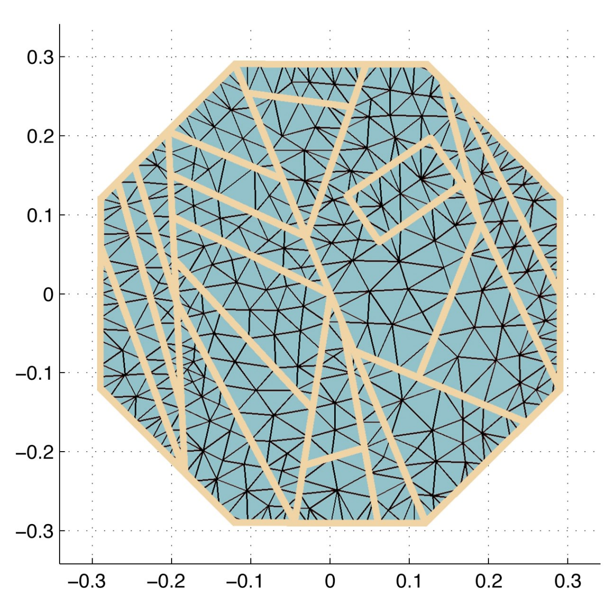
- Structural Object, implemented in Matlab and Comsol:
  - Shell (Subsystem + Global)
  - 3D Euler Beams (Internal + External)

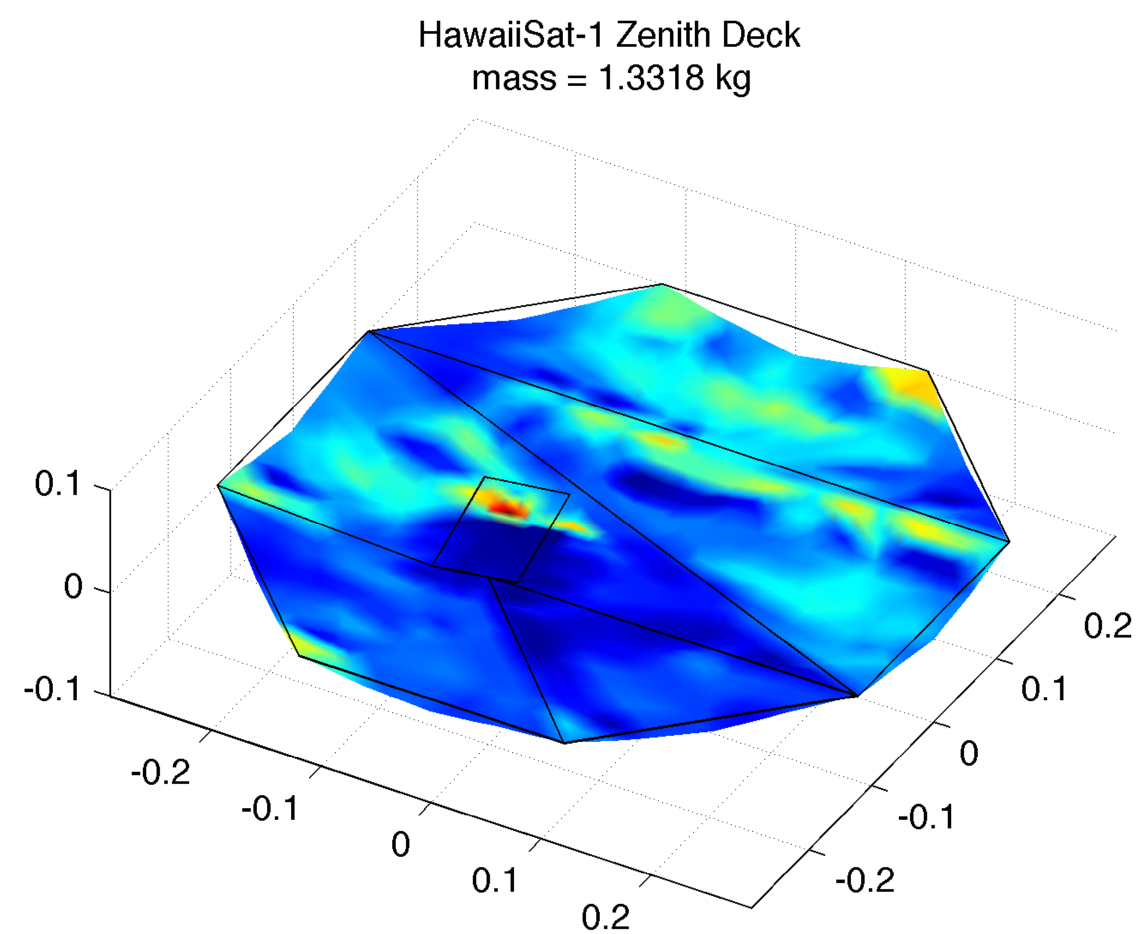


3.0 Structural and Finite Element Models

- Finite Element Model in Comsol Multiphysics
- Output:
    - von Mises Stress
    - Displacement







- **Outline**

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    4. **Software Development**

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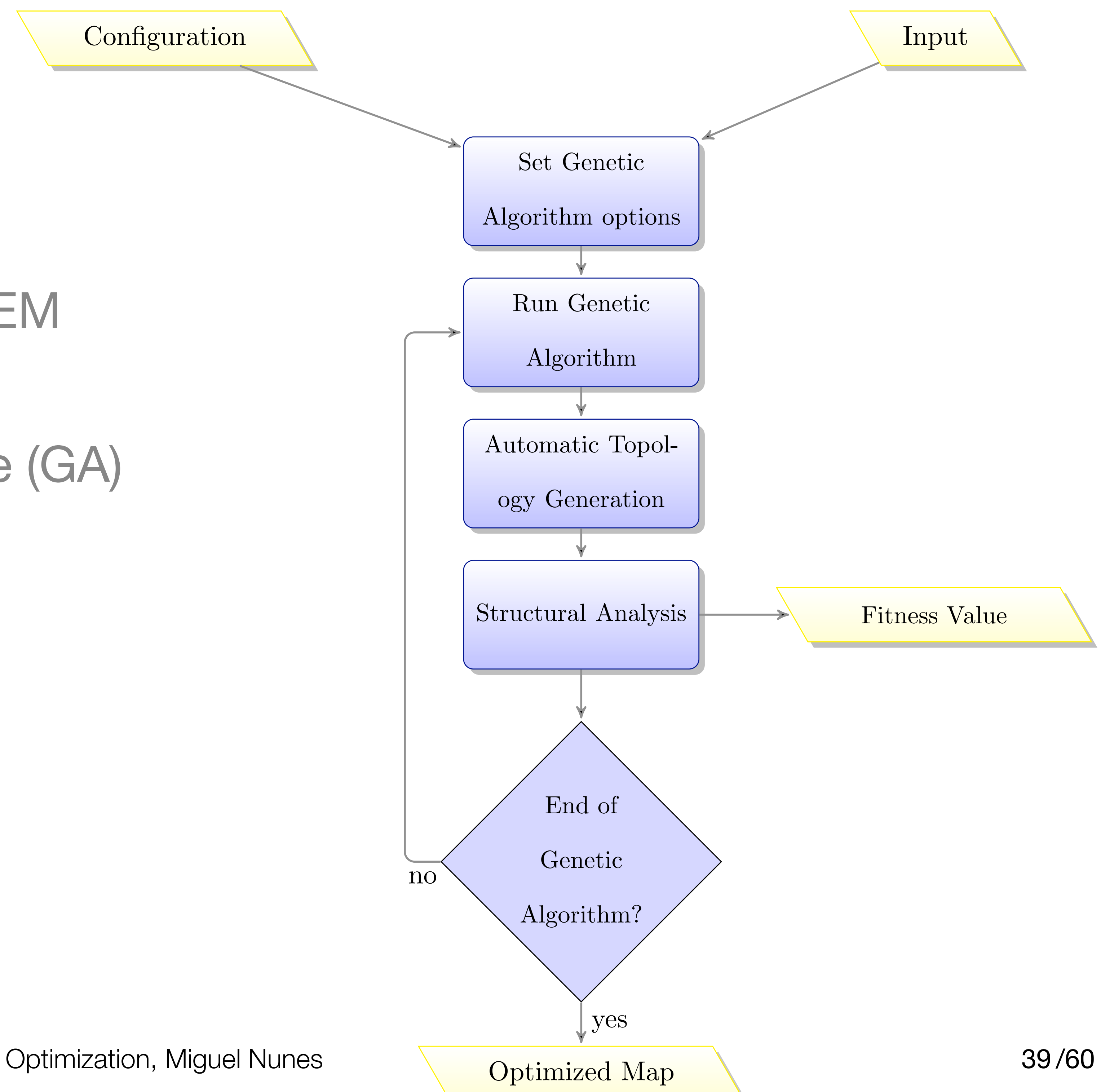
4.0 Software Development

- Automatic Topology Generation (Map L Systems)
- Structural Analysis (Genotype to Phenotype) and FEM
- Search for the Optimal Structure (GA)



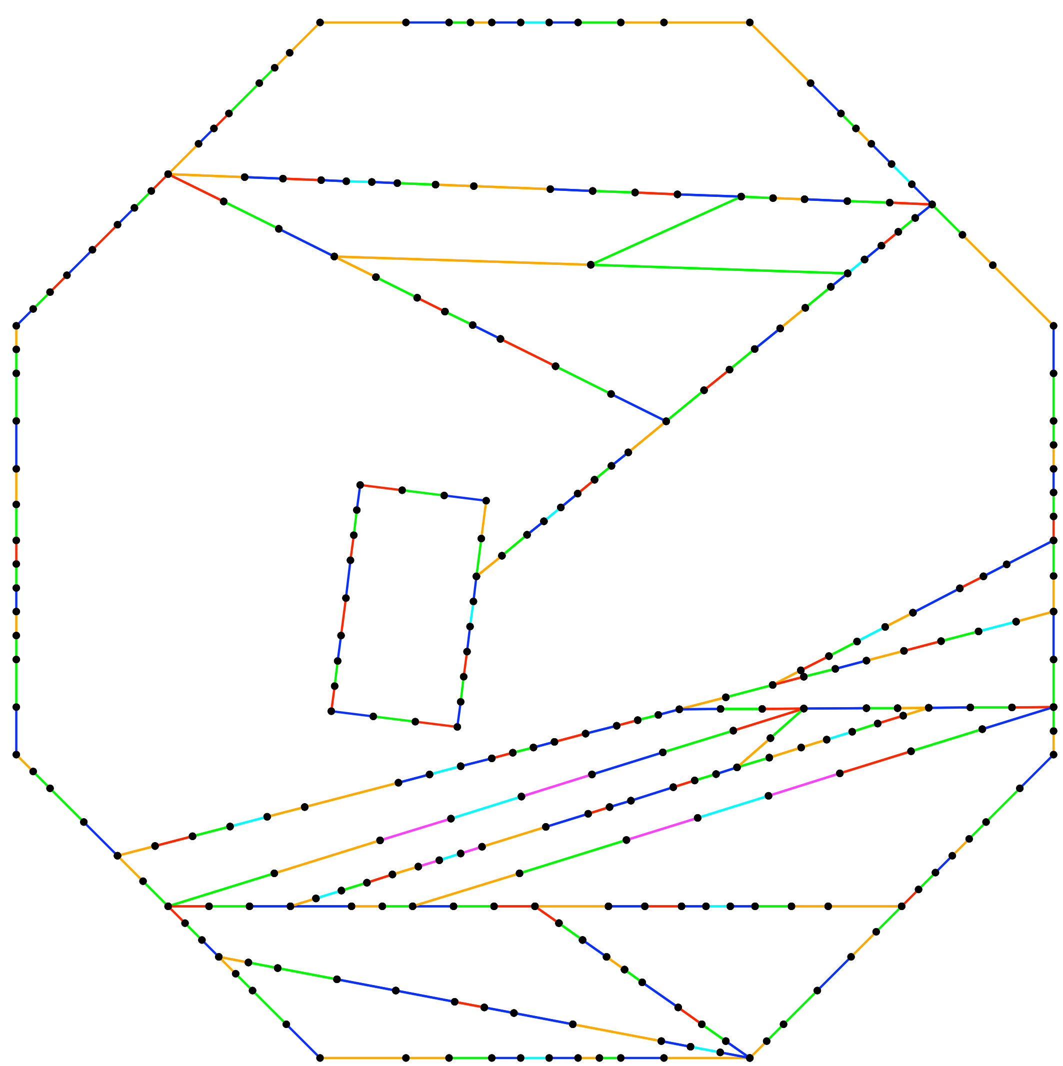
4.1 Software Development / Automatic Topology Generation

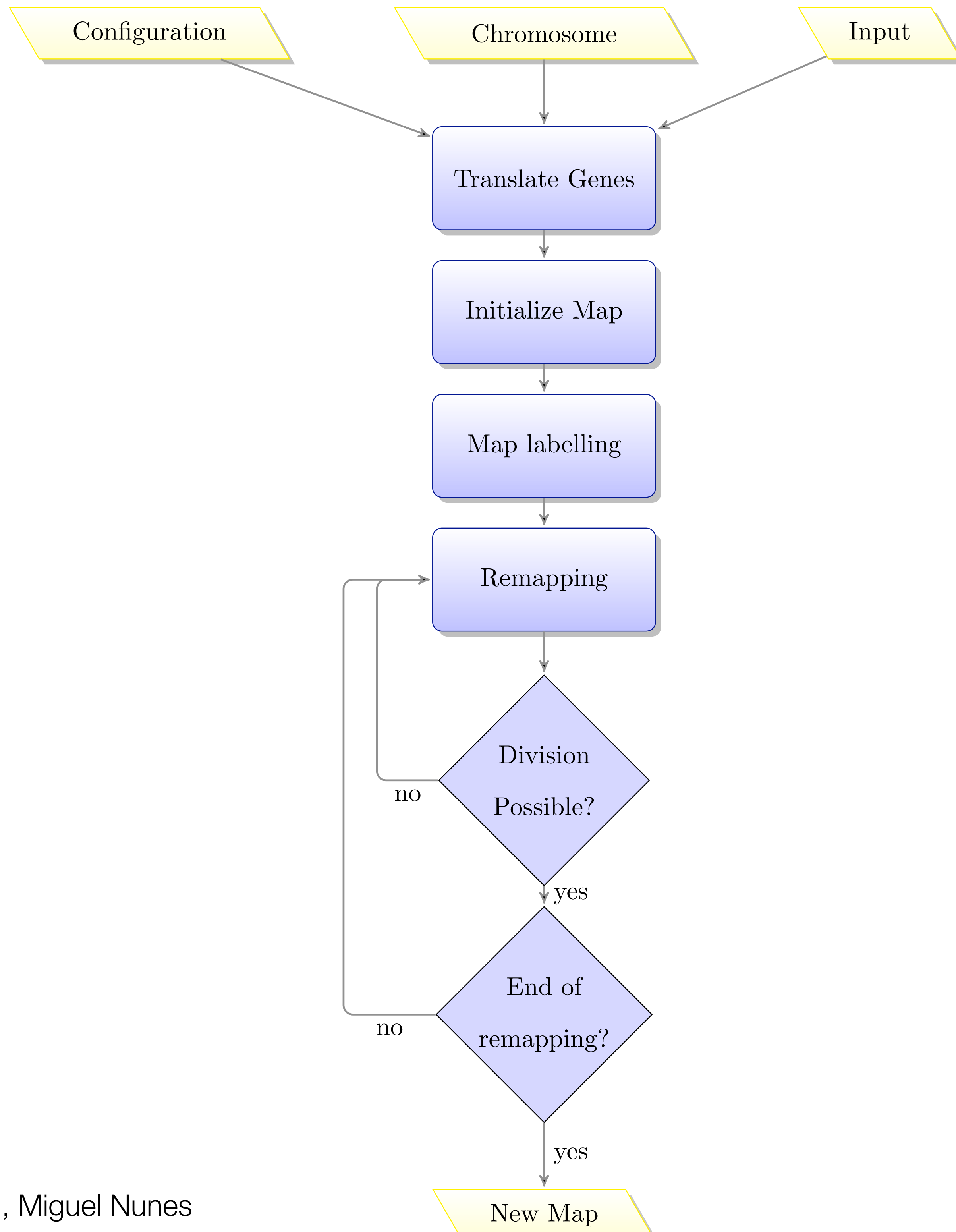
- Objective: create valid topology (gene 3)

genotype/gene 3		phenotype input	range
70.2 →	8	number of iterations for topology division	3 . . . 10
2.6 →	0.4 mm	global shell thickness	0.1 . . . 12.5 mm
80.4 →	10.1 mm	subsystem shell thickness	0.1 . . . 12.5 mm
15.2 →	1.6 mm	external beam feature size	0.1 . . . 10.0 mm
48.0 →	4.9 mm	internal beam feature size	0.1 . . . 10.0 mm
24.7 →	-70.9 mm	subsystem position x	-140 . . . 140 mm
36.8 →	-37.0 mm	subsystem position y	-140 . . . 140 mm
48.0→	172.7 deg	subsystem angle	0.0 . . . 360.0 deg

4.1 Software Development / Automatic Topology Generation

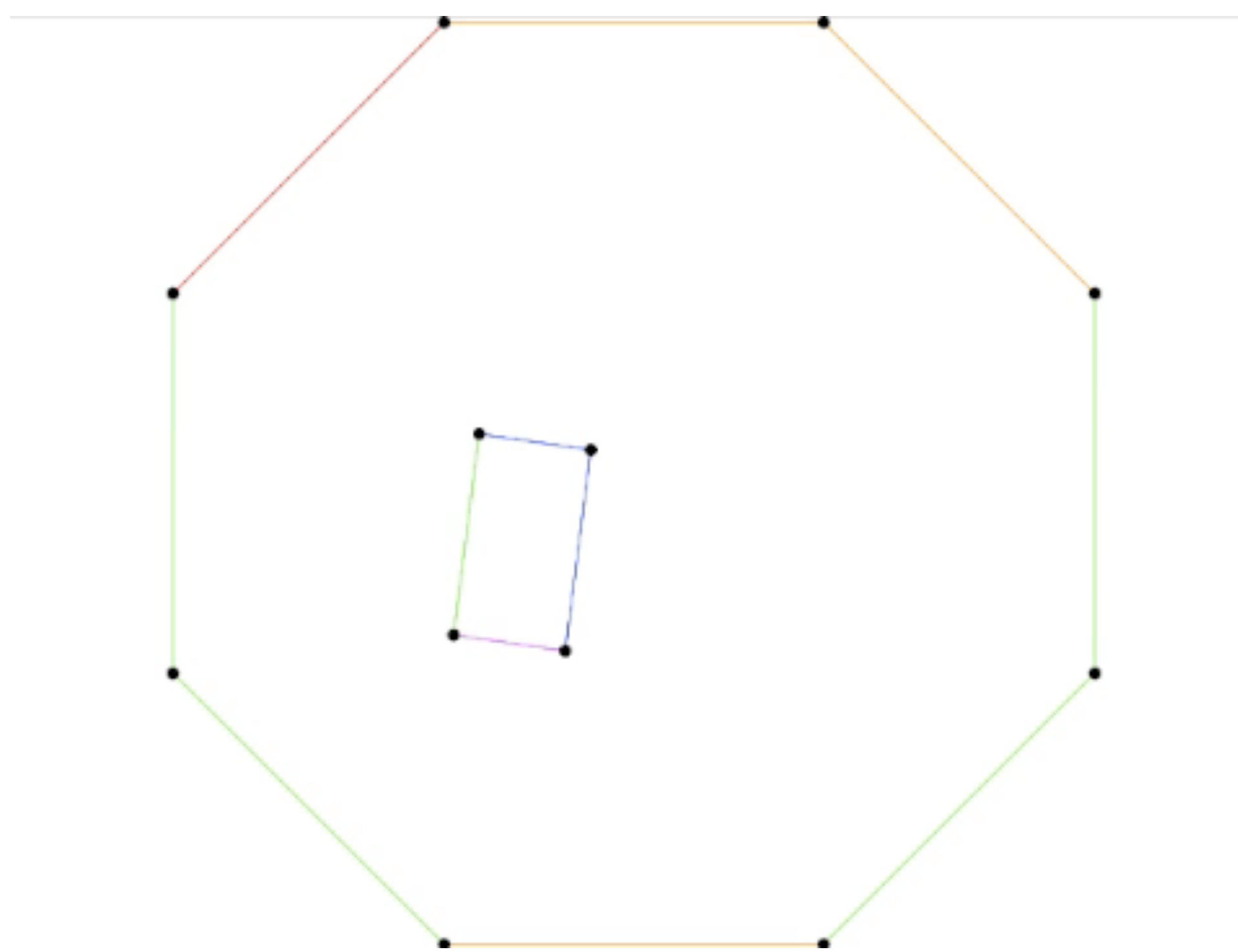
- Objective: create valid topology





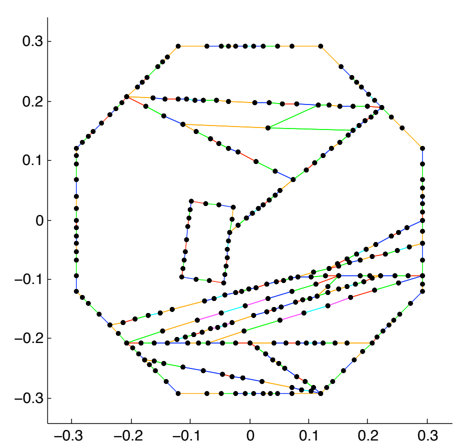
4.1 Software Development / Automatic Topology Generation

- Objective: create valid topology

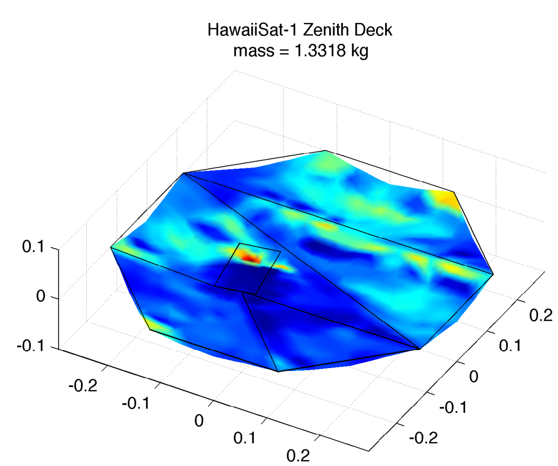


4.2 Software Development / Structural Analysis

- Objective: transform and analyze the topology
  - Analyze and compute using FEM in COMSOL
  - Output: mass, displacement, stress
  - Compute Fitness



(a) Topology given from the Automatic Topology Generation process



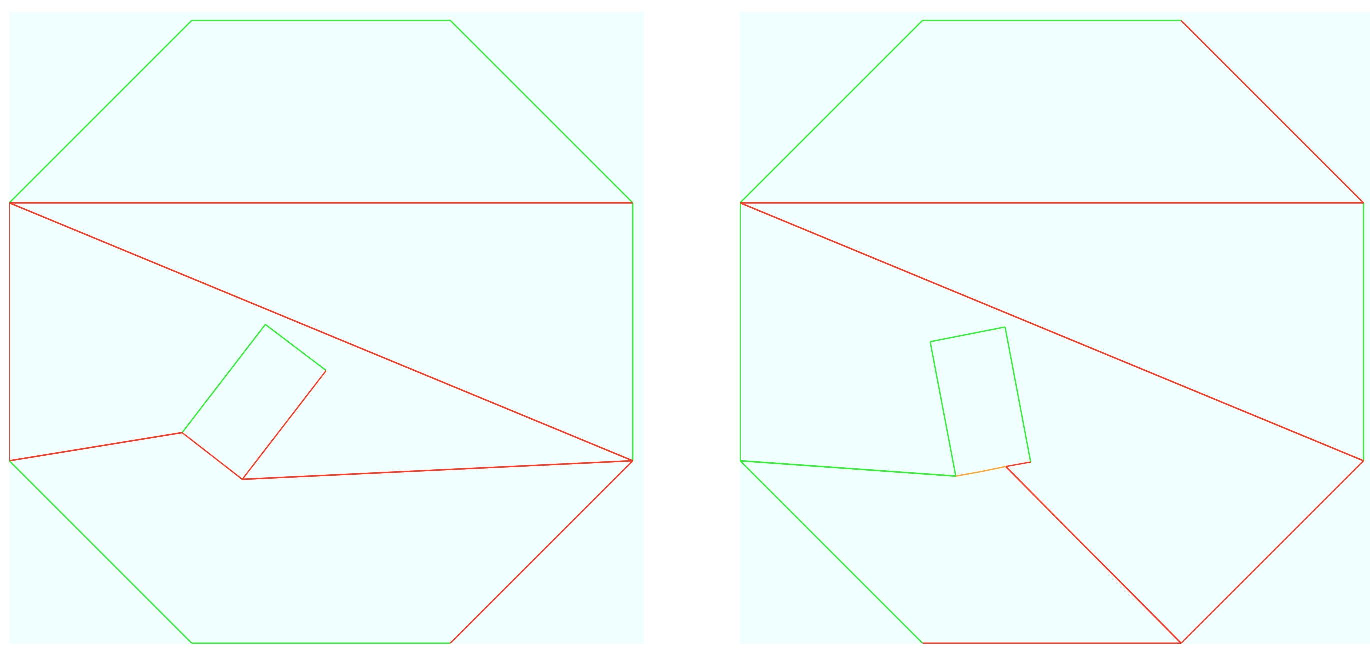
$$fitness = \frac{\text{mass of current map}}{\text{mass benchmark map}}$$

$$+ \lambda_{disp} \times \text{penalization(displacement)}$$

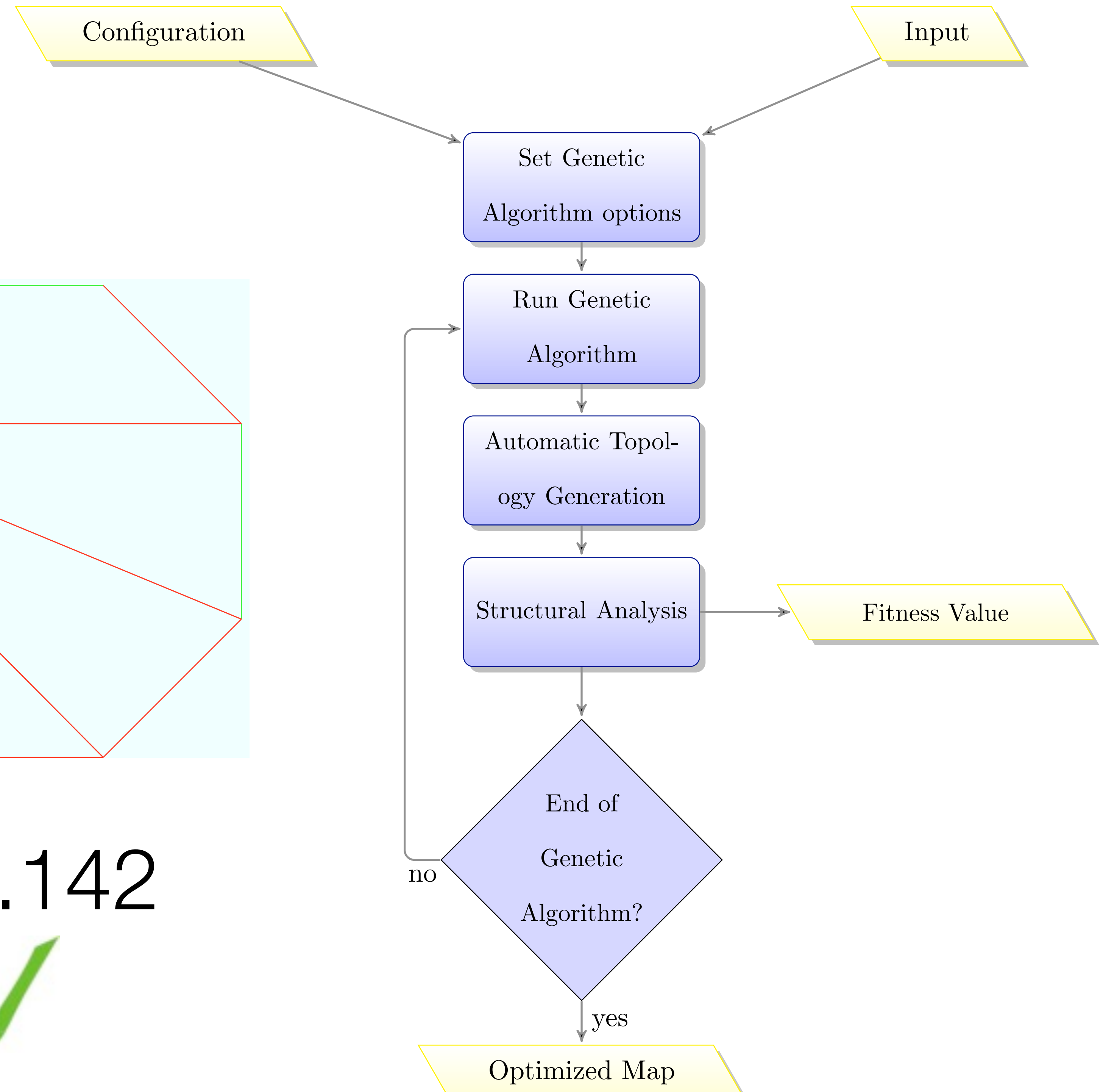
$$+ \lambda_{vMises} \times \text{penalization(von Mises)};$$

4.3 Software Development / Search for the Optimal Structure

- Objective: find best structural element



f = 0.146   f = 0.142 ✓



- **Outline**

  1. Introduction

  2. Methods Used

  3. Structural and Finite Element Models

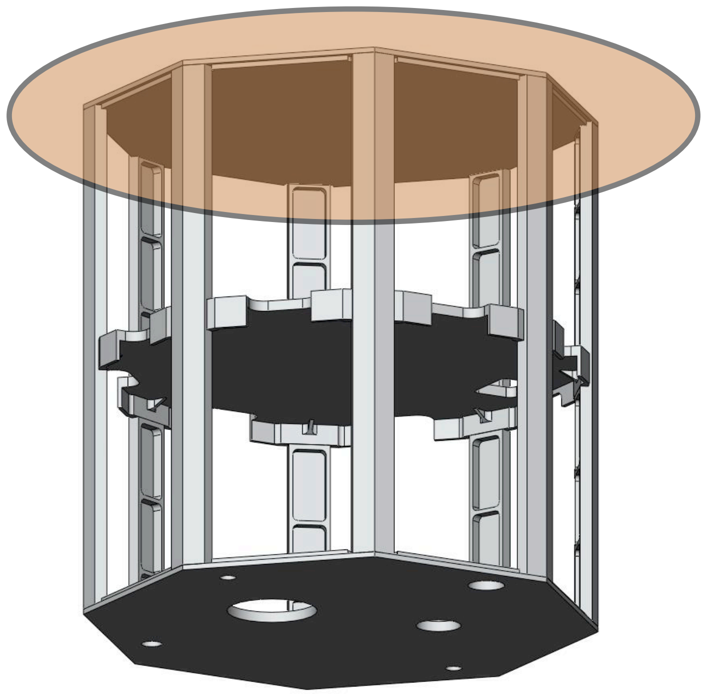
  4. Software Development

  5. **Case Study and Results**

  6. Conclusion and Future Work

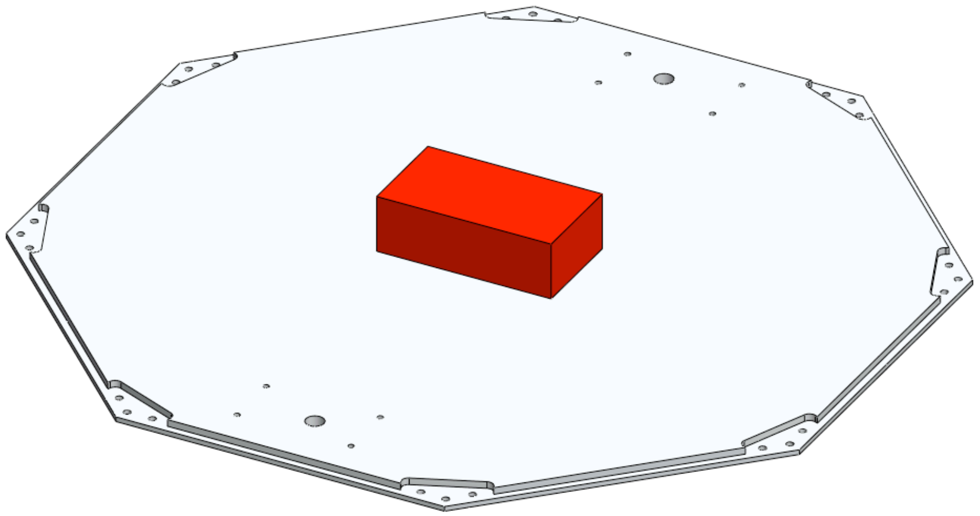
5.1 Case Study and Results / Satellite Panel Design

- Objective function: mass minimization of structural panel in the HawaiiSat-1 satellite.



- Design parameters: topology, plate thickness, beam cross-section side length and sub-system placement (fixed or free to move).

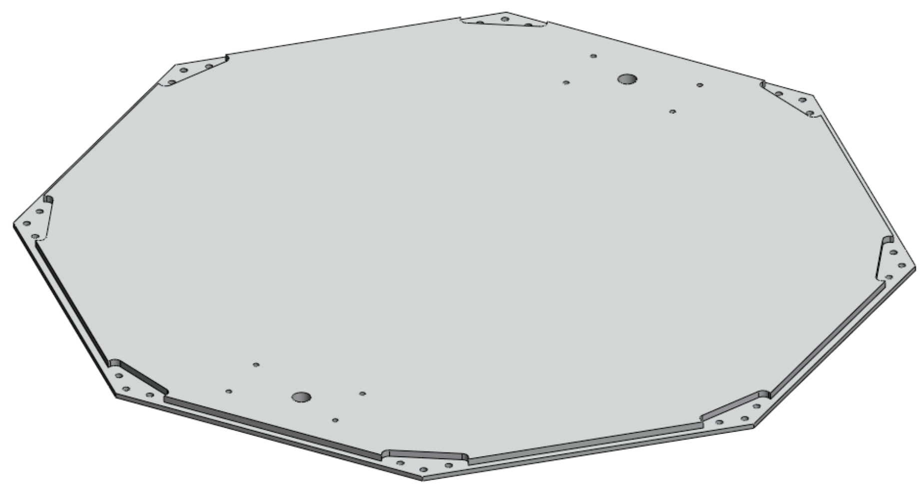
- Constraints: maximum displacement less than or equal to 0.5 mm and stresses within allowable range (yield for Al 6061-T6 is 241 MPa).



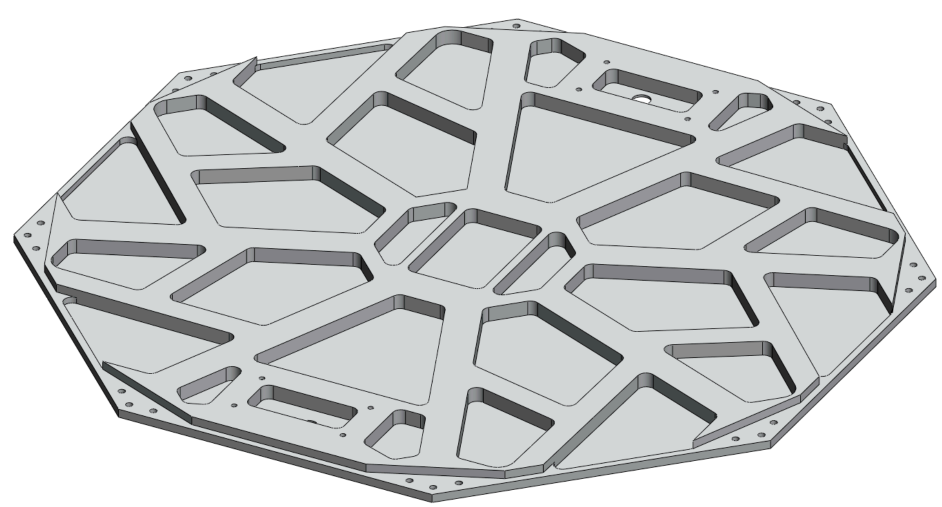
- Boundary conditions: fixed at the vertices of the octagon. The boundary edges are free.

5.3 Case Study and Results / Benchmarks

1. mass = 9.5 kg (100%); 13 µm displacement

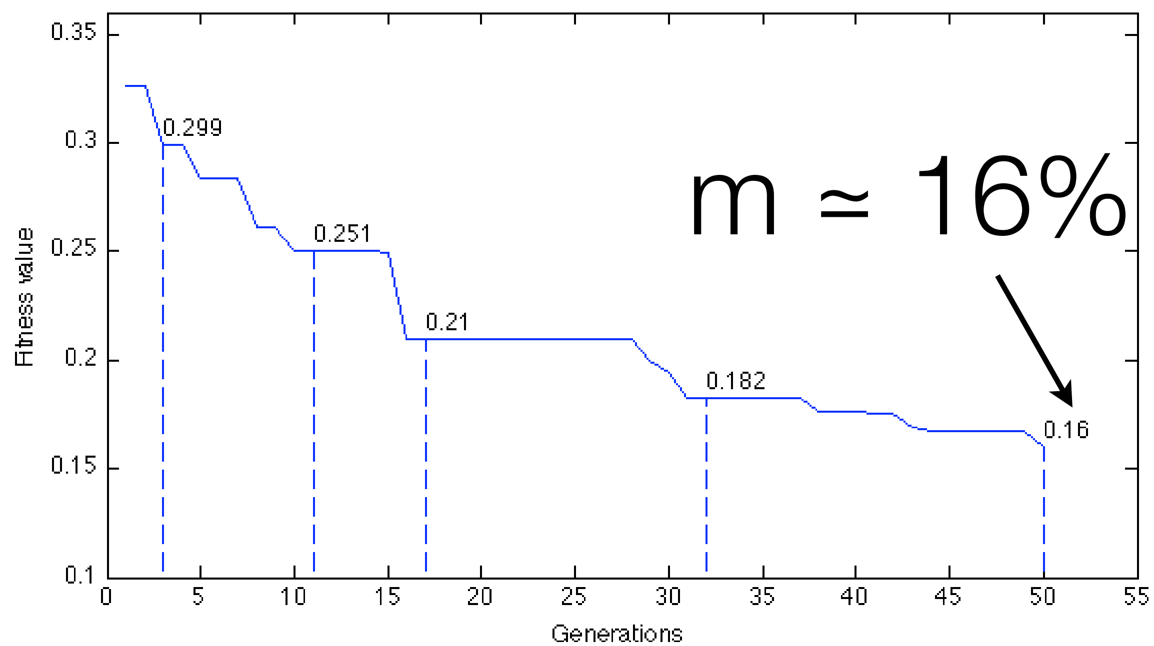


2. mass = 3.8 kg (40%); 81 µm displacement

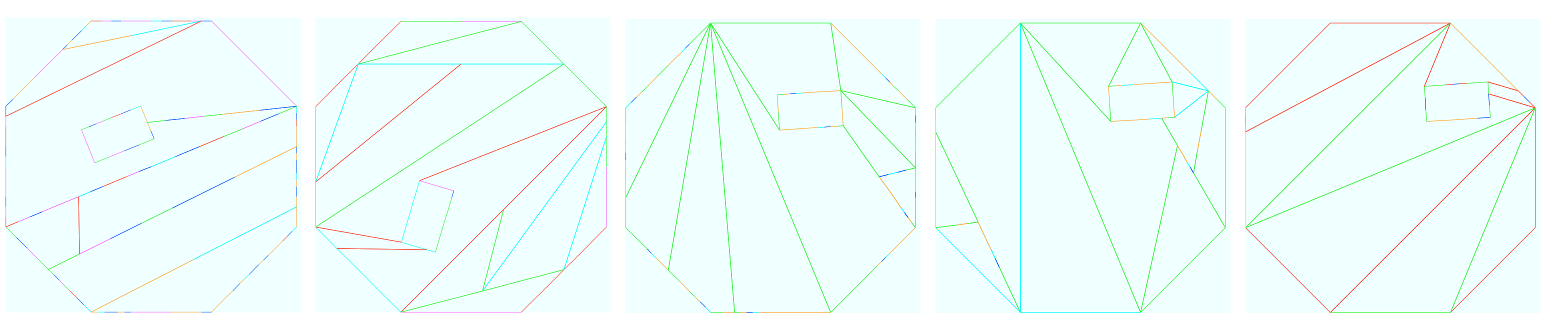


5.4 Case Study and Results / Optimization Run

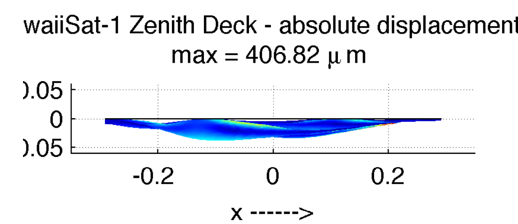
- Optimization Run #1 (50 generations, 100 individuals, subsystem free)
  Best Individual m = **1.443** kg (bench #1: m= 9.5 kg; bench #2: m= 3.8 kg)

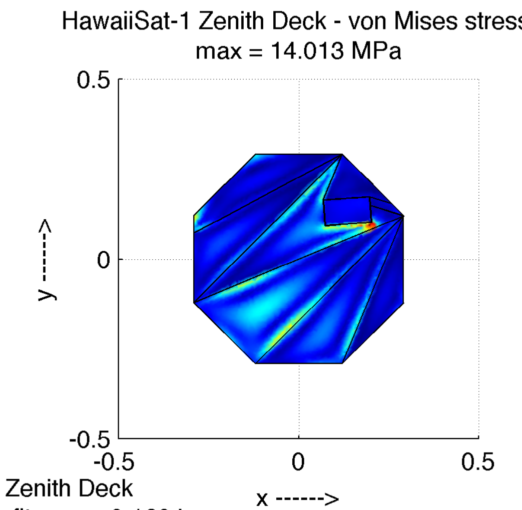


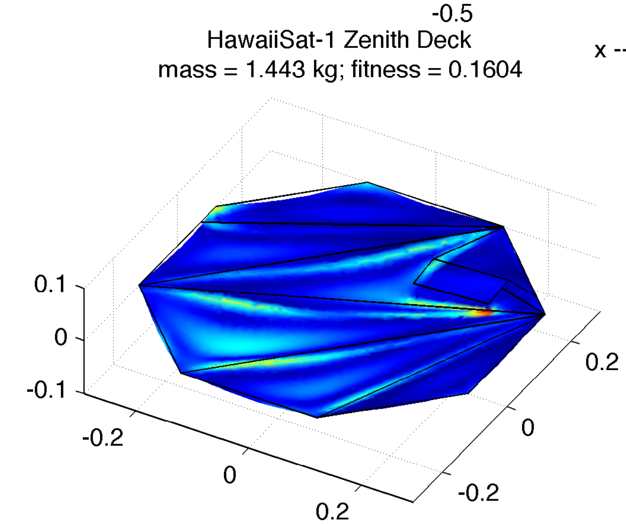
(a) Plot with fitness values for the different generations in the run #1.



(b) Topologies that correspond to the selected fitness values in the fitness plot above.

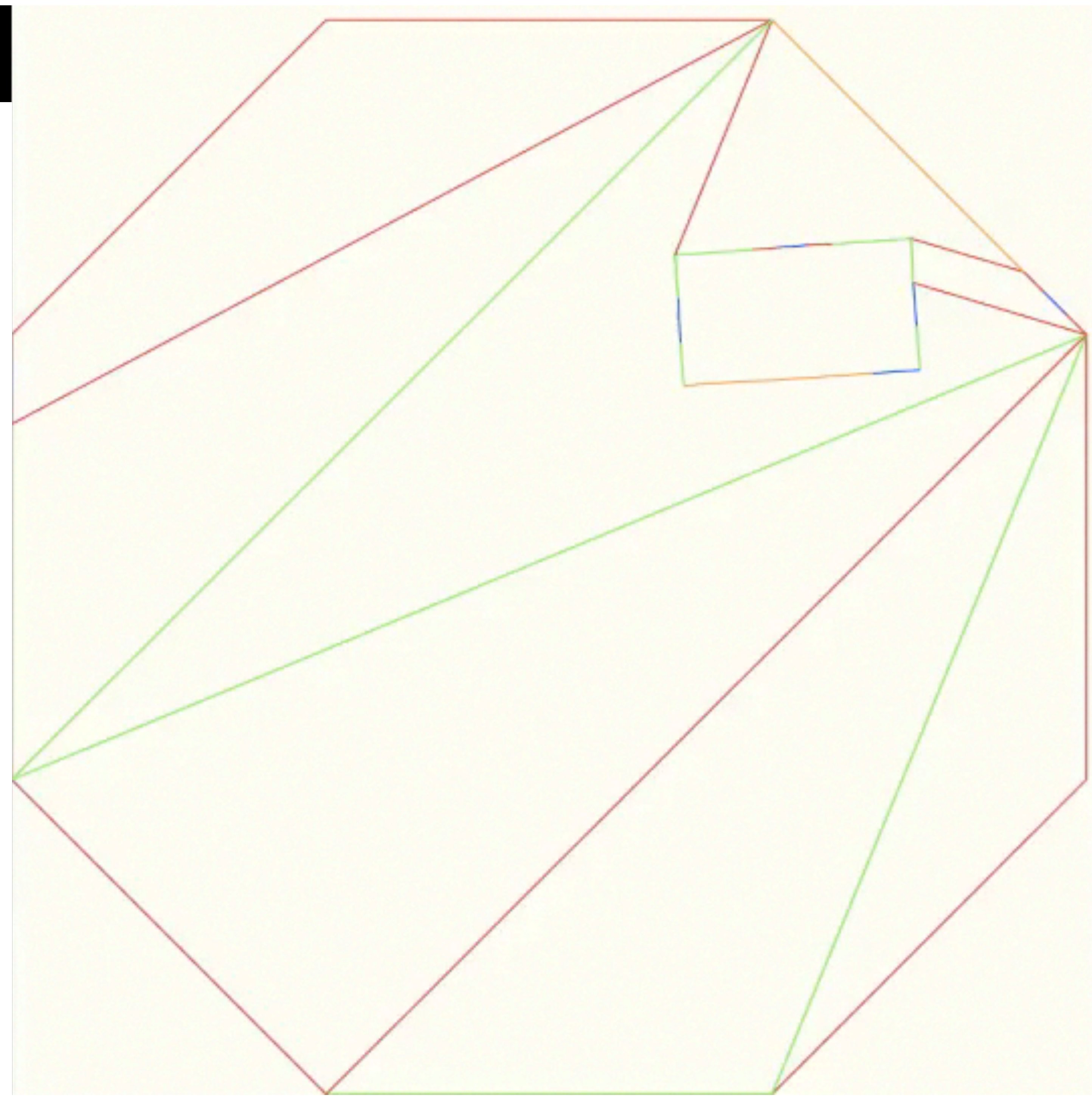






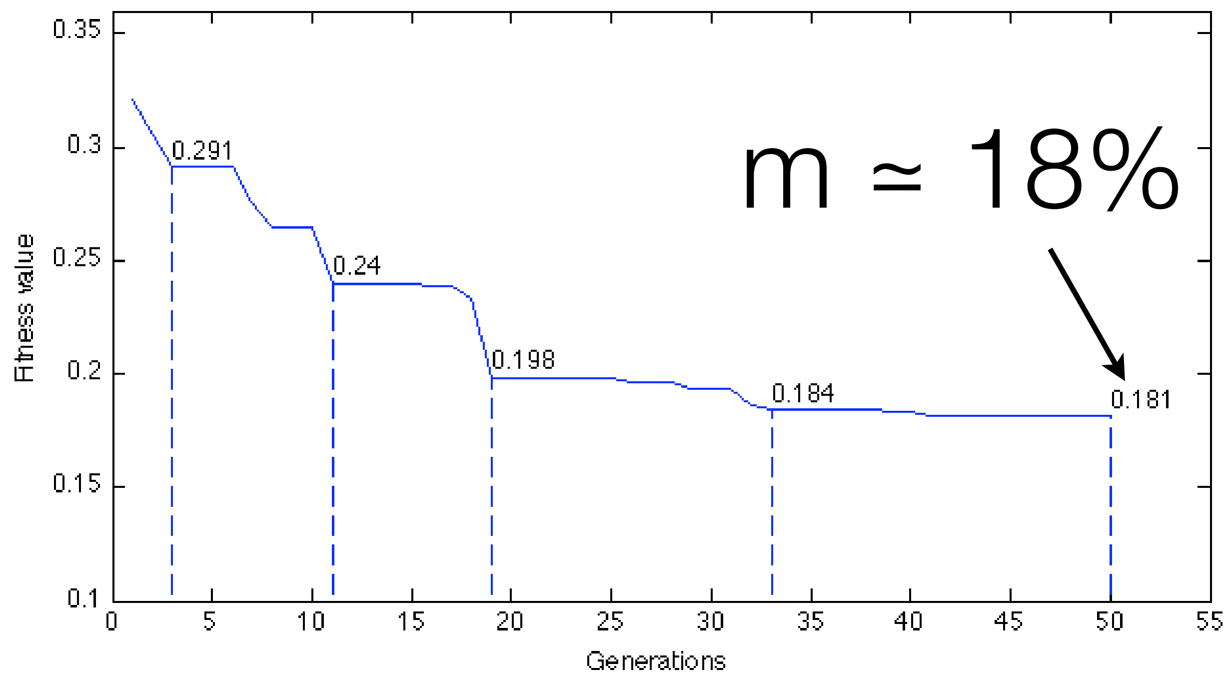
5.4 Case Study and Results / Optimization Run

[redacted]

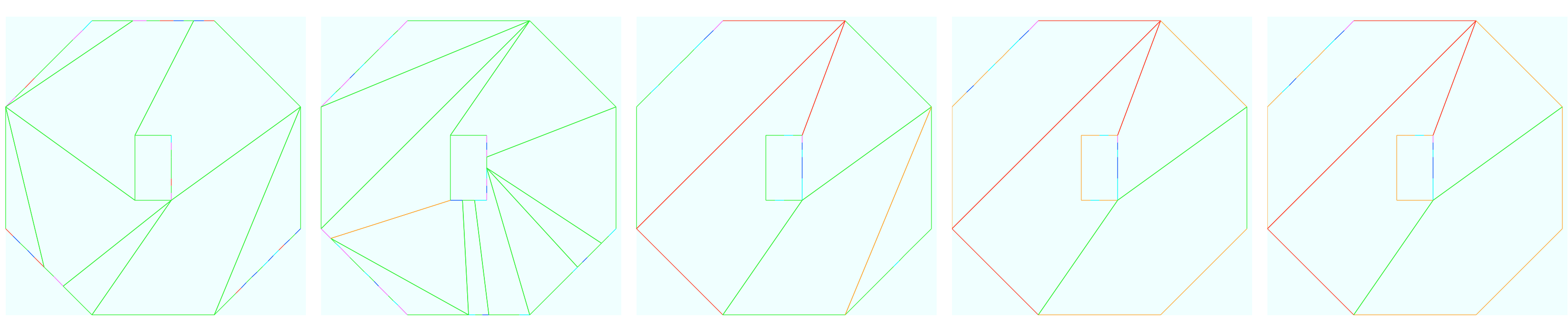


5.4 Case Study and Results / Optimization Run

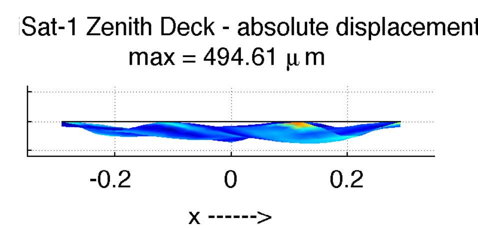
- Optimization Run #2 (50 generations, 200 individuals, subsystem **fixed**)
  Best Individual m = **1.632** kg (bench #1: m= 9.5 kg; bench #2: m= 3.8 kg)

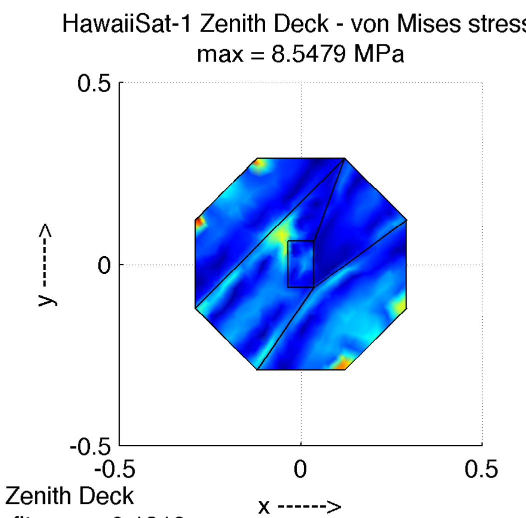


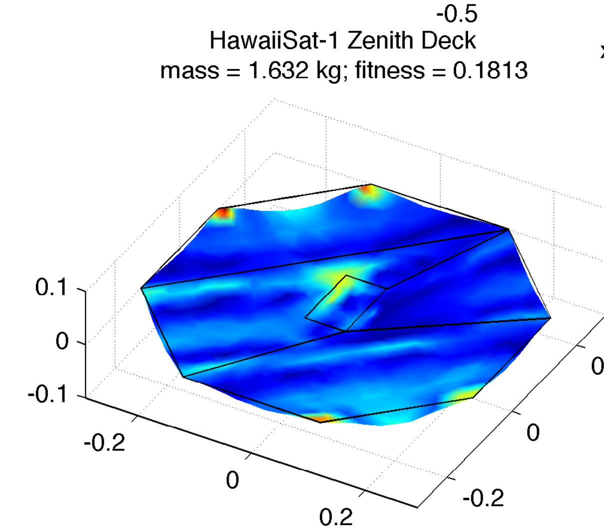
(a) Plot with fitness values for the different generations in the run #2.



(b) Topologies that correspond to the selected fitness values in the fitness plot above.

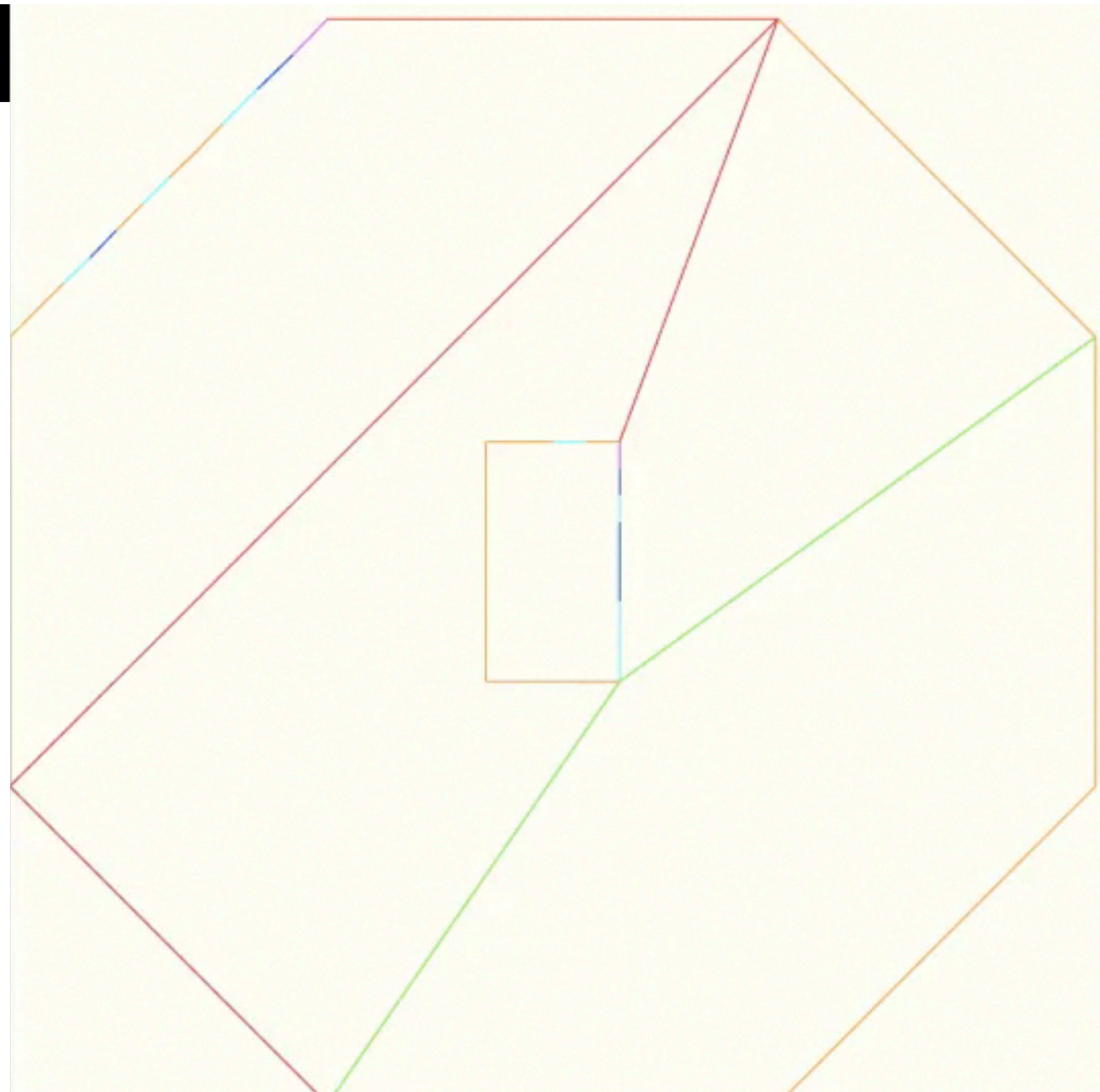






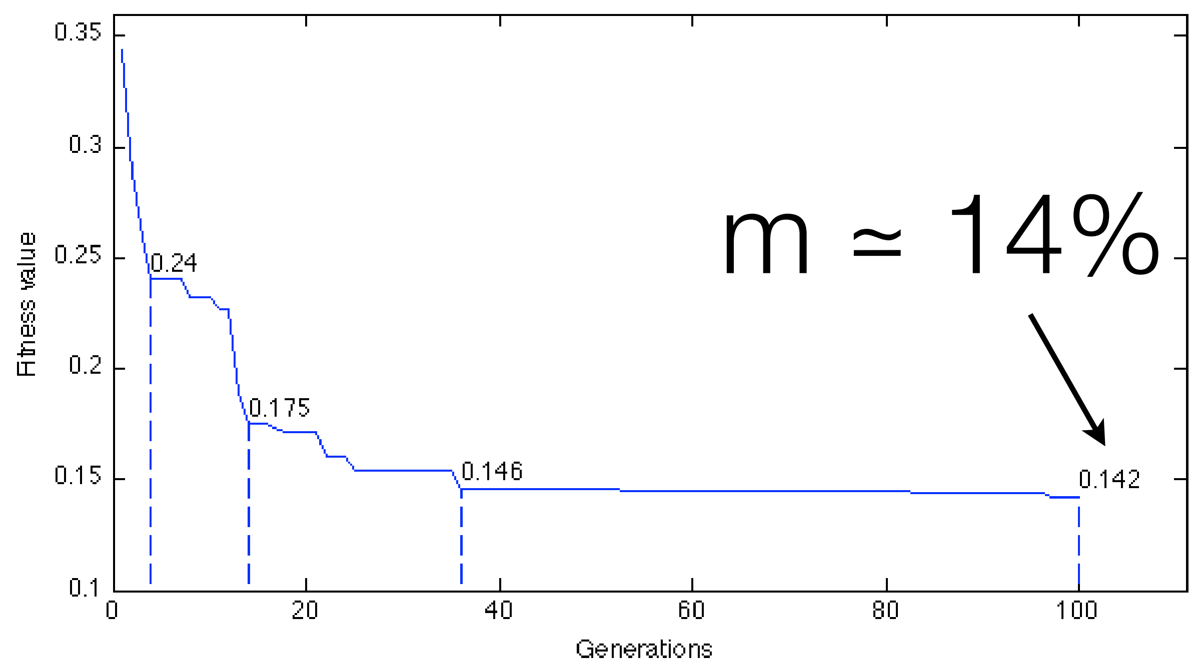
5.4 Case Study and Results / Optimization Run

[redacted]

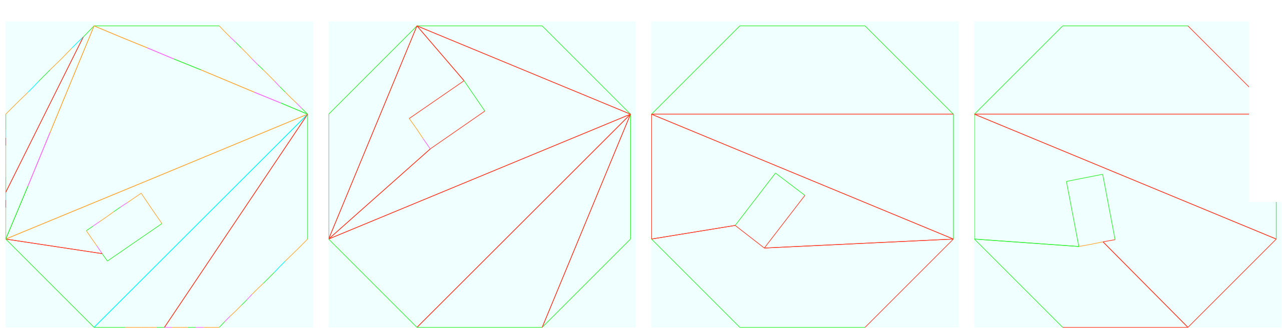


5.4 Case Study and Results / Optimization Run

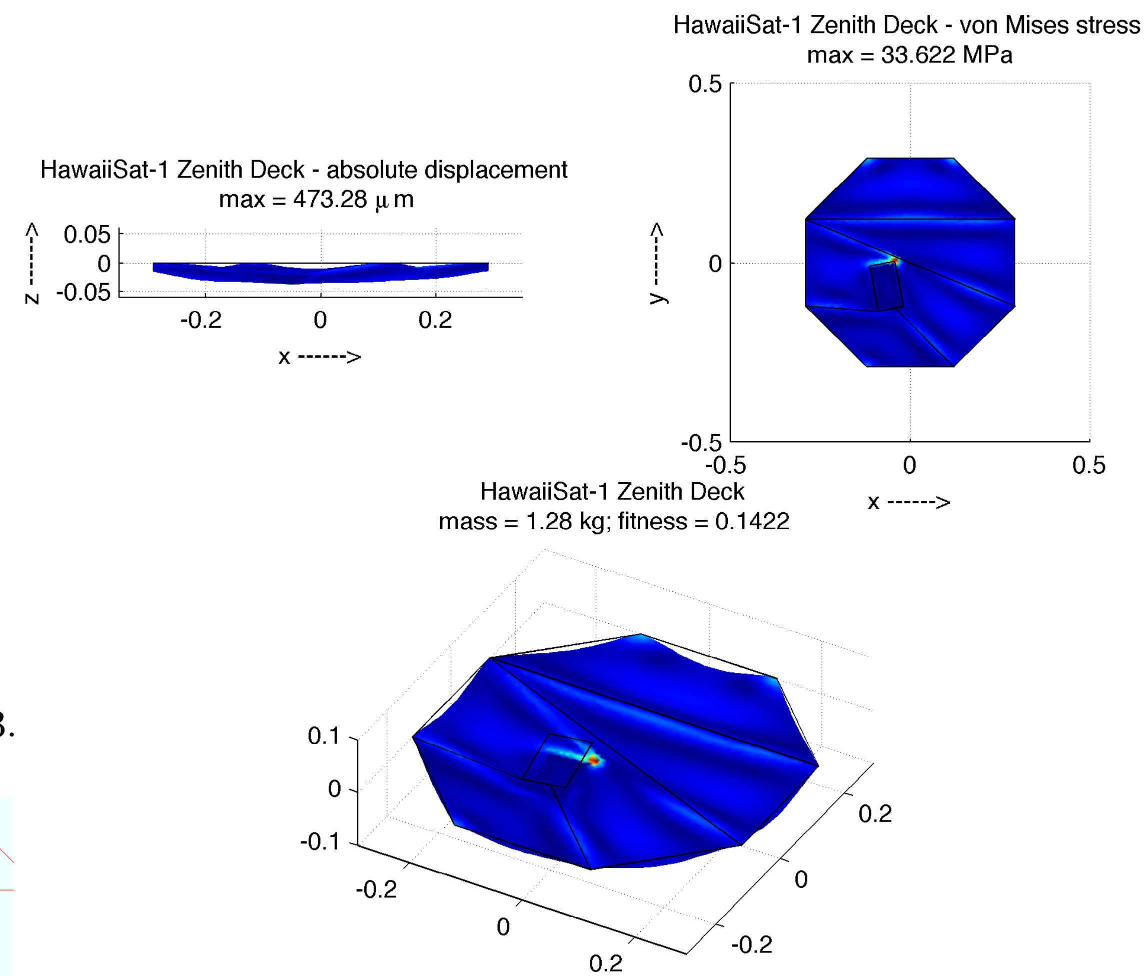
- Optimization Run #3 (100 generations, 200 individuals, subsystem free)
  Best Individual m = **1.280** kg (bench #1: m= 9.5 kg; bench #2: m= 3.8 kg)



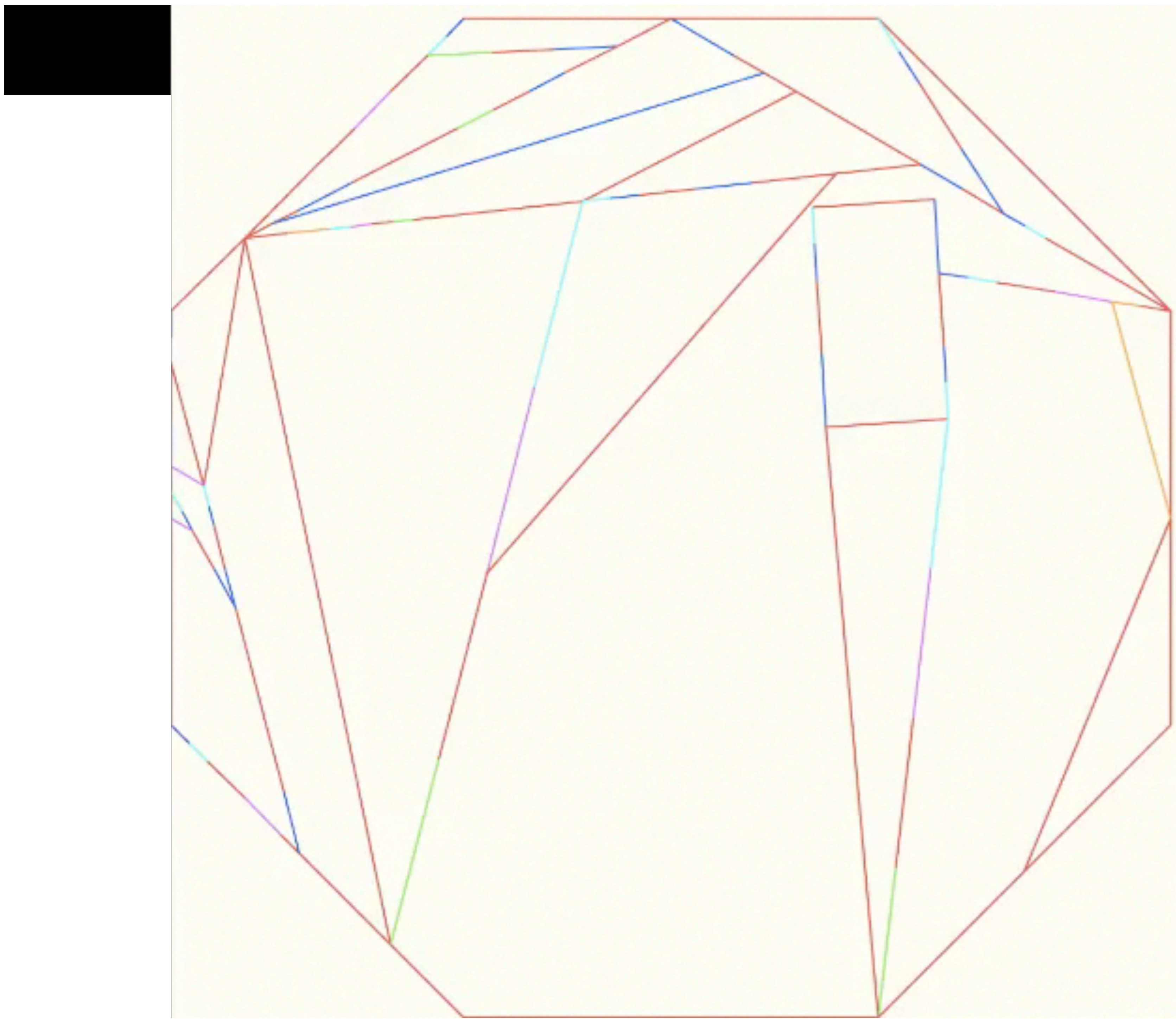
(a) Plot with fitness values for the different generations in the run #3.



(b) Topologies that correspond to the selected fitness values in the fitness plot above.



5.4 Case Study and Results / Optimization Run



5.4 Case Study and Results / Optimization Run

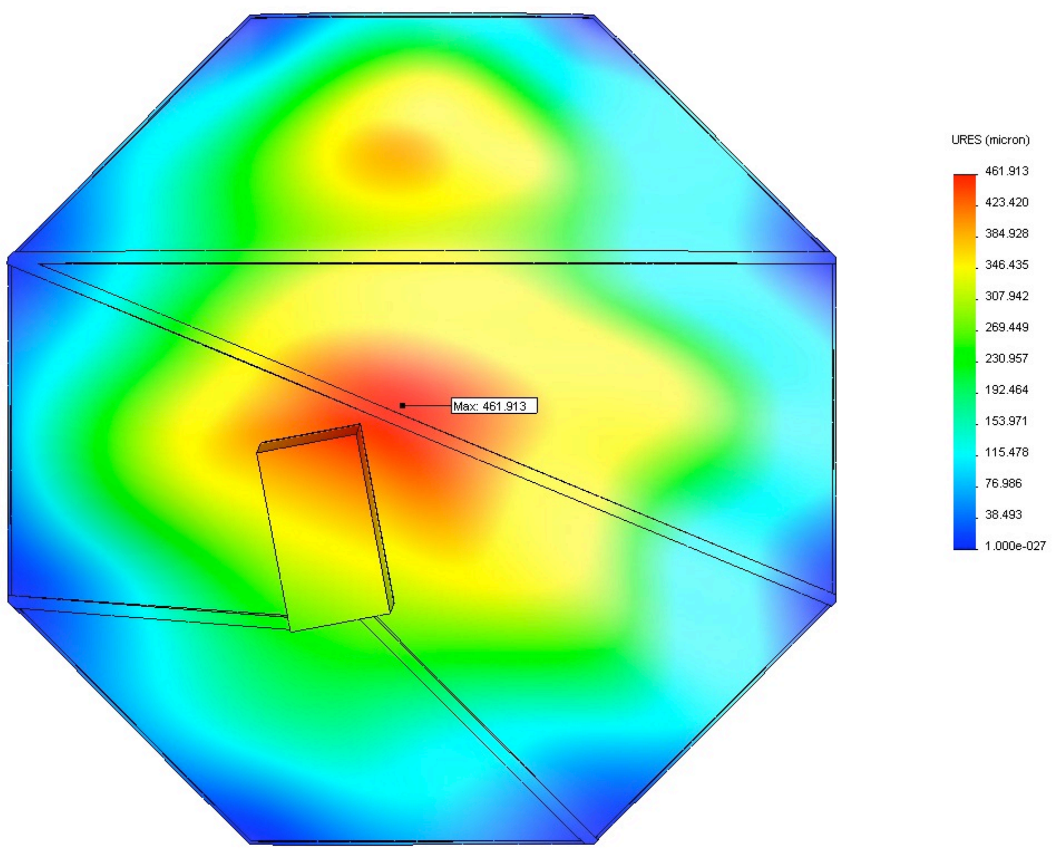
- Summary of results

Run #	Individuals	Generations	Elapsed Time	Fitness	Mass [kg]	Subsystem Position
1	100	50	43h 51m 07s	0.1604	1.443	free
2	200	50	38h 17m 31s	0.1813	1.632	fixed
3.1	200	50	33h 02m 55s	0.1459	1.308	free
3.2	200	50	25h 15m 15s	0.1422	1.280	free

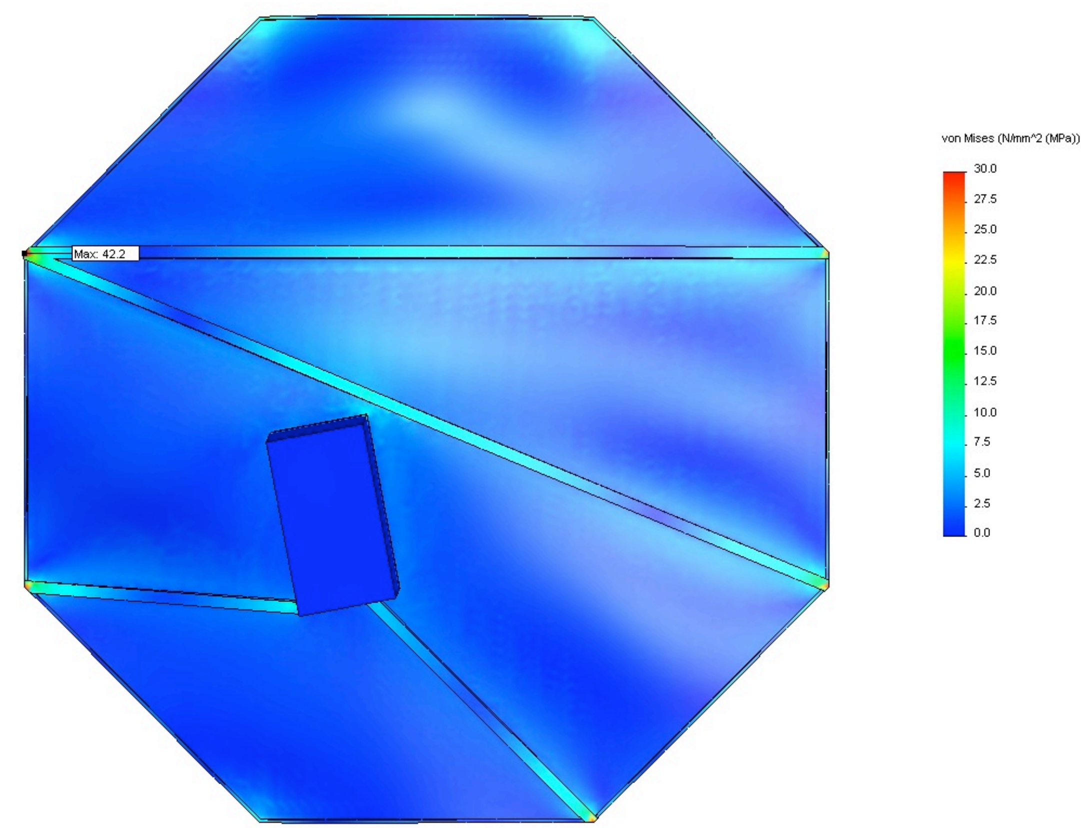
Different optimization runs with the Genetic Algorithm based on the biologically inspired methodology for topology generation

5.4 Case Study and Results / 3D Model

- 3D SolidWorks Model, mass = 1.202 kg



Displacement
max = 461.91 µm

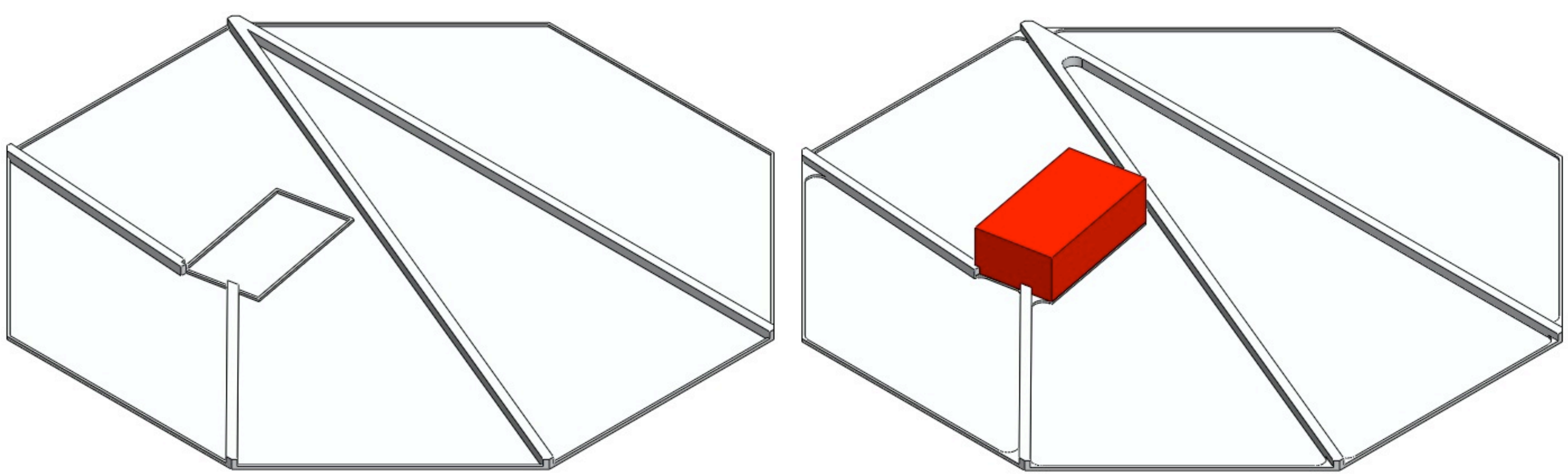


Stress
max = 42.2 MPa

5.4 Case Study and Results

	mass [kg]	Max. Displacement [μm]	Max. Stress [MPa]
COMSOL Multiphysics™ →	1.280	473.28	33.6
SolidWorks→	1.202	461.91	42.2
absolute difference	6%	2%	26%

Comparison between results from COMSOL Multiphysics™ and SolidWorks for the most optimized structure.



SolidWorks model for the best individual. Raw model on the left and finalized model with chamfers on the right.

- **Outline**

1. Introduction
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3. Structural and Finite Element Models
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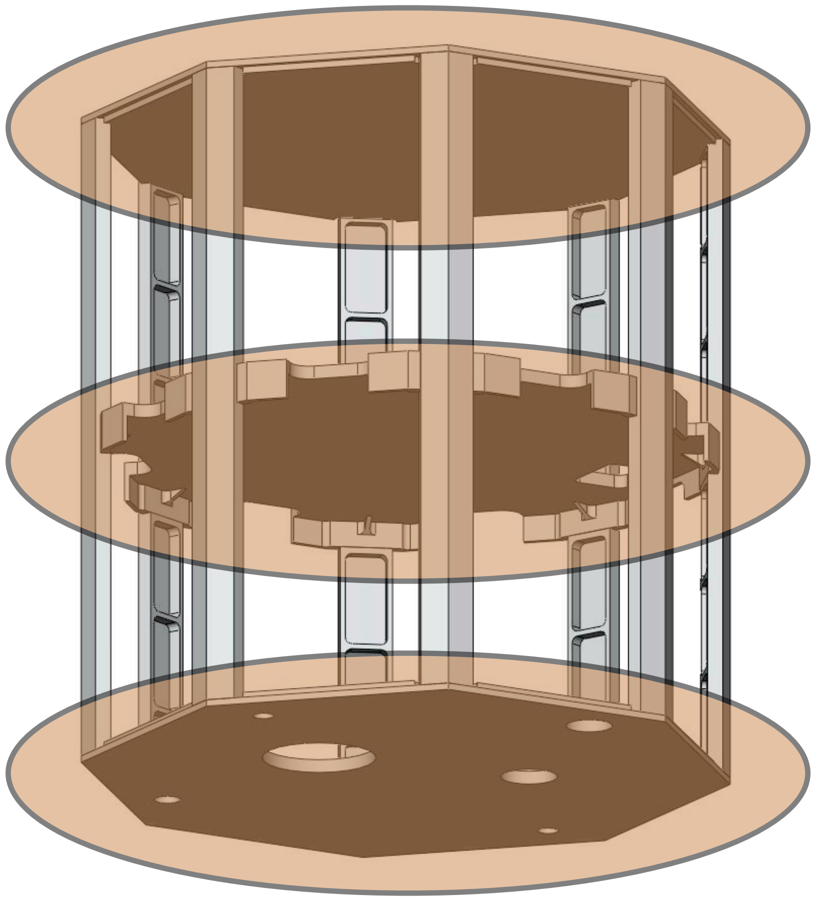
5. Case Study and Results
6. **Conclusion and Future Work**

6.0 Conclusion and Future Work

- Successful development of a new methodology for multidisciplinary system design optimization inspired on nature
- Mass reduction of 83% compared to the un-optimized benchmark
- Mass reduction of 57% compared to the optimized benchmark
- Potential savings in one panel of $78,680 (assuming $10k/kg)
- Potential savings on three panels of $236,040



6.0 Conclusion and Future Work

- Improve the software developed
  - Optimize code
  - Parallel processing capability
  - Integrate Finite Element Method into the code
- Compare analysis with commercial software
- Extend to other structural elements on the satellite
- 3D version

8.0 Any Questions?