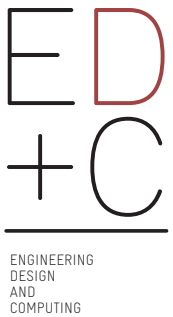
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Computational Design-to-Fabrication: The Role of Simulation

Prof. Dr. Kristina Shea



2014-15-05

Engineering Design and Computing Lab (EDAC)

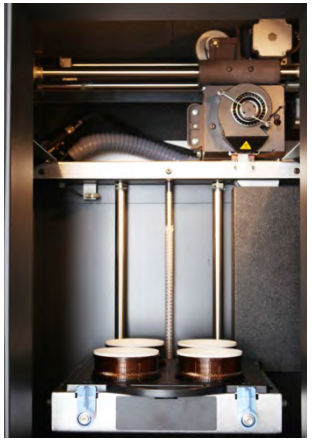
Objectives

- Enable the design of more innovative and complex engineered systems and products through new computational design models, methods and tools
- Automate design and fabrication processes
- Integrate research in practice

Structures

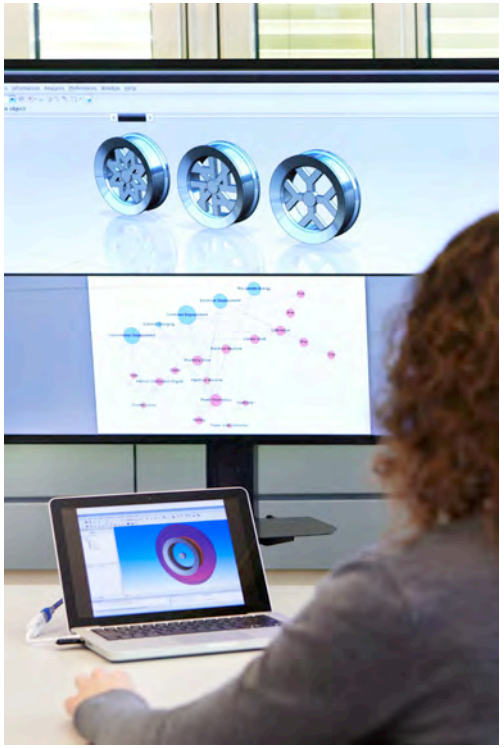
Consumer Products

Mechatronics

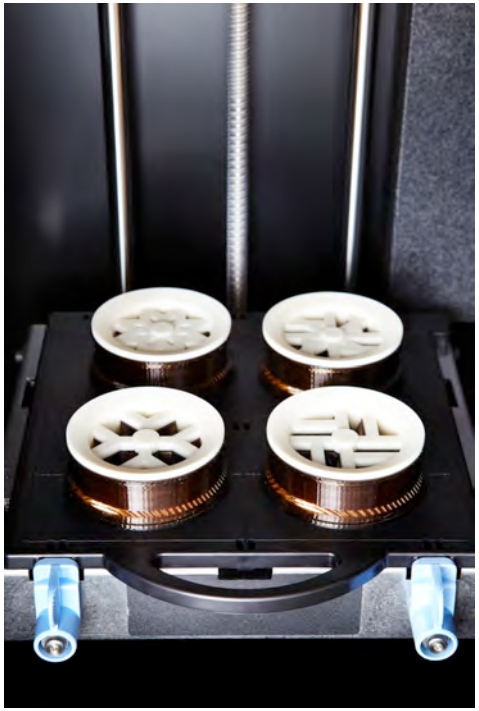


Additive Manufacturing

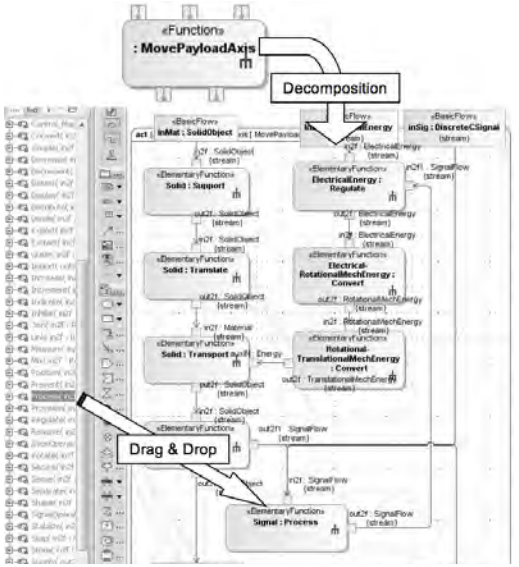
Research Areas



Computational Design Synthesis and Optimization

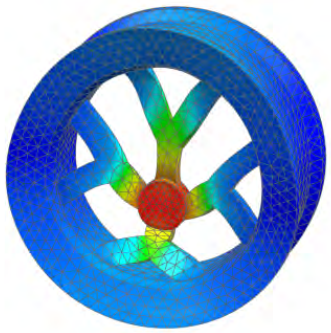


Computational Design-to-Fabrication



Model-Based Design and Systems Engineering

Synthesis vs. Analysis



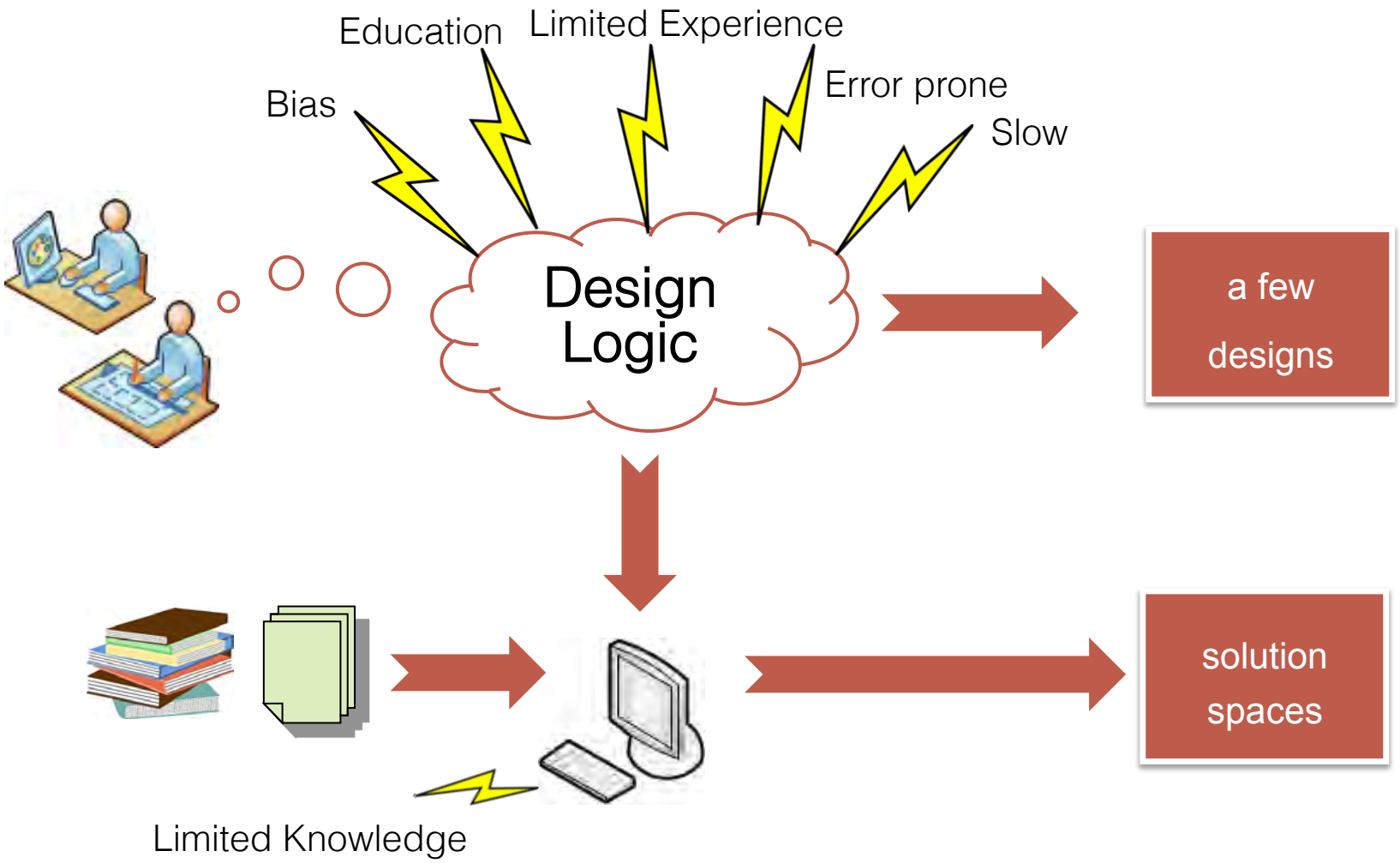
Analysis / Simulation:

Breakdown of a system into its elements and their interrelationships. The construction of a mathematical model to reproduce the effects (behavior) of a phenomenon, system, or process.

Synthesis:

The design and combination of fundamental components, or building blocks, to produce a unified and often complex system behavior that satisfies or optimizes design requirements.

Motivation for Computational Design Synthesis



Why Automate Synthesis and Design?

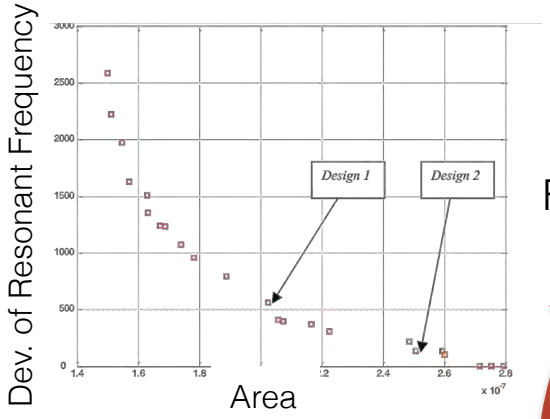
Faster. Automate

Better. Explore Solution Spaces

Cheaper. Optimize

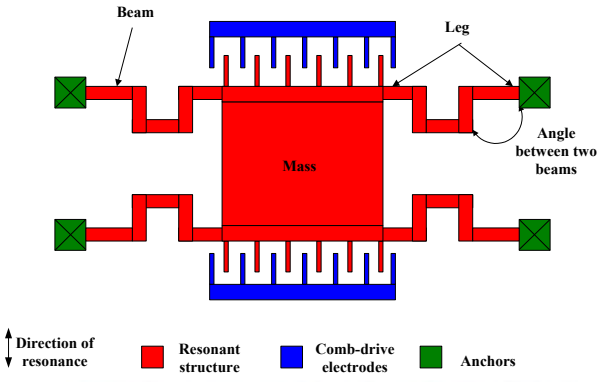
Keep design and innovation internationally competitive!

Basic Research Approach



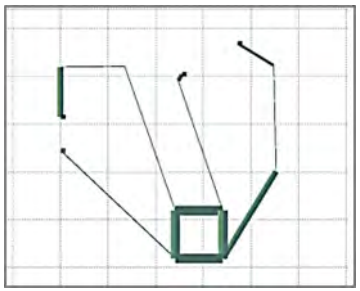
Fabricate + Test

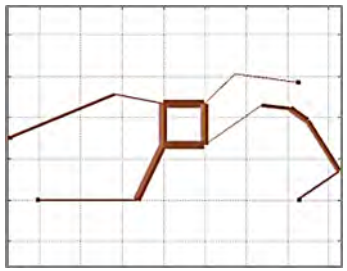
Specify Task



Computational Design Synthesis

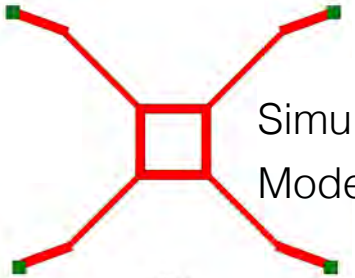
Explore Solution Spaces



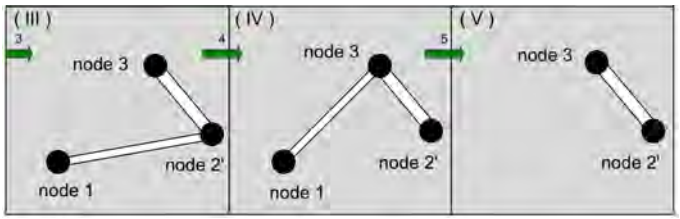


Generate Simulate Optimize

Model



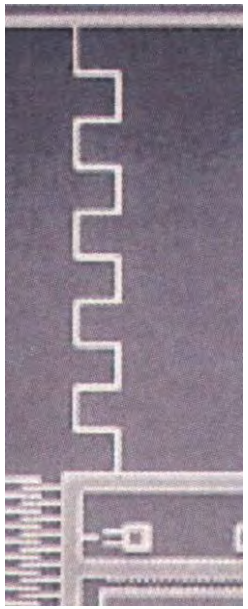
Simulation Model

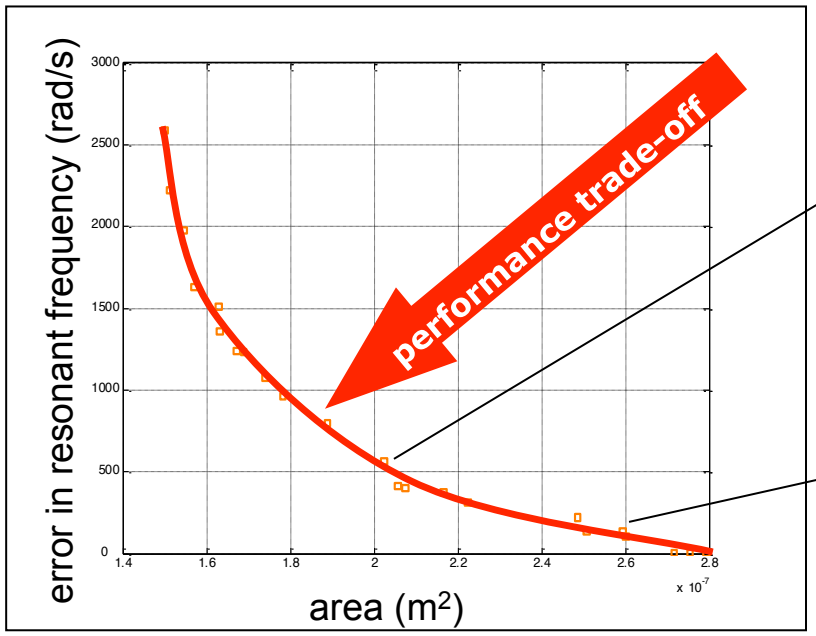


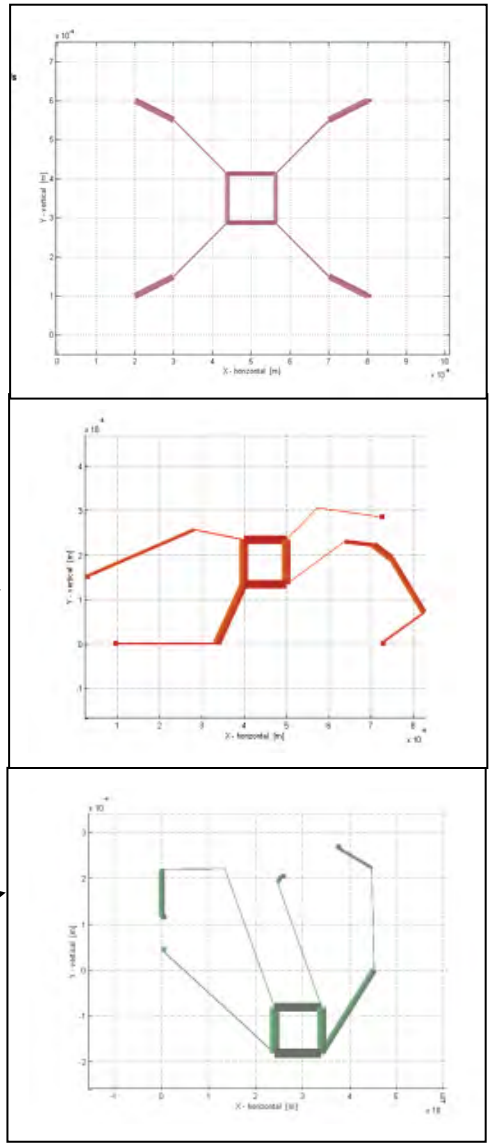
Synthesis Rules

MEMS Synthesis - Meandering Resonator

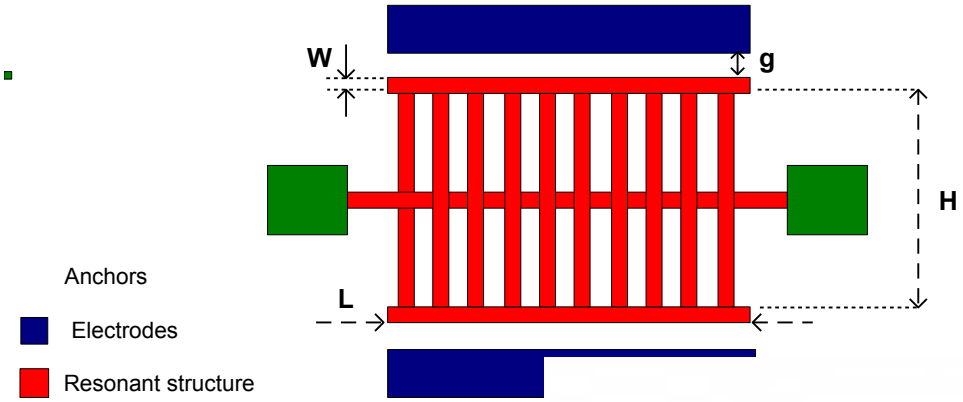
- Center mass supported by four springs
- Synthesis of beam topology, geometry and dimensions of beams
- Min error in frequency and device area subject to stiffness and fabrication constraints





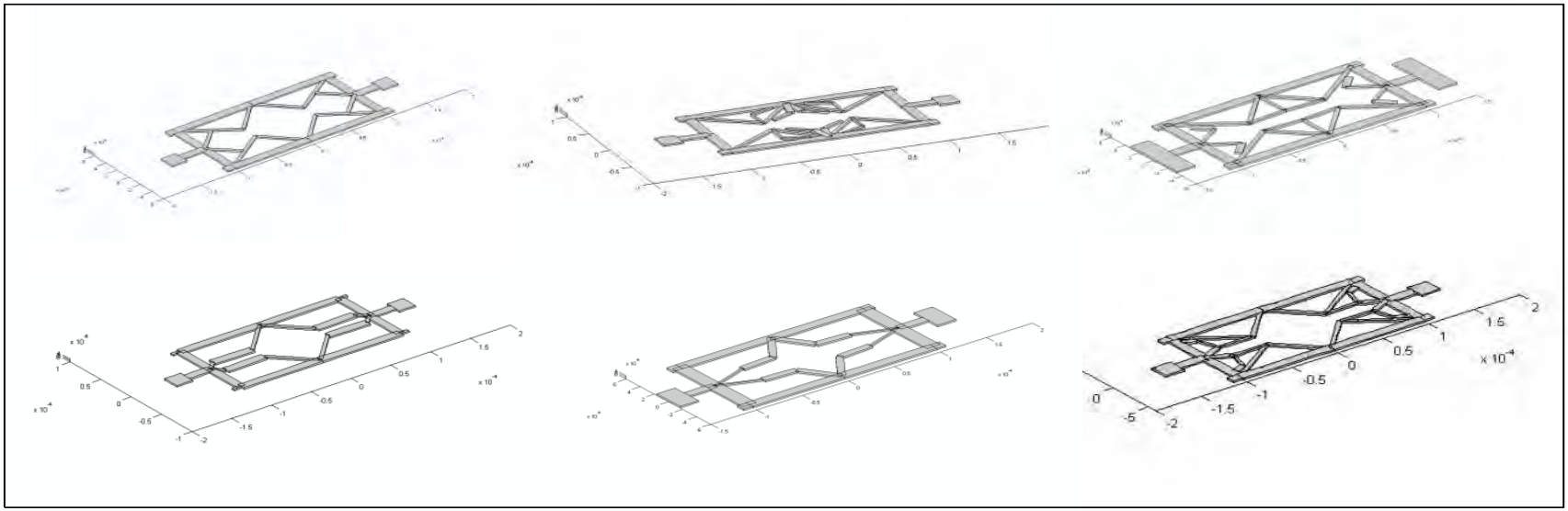


MEMS Synthesis - Sandwich Resonator

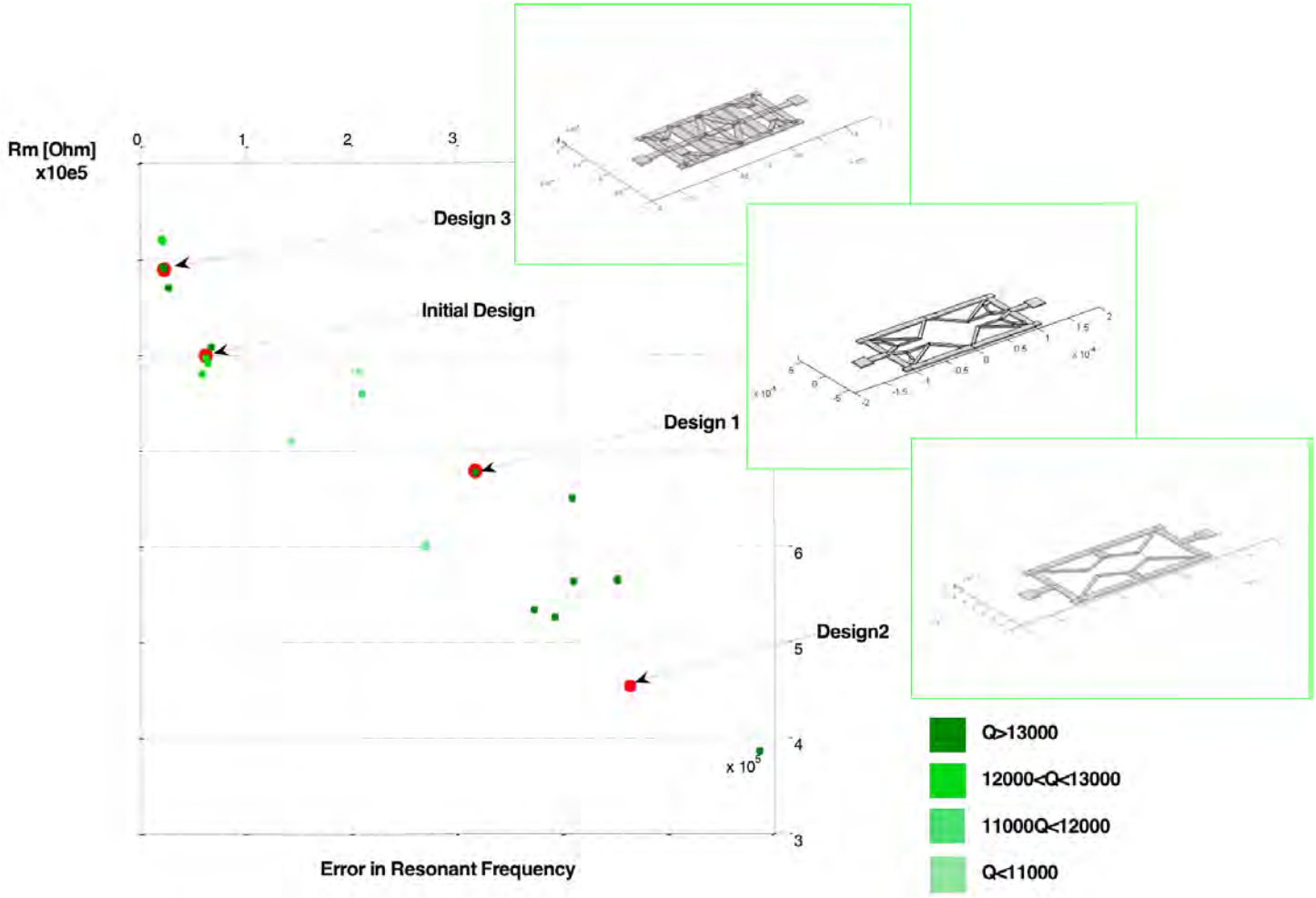


Objectives:

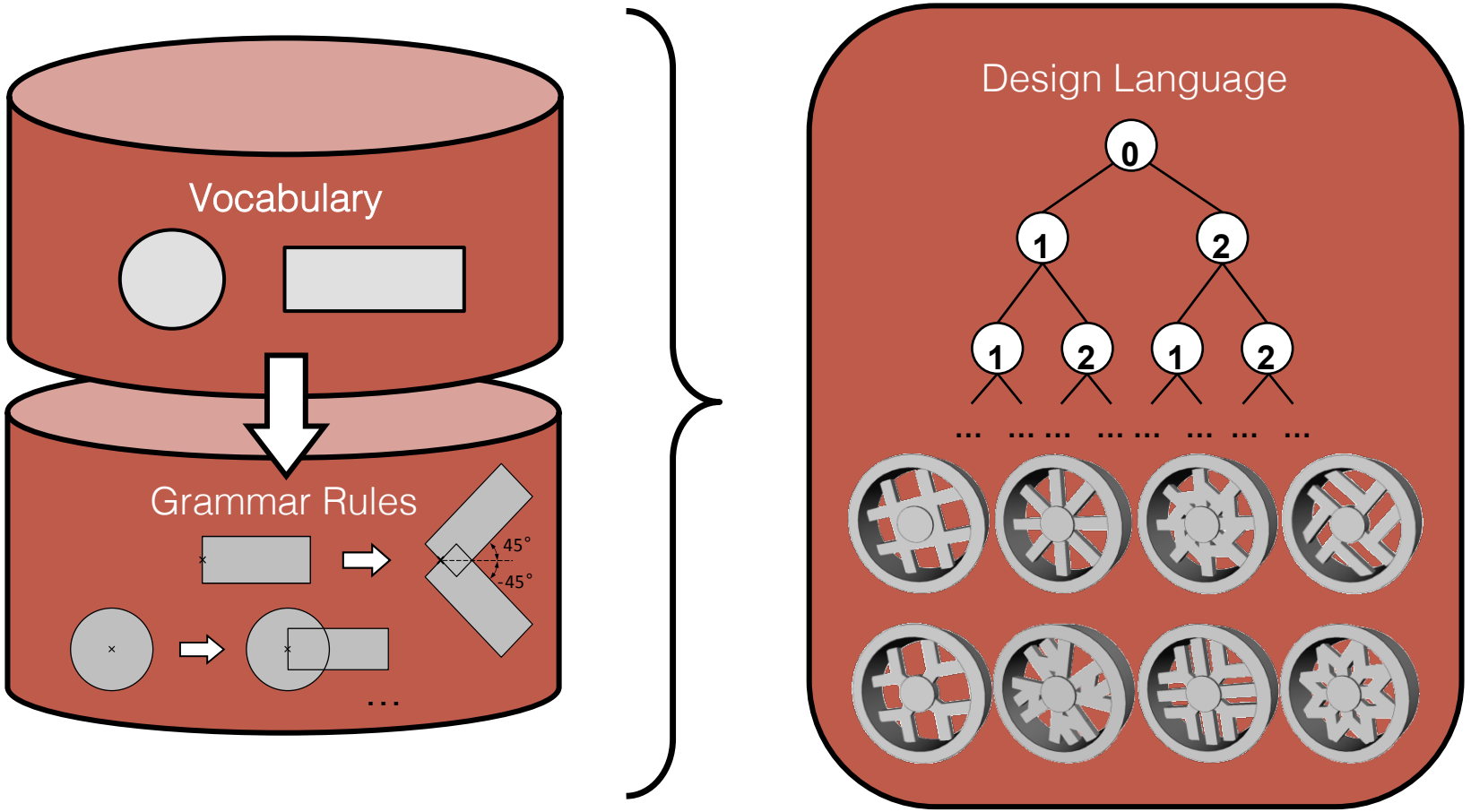
- target operational frequency, f = 25 MHz
- minimize motional resistance, R_m
- maximize quality factor, Q



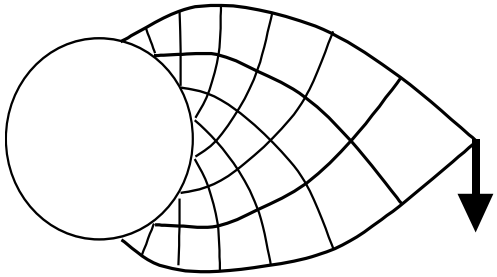
MEMS Synthesis - Sandwich Resonator



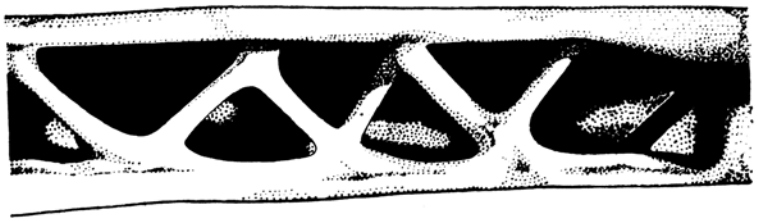
Engineering Design Grammars



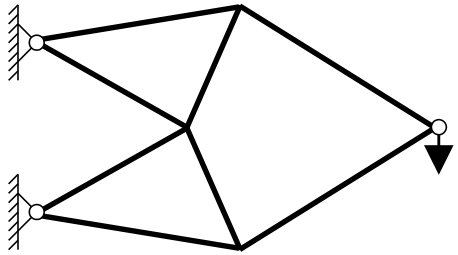
Structural Topology Optimization



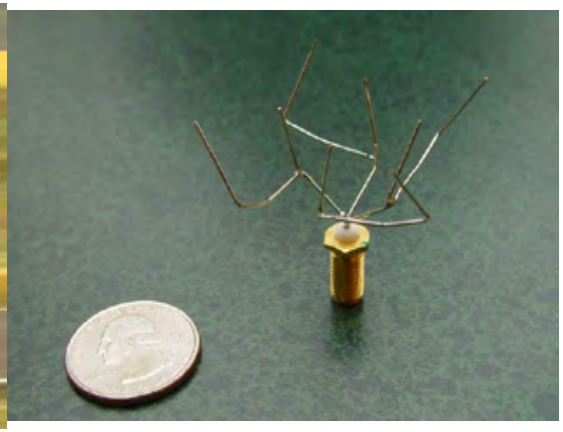
Michell truss (1904)



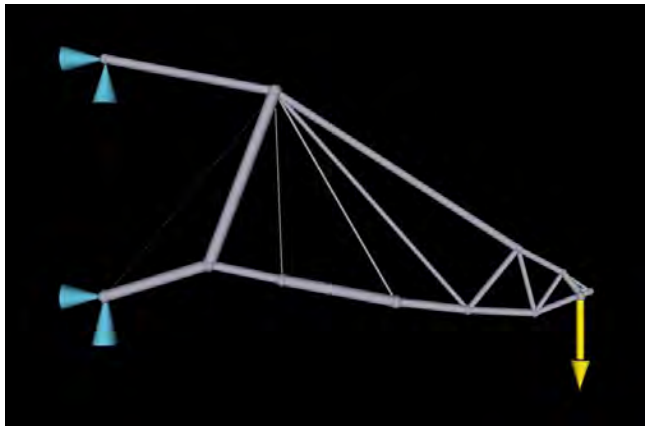
Thompson (1914)



Prager truss (1977)

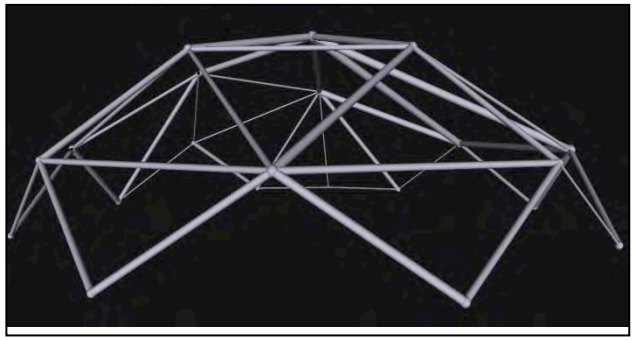


Structural Topology and Shape Annealing

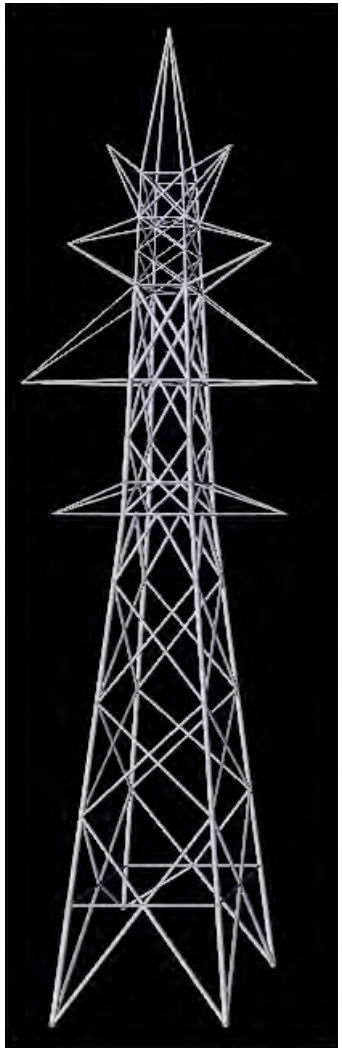


Class I (1995)

Class III (2004)



Class V (1997, 2006)

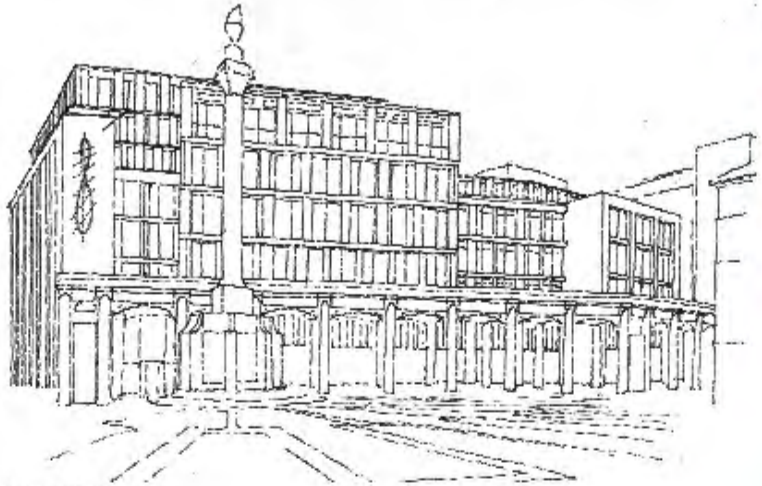


Class VI (1999)

Design Brief

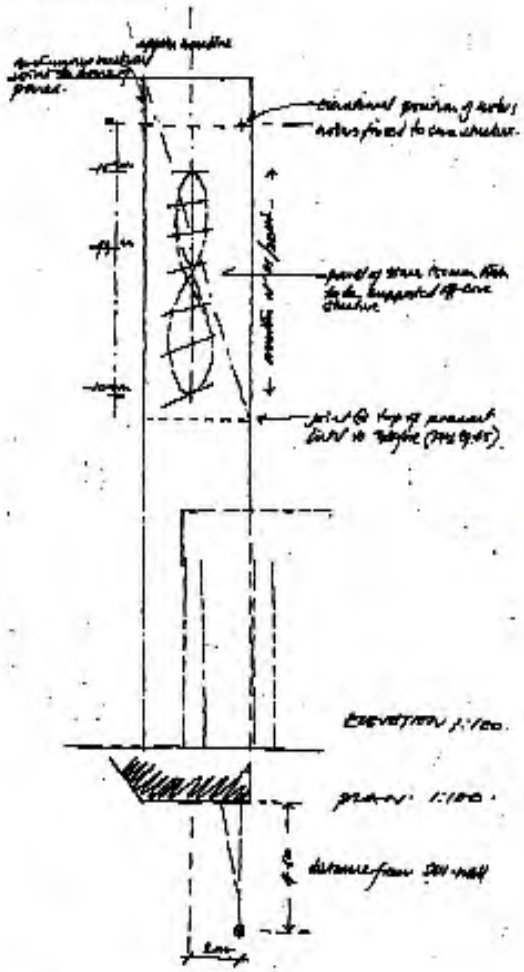
Noon Mark

Proposal for King Edward Court, Building 2, Paternoster Square, City of London

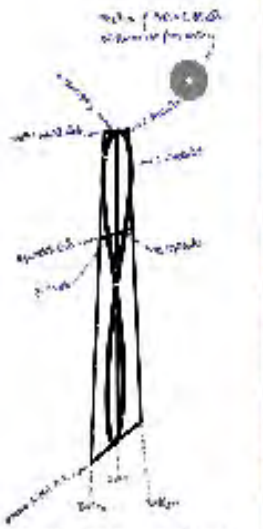


View from South East

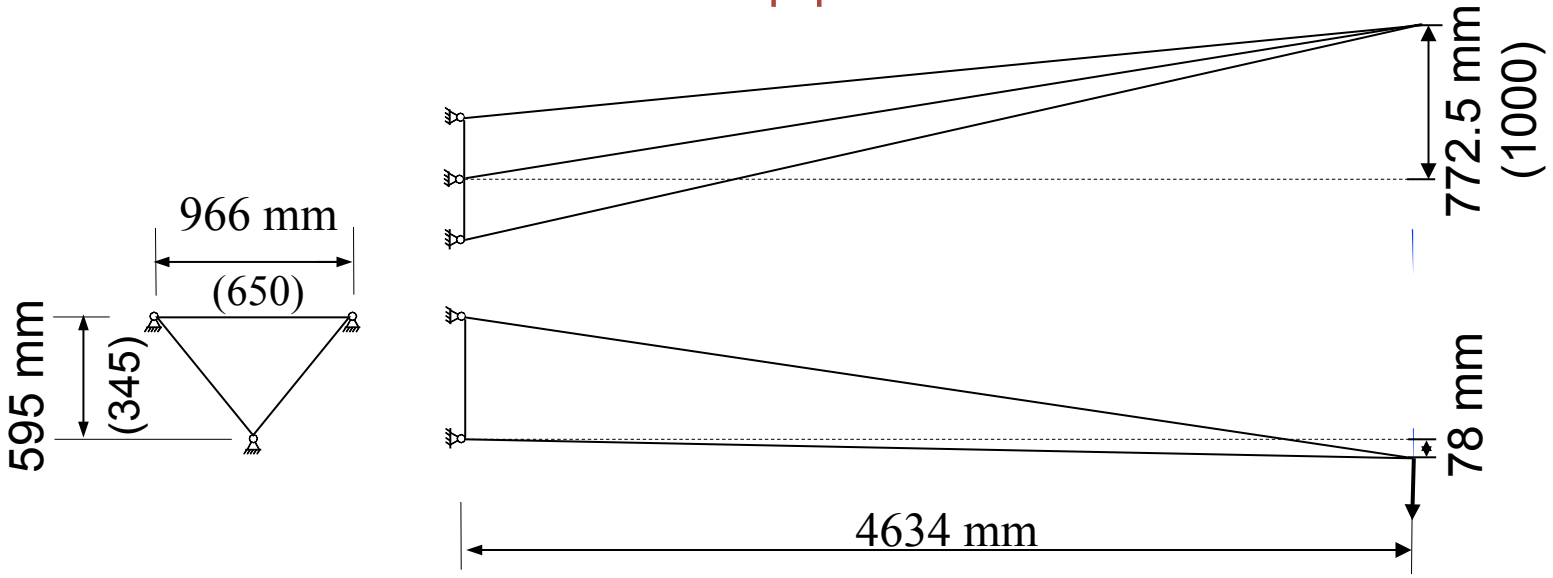
South Elevation to Paternoster Square



Preliminary Elevational Study



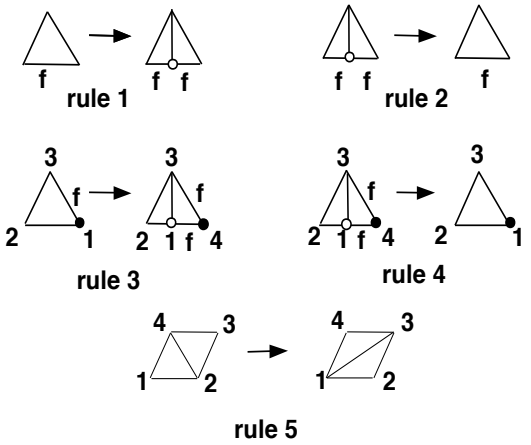
Noon Mark Cantilever Support

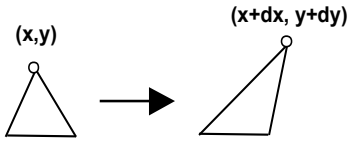


Key parameters and constraints

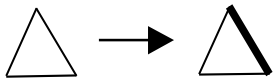
- max tip displacement <= 2 mm (1/2317 of cantilever length)
- thin, “sleek”, visually light novel design
- stainless steel circular hollow sections with OD < 90 mm
- placement in stones and capability for adjustment
- 13 load combinations (self-weight, wind, thermal, support settlement)

Structural Grammar - Class III Truss-Beams



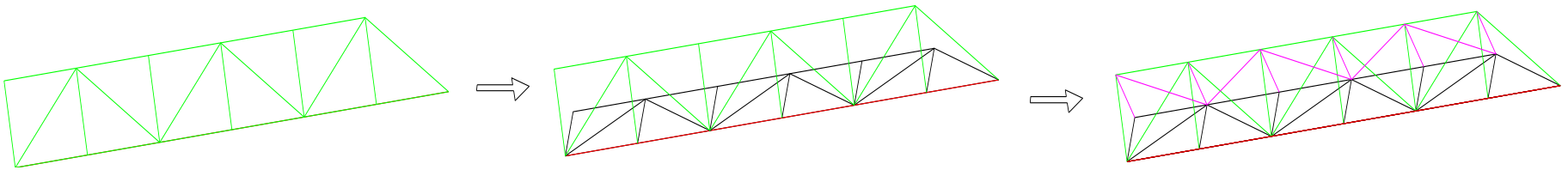


Shape Transformation Rule



Size Transformation Rule

Topology Transformation Rules



generate a planar truss (class I)

copy + geometrically transform

brace

Optimization Model

minimize:

$$\text{mass}(i, \mathbf{l}, \mathbf{a}) = \sum_i (\rho * l_i * a_i),$$

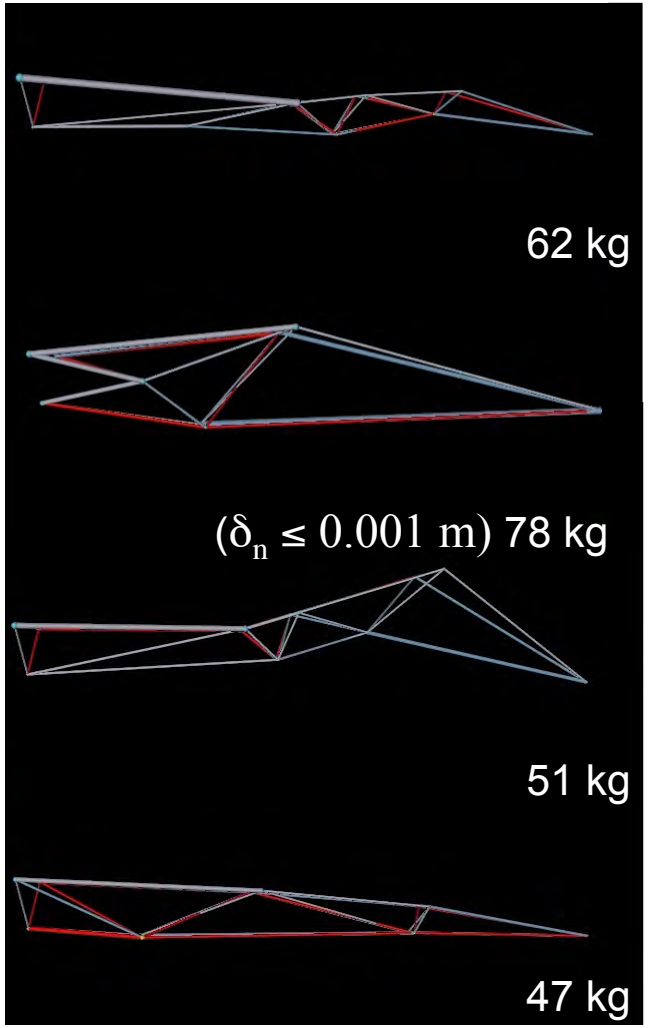
$$\text{where } i = 1 \ldots \text{num\_members}; \mathbf{l} = \text{vector of member lengths};$$

$$\mathbf{a} = \text{vector of gross area for each member}, a_i \in \{s_1 \ldots s_{\text{max available sections}}\}$$

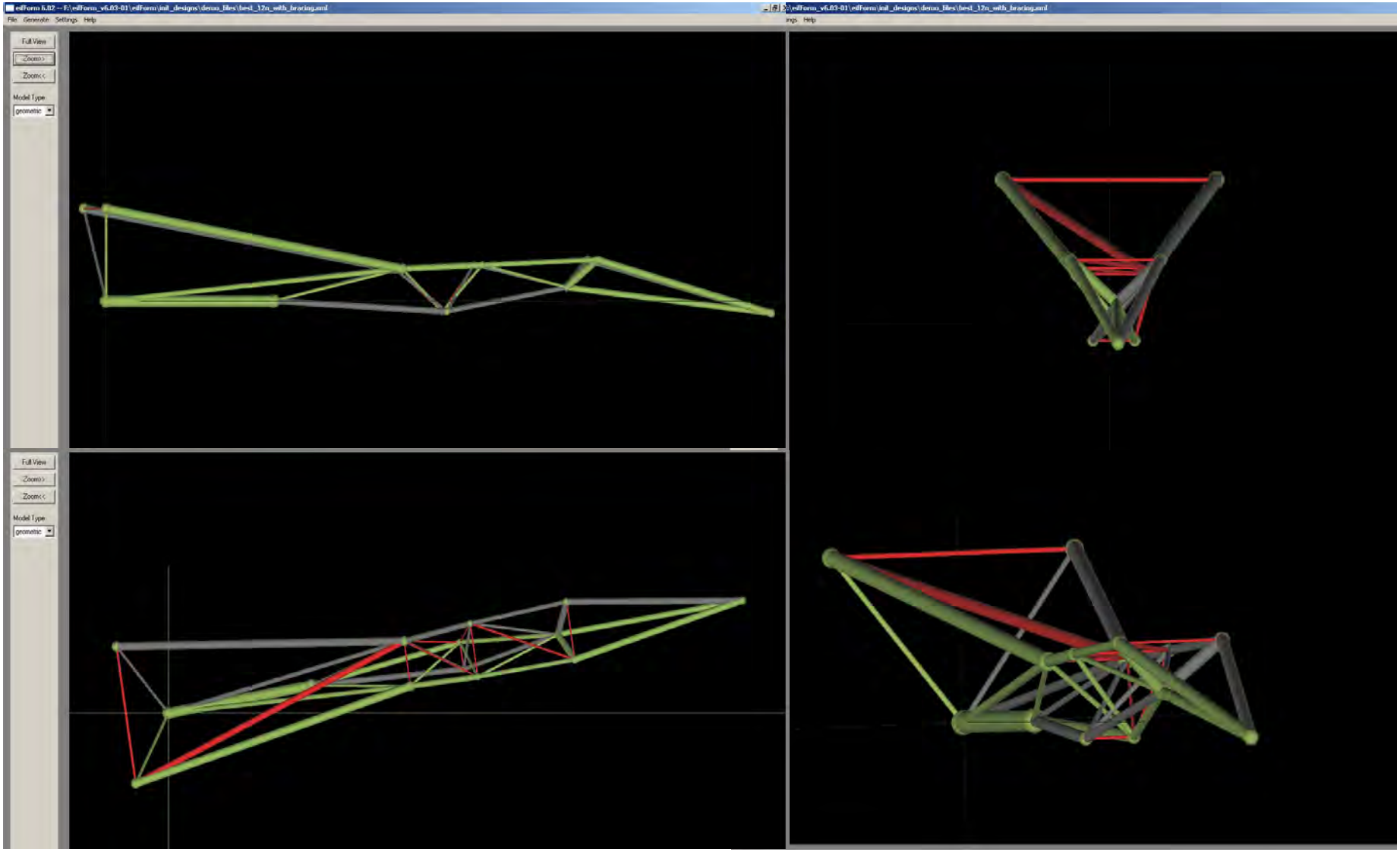
subject to:

$\delta_n \leq 0.002$ m	(max vector displacement for joint n)
$\sigma_i \leq 123$ MPa	(compressive/tensile allowable stress)
$F_i \leq \pi^2 E I_i / l_i^2$	(critical buckling force)
$\lambda_{compression} \leq 180$	(compressive slenderness ratio)
$\lambda_{tension} \leq 220$	(tensile slenderness ratio)
$\lambda_{bracing} \leq 200$	(bracing slenderness ratio)
$l_{max} = 5.0$ m	(max member length)
$l_{min} = 0.03$ m	(min member length)
$\theta_{min} = 1°$	(min angle between members)

Design Generation and Development using STSA



- generate optimised design alternatives
- select 1-2 designs
- analyze full set of 13 load combinations
- re-optimize section sizes and one joint position for
  - wider and taller support; reduced skew
  - reduced section OD < 90 mm
  - vertical wind load down
- select 1-2 designs
- full check according to BS and Eurocode


Full View
Zoom>
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Model Type
geometric
Full View
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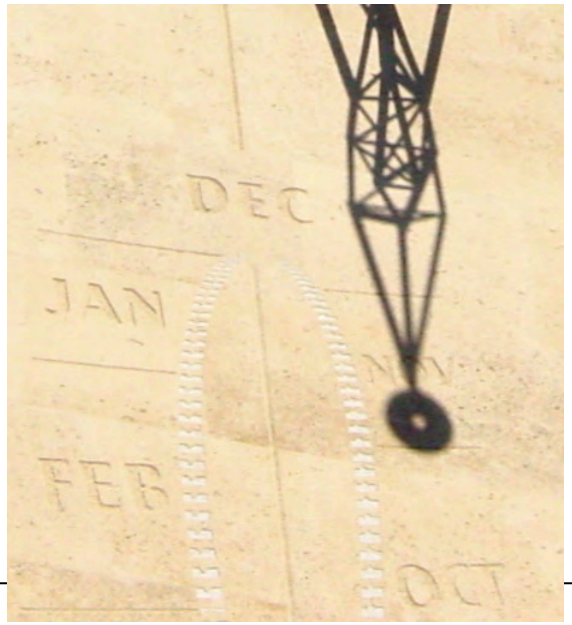
Zoom<<
Model Type
geometric


DEC
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Computational Design Optimization in Building Design

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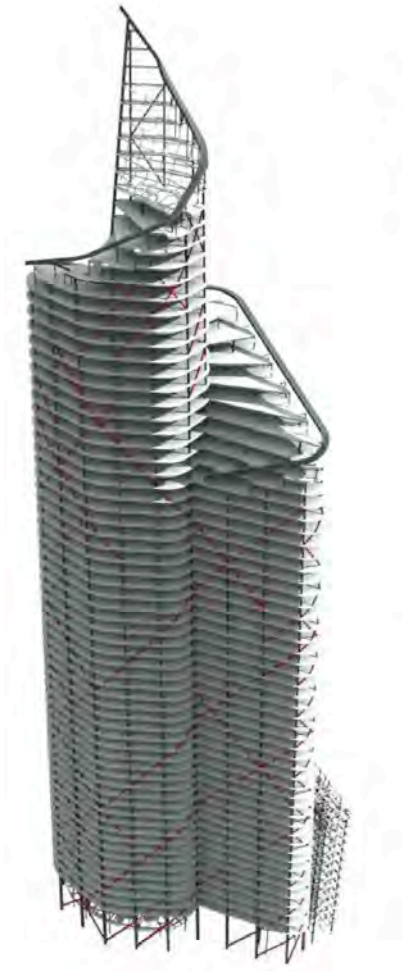
The Pinnacle
London
2013

The Pinnacle - Optimization Model



©Arup

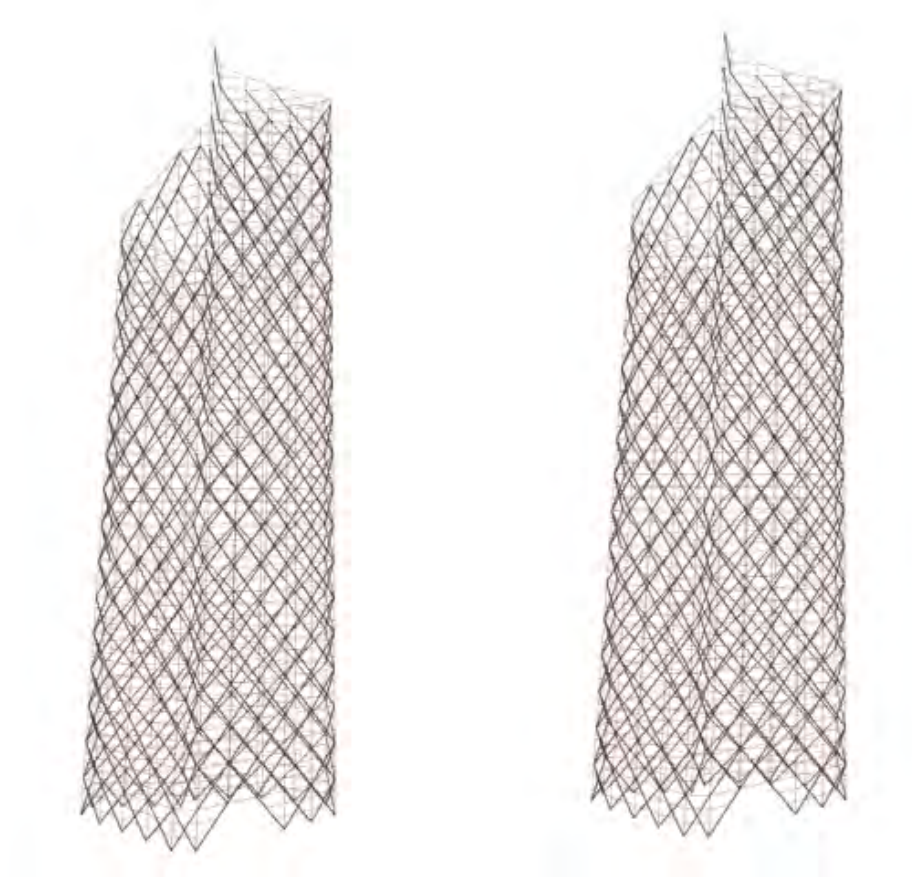
$$\text{Minimize} \quad N = \sum_{S=1}^{n} L_S$$

$$\text{Subject to} \quad F_{bracing} \leq F(\max)_{bracing}$$

$$M_{beams} \leq M(\max)_{beams}$$

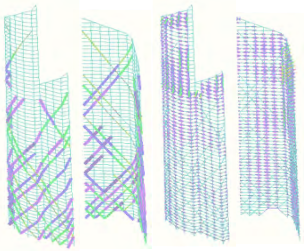
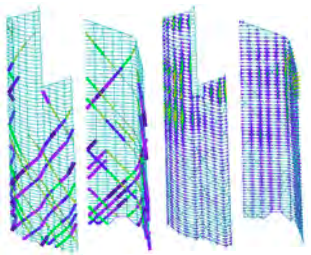
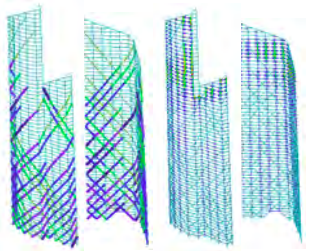
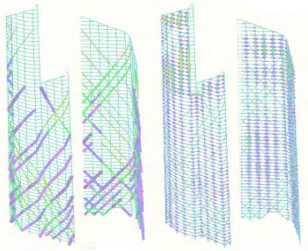
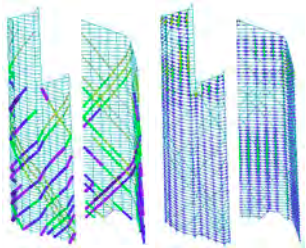
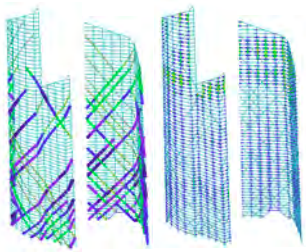
3 x 10^{48} possible designs!!!

Automated Structural Design Generation and Optimization

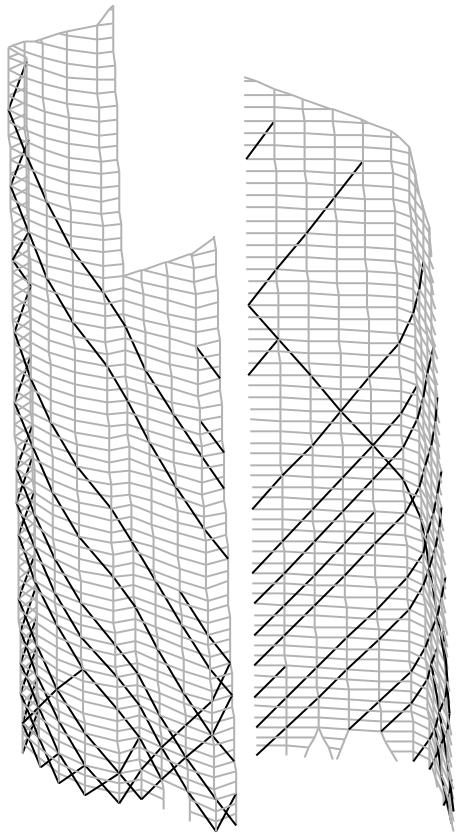


Method: stochastic pattern search with integrated structural simulation

The Pinnacle - Solution Space Exploration

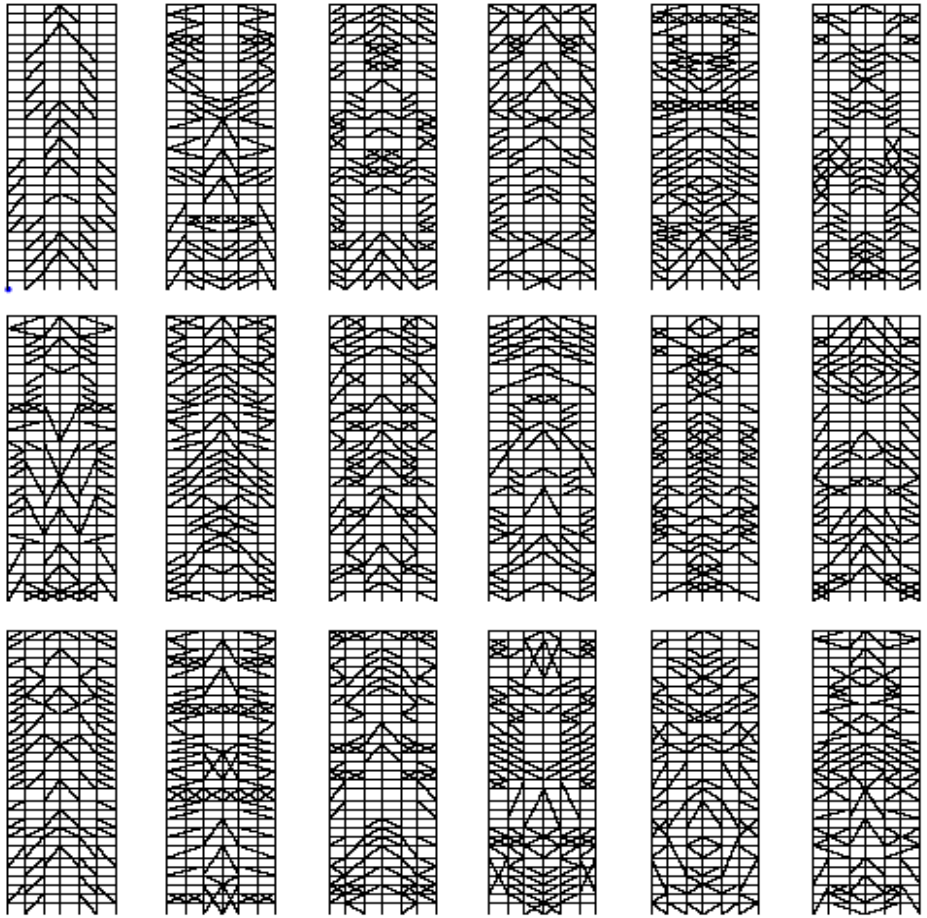
	7,000 kN Bracing force limit	**8,500 kN** Bracing force limit	**10,000 kN** Bracing force limit
750 kNm Bending limit		 **262** bracing elements	 **216** bracing elements
500 kNm Bending limit	 **384** bracing elements	 **296** bracing elements	 **248** bracing elements
400 kNm Bending limit			

Further Method Development



213 elements

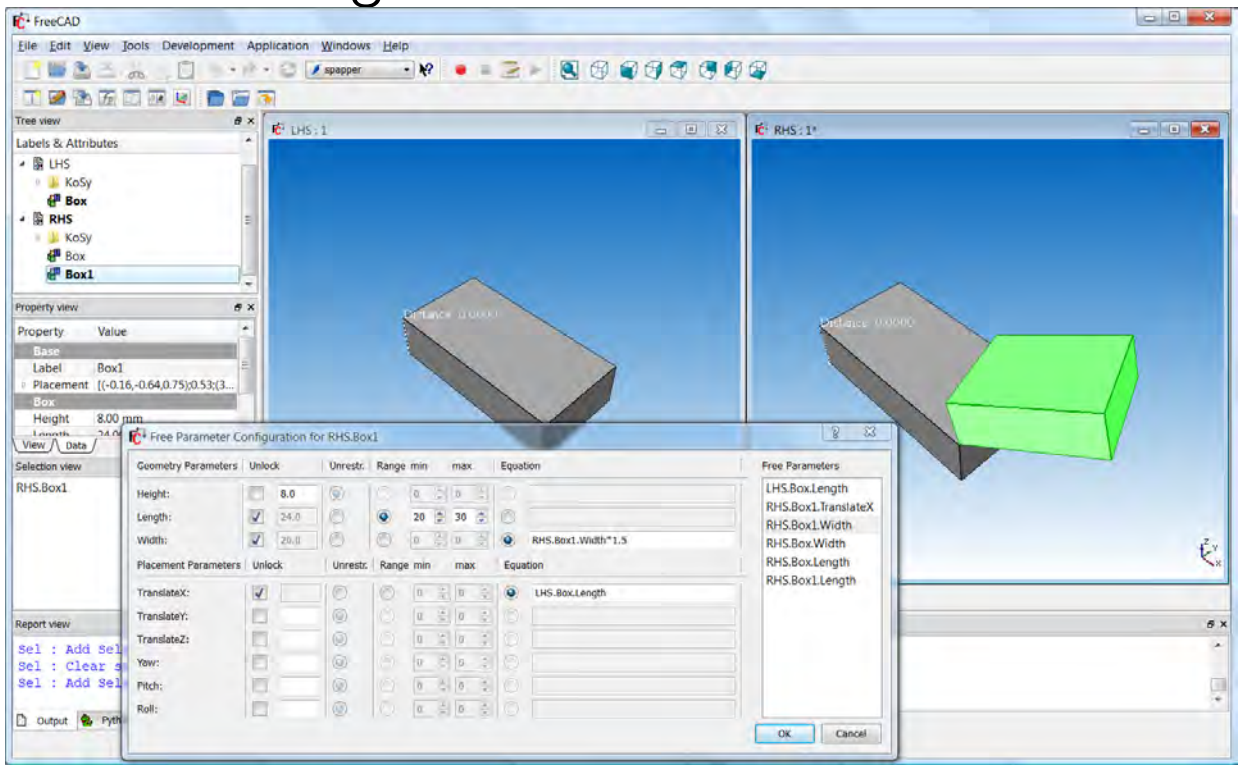
bi-directional method



genetic programming

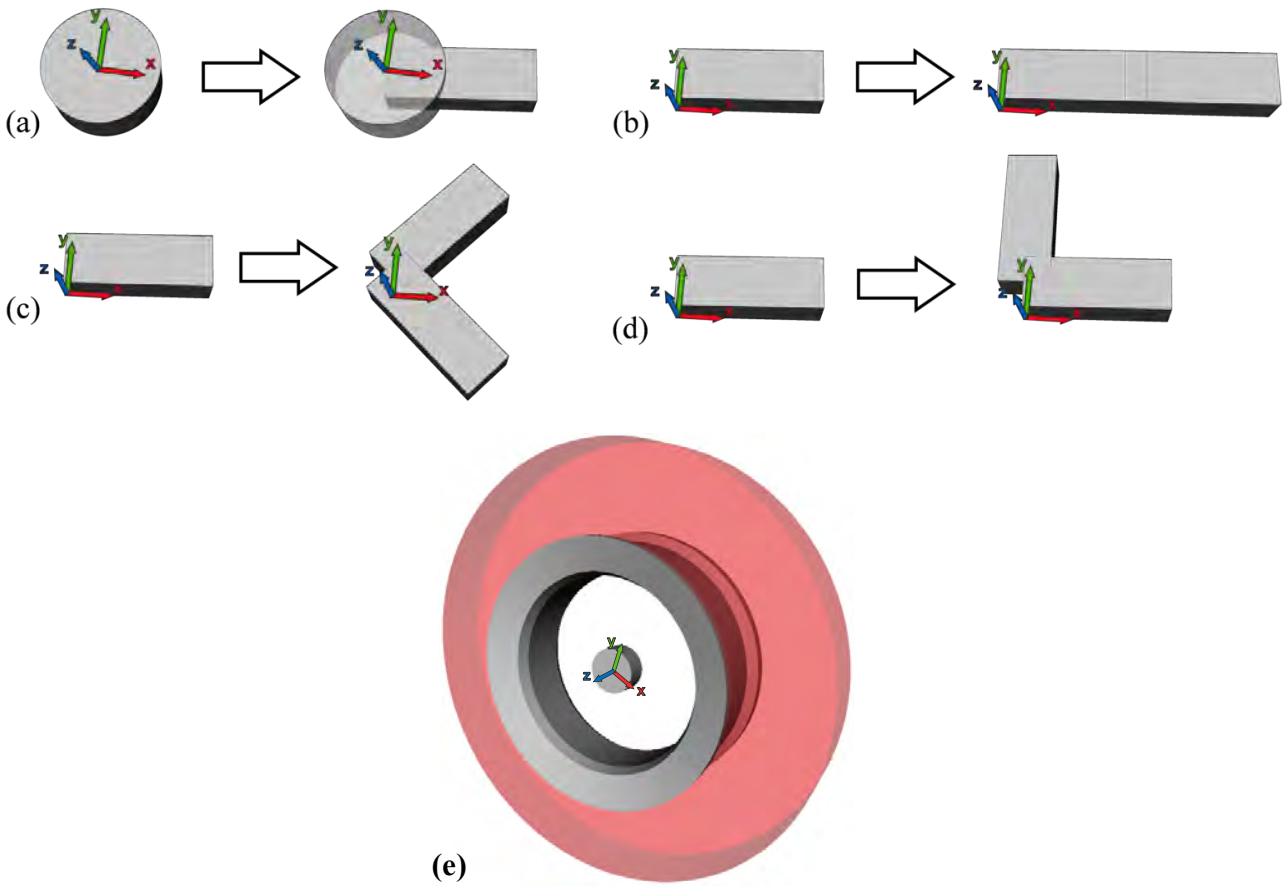
CAD-Based Shape Grammar Interpreter

An interactive environment for parametric shape rule definition and generative design.

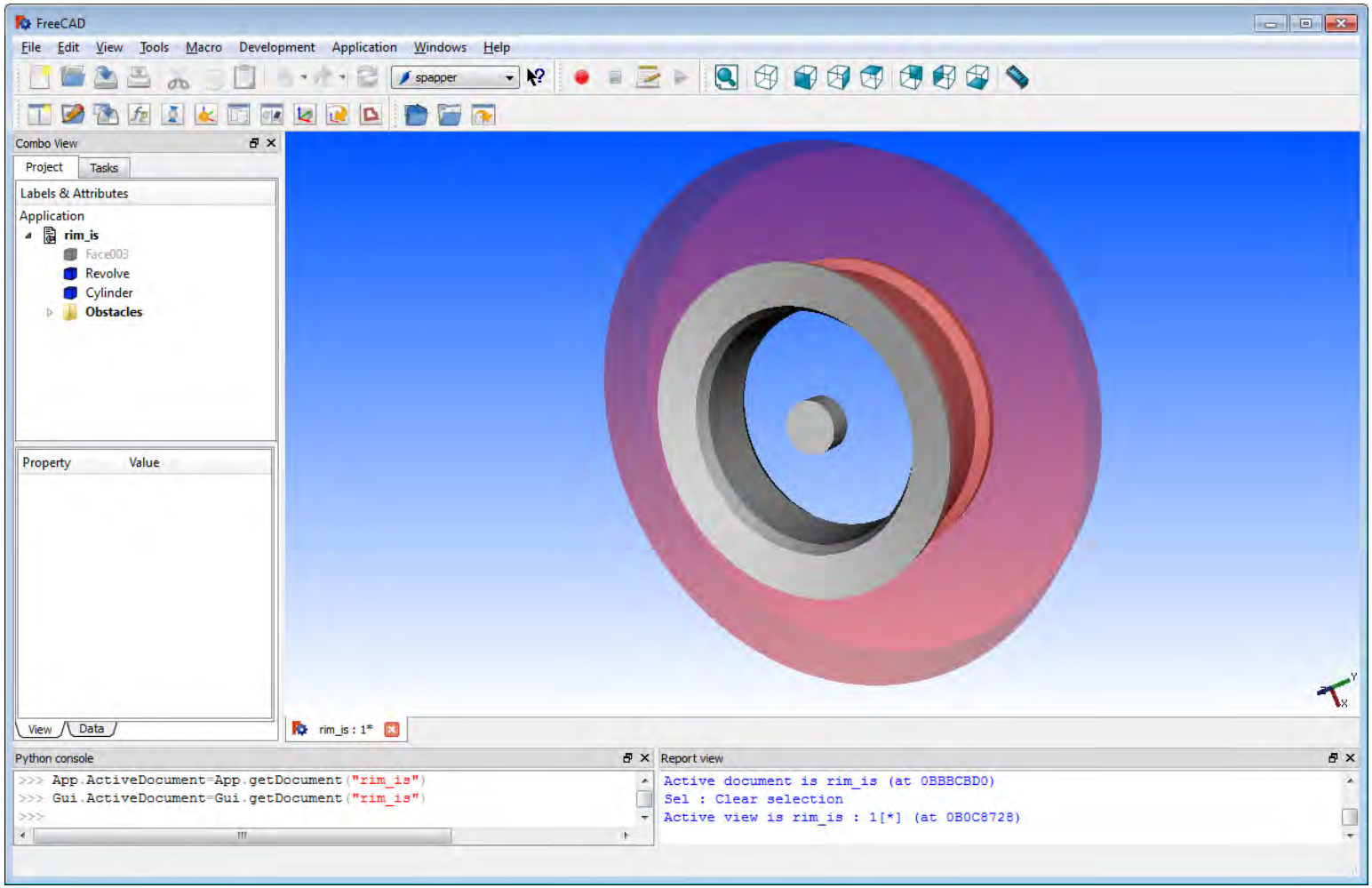


http://sourceforge.net/projects/spapper/

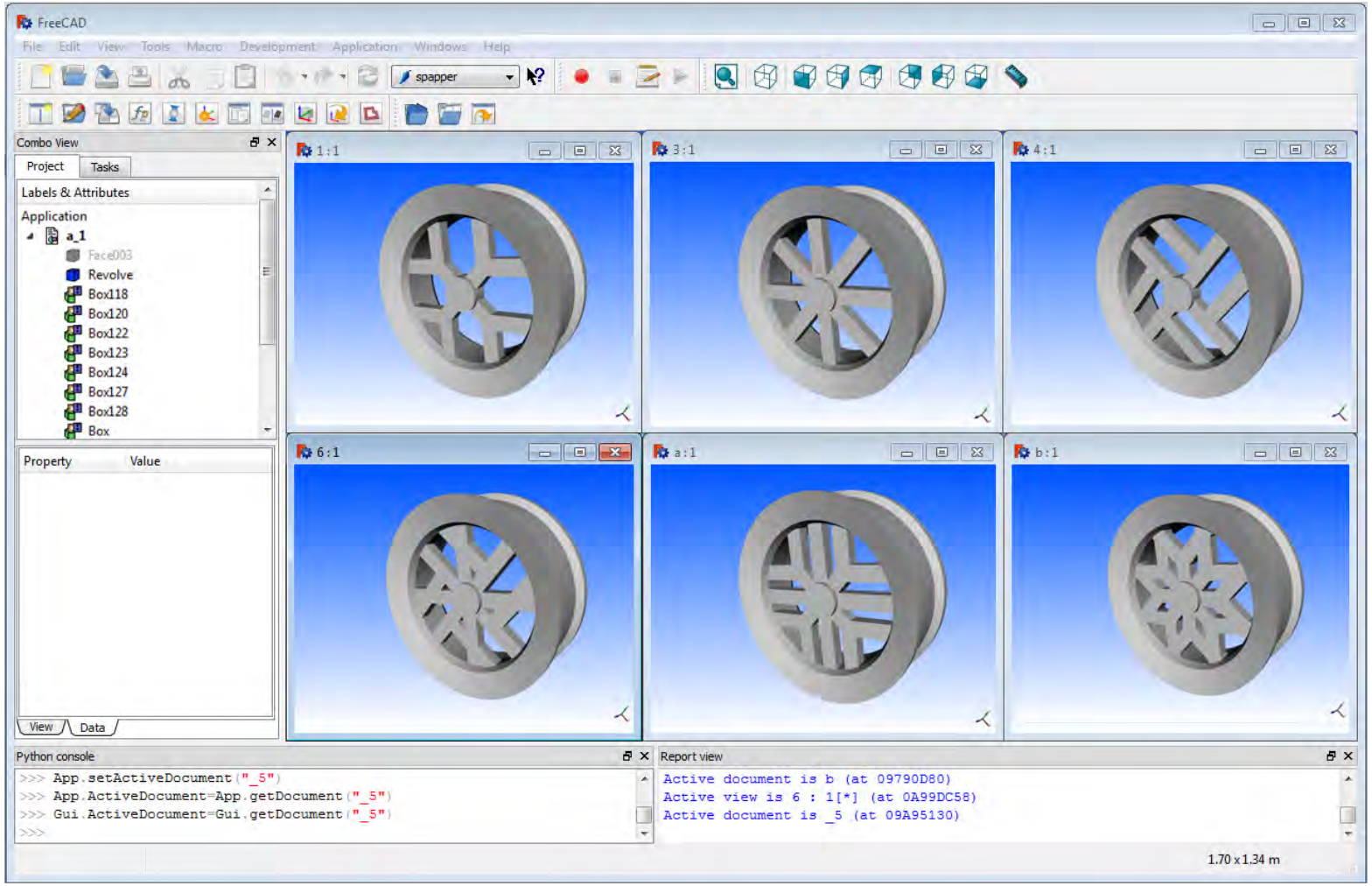
Example: Vehicle Wheel Rim Grammar



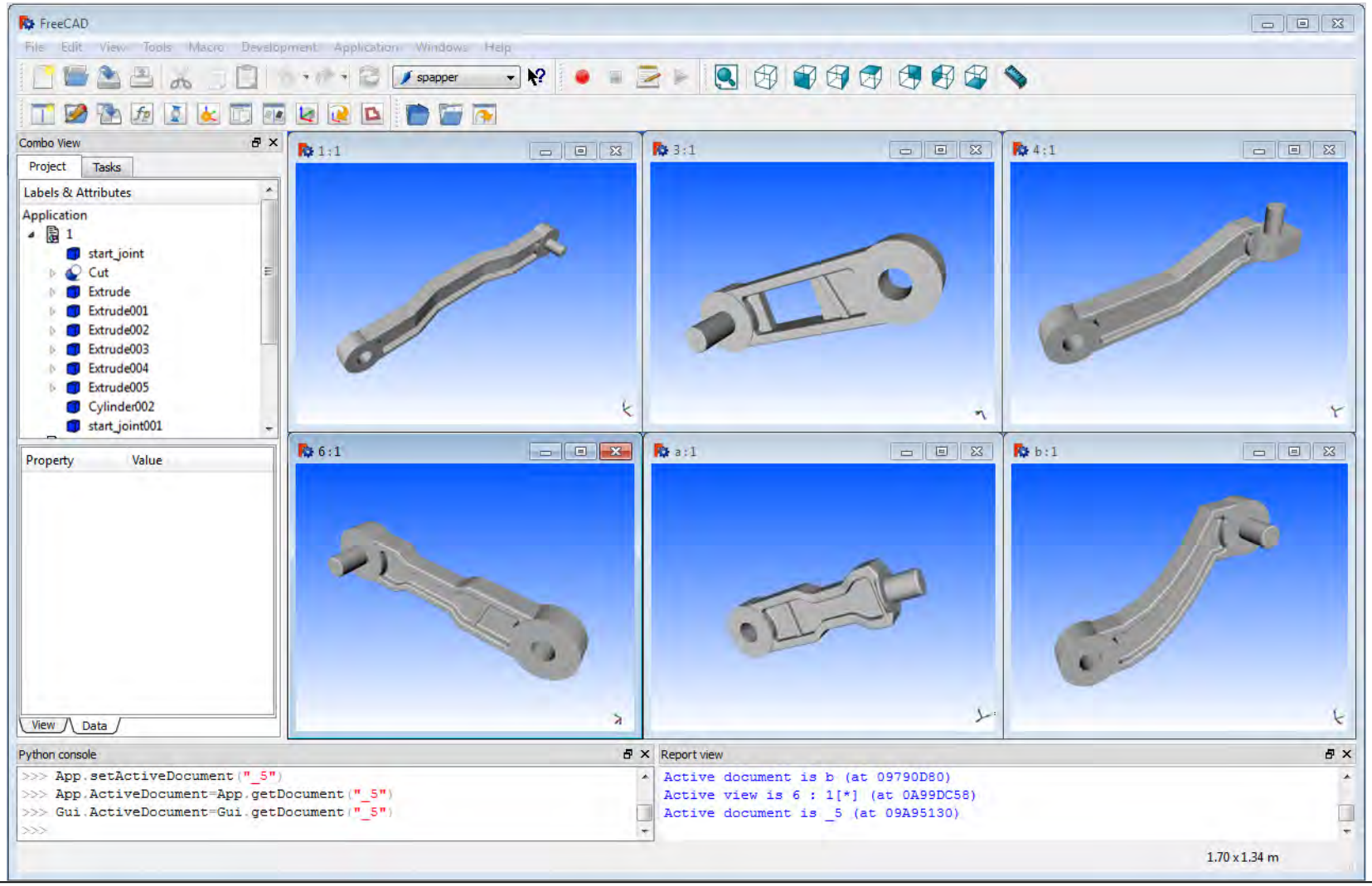
Vehicle Wheel Rims – Initial Shape



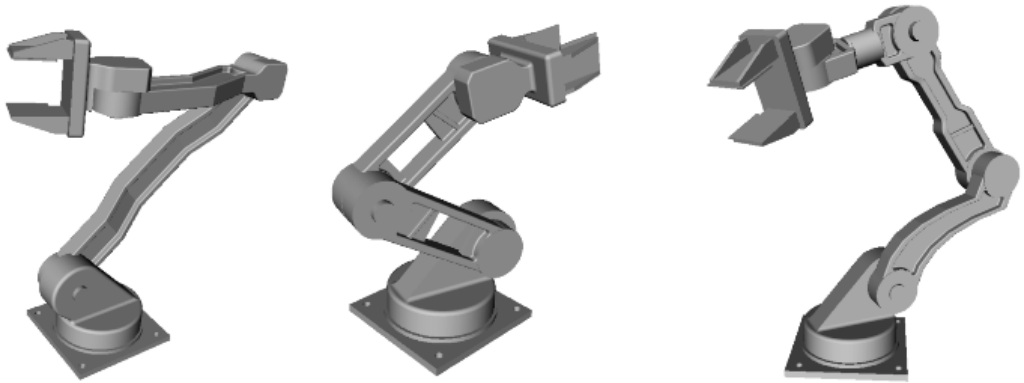
Vehicle Wheel Rims – Example Generated Solutions



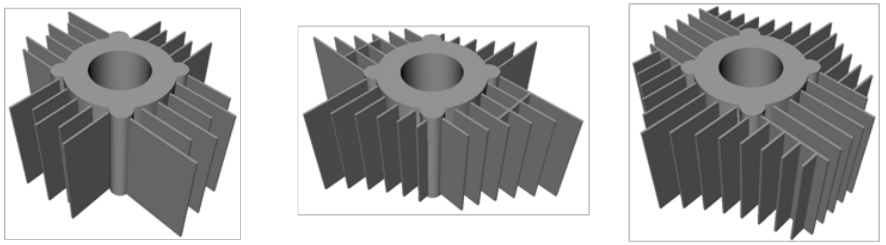
Robot Arm Concept Generation – Parts



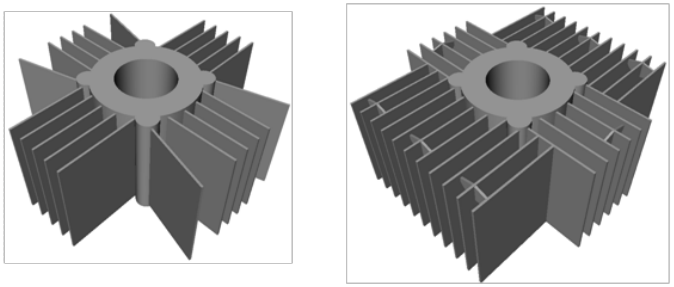
CAD-Based Generative Shape Design - Examples



Customized
Robot Arm Concepts

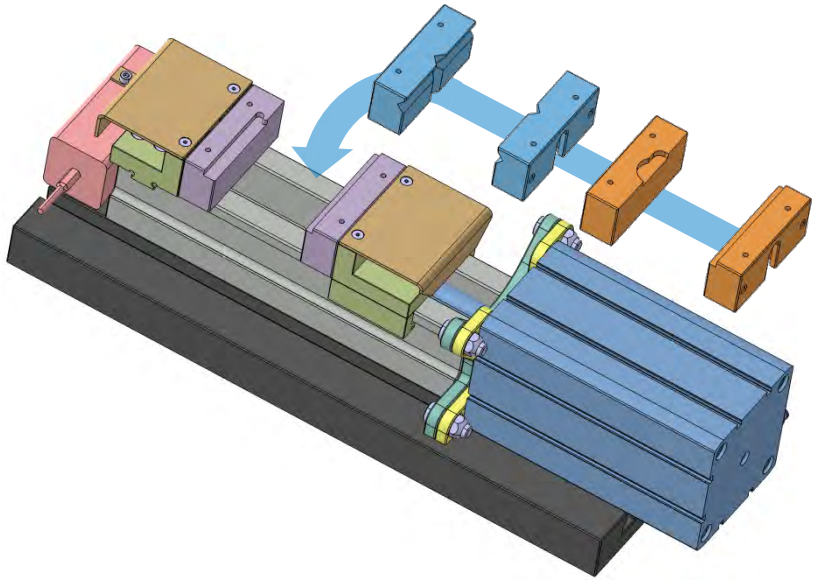


Cooling Fins



Flexible, Autonomous Fixture Device

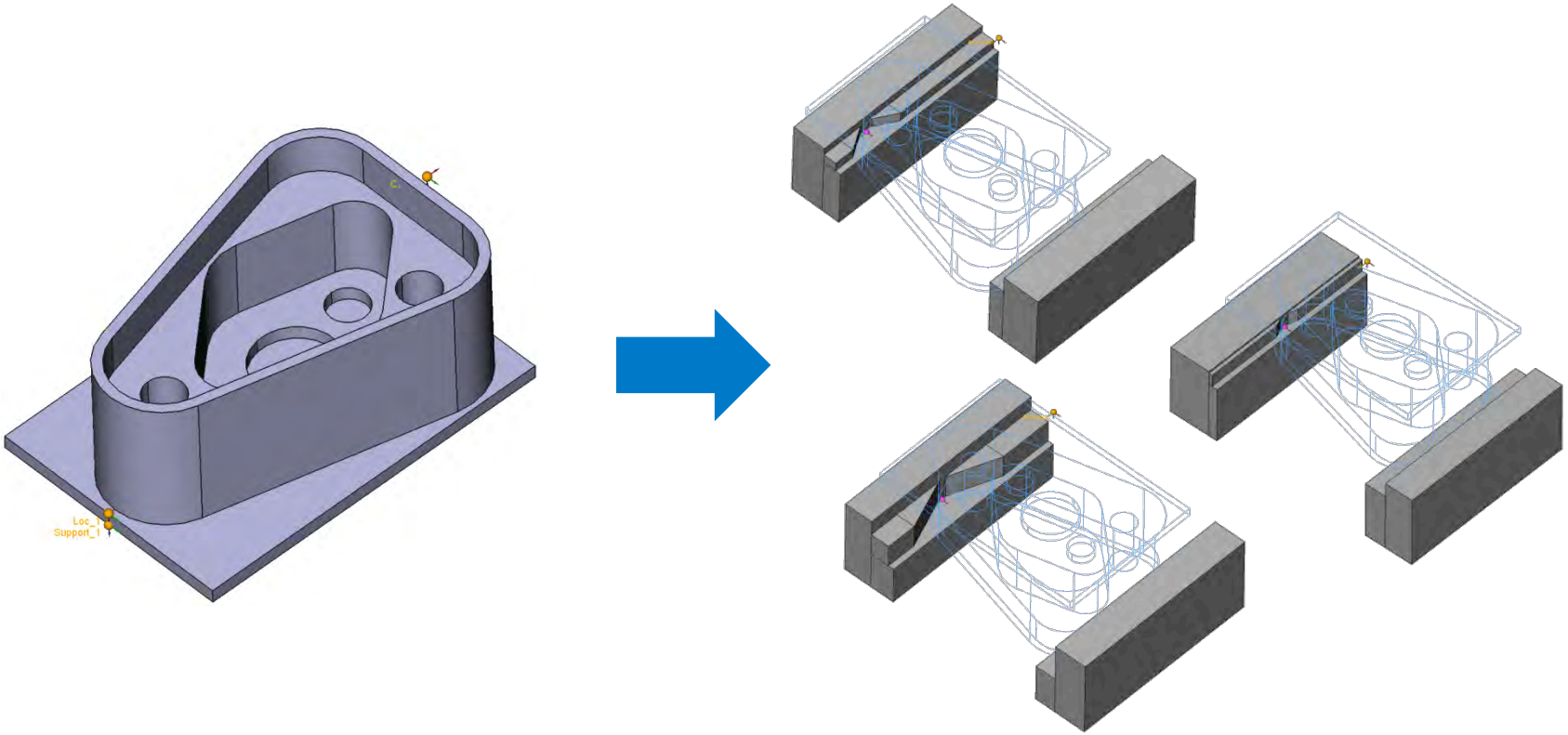
- Autonomous and flexible workholding for low volume production
- Flexible pneumatic vise with exchangeable and adaptable jaws
- Autonomous generation of new jaw designs by:
  - Computational design synthesis (using spatial grammars)
  - Verification of design candidates (using FEA, ...)



CAD Model of Flexible Vise

Prototype of Flexible Vise

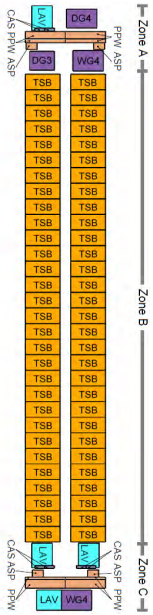
Automated Fixture Design

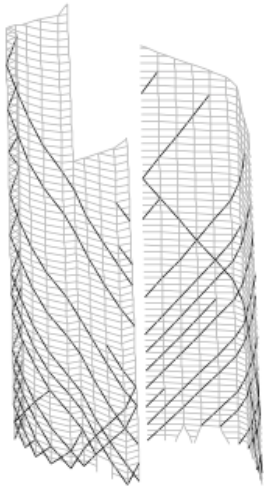


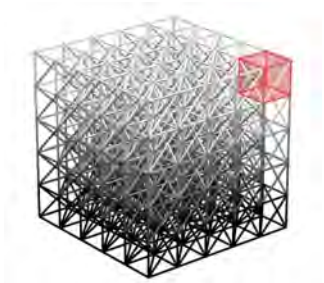
Workpiece (annotated model)

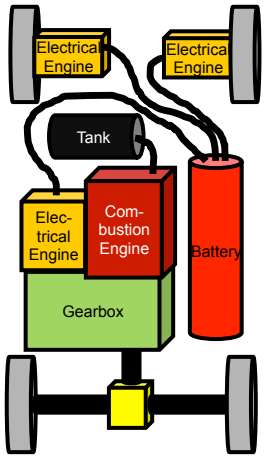
Alternative Generated Jaw Sets

From Static Structures to Mechatronic Machines









Task Specification Increasingly Abstract and Complex
Increasing Variety of Building Blocks and Behaviors
Increasing Complexity of Simulation
Increasing Complexity of Search Space

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