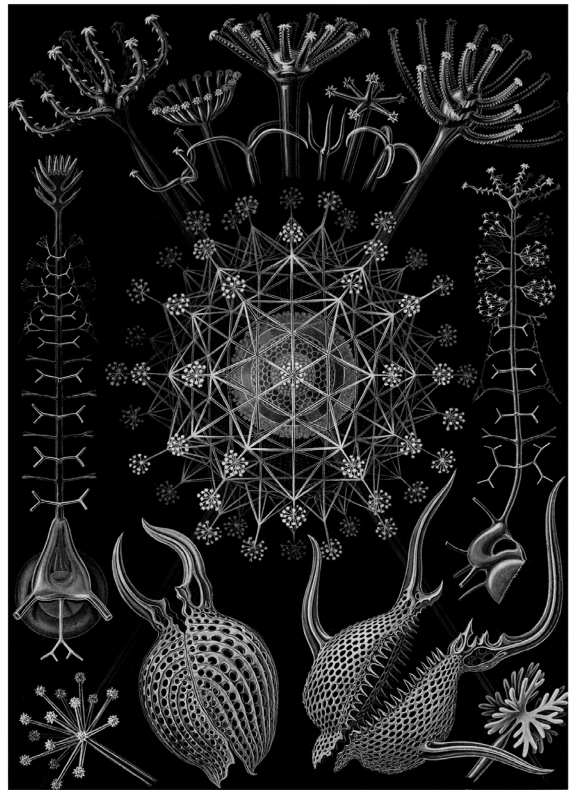
Generative Design
- physical
- computational

Design Optimization
- physical
- computational

Parametric Design
- scalar
- repetitive / modular
- algorithmic

Genetic Design
- search
- optimization
- exploration



Optimization

What to optimize (levels)
- material
- member
- geometry
- topology

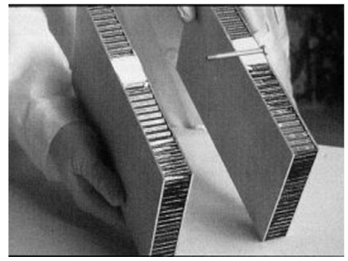
How to optimize (methods)
- physical
- computational

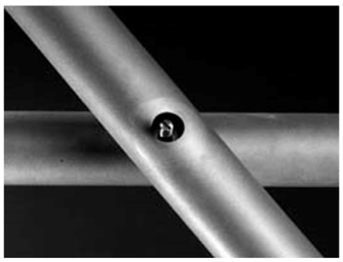
Optimization

Material
Member
Geometry
Topology

Minimize
- Weight
- Volume
- Cost

Maximize
- Strength
- Strain Energy
- Elasticity
- Ductility
- Stiffness





Optimization

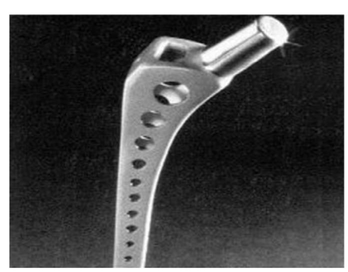
Material
Member
Geometry
Topology

Strength (Full Utilization)
- in section
- in length

Stability (no buckling)
- in section
- in length

Serviceability
- in use
- maintenance

Connections
- stress transfer



Optimization

Material

Member

Geometry

Topology

Arrangement of Nodes

best overall for members

includes optimization of :

- material
- members

Truss: 1 weight = 27246 lb
16 joints 31 members

Truss: 2 weight = 23083 lb
16 joints 31 members

Truss: 3 weight = 22836 lb
16 joints 31 members

Optimization

Material

Member

Geometry

Topology

Arrangement of Members

includes optimization of :

- material
- members
- geometry

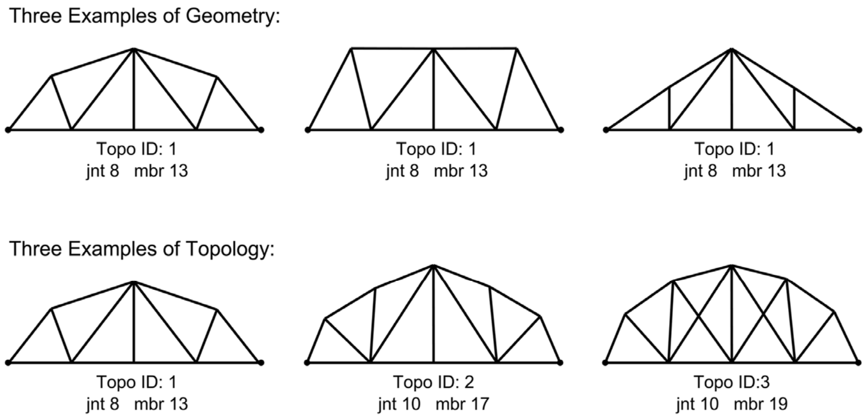
Truss: 1 weight = 25484 lb
16 joints 35 members

Truss: 2 weight = 25050 lb
16 joints 35 members

Truss: 3 weight = 24529 lb
16 joints 35 members

Geometry vs. Topology

definitions



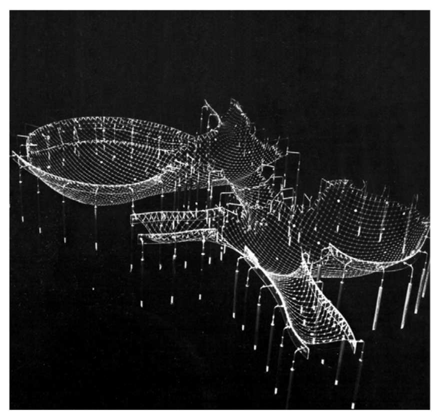
Methods

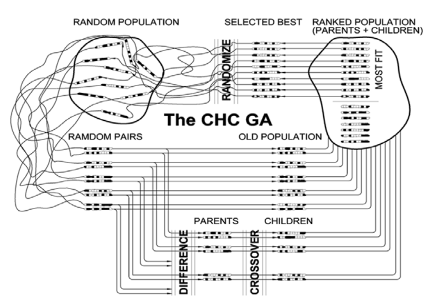
Physical

- structural models
- form finding models
- analog models

Computational

- Linear Programming (Simplex)
- Homogenous – sensitivity
- Stochastic/Probabilistic Algorithms
  - GA (Genetic Algorithms)
  - ES (Evolutionary Strategies)
  - SA (Simulated Annealing)
  - Swarming (Particle Swarm Optimization)





Methods

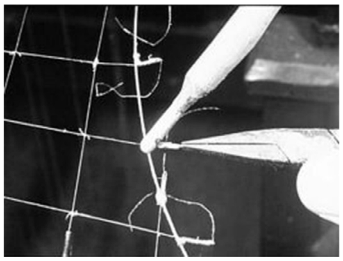
Physical

structural models

form finding models

analog models

Louis I. Kahn's structural model for the Richards Medical Research Laboratory



Frei Otto's model of the cable nets of the 1972 Olympics

Stadium in Munich from 1972 Olympics

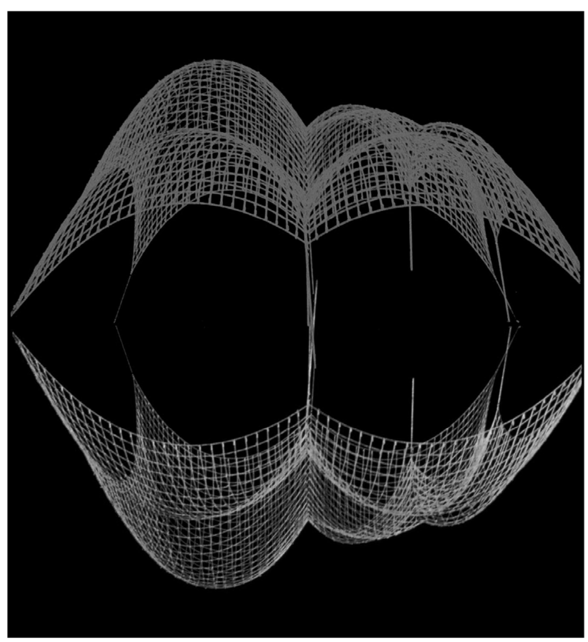
Methods

Physical

structural models

form finding models

analog models

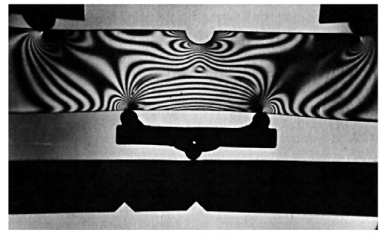


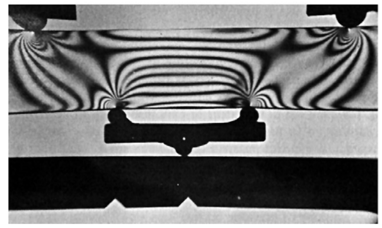
Heinz Isler, Burgdorf

Methods

Physical

- structural models
- form finding models
- analog models

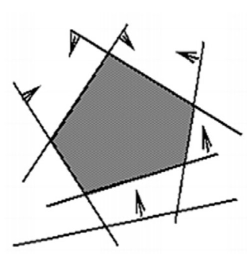


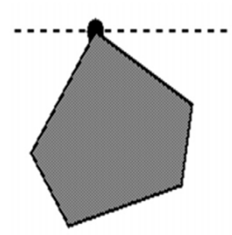


Methods

Computational

- Linear Programming (Simplex)
- Homogenous – sensitivity
- Evolutionary Algorithms
  - ES (Evolutionary Strategies)
  - GA (Genetic Algorithms)





Methods

Computational

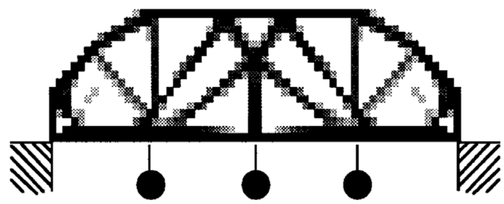
Linear Programming (Simplex)

Homogenous – sensitivity

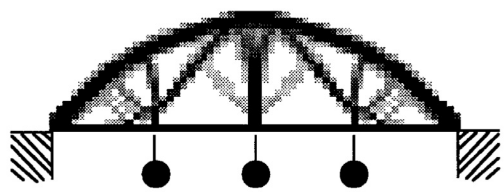
Evolutionary Algorithms

ES (Evolutionary Strategies)

GA (Genetic Algorithms)

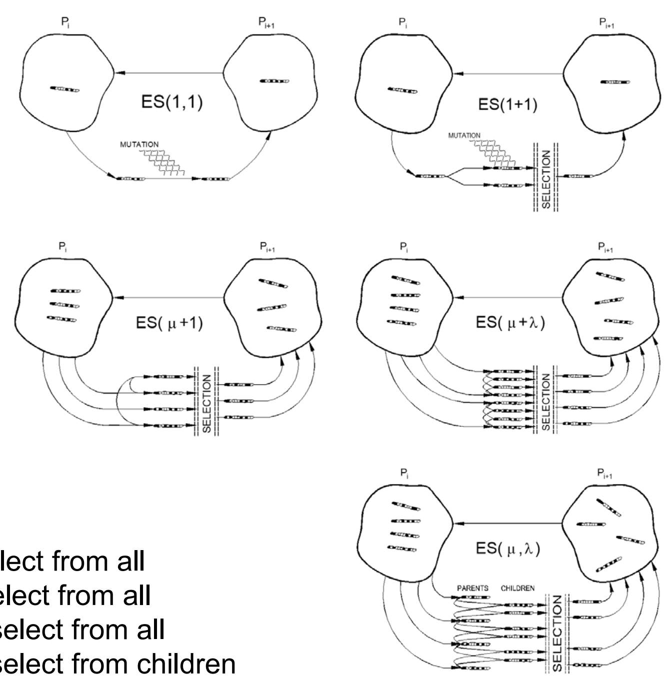


(a) Design I



(b) Design II

Methods



Computational

Linear Programming (Simplex)

Homogenous – sensitivity

Evolutionary Algorithms

ES (Evolutionary Strategies)
Rechenberg & Schwefel

GA (Genetic Algorithms)
John Holland

(1 , 1)	random walk
(1+1)	one parent $\rightarrow$ one child - select from all
(μ+1)	multi-parent $\rightarrow$ one child - select from all
(μ+λ)	multi-parent $\rightarrow$ multi-child - select from all
(μ , λ)	multi-parent $\rightarrow$ multi-child - select from children

(Bäck, 1996)

Methods

Computational

Linear Programming (Simplex)

Homogenous – sensitivity

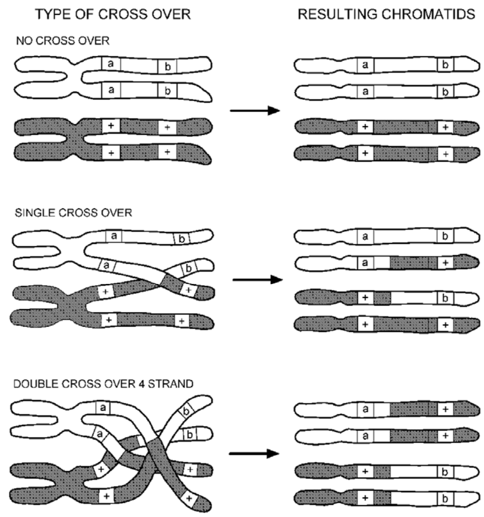
Evolutionary Algorithms

ES (Evolutionary Strategies)

GA (Genetic Algorithms)

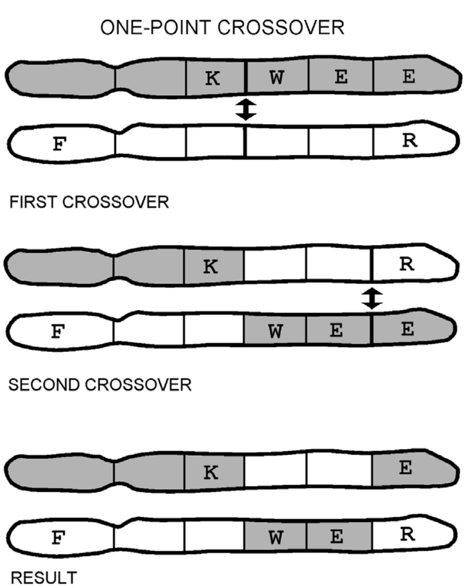
Selectorecombinative

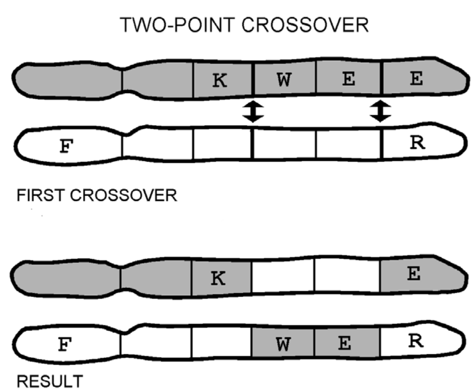
- selection
- crossover
- mutation



Genetic Algorithms

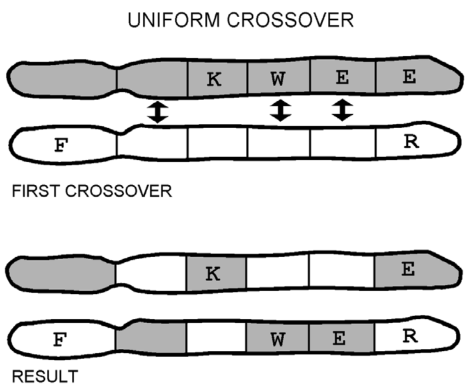
crossover



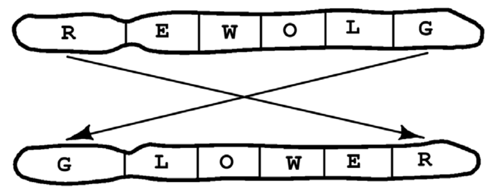


Genetic Algorithms

crossover

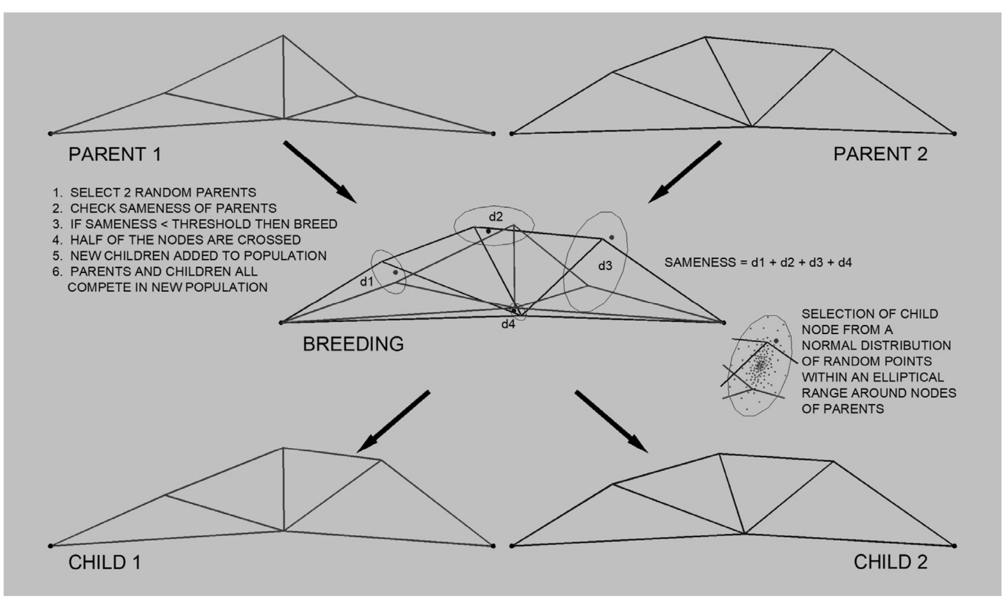


inversion



Genetic Algorithms - Geometry

half-uniform crossover

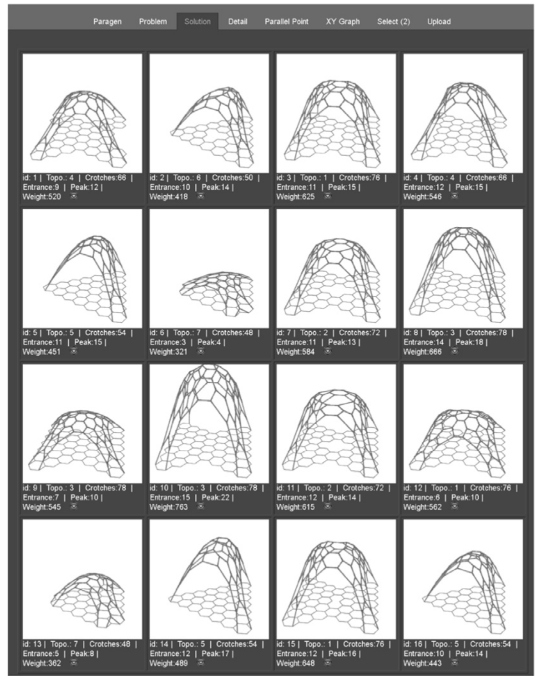


Genetically Enhanced Parametric Design for Performance Optimization and Design Exploration

The ParaGen Method

Form Exploration in Early Design Phases

Based on Parametric Geometry, GA search with a SQL database



Peter von Buelow, Dr. –Ing.
Professor in Architecture
University of Michigan

Aspects of Early Design

Purposeful

directed – not merely random

Goal Oriented

search to find good solution

Creative

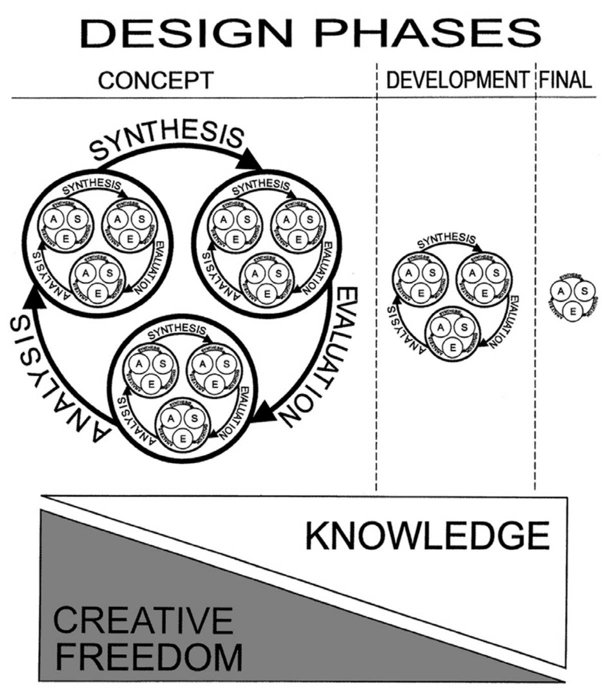
seeks *new* solutions

Ill Structured Problems

problem space not fully defined

cannot solve directly – cyclic

exploration is needed



Exploration with Evolutionary Computation

deterministic optimization focuses on one ‘best’ solution

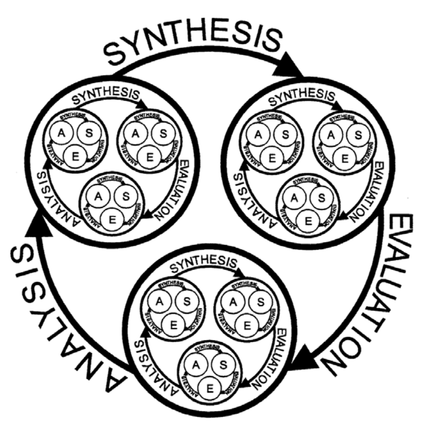
It is better suited for later design phases

exploration tries to expose a range of ‘pretty good’ solutions

it aids ideation and creativity in early design phases

Why GA’s fit well to early design

Early Design	GA Design
Explorative	Populations of solutions
Recursive	Operates in cycles
Serendipitous	Random mutations
Knowledge of design is low	No knowledge of fitness function



The ParaGen Exploration Method

Based on an NDDP-GA

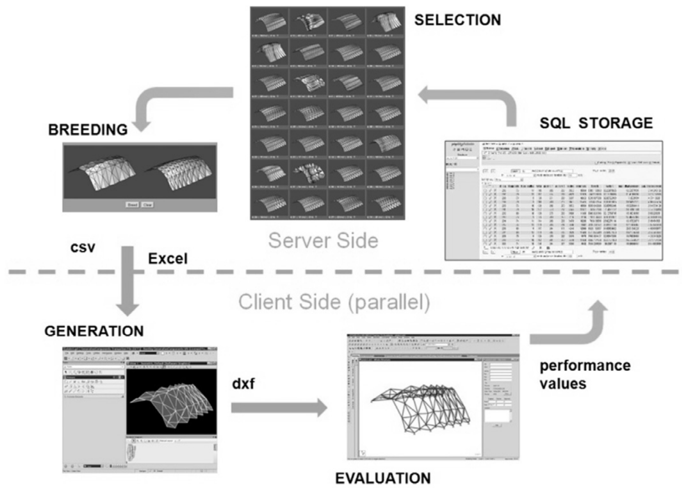
Oriented toward Exploration
- Helps designer understand the range of solutions

Non-Destructive
- All solutions are visible

Dynamic Populations
- Well suited for multi-objectives

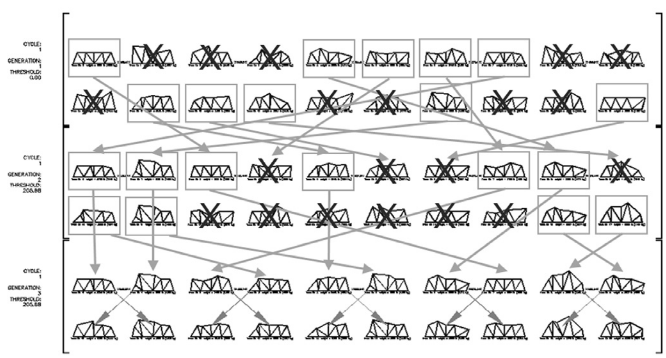
Both Interactive and Algorithmic
- Can consider non-computational criteria, e.g. aesthetics

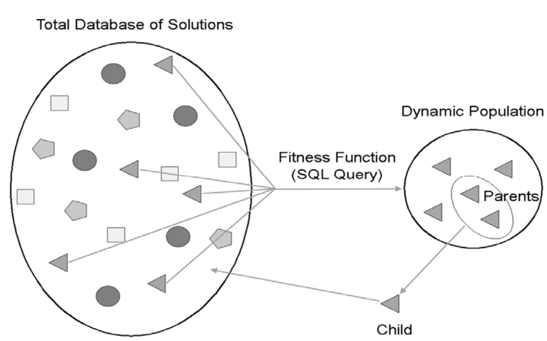
The ParaGen Framework



ParaGen is Non-Destructive

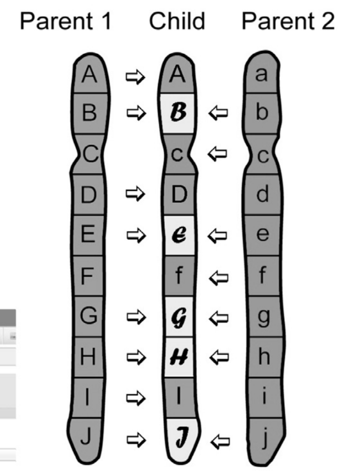
Traditional GAs are destructive – solutions are lost





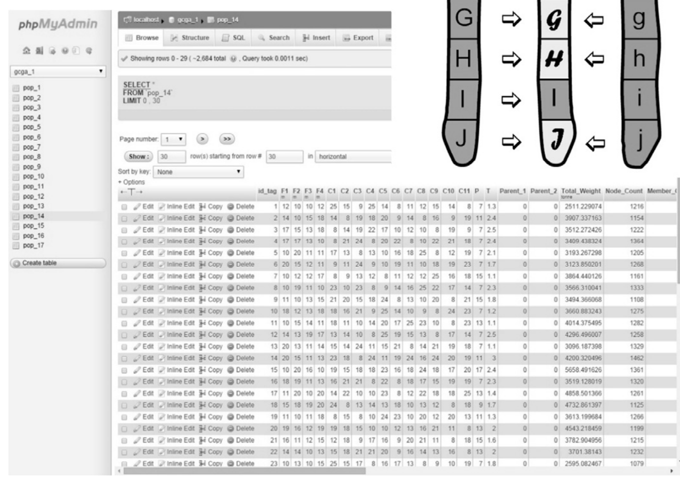
An NDDP-GA is non-destructive
no solutions are lost

GA + SQL = Exploration

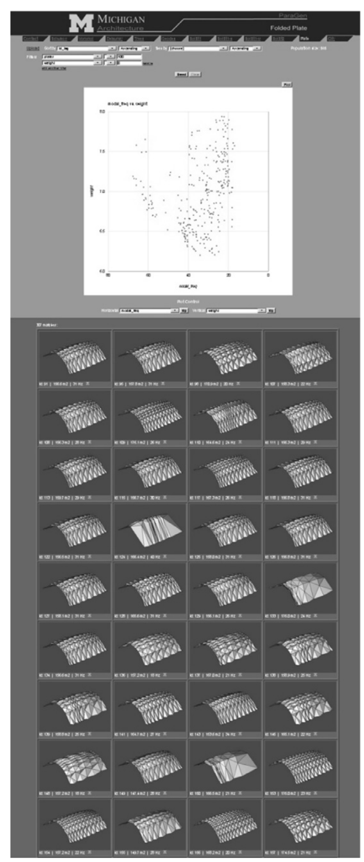


Seven Points:

1. Store no duplicates
2. Multi-objective
3. Dynamic populations
4. Changeable search direction - corrective
5. Interactive search
6. Pareto optimization
7. Parallel computation



1. Store All Solutions without Duplicates



Relational Database Size

- terabyte range (e.g. 256 TB in MySQL, but limited by system)

SQL unique index

- set at child generation
- checked at data entry

Faster analysis

- no duplicate solutions to analyze

More effective post analysis

- no duplicate solutions to view
- more descriptive graphing

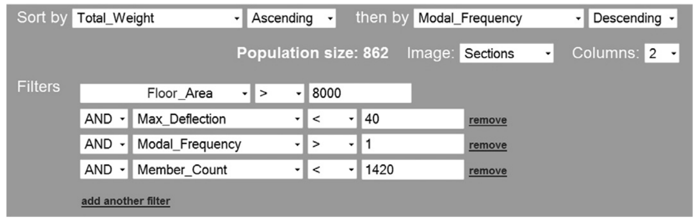
Less storage space needed

- only unique solutions are retained

2. Use Multi-Objective Fitness Functions

Fitness defined by SQL query

- simple sorts – single variable
  e.g. 20 best
- defined range – single variable
  e.g. between max. and min.
- Multi-objective query
  e.g. Pareto set optimization
  e.g.
  weight less than x AND
  height more than y AND
  heat gain less than z



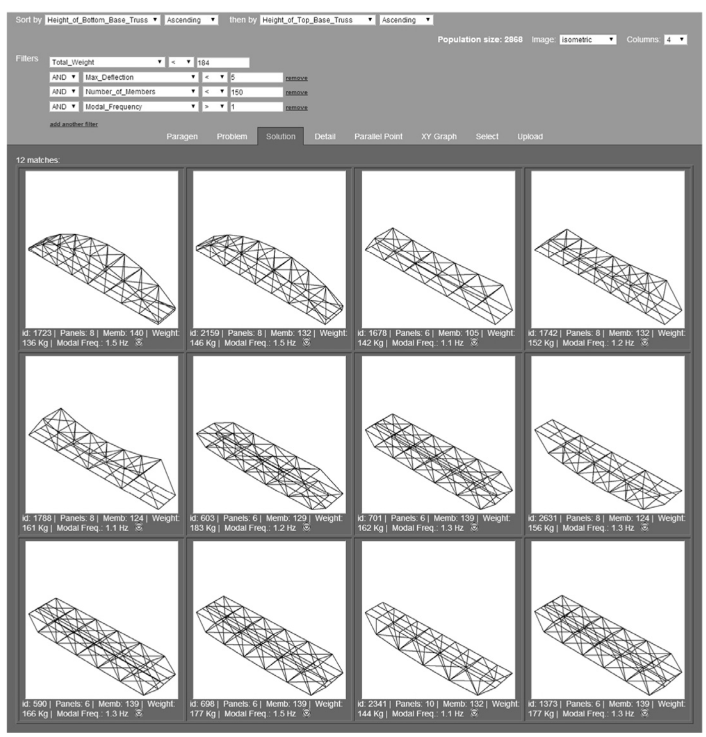
Separate fitness for each parent

- each parent can be obtained
  using a different query set

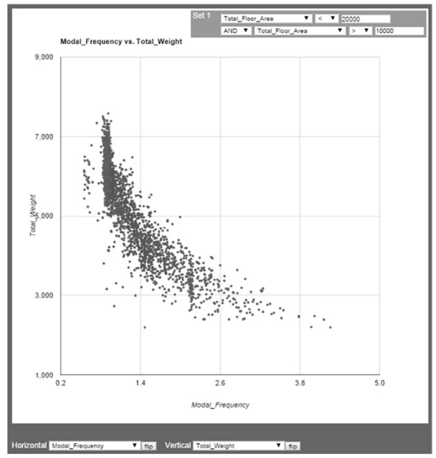
3. Create Dynamic Parent Populations

Independent breeding population

- Not dependent on previous population
- Non-generational or static population
- Evolution through addition (no loss)



4. Change Search Direction



Search different parts of solution space

- see range of solutions
- bracket uncertainty
- conflicting design desires

Change fitness without restarting

- changing the fitness criteria merely shifts the view

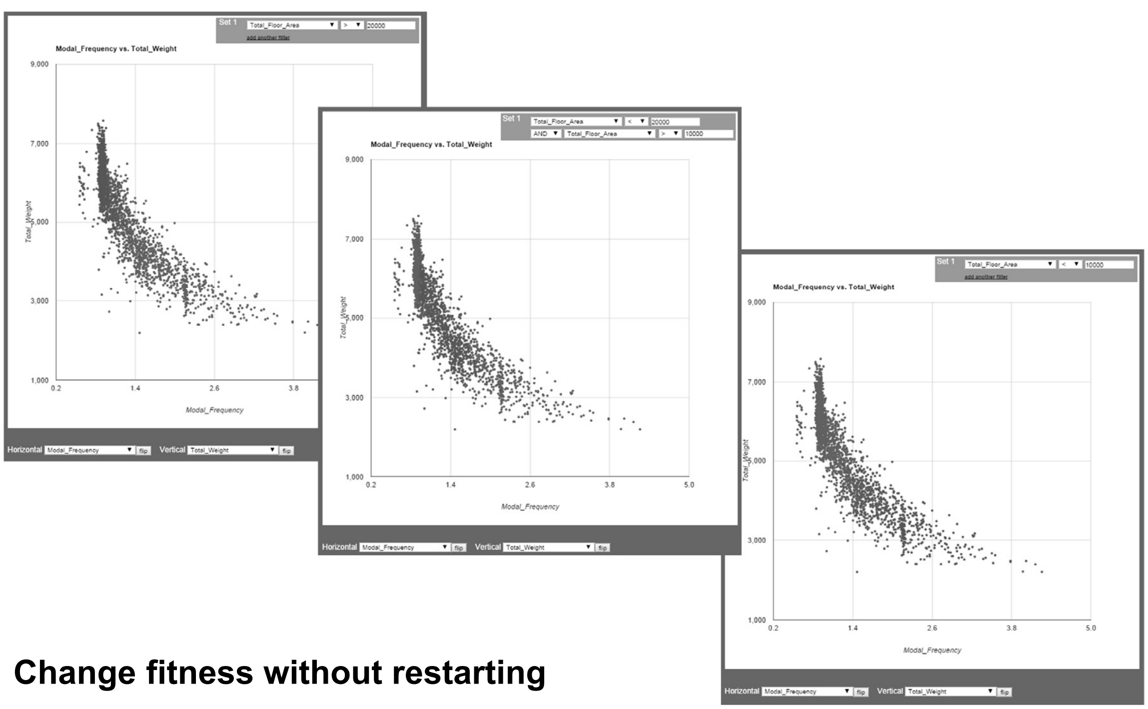
Aids in post analysis

- allows for the comparison of conflicting solutions

Allows correction of objectives

- objectives can be easily refined as more data is made available

Search different parts of solution space



Change fitness without restarting

5. Interactive Exploration of Solutions

No delay for analysis

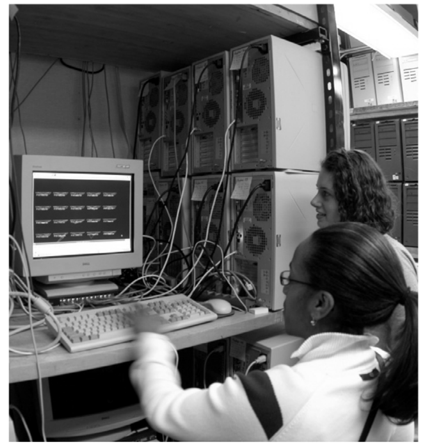
- near immediate response to queries

Variety of graphic depiction

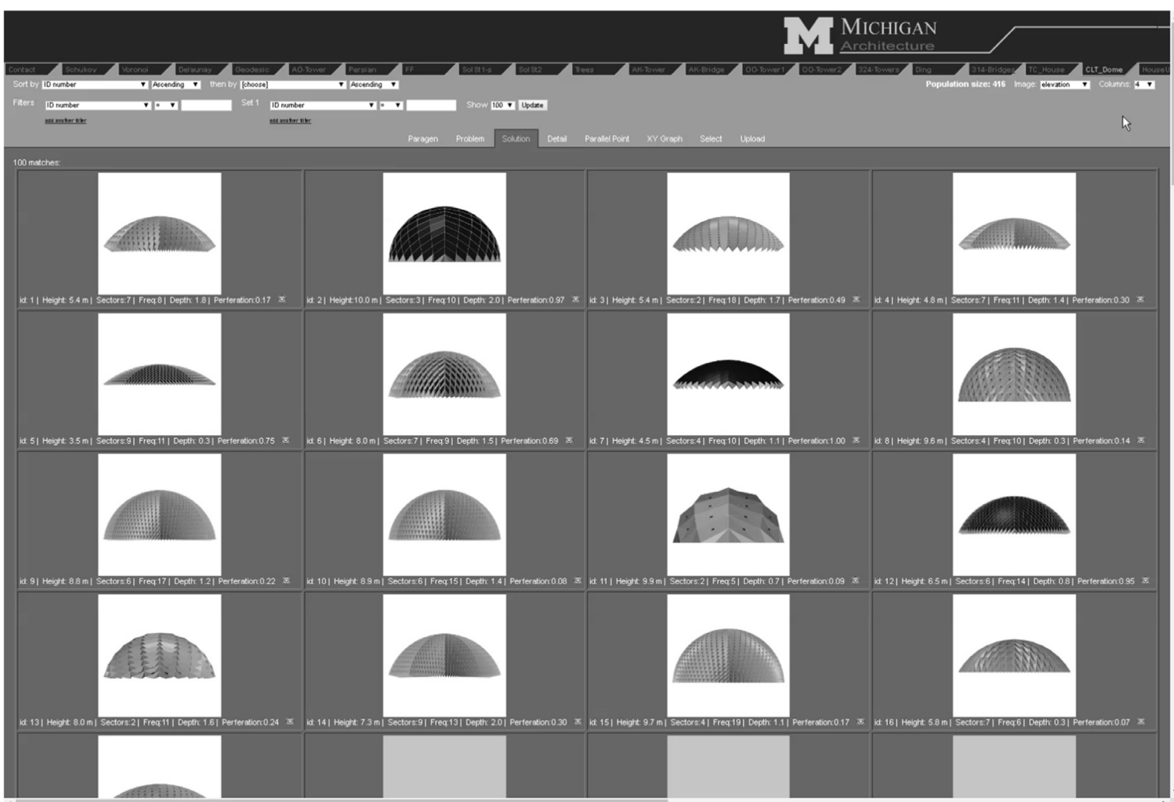
- multiple image views (different information)
- control visual array display

Aids in post analysis

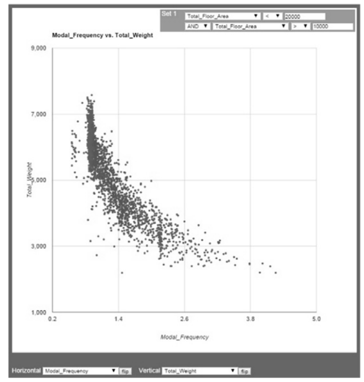
- allows for the comparison of conflicting solutions



Control visual array display



6. Versatile Graphing Data Analysis

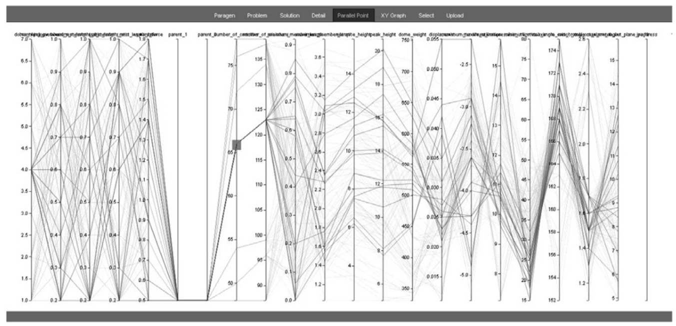


x-y scatter graphs

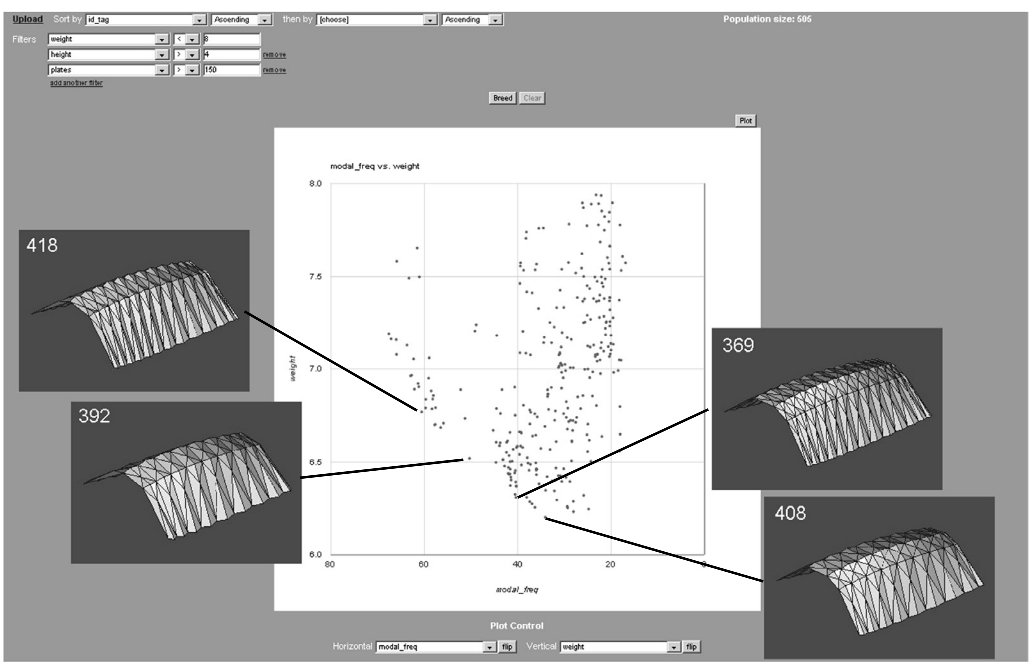
- filters to set range of points
- plot any two variables or values
- control axis direction
- Show third parameter with color

parallel coordinate graphs

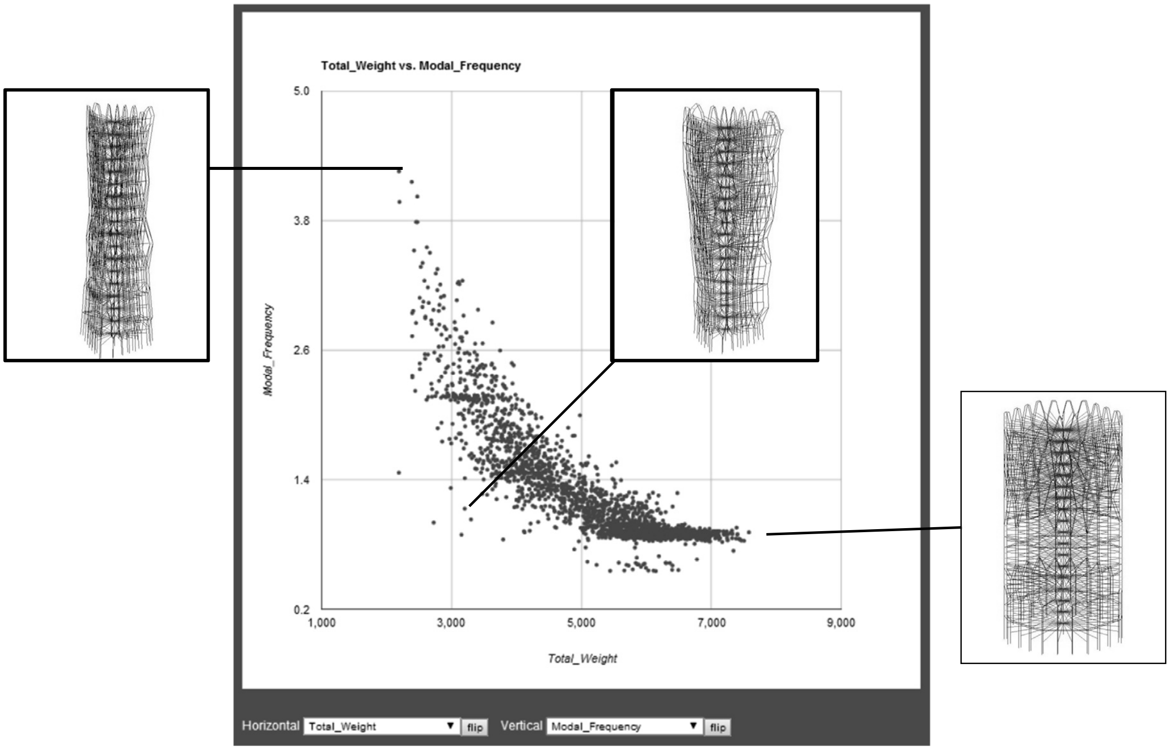
- filters to set range of points
- highlight any set (box select)



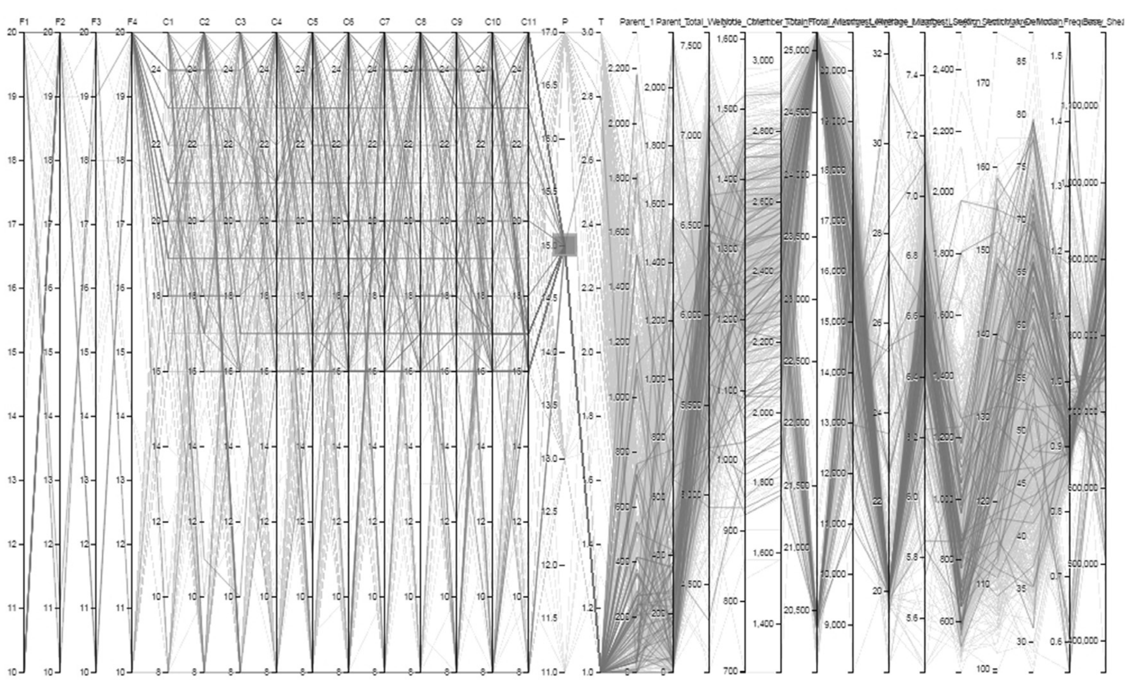
x-y scatter graphs



x-y scatter graphs



parallel coordinate graphs



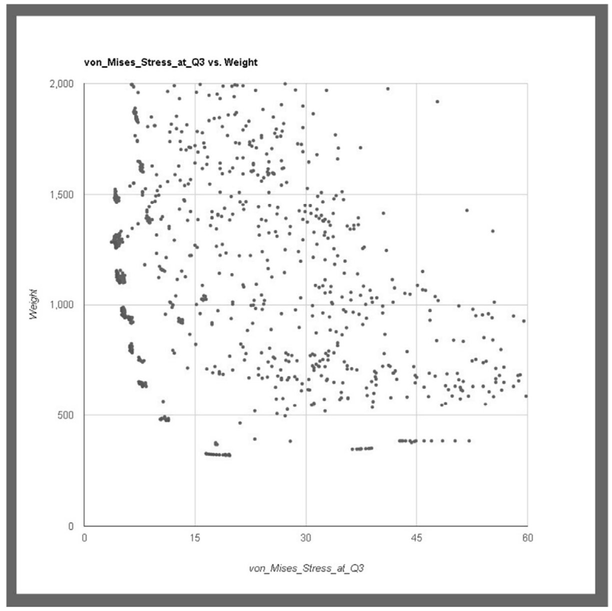
Pareto optimization

Define conflicting objectives
e.g.
weight and stiffness

Determine non-dominated solutions
e.g.
For a given solution there is no lower weight with a higher stiffness

Define the Pareto set of non-dominated solutions

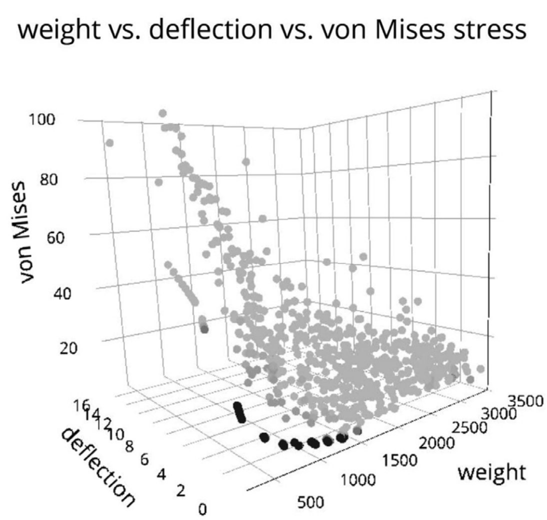
Sort and breed neighbors
or
Select and mutate individuals



Pareto optimization

Selection can contain any number of objectives

e.g.
weight and deflection and stress



7. Utilize Parallel Hardware

Dedicated cluster (cloud)

or

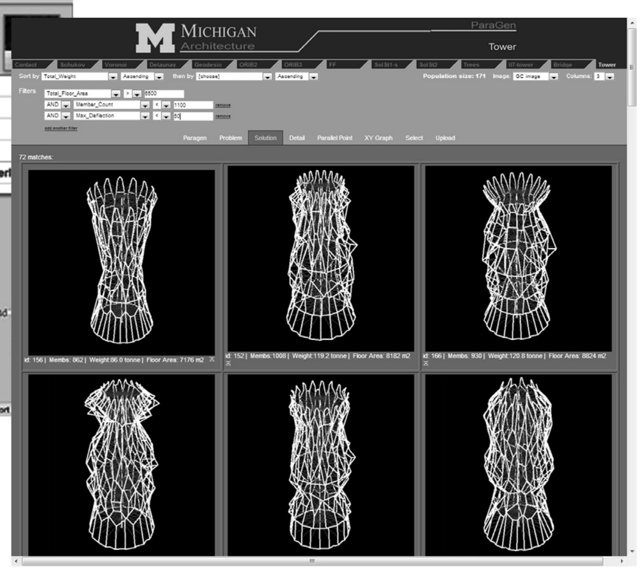
ad hoc cluster

- Simple web browser connection

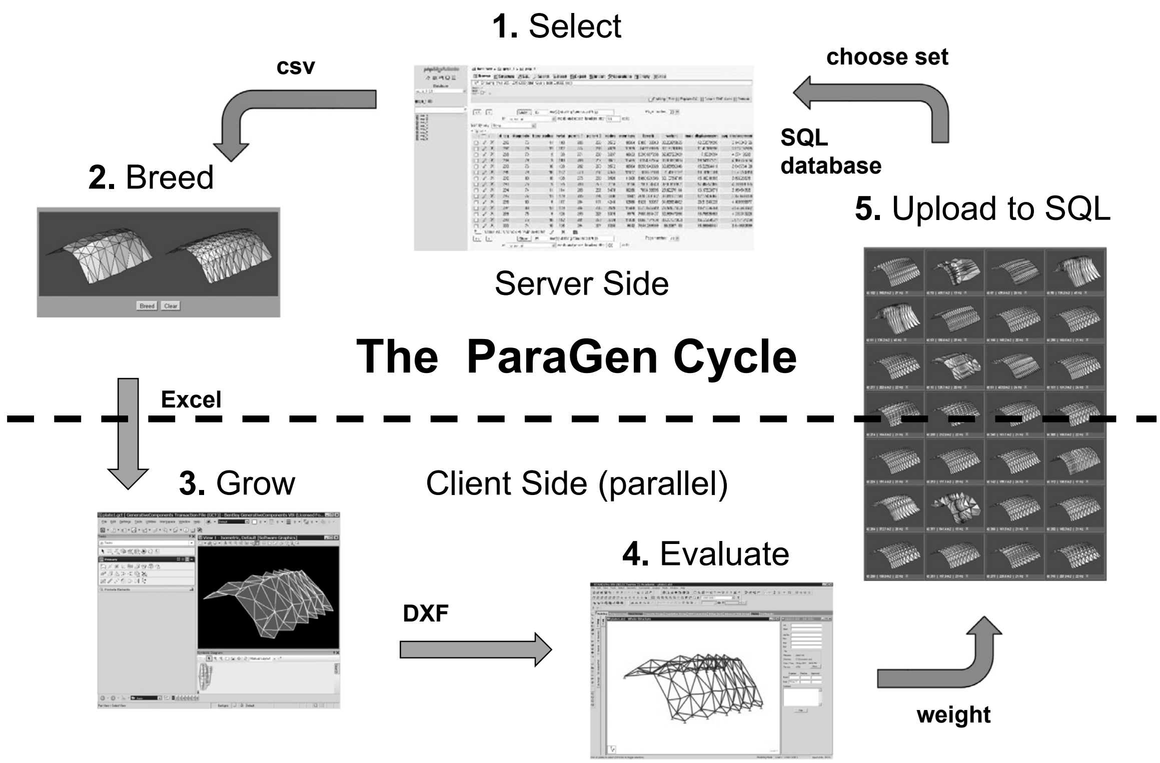
Exploration as Database Mining

Google maps

ParaGen maps

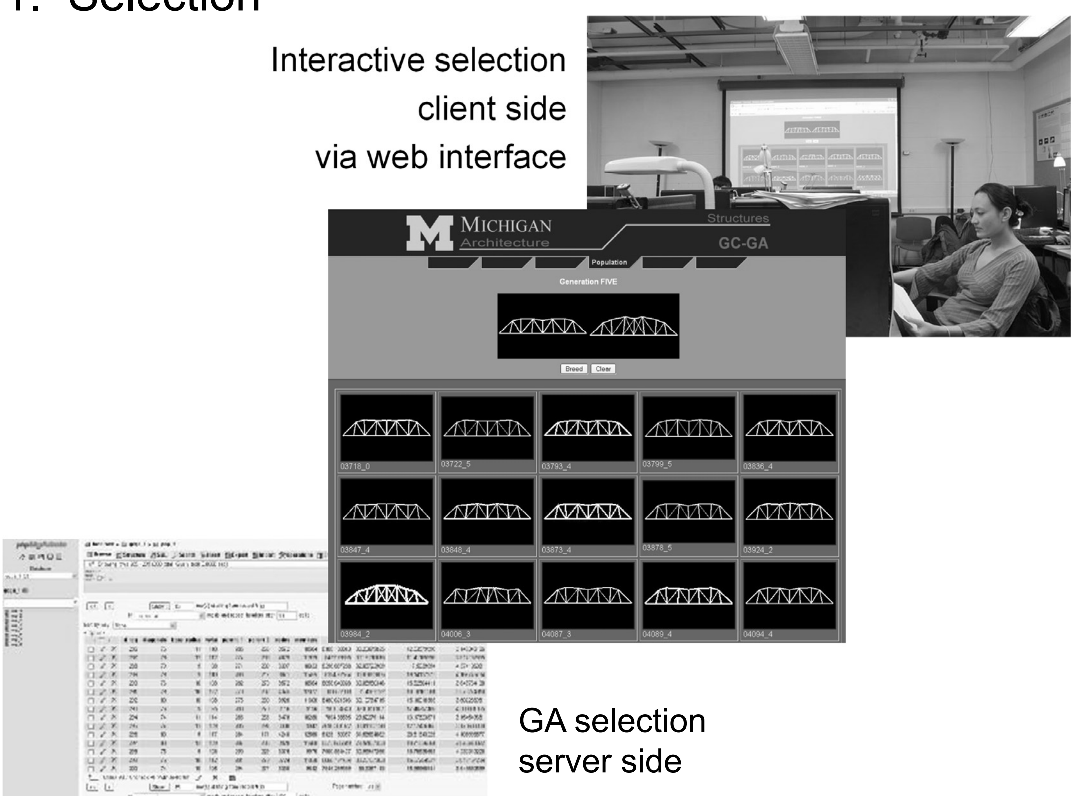


How it works



1. Selection

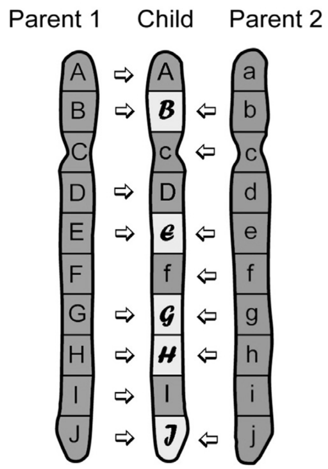
Interactive selection
client side
via web interface



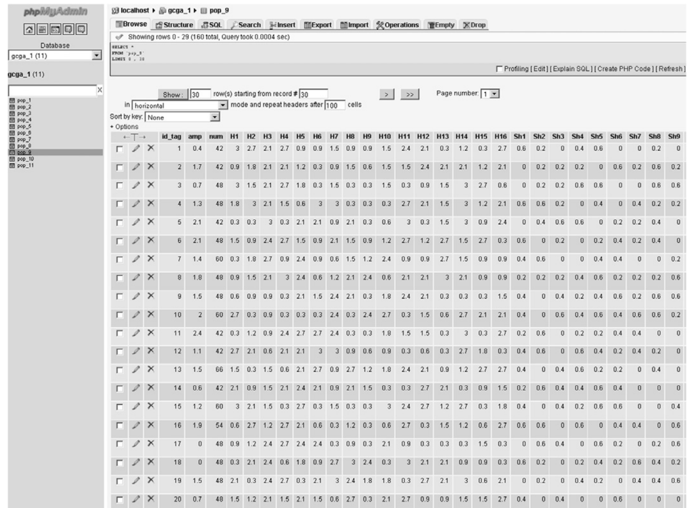
GA selection
server side

2. Breeding

- Create population from data
- Crossover of data variables
- Half Uniform Crossover
- Output to Excel



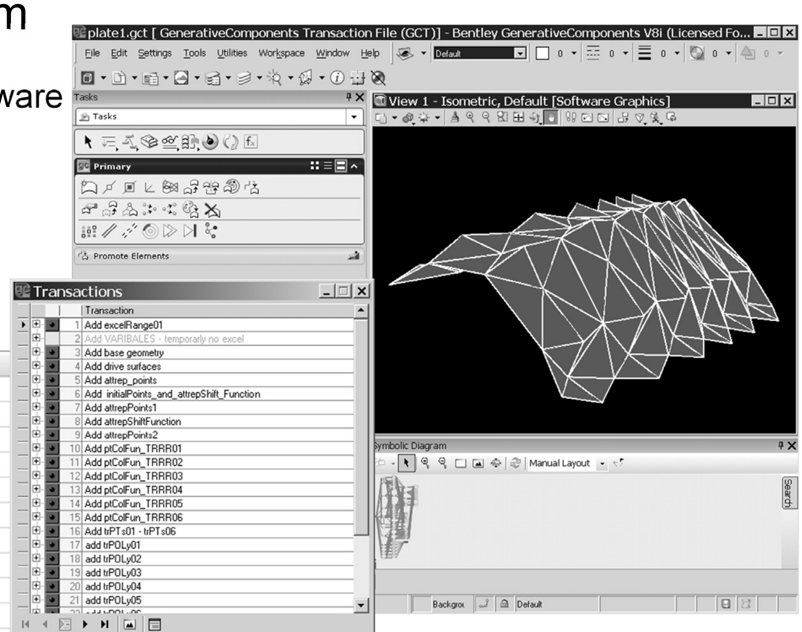
HUX

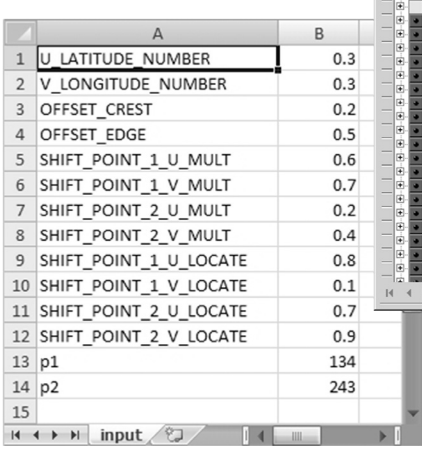


SQL database

3. Grow the Form

- Run parametric software with Excel input.
- Generate form.
- Output dxf file.
- Capture image.

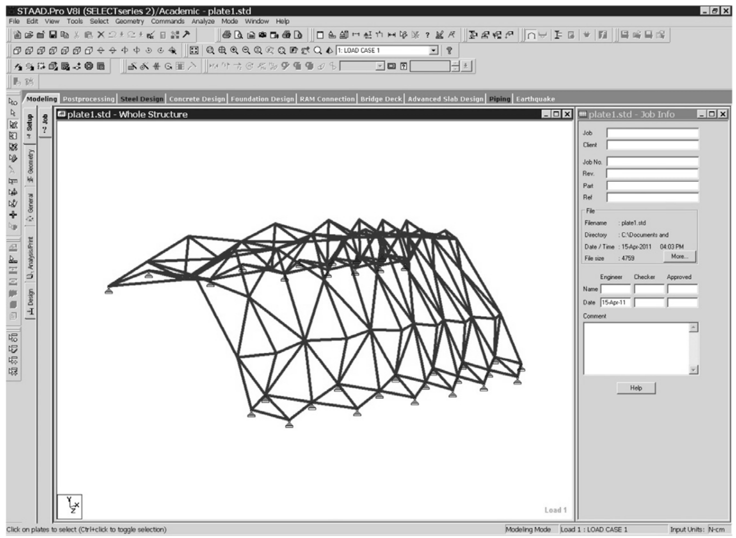




	A	B
1	U_LATITUDE_NUMBER	0.3
2	V_LONGITUDE_NUMBER	0.3
3	OFFSET_CREST	0.2
4	OFFSET_EDGE	0.5
5	SHIFT_POINT_1_U_MULT	0.6
6	SHIFT_POINT_1_V_MULT	0.7
7	SHIFT_POINT_2_U_MULT	0.2
8	SHIFT_POINT_2_V_MULT	0.4
9	SHIFT_POINT_1_U_LOCATE	0.8
10	SHIFT_POINT_1_V_LOCATE	0.1
11	SHIFT_POINT_2_U_LOCATE	0.7
12	SHIFT_POINT_2_V_LOCATE	0.9
13	p1	134
14	p2	243
15		

4. Evaluate Form

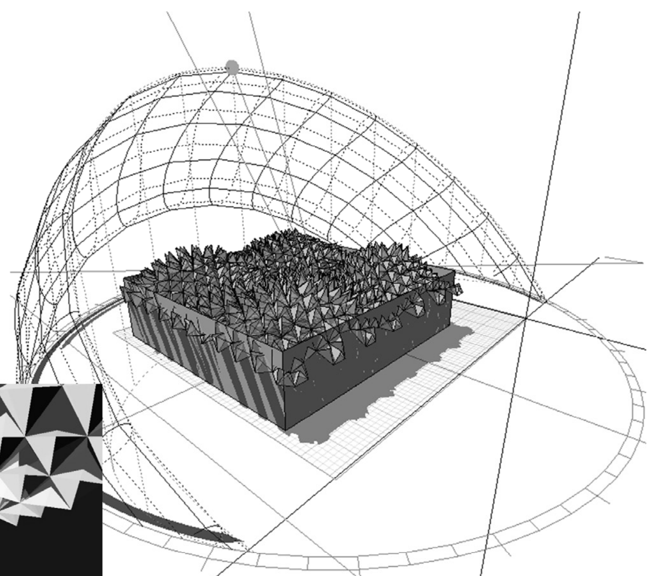
- Read into STAAD.Pro
- Add material, support and load conditions
- Find force and deflection
- Size members
- Determine weight
- Output data to Excel

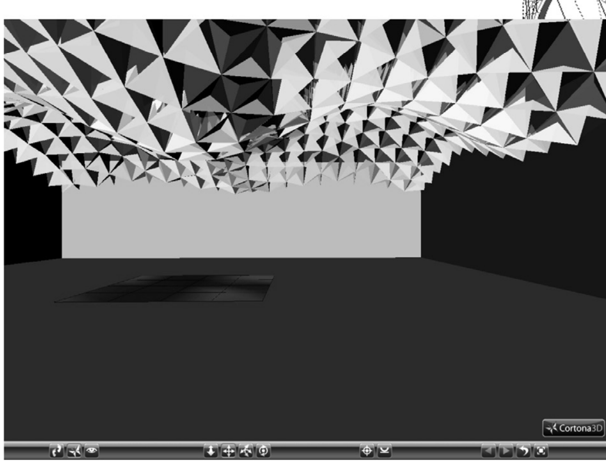


4. Evaluate Form

Other performance evaluations can be made with any Windows software package.

Example from Ecotect

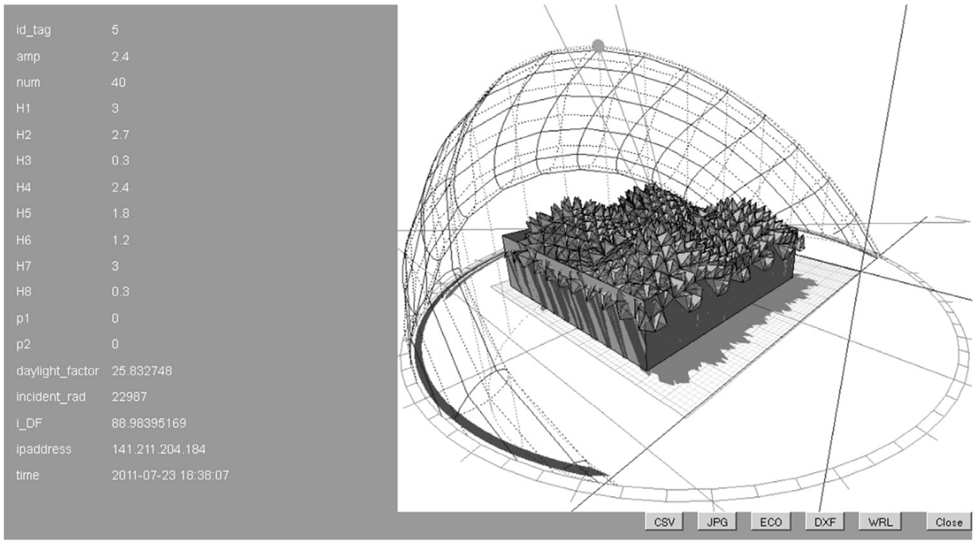




5. Upload Files and Data to Web Server

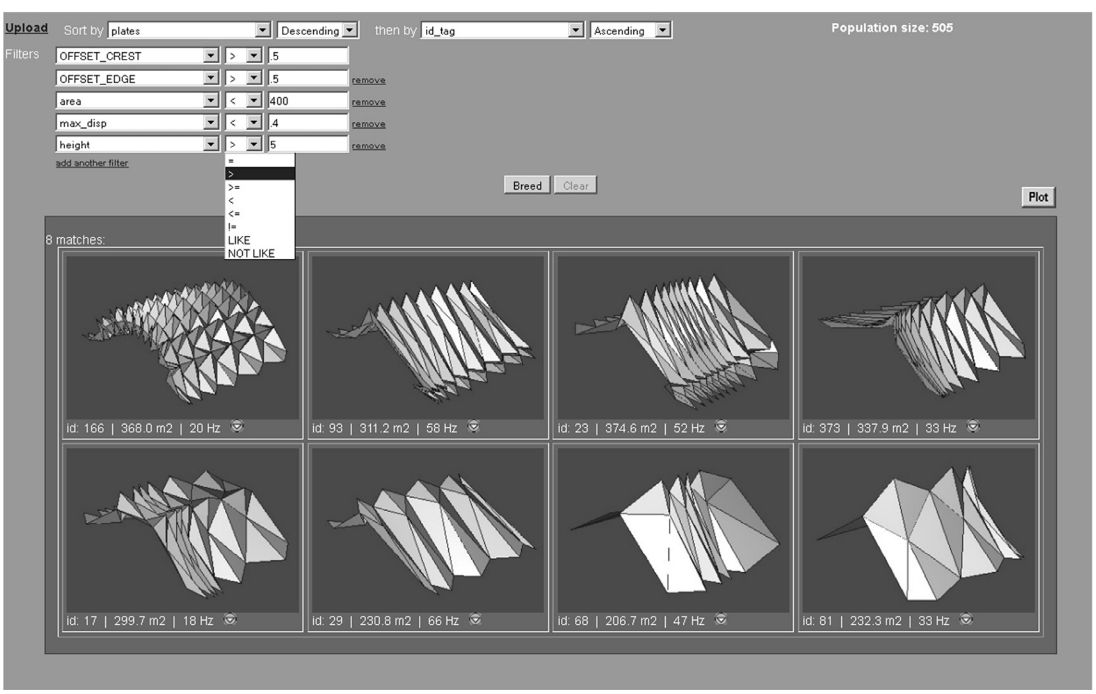
All variables and performance values are stored in a SQL database

Useful files are retained for later inspection: e.g. DXF, JPG, VRLM, and input files for FEA and Ecotect



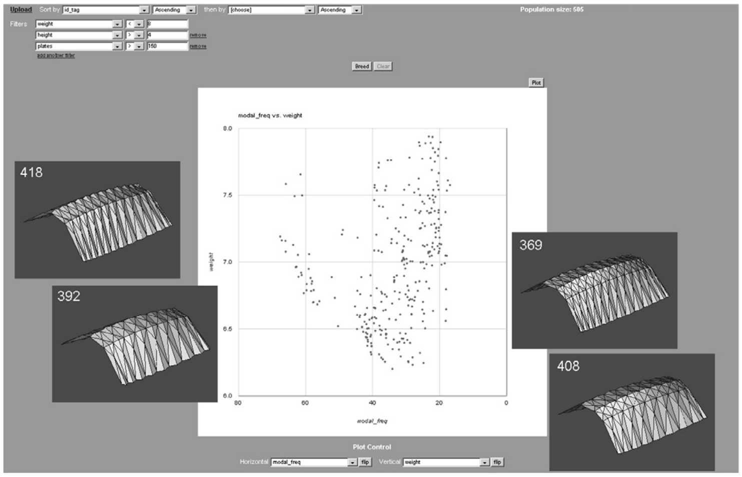
5. Store and Rank Data

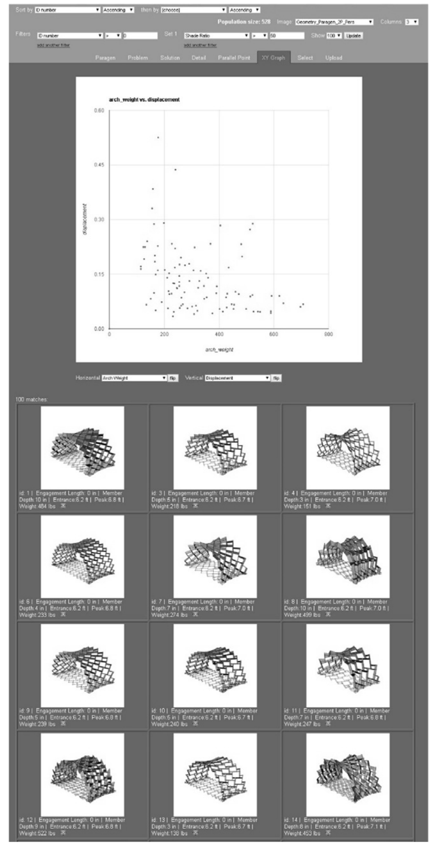
Multi level sort options + multi level filters, together with image browsing of solutions provides robust exploration potential.



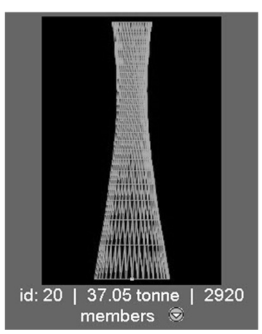
How to use it

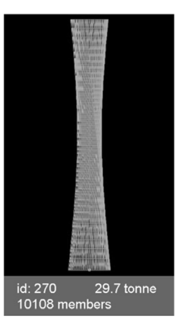
Post processing
Exploration
Selection



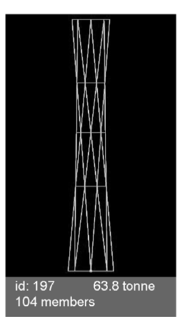


Examples - Shukhov Tower

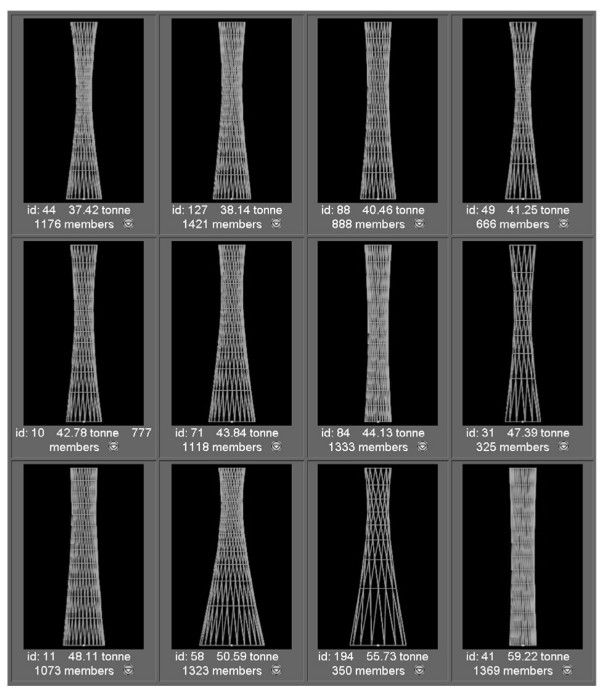




lightest weight

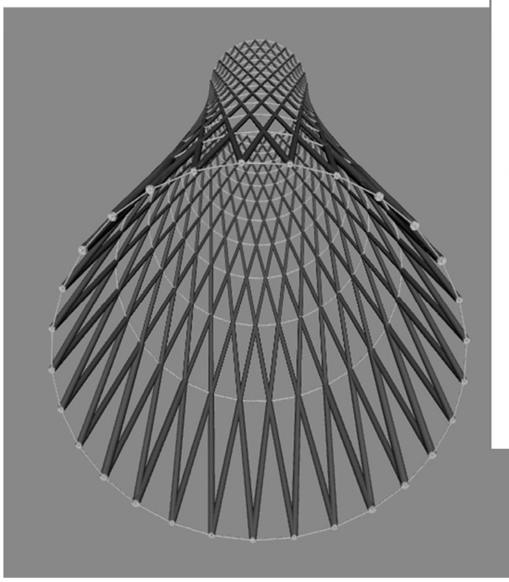


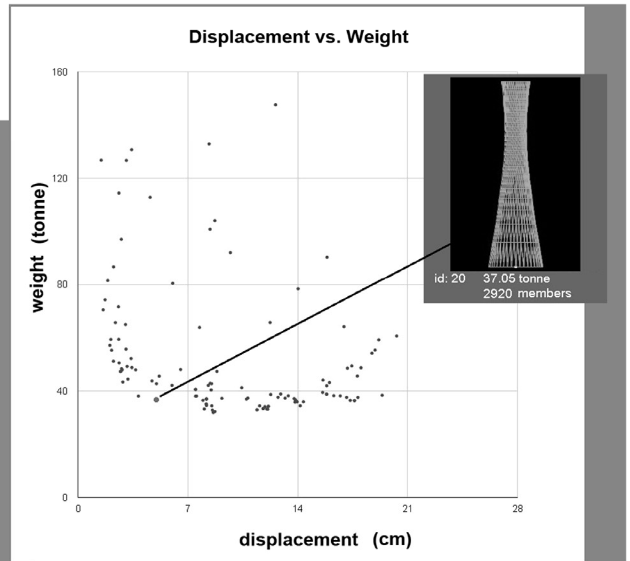
least members



Dead + Wind Load

Examples - Shukhov Tower

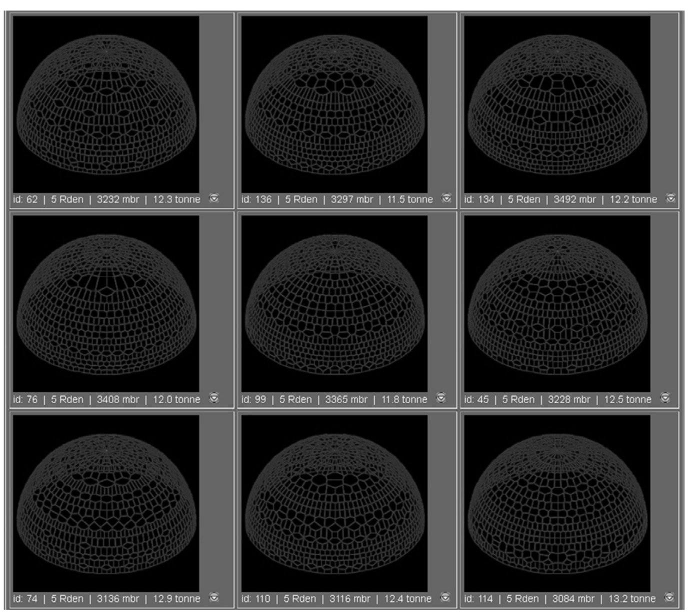




Plot of weight vs. members

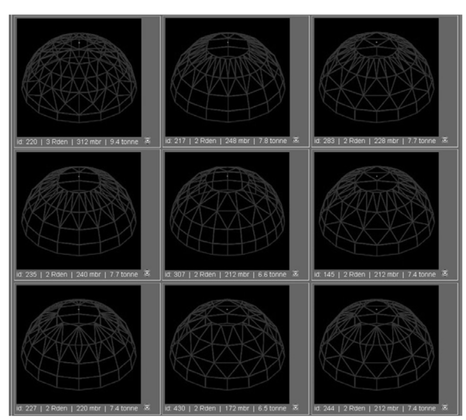
VRML perspective

Examples (with Michela Turrin & Maria Van Embden Andres)

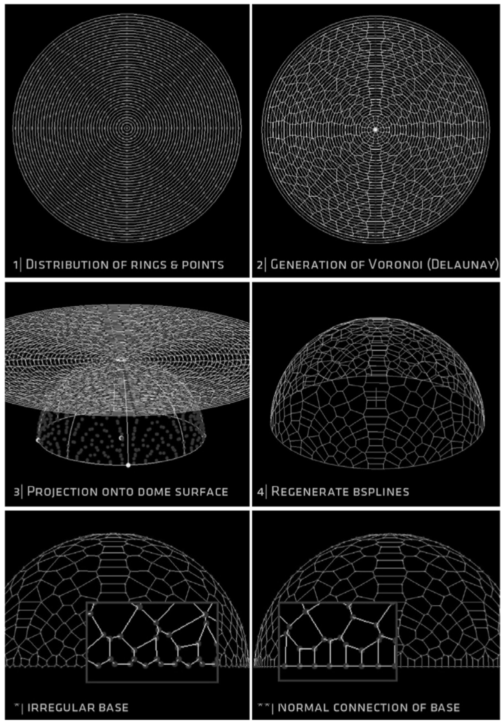


Voronoi Domes

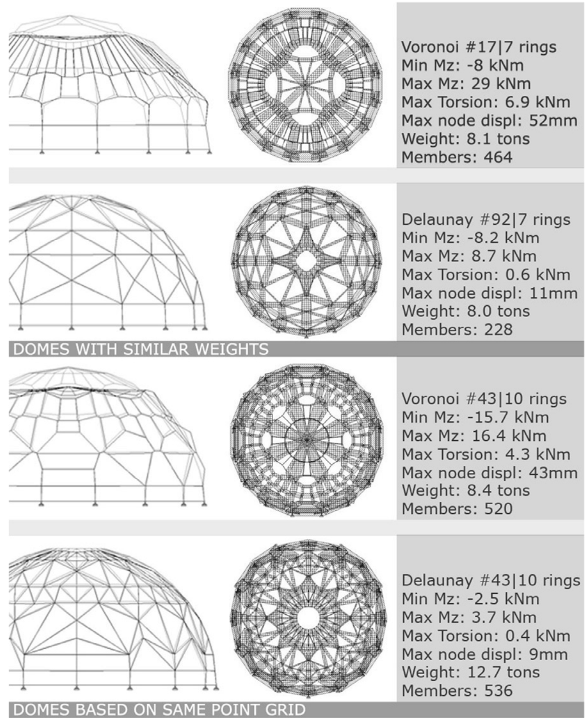
Delaunay Domes



Examples (with Michela Turrin & Maria Van Embden Andres)

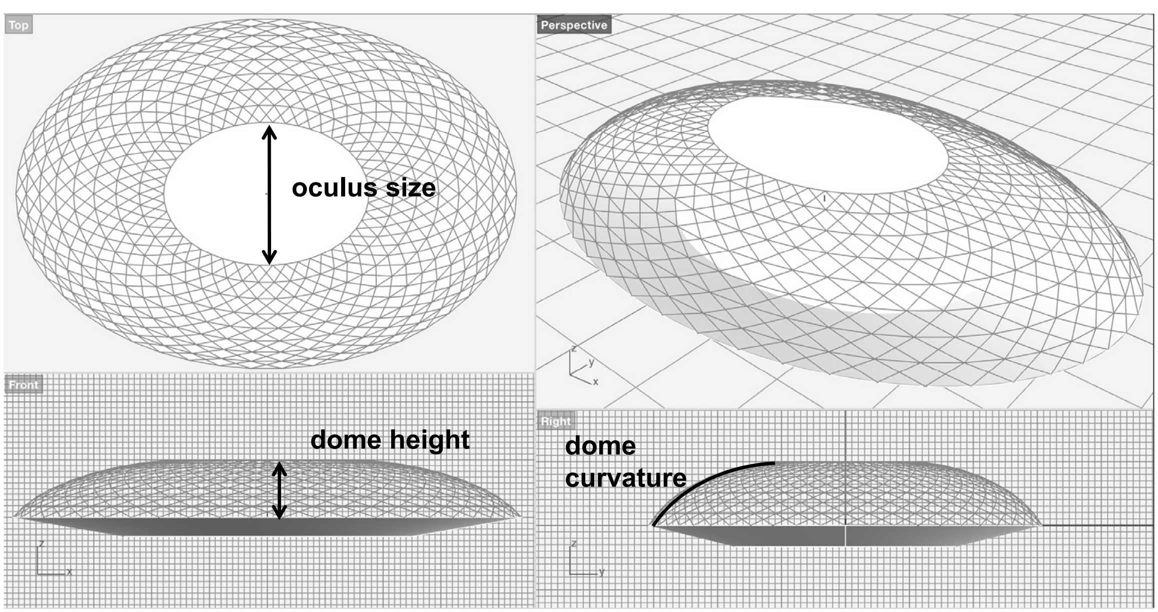


Geometry Generation



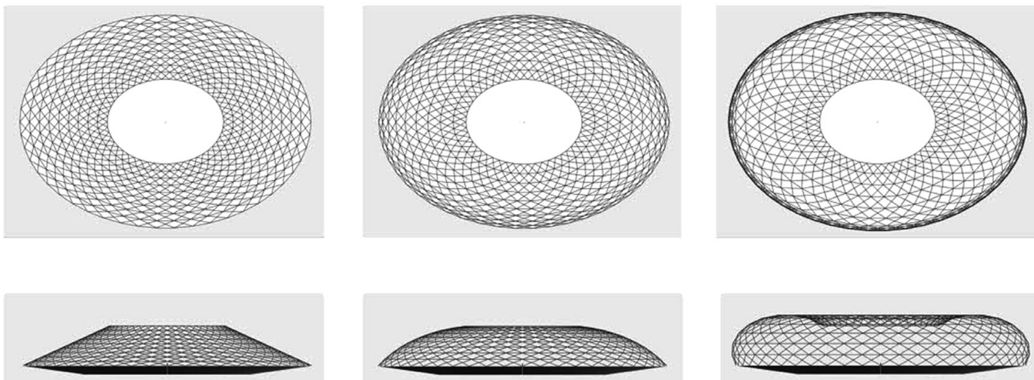
Structural Performance

Examples (with Andre Chaszar)
Soccer Stadium - variables

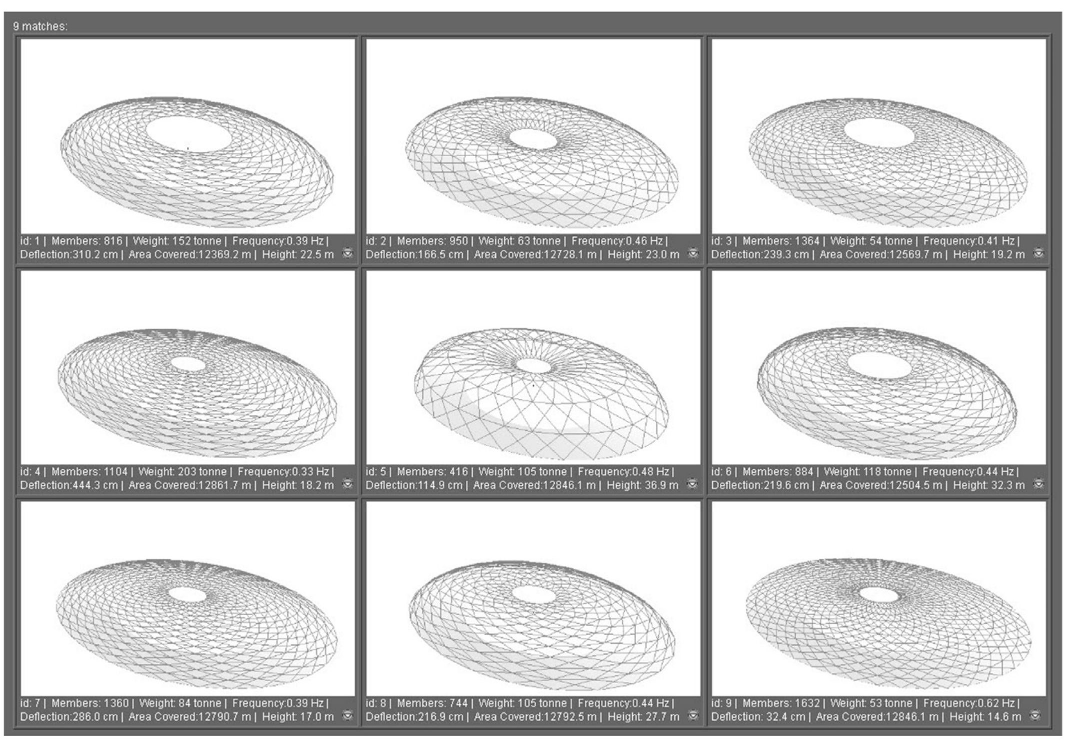


Examples (with Andre Chaszar)
Soccer Stadium - performance

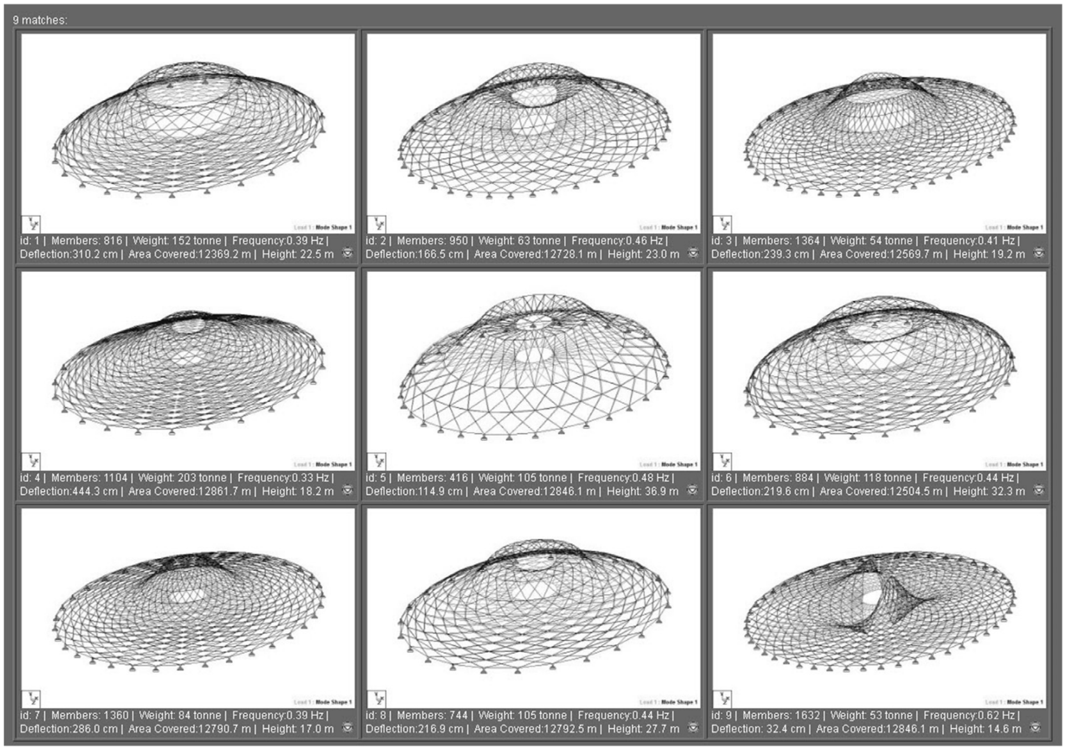
- Geometry: curvature, oculus, mesh density, number of elements
- Structural: weight, deflection, modal frequency
- Daylighting: light intensity and distribution on field



Examples (with Andre Chaszar)
Soccer Stadium - geometry



Examples (with Andre Chaszar)
Soccer Stadium - modal frequencies

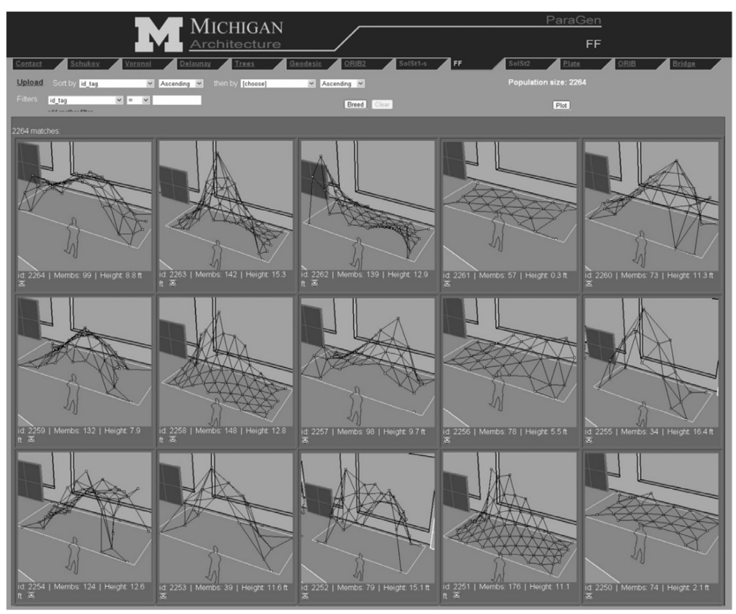


Examples - Foam & Fabric with M. Wright & M. Jensen
Examples - Foam & Fabric with M. Wright & M. Jensen

Designer selected populations based on visual criteria.
Designer selected populations based on visual criteria.

Generated with a Python script in Rhino
Generated with a Python script in Rhino

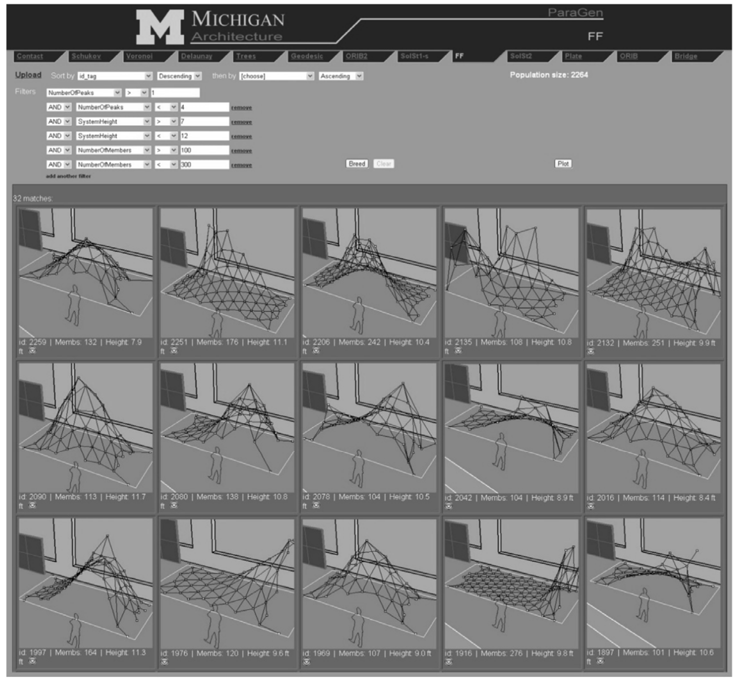
Full solution set of 2200
Full solution set of 2200



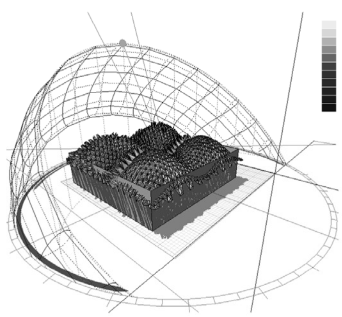
Examples - Foam & Fabric with M. Wright & M. Jensen
Examples - Foam & Fabric with M. Wright & M. Jensen

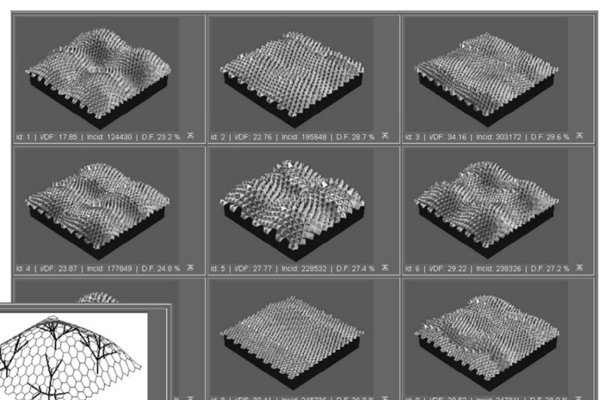
Post process exploration with SQL sorts and filters
Post process exploration with SQL sorts and filters

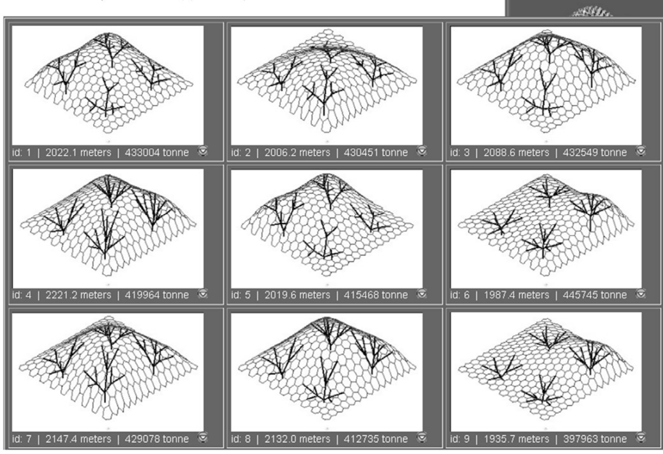
Reduced set of 32
Reduced set of 32



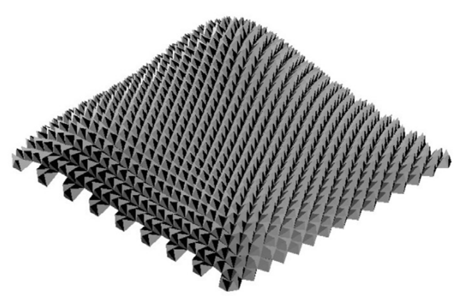
Examples (with Michela Turrin & Andreas Falk) SolSt





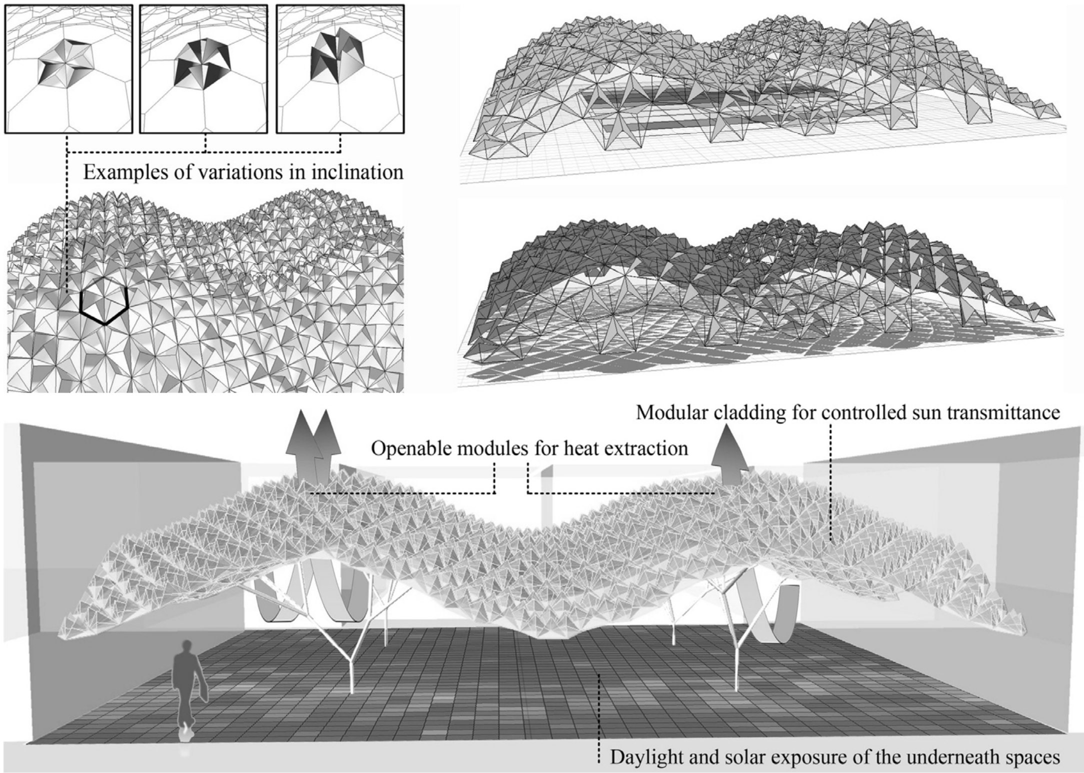


Shading / Ventilation

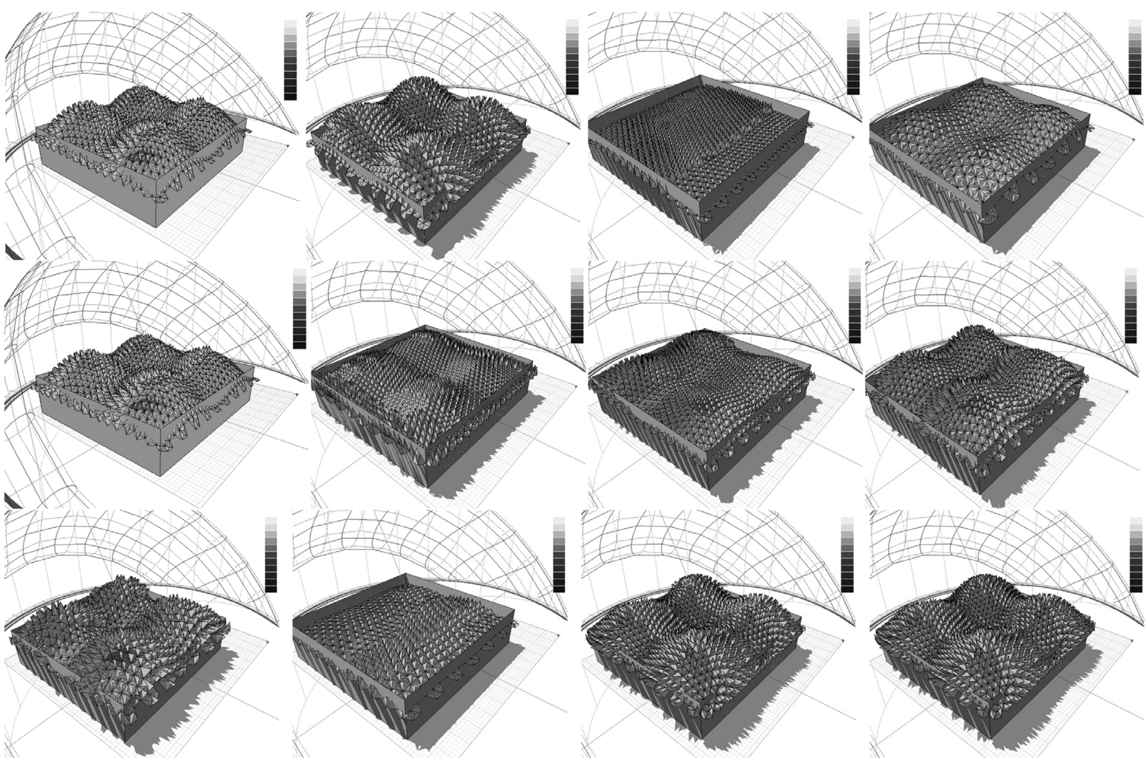


Branching Columns

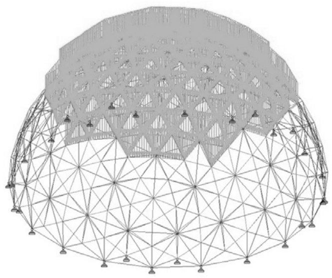
Examples (with Michela Turrin & Andreas Falk) SolSt



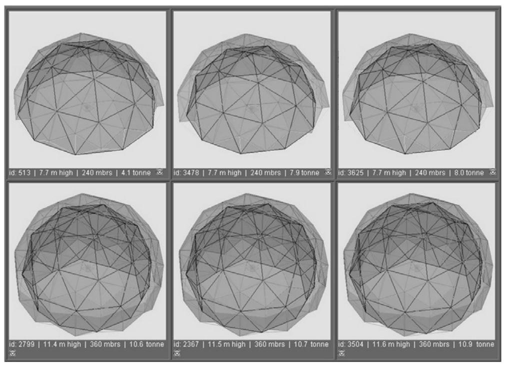
Examples (with Michela Turrin & Andreas Falk) SolSt

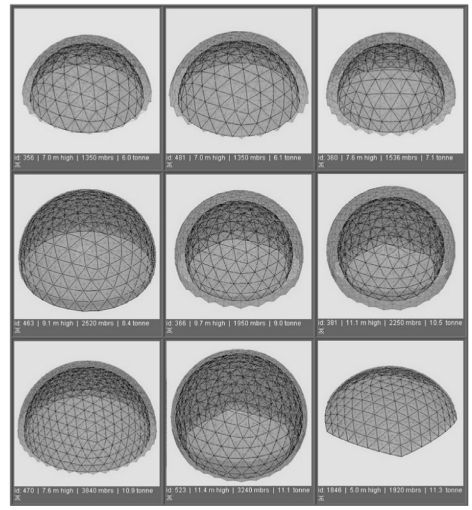


Examples – Geodesic Domes (with Ted Hall)



Snow Loading



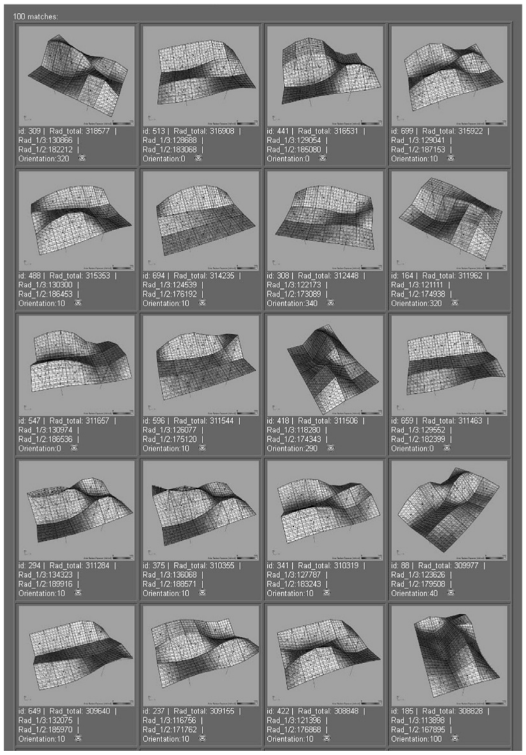


Variable parameters

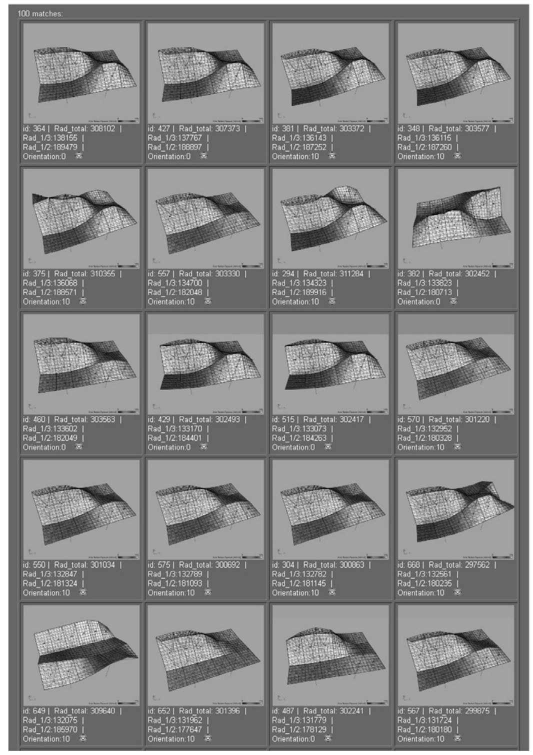
- Outer shell polyhedral type
- Power – subdivisions
- Frequency
- Base trim
- Distance between layers

Examples – NetZeroEnergy (with Studio [Ci] + Constance Bodurow)

Examples – NetZeroEnergy (with Studio [Ci] + Constance Bodurow)



PV on all panels



PV on 6 panels

Examples – LIMB (with Steven Mankouche & Kasey Vliet)

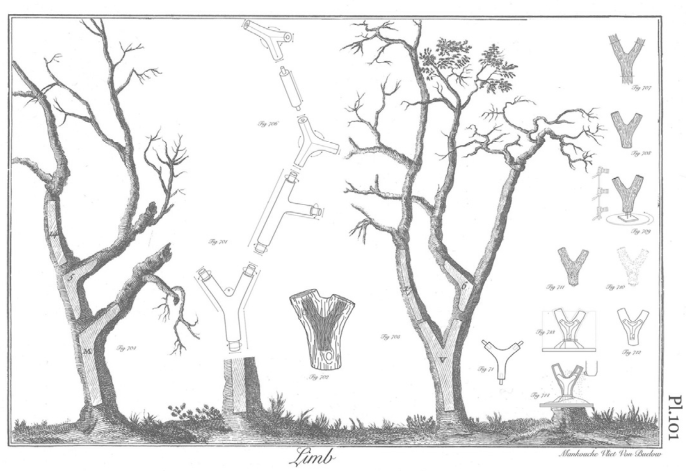
Tree Crotch Joints

Used in 18th century ship building

Replaces mortise and tendon joint with a single element

Grain of wood follows the force path

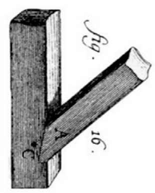
Can be milled to fit dimensions of a given structure

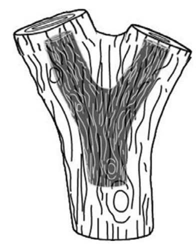


Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Tree Crotch Joints

Final joints milled from the raw tree crotch





Examples – LIMB (with Steven Mankouche & Kasey Vliet)

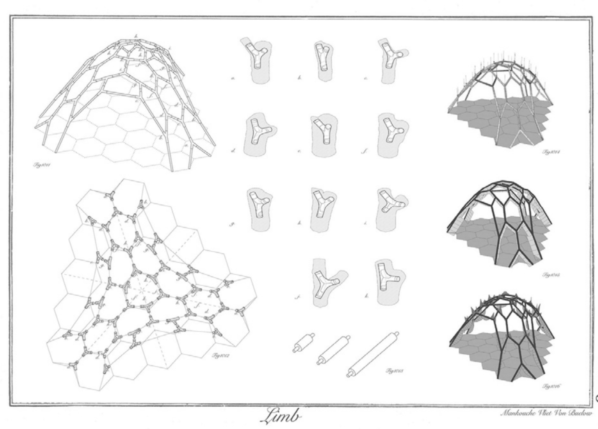
Based on hexagonal mesh

Joints connect 3 struts

Designed as a catenary vault

Form adjusted to fit given joints

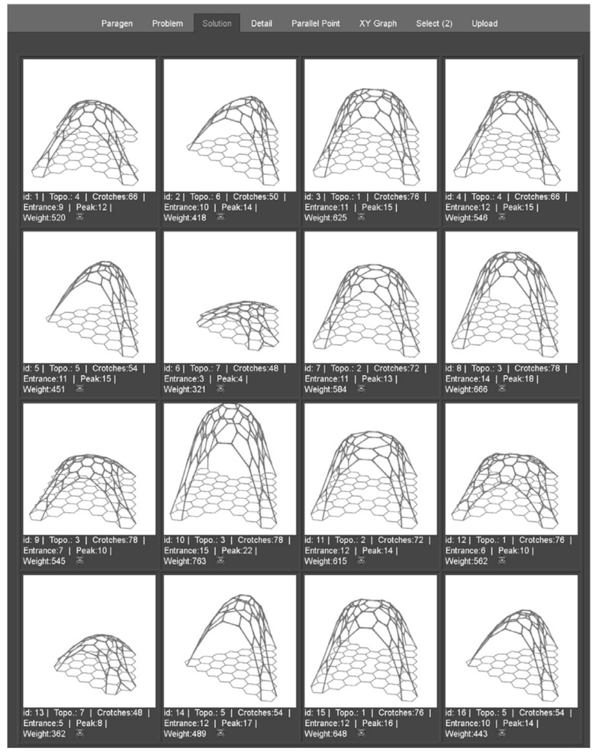
Parametric exploration of topology and geometry options using Rhino/Grasshopper with Kangaroo and Karamba



Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Design Parameters

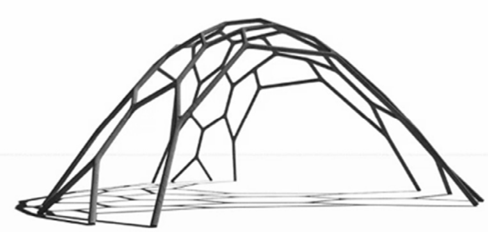
- Minimize out of plane curvature
- Naturally occurring bifurcation angles (30-90°)
- Axially aligned joints and connectors
- Minimize number of joints
- Smooth shell surface
- Entrance and center height
- Weight
- Member forces
- Deformation



Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Form Generation

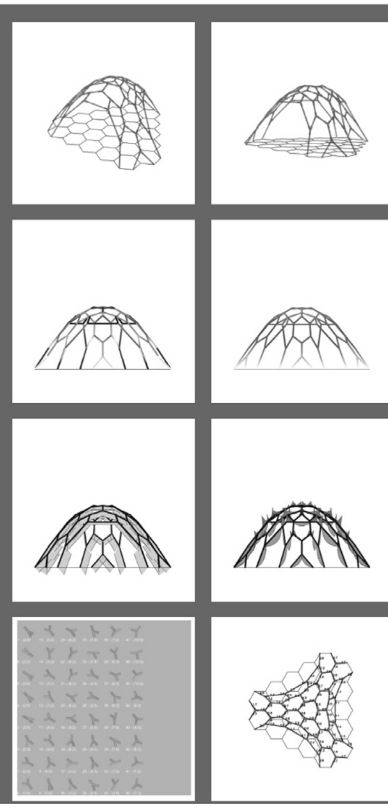
- Using ParaGen exploration method with Grasshopper
- Each solution analyzed in Grasshopper
- Solutions saved with images in MySQL
- Initial generation ca. 500
- Breeding for:
  entrance > 2 m (6.5 ft)
  peak < 3 m (10 ft)
  minimum joints



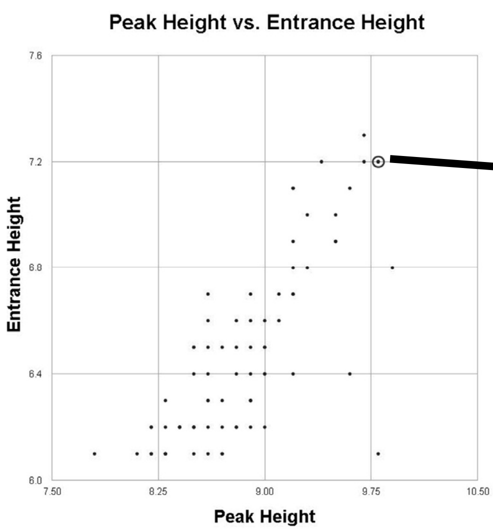
Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Collected Data

ID number	241
Dome Typology	7
Branching Members Rest Length Ratio	0.4
Boundry Members Rest Length Ratio	1
Central Members Rest Length Ratio	0.4
Upward Force	1.7
Parent 1	0
Parent 2	0
Number of Crotches	48
Number of Members	87
Minimum Member Length	0.36 FT
Maximum Member Length	2.64 FT
Entrance Height	7.2 FT
Peak Height	9.8 FT
Dome Weight	395 LBS
Displacemnt	0.012 IN
Maximum Tensile Utilization	-2.3
Maximum Compressive Utilization	7.1
Minimum Crotch Angle	36 degrees
Maximum Crotch Angle	167 degrees
Min Crotch Out-of-Plane Angle	2.6 degrees
Max Crotch Out-of-Plane Angle	10.9 degrees
Machine IP	67.194.43.88
Run Time	2018-06-20 14:42:32



Examples – LIMB (with Steven Mankouche & Kasey Vliet)



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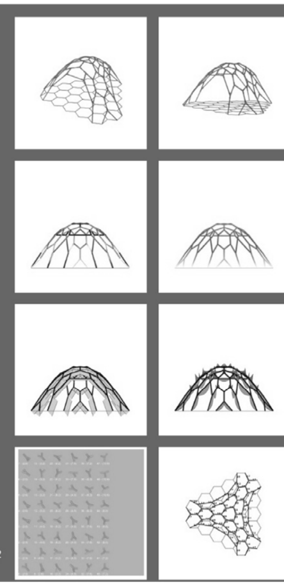
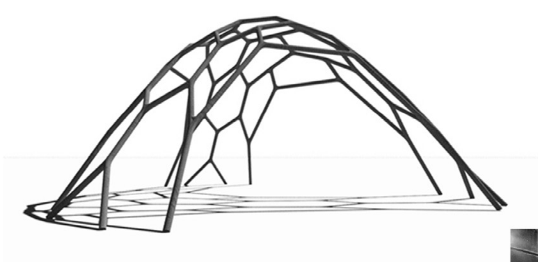


Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Constructed Prototype



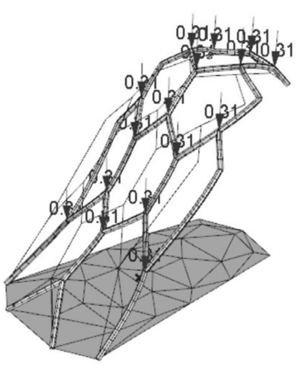
Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Load Testing

- Load test to failure
- Hung sand buckets from nodes
- Deflection measurements on cards
- Maximum load: 311 N/node = 0.67kN/m2
- (70 lbs/node = 14 psf)
- Wood cracked at node

Examples – LIMB (with Steven Mankouche & Kasey Vliet)

Load Testing



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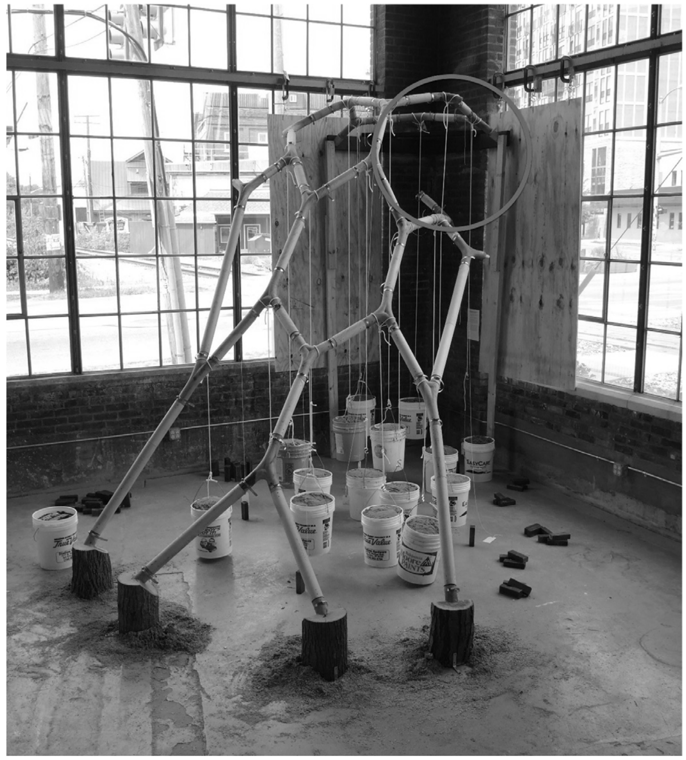
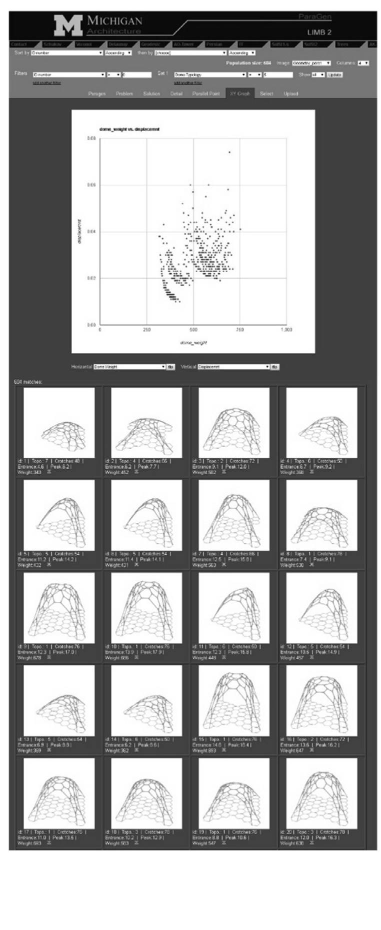


Genetically Enhanced Parametric Design for Performance Optimization and Design Exploration



Additional Information:

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Taubman College
University of Michigan