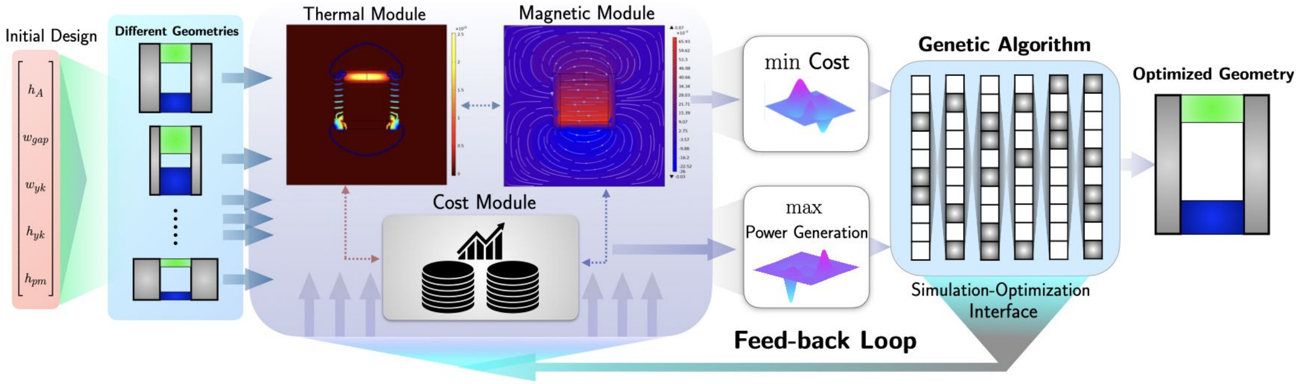
TherMaG: Engineering Design of Thermo-Magnetic Generator with Multidisciplinary Design Optimization



Will Hintlian, Mads Berg, Hanfeng Zhai

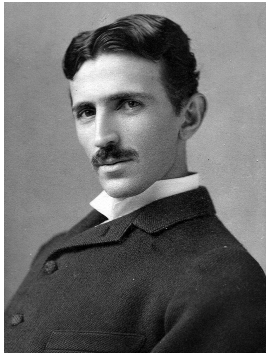
Cornell University

December 2, 2021

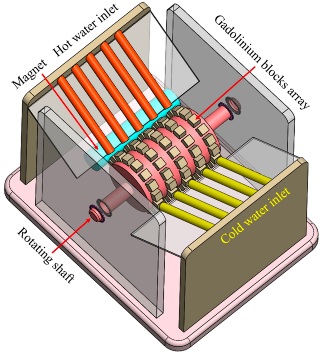
CONTENT

Background & Motivation

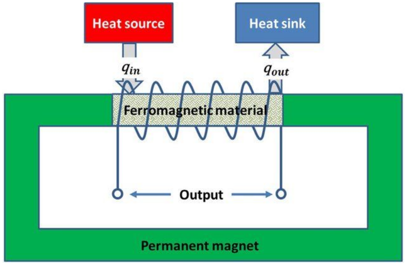
Source: NBC News



Source: Wikipedia

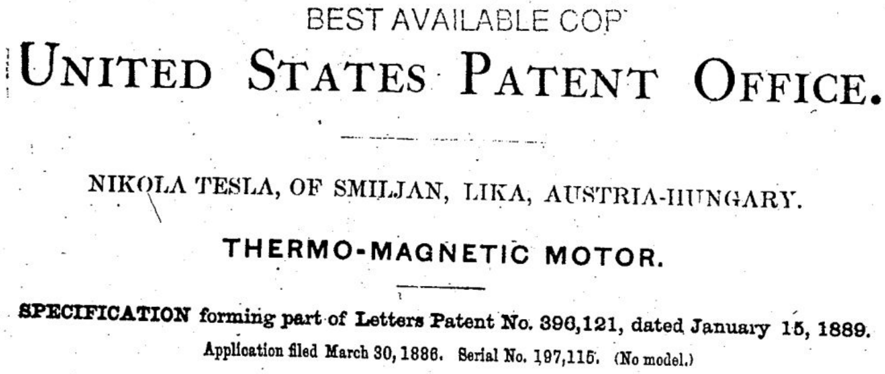


Ahmed et al., Int. J. Ener. Res., 2021



Kishore and Priya, Renew. Sust. Ener. Rev., 2021

Source: Forbes



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UNITED STATES PATENT OFFICE.

NIKOLA TESLA, OF SMILJAN, LIKA, AUSTRIA-HUNGARY.

THERMO-MAGNETIC MOTOR.

SPECIFICATION forming part of Letters Patent No. 396,121, dated January 15, 1889.

Application filed March 30, 1888. Serial No. 197,115. (No model.)

Source: Google Patent

Project Description

- **PROBLEM: Design of Thermo-Magnetic Generator**
  - Consists of active materials, yoke, permanent magnet
  - Generate energy from temperature induced magnetic field change
- **GOAL: Provide insights for NextGen clean energy**
  - Numerous research addressed on electrochemical, hydrogen, nuclear, and other forms of clean energies
  - Very few tackles possible applications of TMG
- **METHOD: Utilize the power of numerical simulation**
  - Black box code
  - Platform for connecting commercial softwares
  - Optimization toolbox in MATLAB

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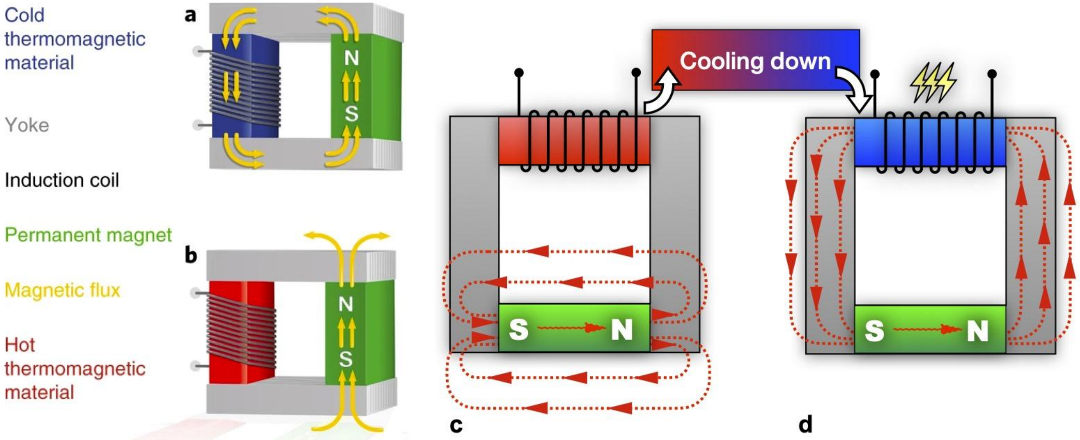

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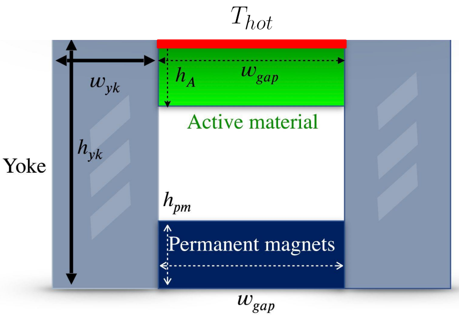
Problem Formulation

- **Objective**

$$\mathbf{J}(\mathbf{x},\mathbf{p}) = \begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \begin{bmatrix} -\text{Power output} \\ -\text{Efficiency} \\ \text{Cost} \end{bmatrix}$$

- **Design vector** $\mathbf{x} = [x_i]^{\mathrm{T}}, \quad i = 1, 2, \ldots, 5$
- **Constraints** $\mathbf{g},\ \mathbf{h}$
- **Parameters** $\mathbf{p}$



$$\begin{aligned} \min\ & \mathbf{J}(\mathbf{x},\mathbf{p}) \\ \text{s.t.}\quad & \mathbf{g}(\mathbf{x},\mathbf{p}) < \mathbf{0} \\ & \mathbf{h}(\mathbf{x},\mathbf{p}) = \mathbf{0} \\ & x_{i,LB} \le x_i \le x_{i,UB} \end{aligned}$$

Design Variables	Modules	Description	Lower Bounds	Nominal	Upper Bounds
w_{yk}	**Therm., Magn., Cost**	**Yoke Width**	**0.01**	**0.05**	**0.5**
h_{yk}	**Therm., Magn., Cost**	**Yoke Height**	**0.01**	**0.4**	**0.5**
h_A	**Therm., Magn., Cost**	**Active Material Height**	**0.01**	**0.1**	**0.5**
h_{pm}	**Therm., Magn., Cost**	**Permanent Magnet Height**	**0.01**	**0.1**	**0.5**
w_{gap}	**Therm., Magn., Cost**	**Gap Width**	**0.01**	**0.15**	**0.5**

Problem Formulation

- **Constraints** $\mathbf{g}(\mathbf{x}, \mathbf{p}) = [g_i(\mathbf{x}, \mathbf{p})]^T, \quad i = 1, ..., 3$ - **No equality constraints**

Effect of Constraints	Type	Bound
Maximum device height	**Inequality Constraint**	$h_{yk} - L_{\max} < 0$
Maximum device width	**Inequality Constraint**	$\left(2 \cdot w_{yk} + w_{gap}\right) - L_{\max} < 0$
Maximum device volume	**Inequality Constraint**	$h_{yk} \cdot \left(2 \cdot w_{yk} + w_{\text{gap}}\right) - V_{max} < 0$
No overlap	**Inequality Constraint**	$h_A + h_{pm} - h_{yk} < 0$

- **Parameters** $\mathbf{p} = p_i$ $\qquad V_{max} = 0.125m^2 \quad L_{max} = 0.5m$

Item	Physical properties	Unit	Value
Material of Active Material	Magnetic permeabilities, thermal diffusivity, heat capacity, price	[H/m], [m^2/s], [J/(kg*K)], USD/m^2	(4 Pi 10^-7, 80 Pi 10^-7), built-in, 1.7e5
Material of Permanent Magnet	Magnetic permeabilities, thermal diffusivity, heat capacity, rem. flux density, price	[H/m], [m^2/s], [J/(kg*K)], [T], USD/m^2	built-in, built-in,built-in, 1.3, 1.4e3
Material of Yoke	Magnetic permeabilities, thermal diffusivity, heat capacity, price	[H/m], [m^2/s], [J/(kg*K)], [T], USD/m^2	built-in, built-in, built-in, 1.63e5
Ambient conditions	Temperature, magnetic permeability	[K], [H/m]	300, 4 Pi, 10^-7

Physical Modeling

- **Total power output**

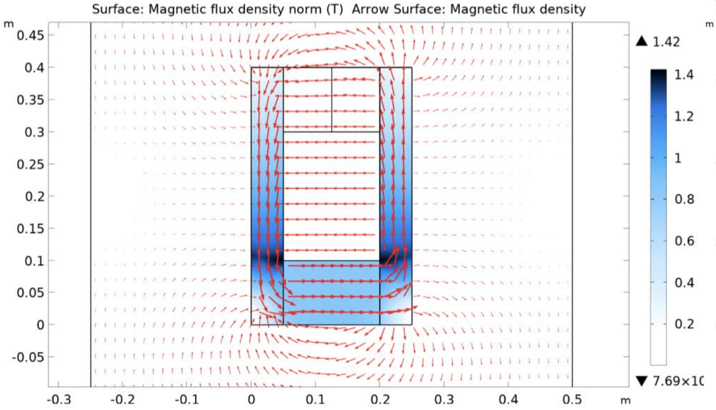
$$P = K \cdot \Delta\Phi^2 \cdot t^{-1}$$

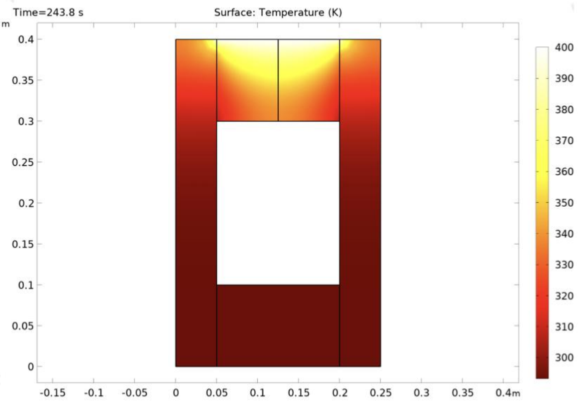
K Proportionality constant
t Time
Φ Magnetic flux

- **Energy efficiency of the TMG system**

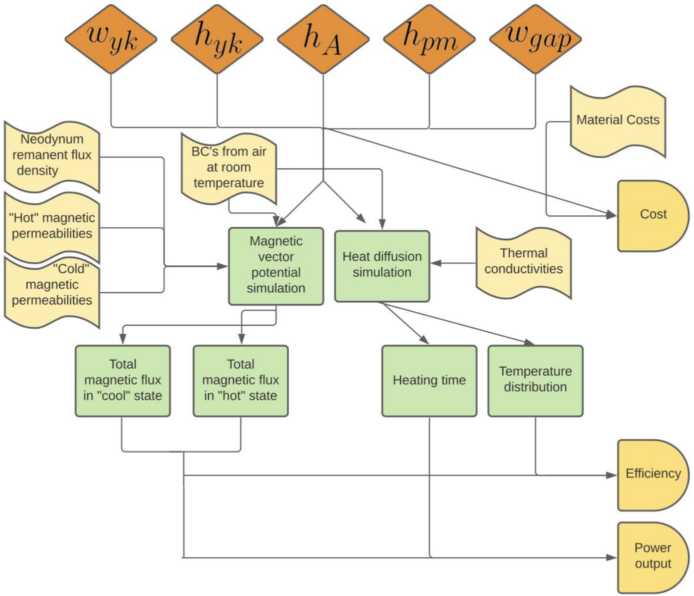
$$\eta = G \cdot \frac{\Delta\Phi^2}{\int_{\delta V} C_V \cdot (T - 293.15K)dV}$$

G Proportionality constant
C_V Heat capacity
T Temperature





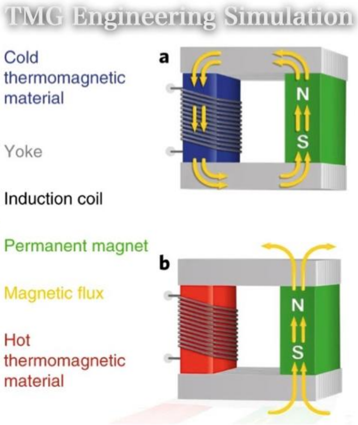
Modeling & Simulation



w_{yk}
h_{yk}
h_A
h_{pm}
w_{gap}
Material Costs
Neodynum remanent flux density
BC's from air at room temperature
Cost
"Hot" magnetic permeabilities
Magnetic vector potential simulation
Heat diffusion simulation
Thermal conductivities
"Cold" magnetic permeabilities
Total magnetic flux in "cool" state
Total magnetic flux in "hot" state
Heating time
Temperature distribution
Efficiency
Power output

Image acquired and reproduced from Waske *et al.*, *Nat. Ener.*, 2018

Tuned



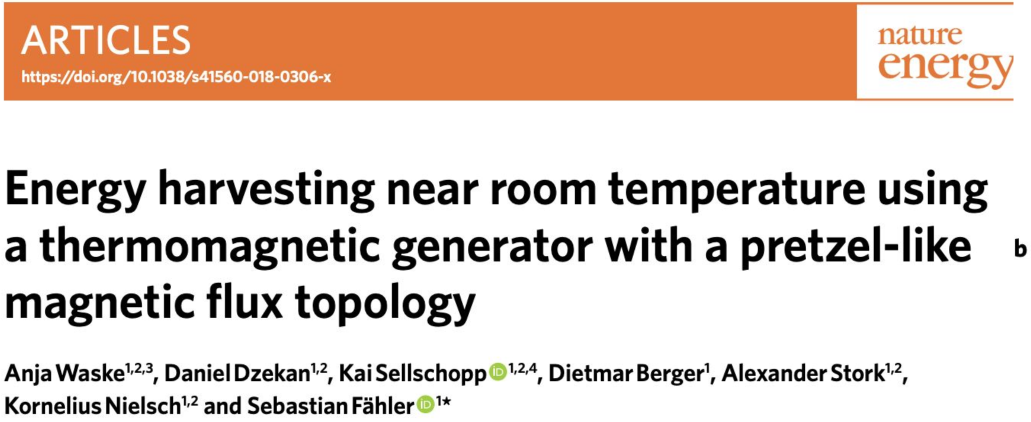
Disciplines: 3

Run time:~10s-5min

N^2 Diagram

(x, p)	Geo. design var. & material cost	Geo. design var. & thermal param.	Geo. design var. & magnetic param.			
	Cost					Device cost
		Thermal		Exergy expense per cycle	Heating time per cycle	
			Magnetic	Power generated per cycle	Power generated per cycle	
				Efficiency		Efficiency
					Power output	Power output
						$J(x, p),\ g(x, p)$

Model Validation



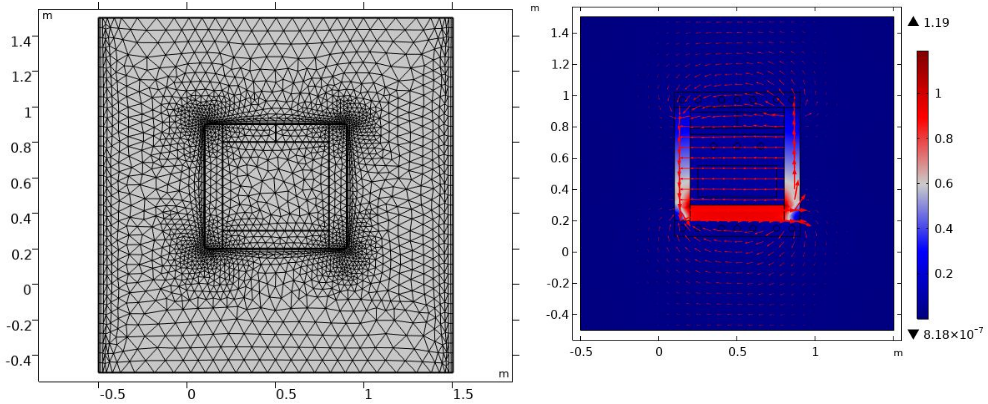
ARTICLES

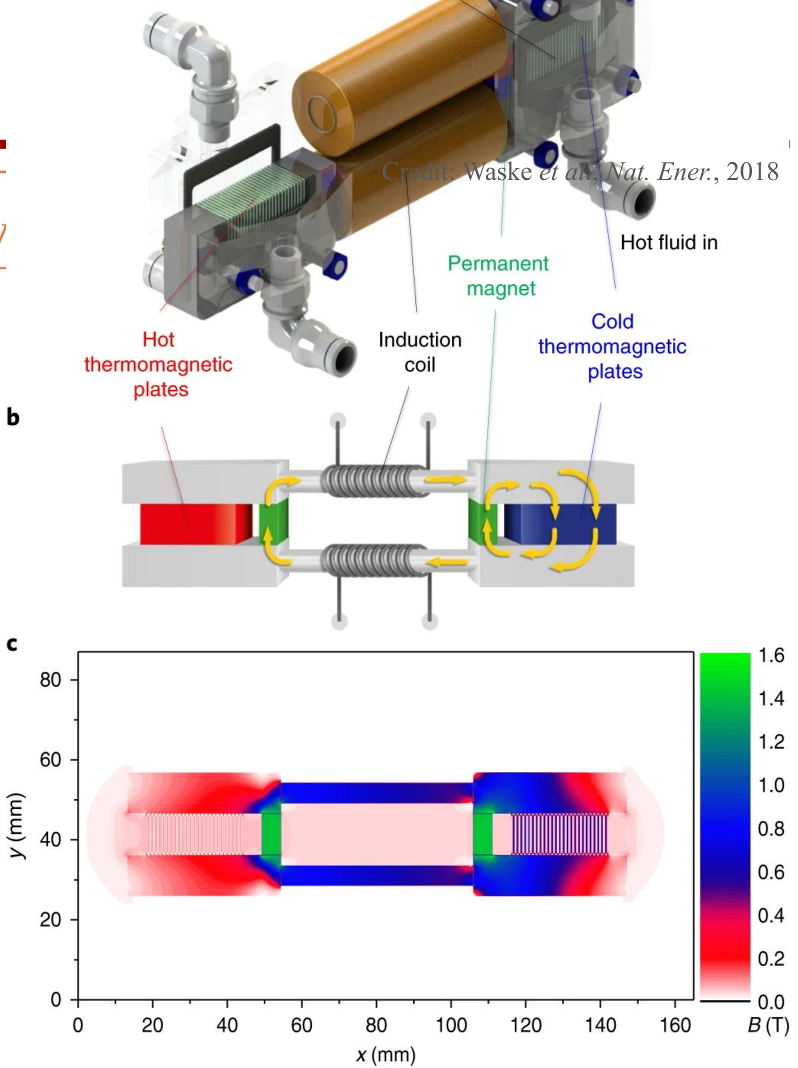
https://doi.org/10.1038/s41560-018-0306-x

nature energy

Energy harvesting near room temperature using a thermomagnetic generator with a pretzel-like magnetic flux topology

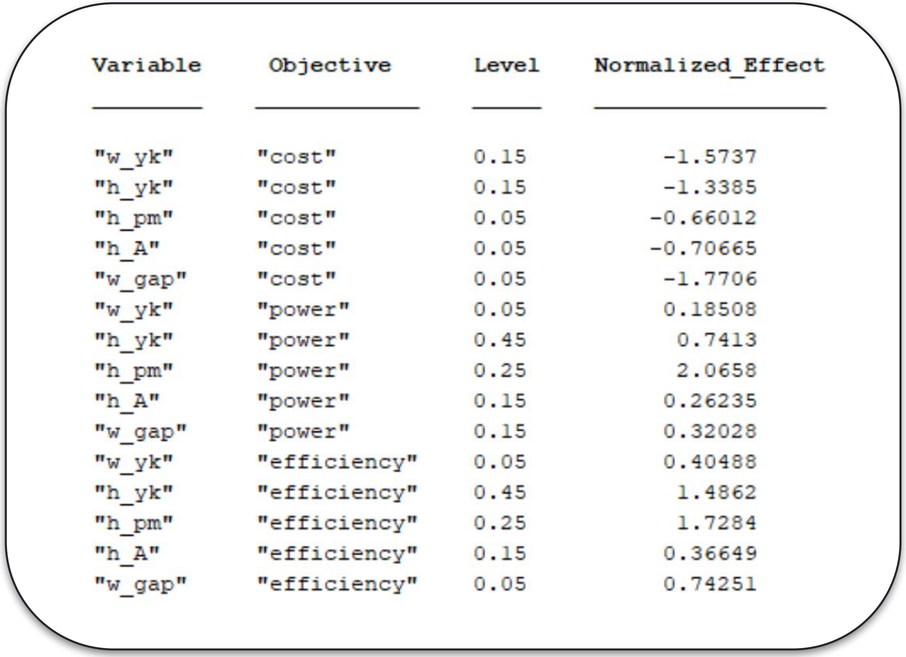
Anja Waske[1,2,3], Daniel Dzekan[1,2], Kai Sellschopp[1,2,4], Dietmar Berger[1], Alexander Stork[1,2], Kornelius Nielsch[1,2] and Sebastian Fähler[1*]





Credit: Waske *et al.*, *Nat. Ener.*, 2018

Single-objective Optimization: Design of Experiments

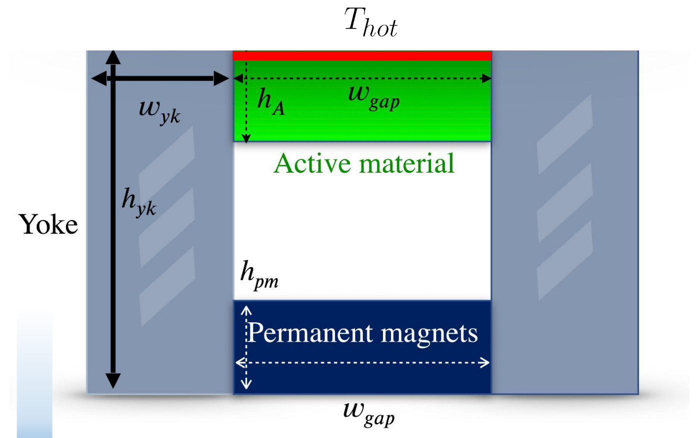


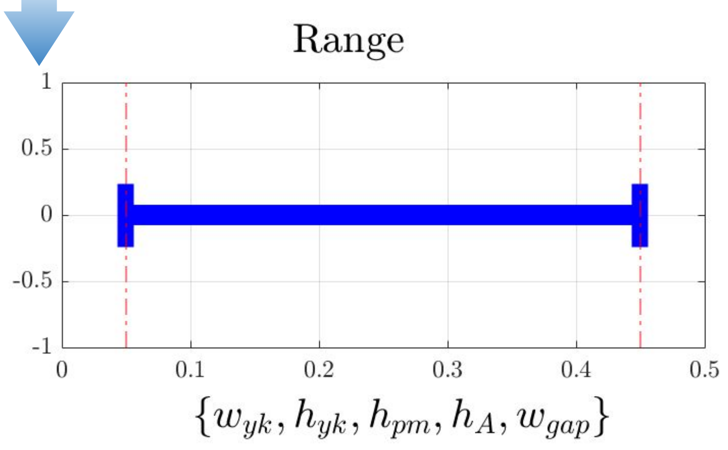
```
Variable     Objective       Level    Normalized_Effect
________    ____________    _____    _________________

"w_yk"      "cost"          0.15          -1.5737
"h_yk"      "cost"          0.15          -1.3385
"h_pm"      "cost"          0.05         -0.66012
"h_A"       "cost"          0.05         -0.70665
"w_gap"     "cost"          0.05          -1.7706
"w_yk"      "power"         0.05          0.18508
"h_yk"      "power"         0.45           0.7413
"h_pm"      "power"         0.25           2.0658
"h_A"       "power"         0.15          0.26235
"w_gap"     "power"         0.15          0.32028
"w_yk"      "efficiency"    0.05          0.40488
"h_yk"      "efficiency"    0.45           1.4862
"h_pm"      "efficiency"    0.25           1.7284
"h_A"       "efficiency"    0.15          0.36649
"w_gap"     "efficiency"    0.05          0.74251
```

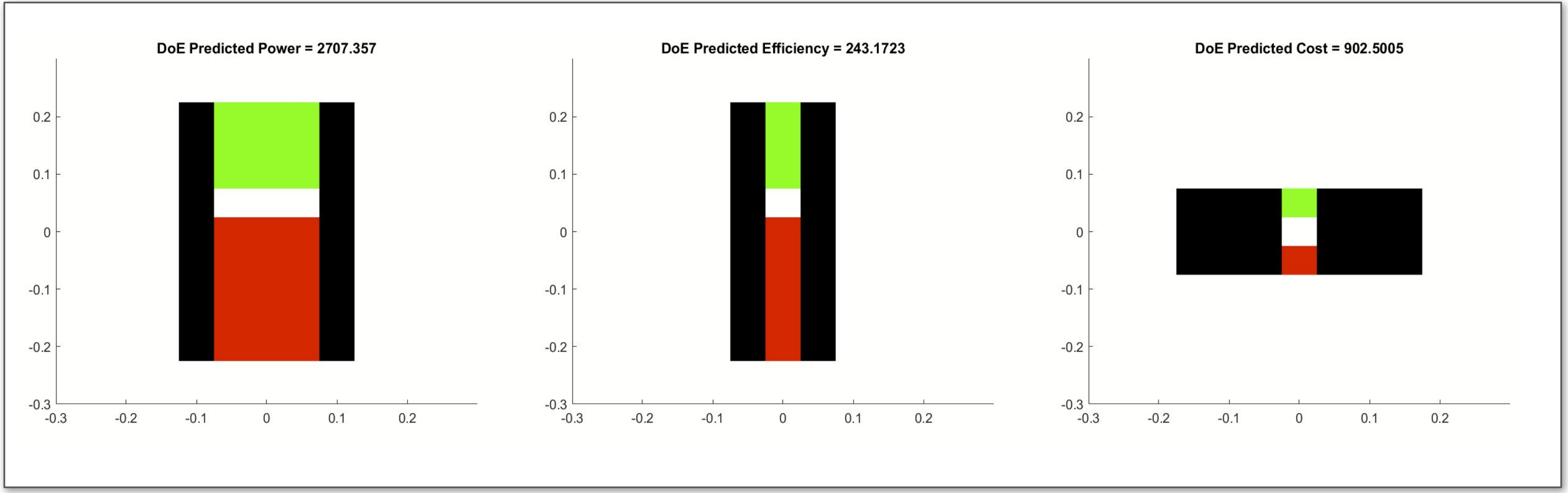
Lower bounds: `0.05 m`

Upper bounds: `0.45 m`

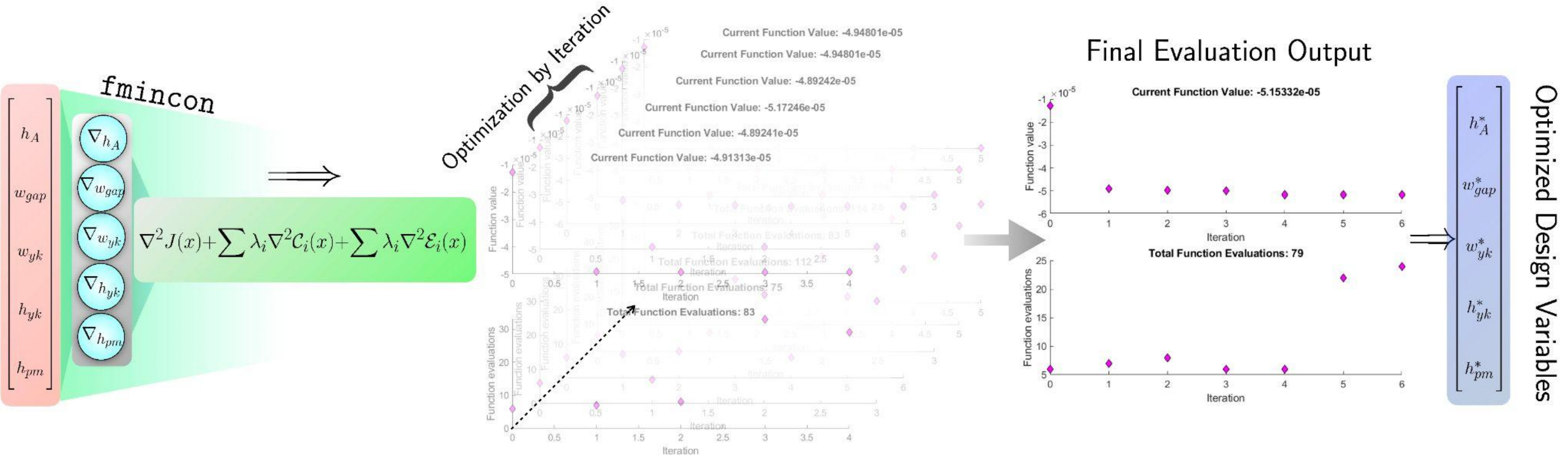




Single-objective Optimization: Design of Experiments

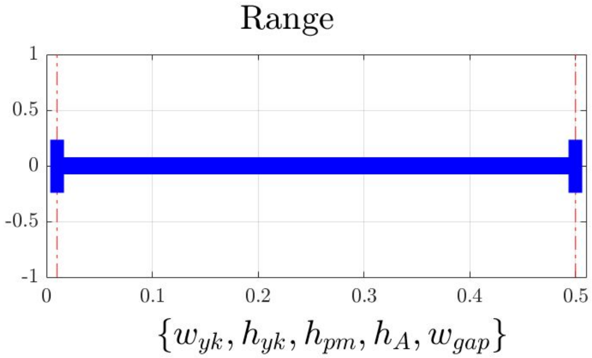


Single-objective Optimization: Gradient Algorithms

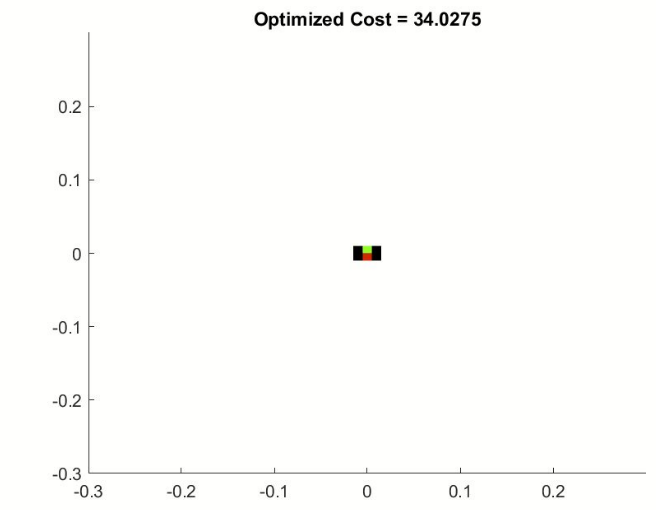


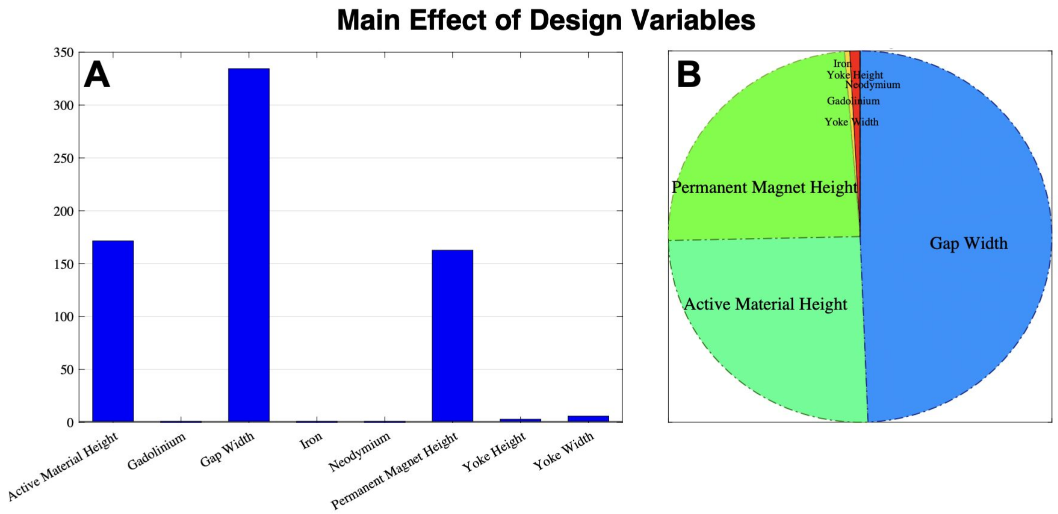
Upper bounds: `0.01 m`

Lower bounds: `0.5 m`



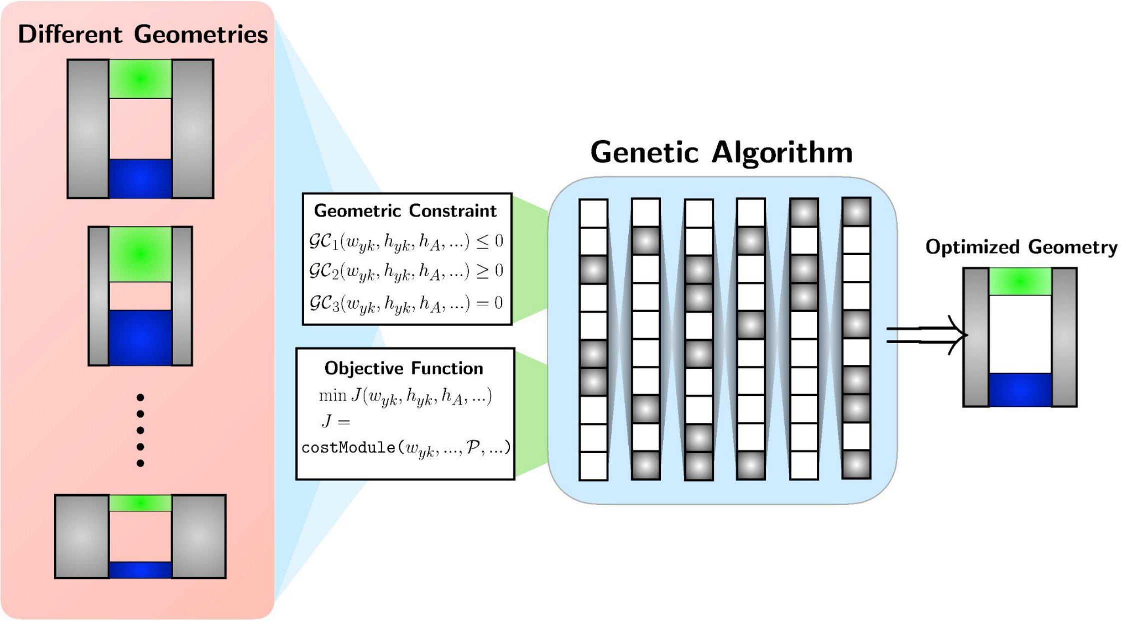
Single-objective Optimization: Gradient Algorithms


Optimized Cost = 34.0275


Main Effect of Design Variables

```
Optimization completed: The relative first-order optimality measure, 1.426149e-10,
is less than options.OptimalityTolerance = 1.000000e-06, and the relative maximum constraint
violation, 0.000000e+00, is less than options.ConstraintTolerance = 1.000000e-06.
```

Single-objective Optimization: Genetic Algorithms



Different Geometries

Geometric Constraint

$\mathcal{GC}_1(w_{yk}, h_{yk}, h_A, ...) \leq 0$

$\mathcal{GC}_2(w_{yk}, h_{yk}, h_A, ...) \geq 0$

$\mathcal{GC}_3(w_{yk}, h_{yk}, h_A, ...) = 0$

Objective Function

$\min J(w_{yk}, h_{yk}, h_A, ...)$

$J =$

`costModule`$(w_{yk}, ..., \mathcal{P}, ...)$

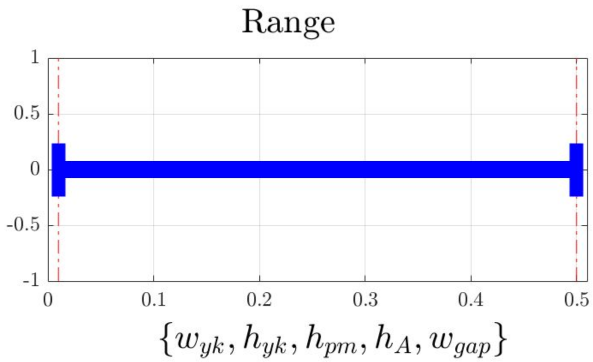
Genetic Algorithm

Optimized Geometry

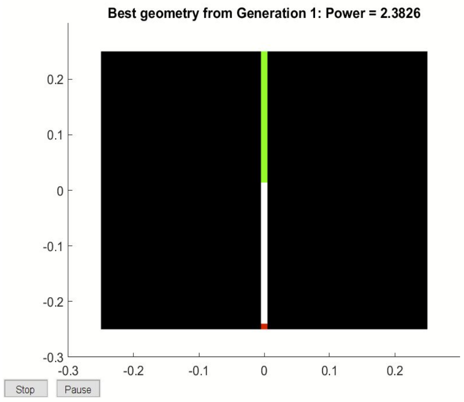
```
% set optimization options
funcTol = 1e-4;
conTol = 1e-4;
popSize = 50;
eliteCount = ceil(.05*popSize);
crossoverRatio = 1.2;
crossoverFraction = .8;
maxStallGens = 4;
```

Lower bounds: `0.01 m`

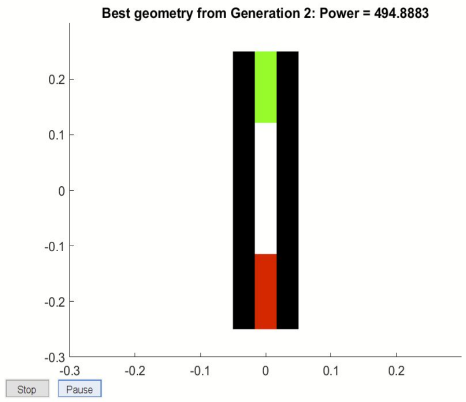
Upper bounds: `0.5 m`



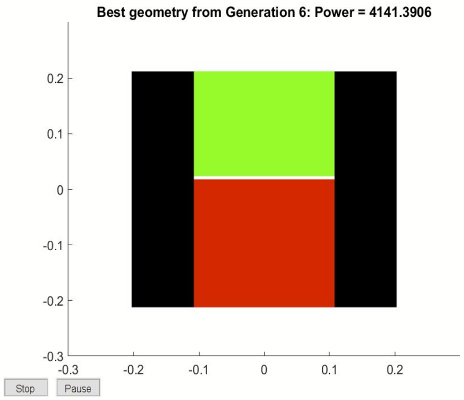
Single-objective Optimization: Genetic Algorithms



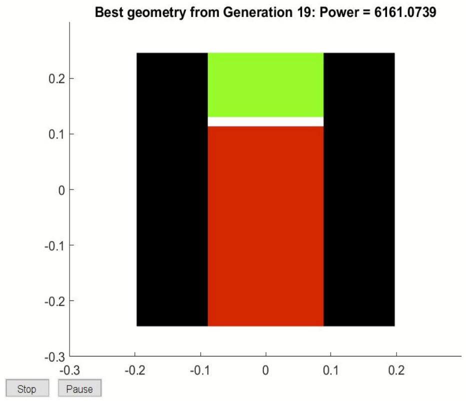
Best geometry from Generation 1: Power = 2.3826



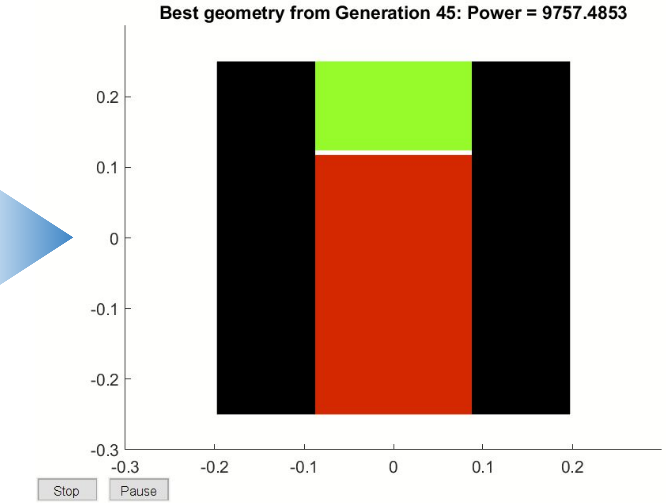
Best geometry from Generation 2: Power = 494.8883



Best geometry from Generation 6: Power = 4141.3906

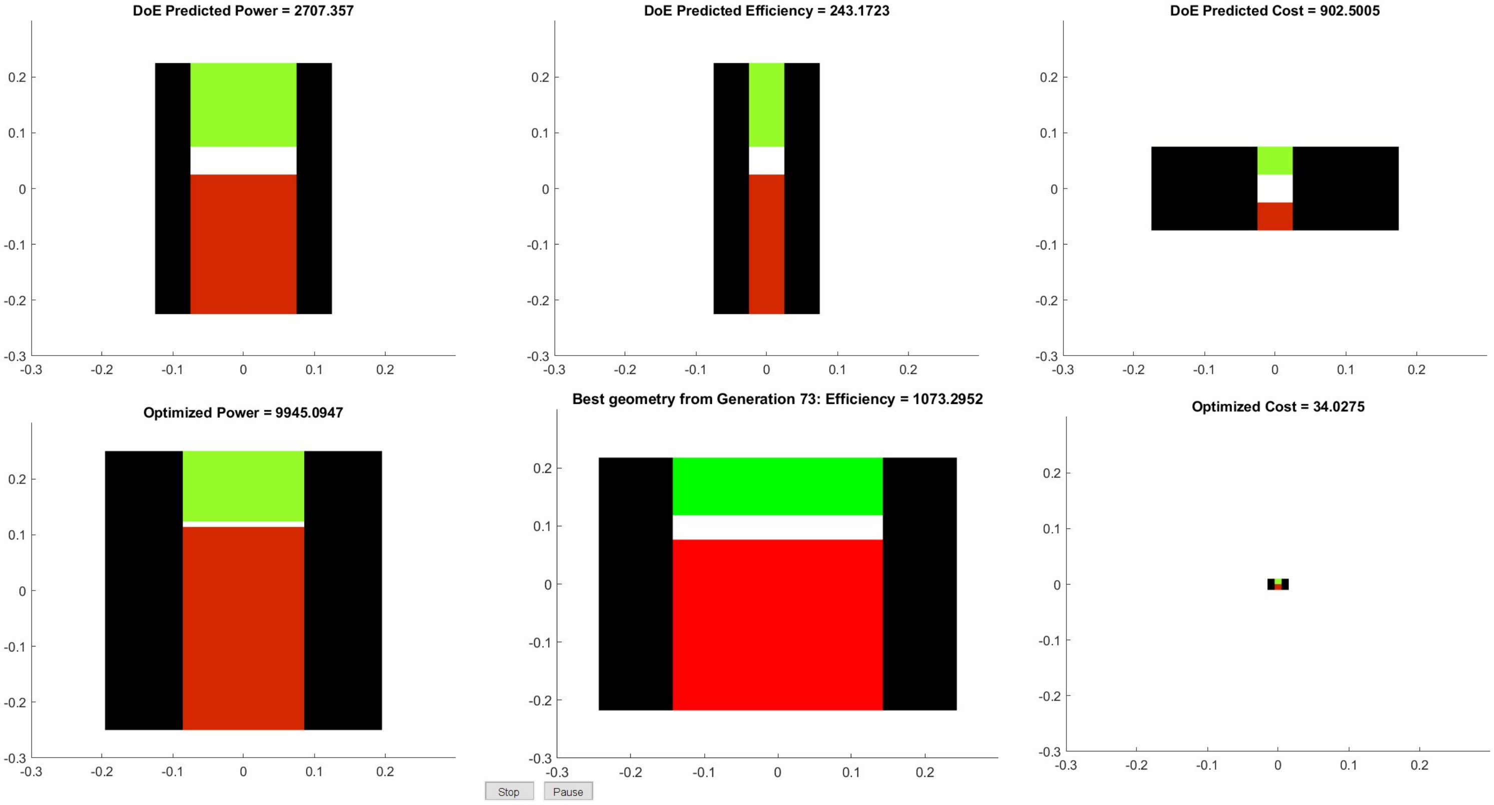


Best geometry from Generation 19: Power = 6161.0739



Best geometry from Generation 45: Power = 9757.4853

Comparing the DoE and Full Optimizations:



DoE Predicted Power = 2707.357

DoE Predicted Efficiency = 243.1723

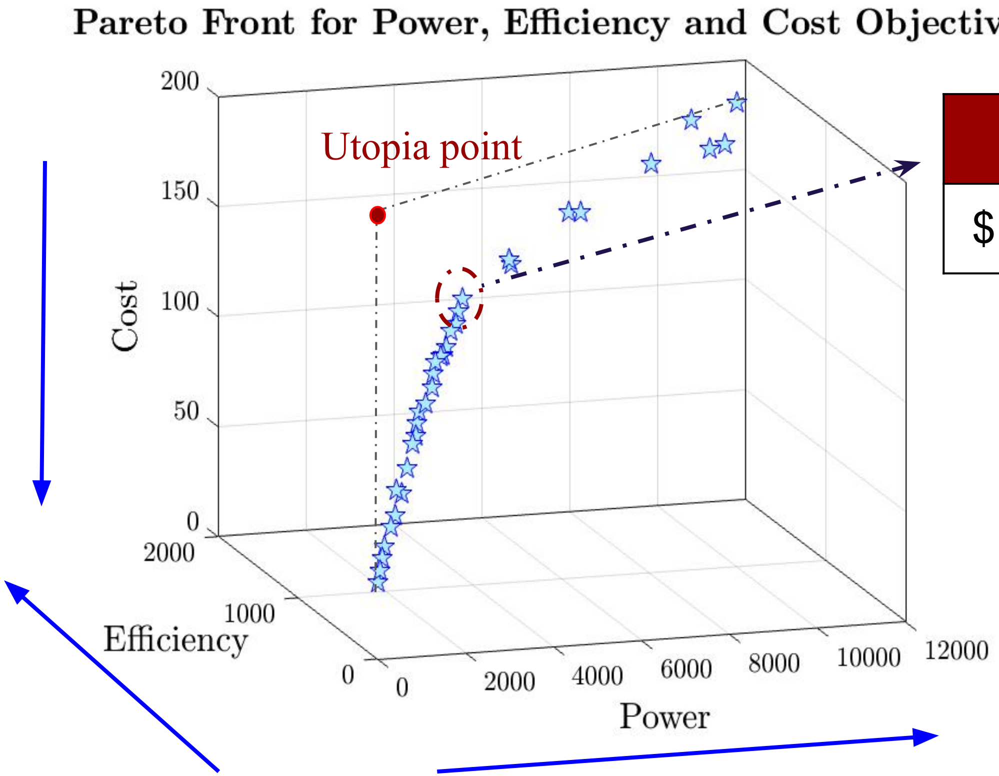
DoE Predicted Cost = 902.5005

Optimized Power = 9945.0947

Best geometry from Generation 73: Efficiency = 1073.2952

Optimized Cost = 34.0275

Multiobjective Optimization

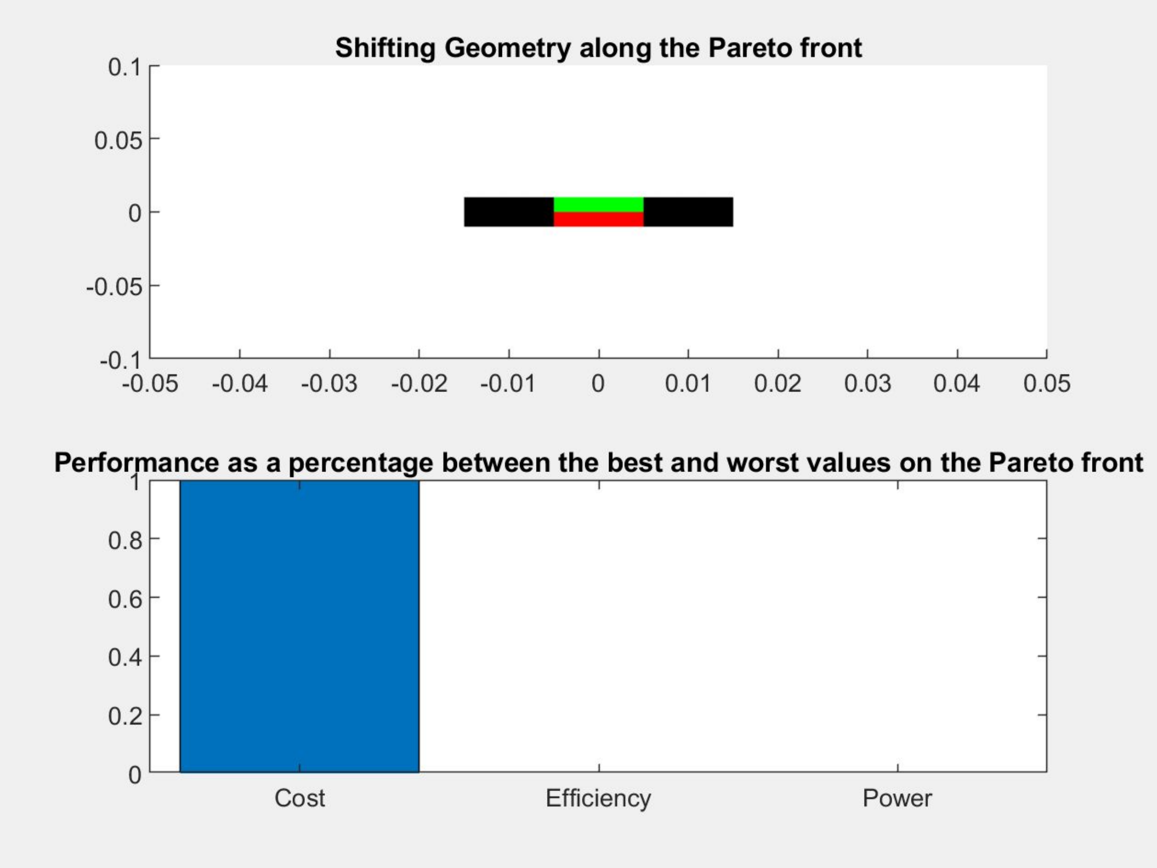


Pareto Front for Power, Efficiency and Cost Objectives

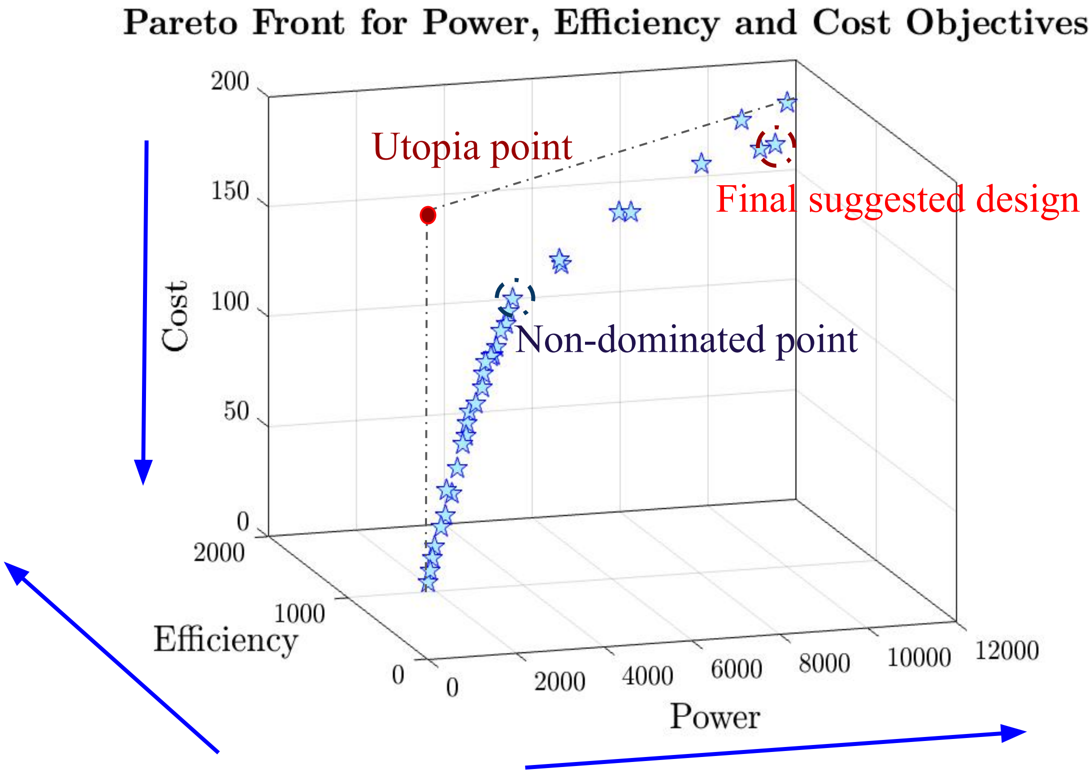
Cost	Power output	Efficiency
$166.3520	9220.7153	1650.3051

```
% set optimization options
funcTol = 1e-4;
conTol = 1e-5;
popSize = 100;
crossoverRatio = 1.2;
crossoverFraction = .8;
maxStallGenerations = 2;
```

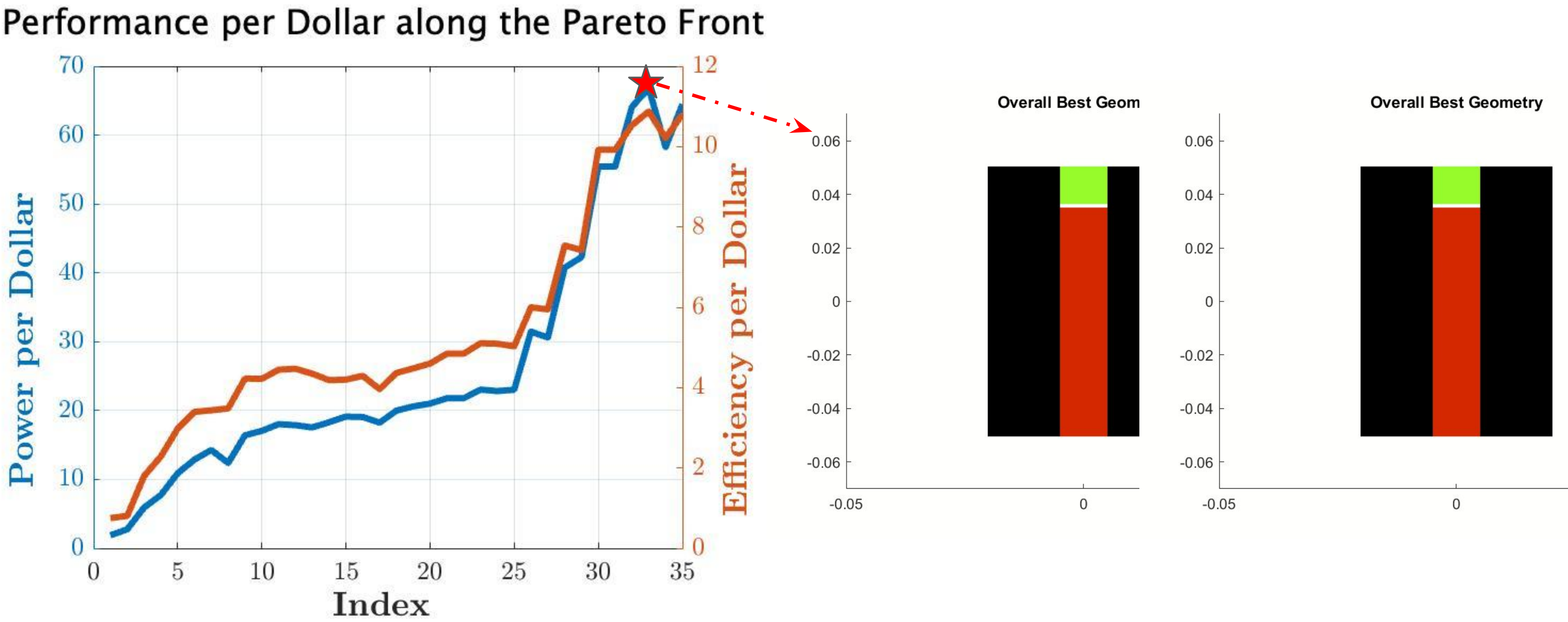
Multiobjective Optimization: Walking the Pareto Front



Final Recommendations: 3 Objective Optimization



Final Recommendations: 3 Objective Optimization



Summary & Future Works

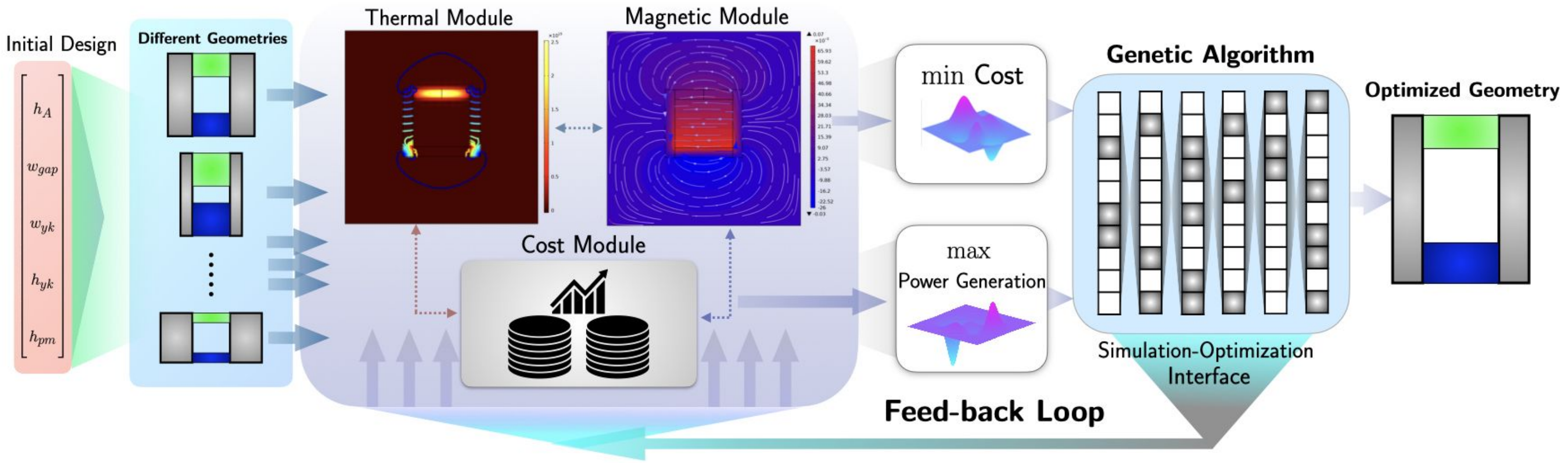
Summary & Takeaways

- Gradient-based methods are mathematically more rigorous and consumes less computational resources
- Heuristic methods are handy and powerful for some black box simulations and general engineering applications
- Each of us has gotten a taste of applying MDO algorithms to engineering problems and hopes to use them more
- We leave the course armed with tools and knowledge to begin applying MDO techniques after graduation!

Next Steps

- Implementing meshing of the TMG as design variables will provide a more comprehensive geometric design
- Include modules for fluid mechanics, wire coils, pumps, etc. for a more comprehensive system model
- Build up 3D simulation model for TMG design and optimization
- Consideration of different materials properties
- Manufacture the TMG in a lab

Q & A


Initial Design
h_A
w_{gap}
w_{yk}
h_{yk}
h_{pm}
Different Geometries
Thermal Module
Magnetic Module
Cost Module
min Cost
max
Power Generation
Genetic Algorithm
Optimized Geometry
Simulation-Optimization Interface
Feed-back Loop