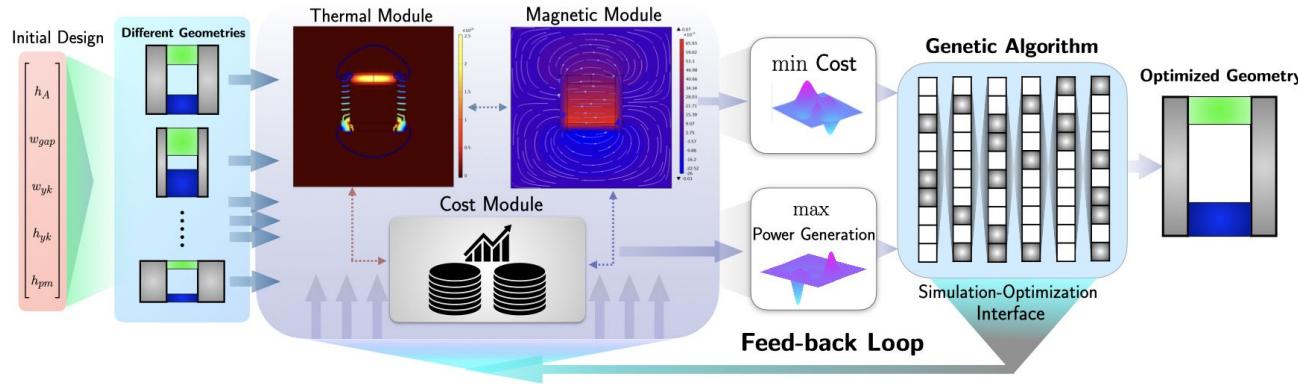


TherMaG: Engineering Design of Thermo-Magnetic Generator with Multidisciplinary Design Optimization



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CORNELL UNIVERSITY

December 2, 2021

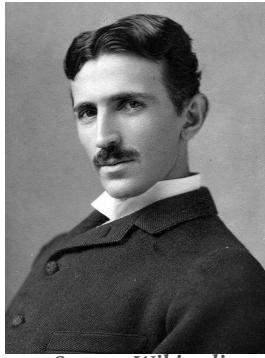
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Background & Motivation



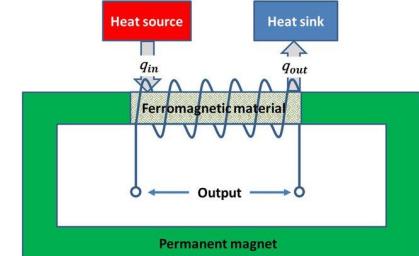
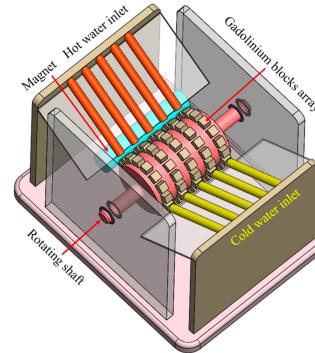
Source: NBC News



Source: Wikipedia



Source: Forbes



Kishore and Priya, Renew. Sust. Ener. Rev., 2021
Ahmed et al., Int. J. Ener. Res., 2021

BEST AVAILABLE COPY
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, 1886. 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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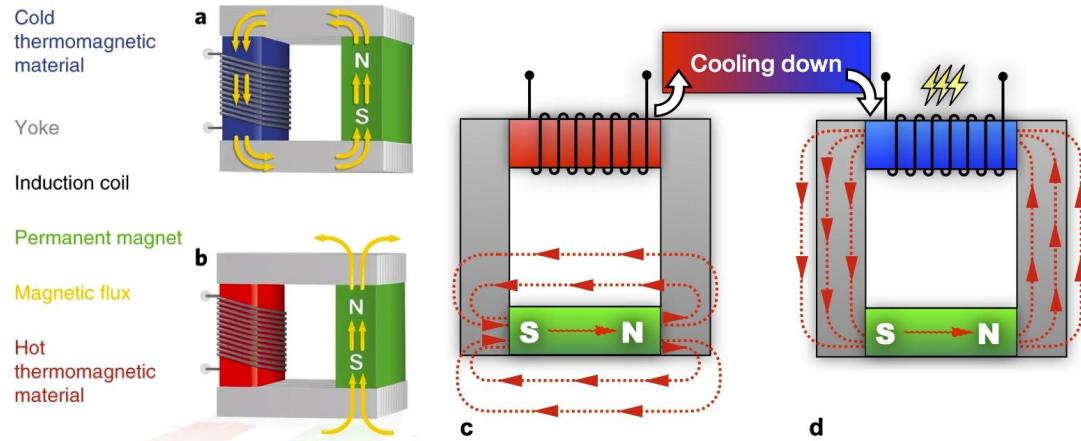
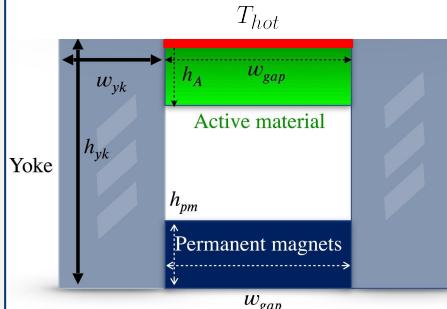


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Problem Formulation

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



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

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

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

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

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,	[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

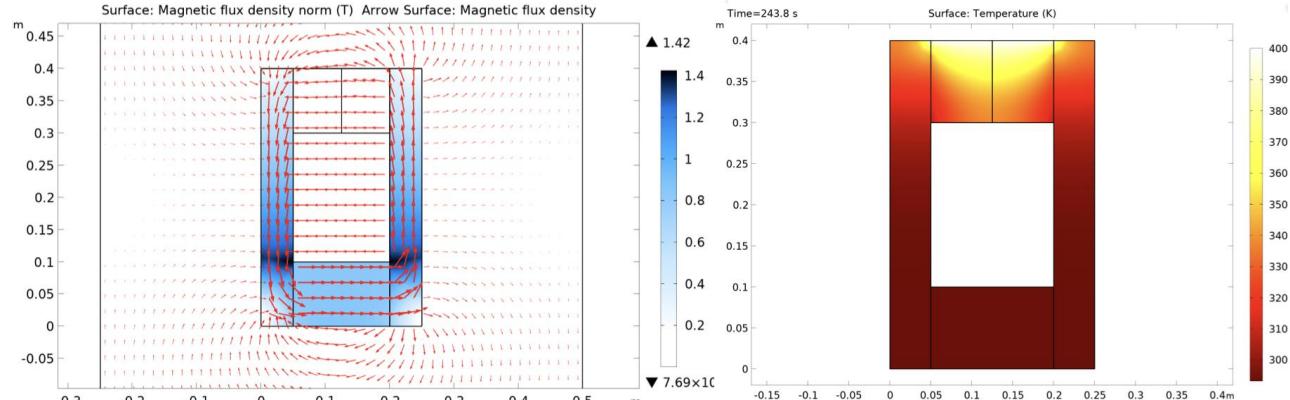
$$P = K \cdot \Delta\Phi^2 \cdot t^{-1}$$

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

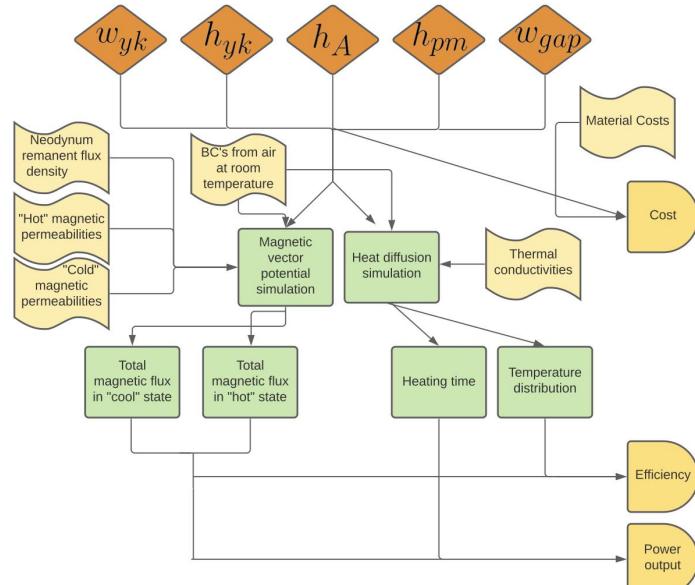
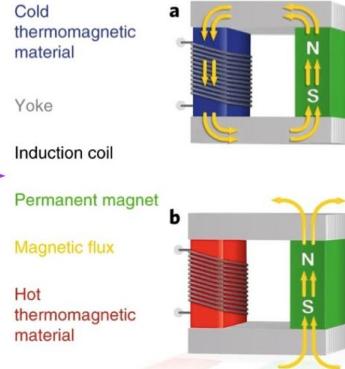


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TMG Engineering Simulation



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

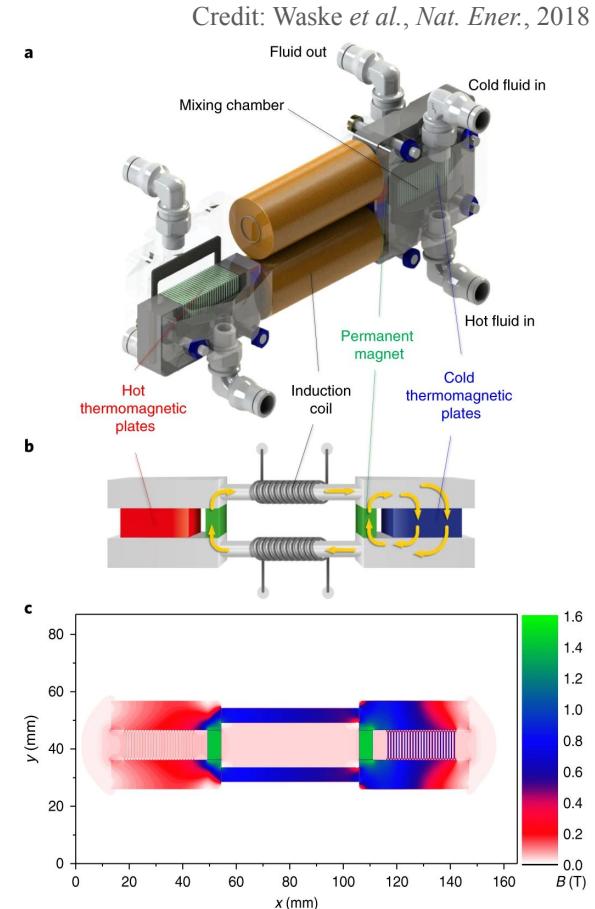
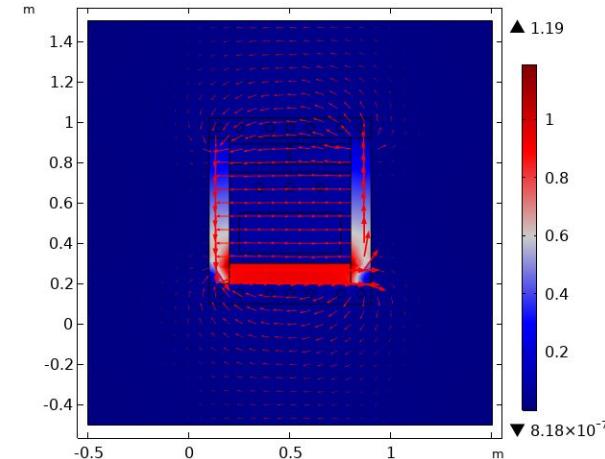
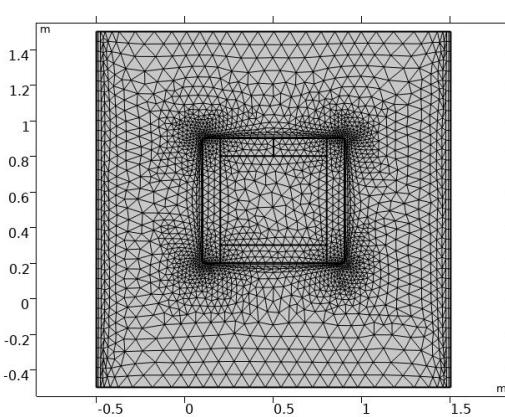
ARTICLES

<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

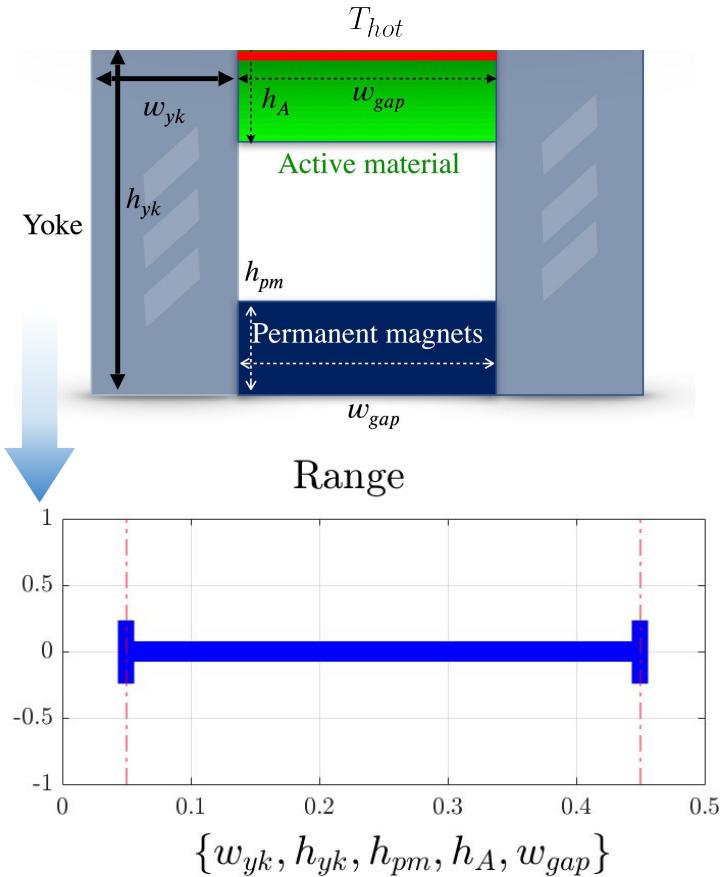
Anja Waske^{1,2,3}, Daniel Dzekan^{1,2}, Kai Sellschopp^{1,2,4}, Dietmar Berger¹, Alexander Stork^{1,2},
Kornelius Nielsch^{1,2} and Sebastian Fähler^{1,2*}



Single-objective Optimization: Design of Experiments

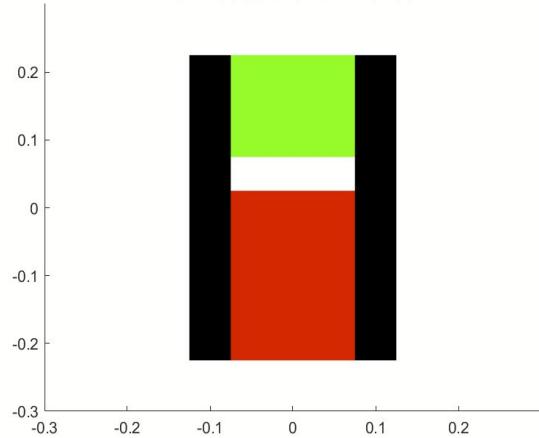
Variable	Objective	Level	Normalized_Effect
"w_yk"	"cost"	0.15	-1.5737
"h_yk"	"cost"	0.15	-1.3385
"h_pm"	"cost"	0.05	-0.66012
"h_A"	"cost"	0.05	-0.70665
"w_gap"	"cost"	0.05	-1.7706
"w_yk"	"power"	0.05	0.18508
"h_yk"	"power"	0.45	0.7413
"h_pm"	"power"	0.25	2.0658
"h_A"	"power"	0.15	0.26235
"w_gap"	"power"	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

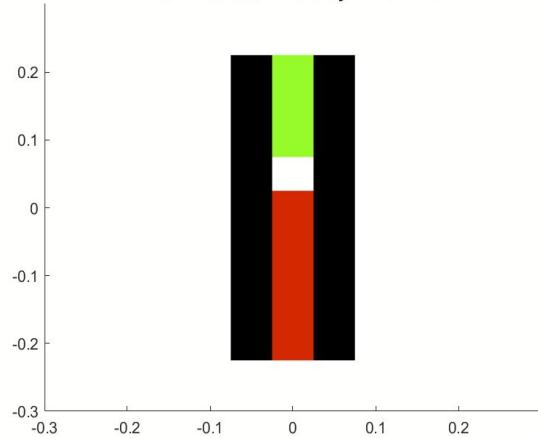


Single-objective Optimization: Design of Experiments

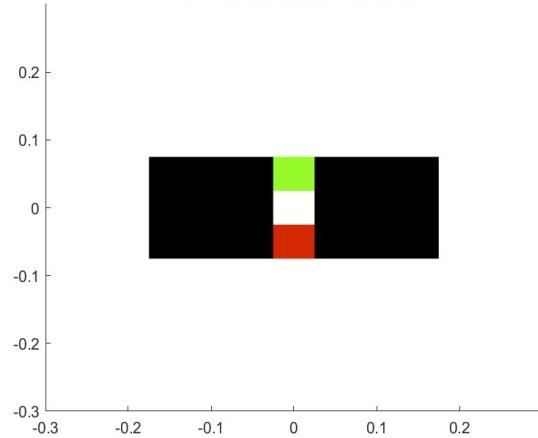
DoE Predicted Power = 2707.357



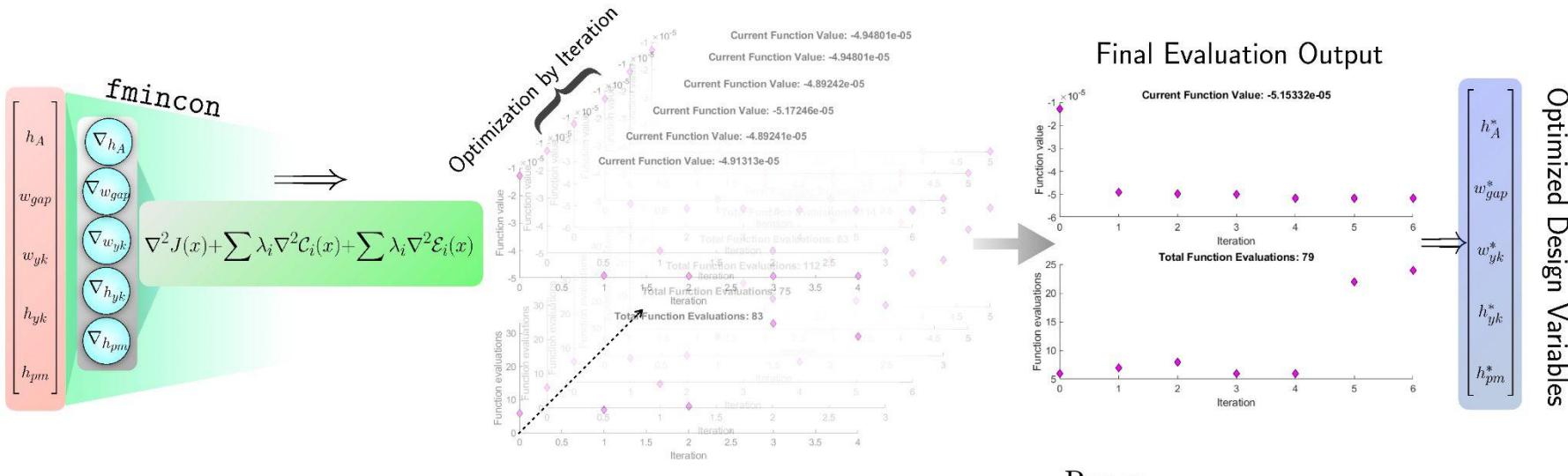
DoE Predicted Efficiency = 243.1723



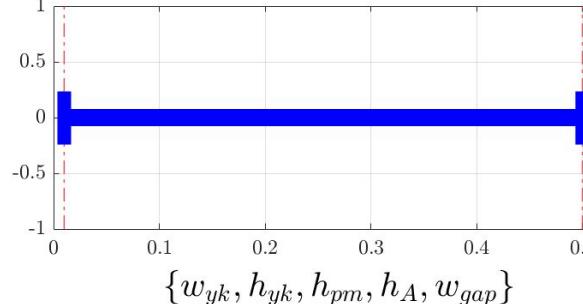
DoE Predicted Cost = 902.5005



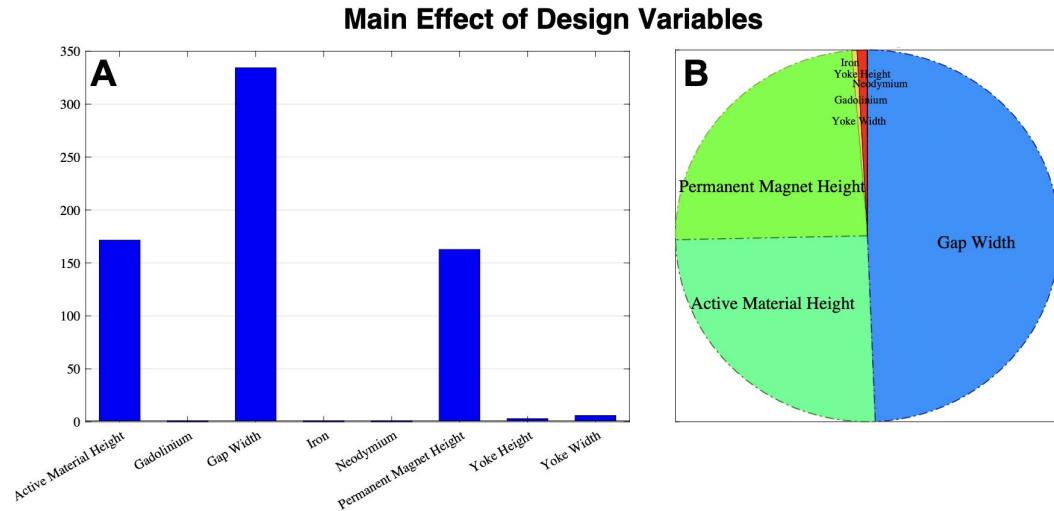
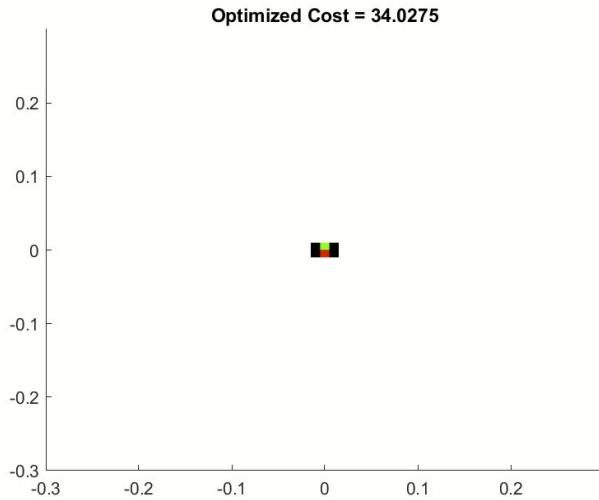
Single-objective Optimization: Gradient Algorithms



Upper bounds: 0.01 m
Lower bounds: 0.5 m



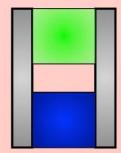
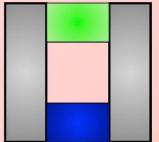
Single-objective Optimization: Gradient Algorithms



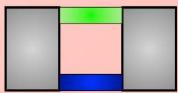
Optimization completed: The relative first-order optimality measure, $1.426149e-10$, is less than options.OptimalityTolerance = $1.000000e-06$, and the relative maximum constraint violation, $0.000000e+00$, is less than options.ConstraintTolerance = $1.000000e-06$.

Single-objective Optimization: Genetic Algorithms

Different Geometries



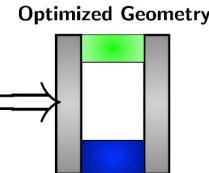
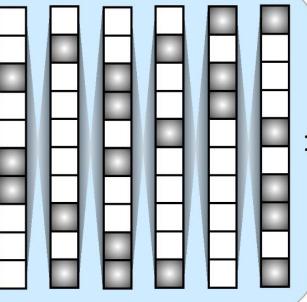
⋮



Geometric Constraint
 $\mathcal{GC}_1(w_{yk}, h_{yk}, h_A, \dots) \leq 0$
 $\mathcal{GC}_2(w_{yk}, h_{yk}, h_A, \dots) \geq 0$
 $\mathcal{GC}_3(w_{yk}, h_{yk}, h_A, \dots) = 0$

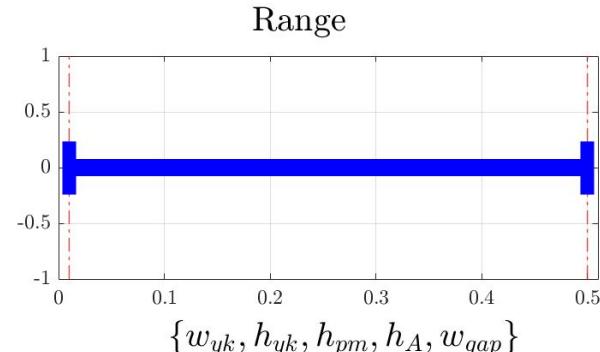
Objective Function
 $\min J(w_{yk}, h_{yk}, h_A, \dots)$
 $J =$
 $\text{costModule}(w_{yk}, \dots, \mathcal{P}, \dots)$

Genetic Algorithm

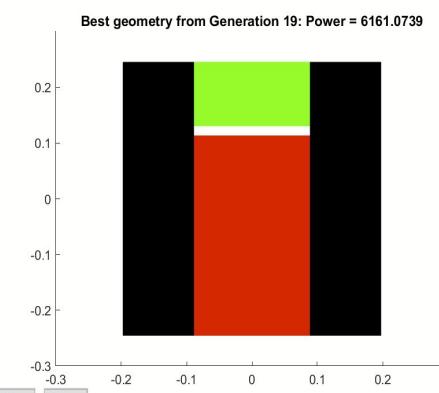
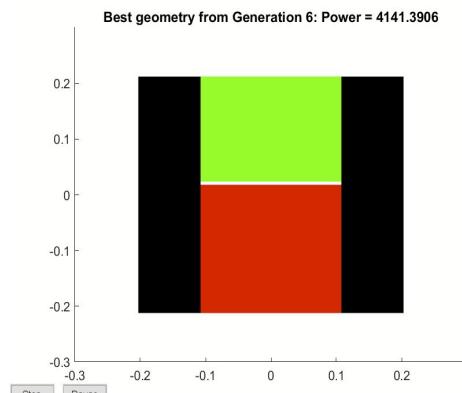
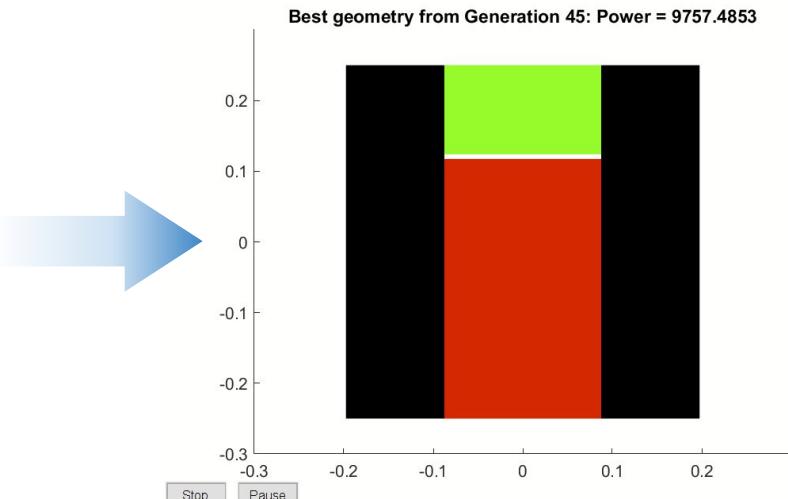
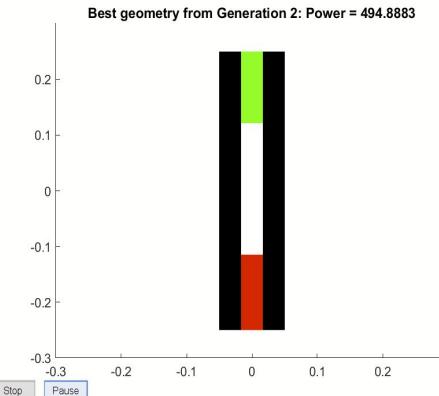
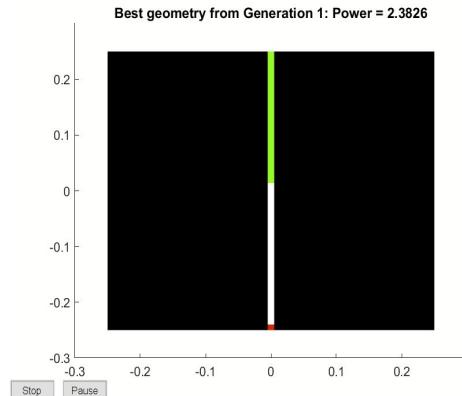


```
% set optimization options
funcTol = 1e-4;
conTol = 1e-4;
popSize = 50;
eliteCount = ceil(.05*popSize);
crossoverRatio = 1.2;
crossoverFraction = .8;
maxStallGens = 4;
```

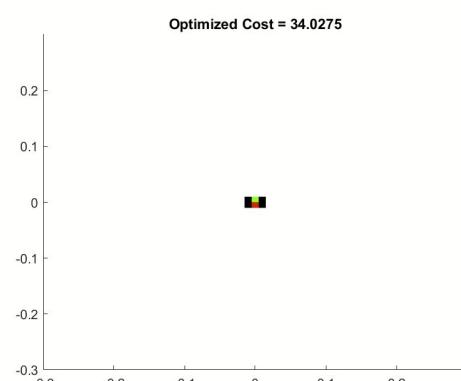
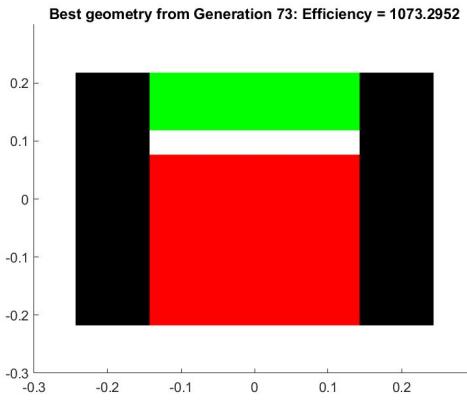
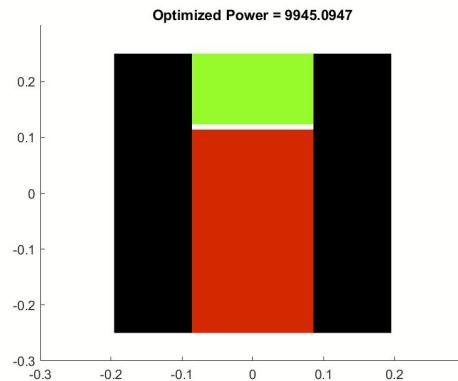
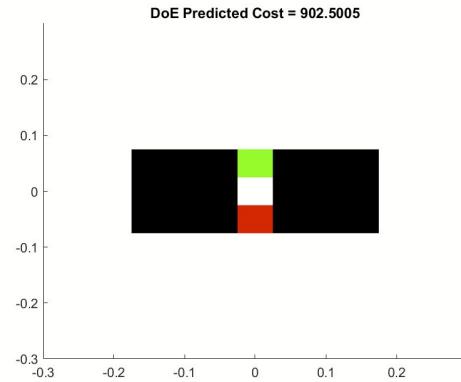
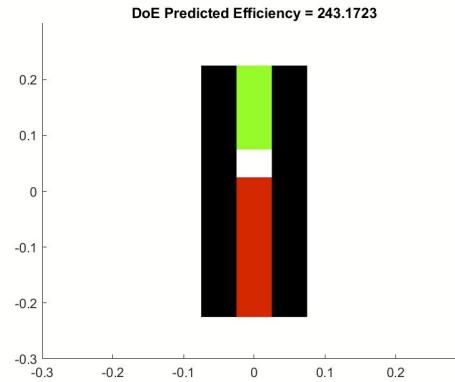
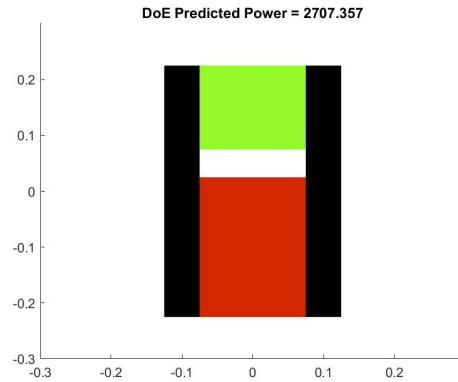
Lower bounds: 0.01 m
Upper bounds: 0.5 m



Single-objective Optimization: Genetic Algorithms

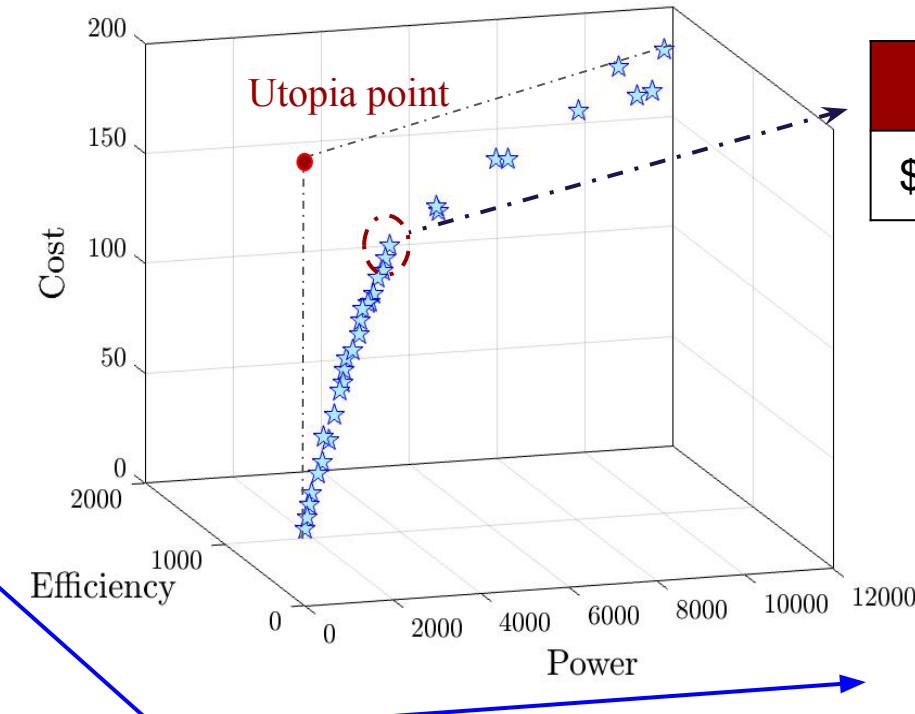


Comparing the DoE and Full Optimizations:



Multiobjective Optimization

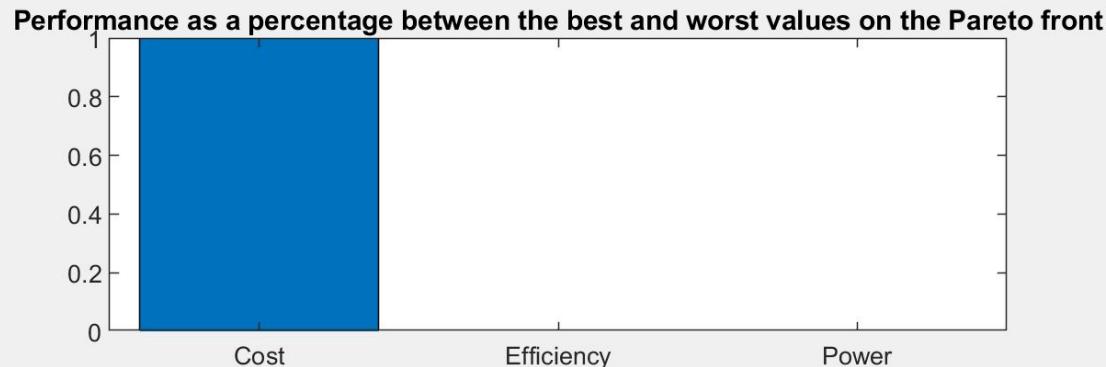
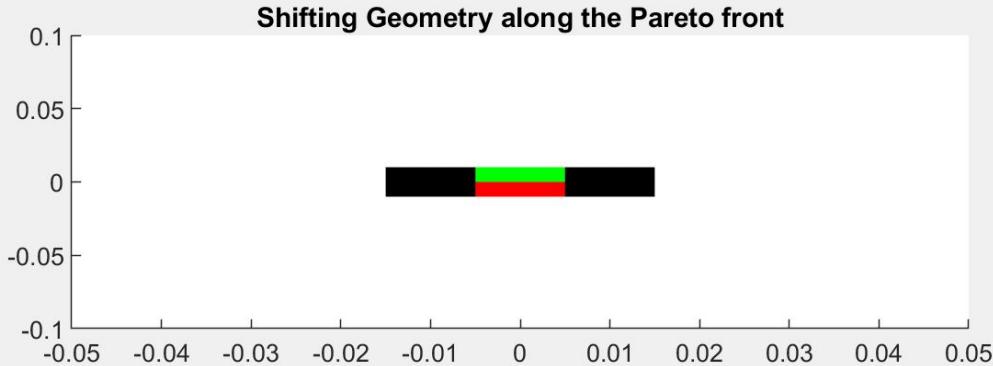
Pareto Front for Power, Efficiency and Cost Objectives



Cost	Power output	Efficiency
\$166.3520	9220.7153	1650.3051

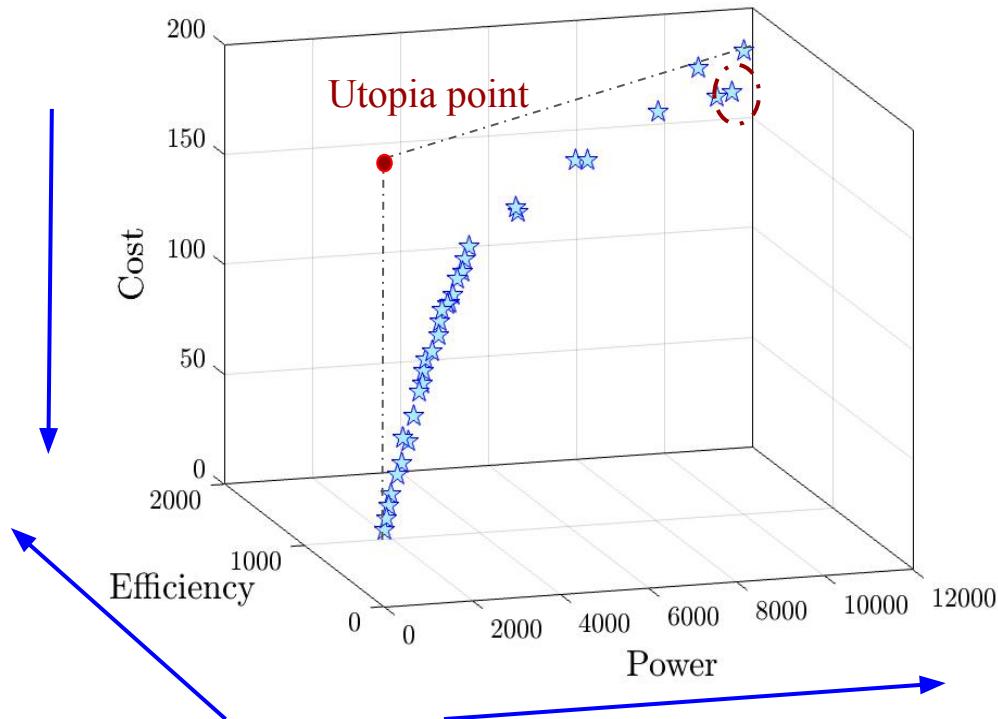
```
% set optimization options
funcTol = 1e-4;
conTol = 1e-5;
popSize = 100;
crossoverRatio = 1.2;
crossoverFraction = .8;
maxStallGenerations = 2;
```

Multiobjective Optimization: Walking the Pareto Front



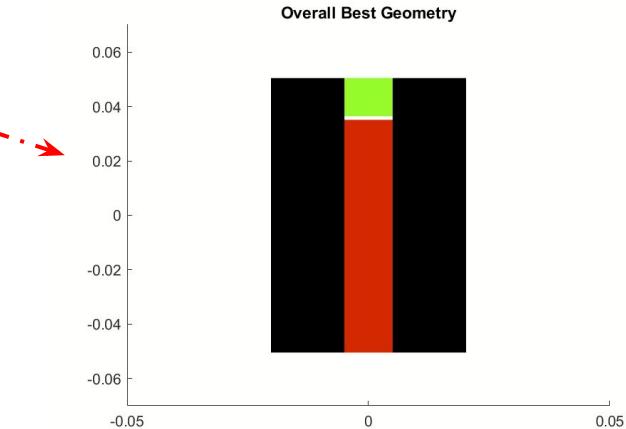
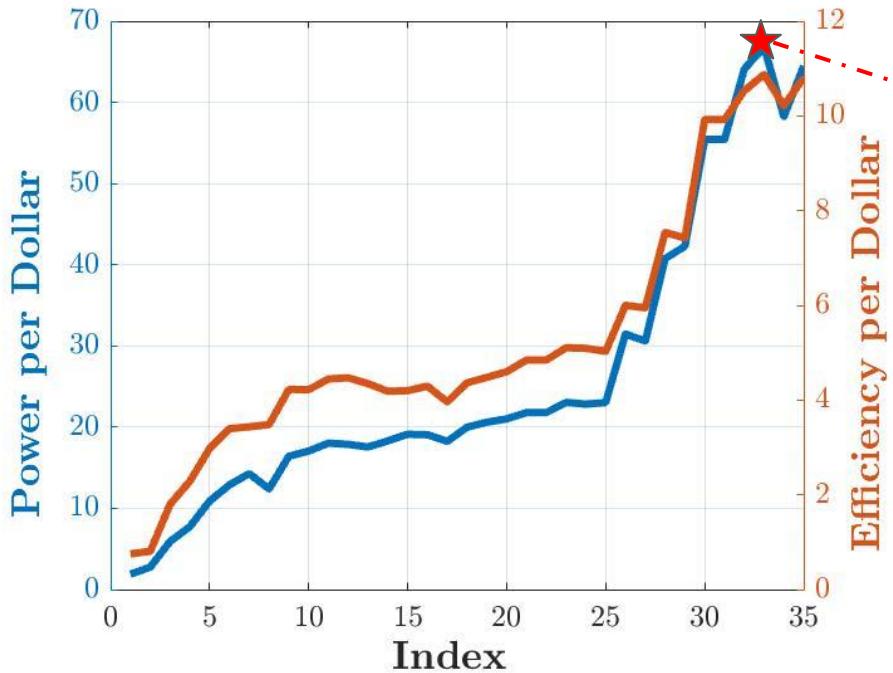
Final Recommendations: 3 Objective Optimization

Pareto Front for Power, Efficiency and Cost Objectives



Final Recommendations: 3 Objective Optimization

Performance per Dollar along the Pareto Front



Cost	Power output	Efficiency
\$167.71	11,205	1832.6

$$\begin{aligned} & [w_{yk}, h_{yk}, h_{pm}, h_A, w_{gap}] \\ & [.0152; .1009; .0855; .0140; .0100] \end{aligned}$$

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

