NREL
NATIONAL RENEWABLE ENERGY LABORATORY

MADE3D: Enabling the Next-Generation High-Torque- Density Wind Generators by Additive Design and 3D Printing

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5th Conference for Wind Power Drives CWD 2021

CWD 2021 & ATK 2021
9.-11.03.2021
VIRTUAL LIVE EVENT

Recent Trends in Large Wind Turbine Projects

New offshore wind project with a trend toward direct-drive generators

- Size and mass bring challenges
- Diameter > 10 m
- Original equipment manufacturers are moving their factories to port locations
- Huge cranes to lift to a 140-m hub height
- High dependence on rare-earth elements
- **Generator costs >$3 million**

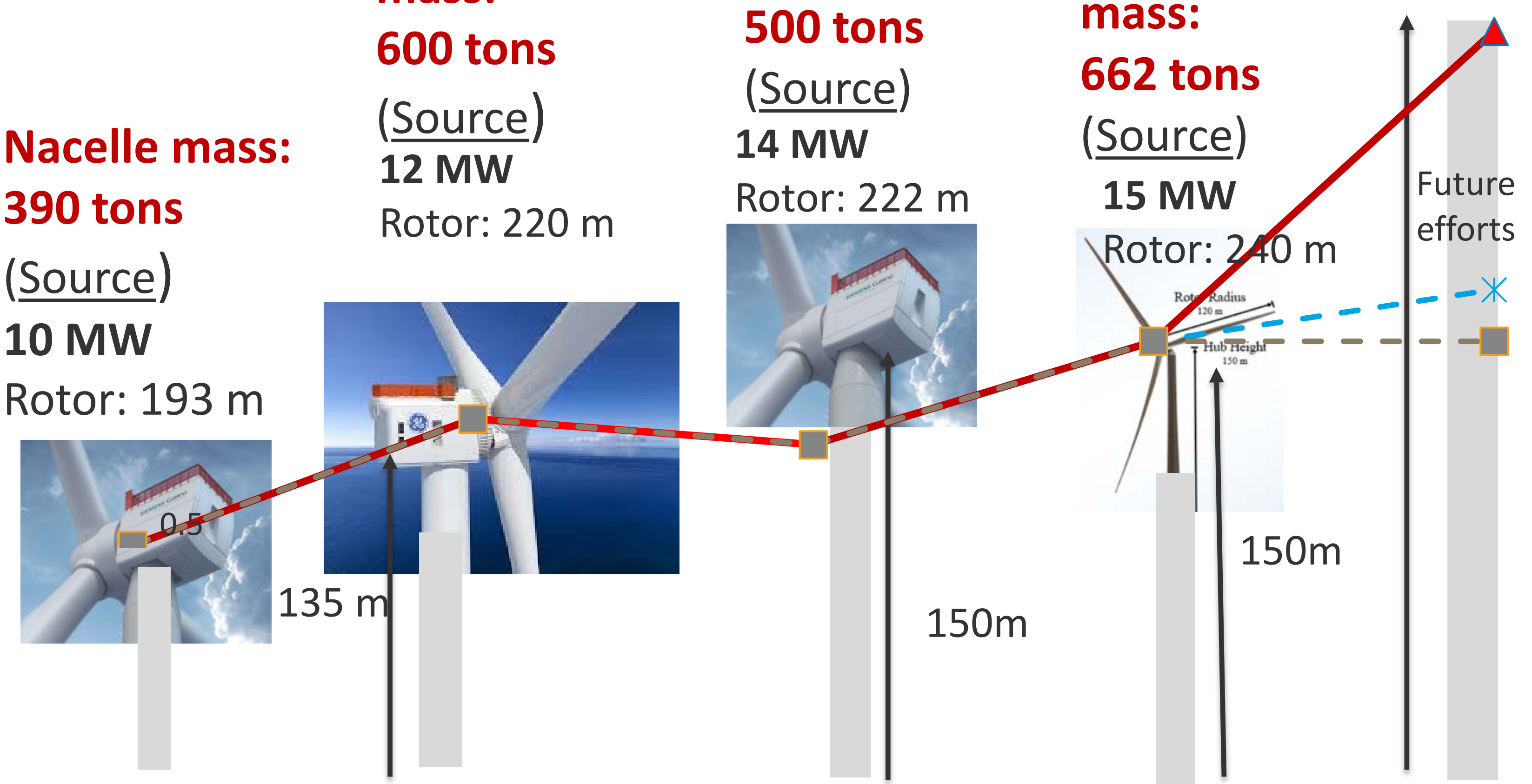
Nacelle mass: 390 tons (Source)
10 MW
Rotor: 193 m

Nacelle mass: 600 tons (Source)
12 MW
Rotor: 220 m

Nacelle mass: 500 tons (Source)
14 MW
Rotor: 222 m

Nacelle mass: 662 tons (Source)
15 MW
Rotor: 240 m

Nacelle mass: unknown
20 MW
Rotor: 252 m



Siemens Gamesa
Photo credit : *SGRE*
Hollandse Kust South 1&2 project in the Dutch North Sea

GE Haliade-X
Photo credit :*GE*
Ocean Wind off the coast of New Jersey, and the 120MW Skipjack off Maryland

Siemens Gamesa
Photo credit :*SGRE*
Coastal Virginia Offshore Wind (CVOW) project

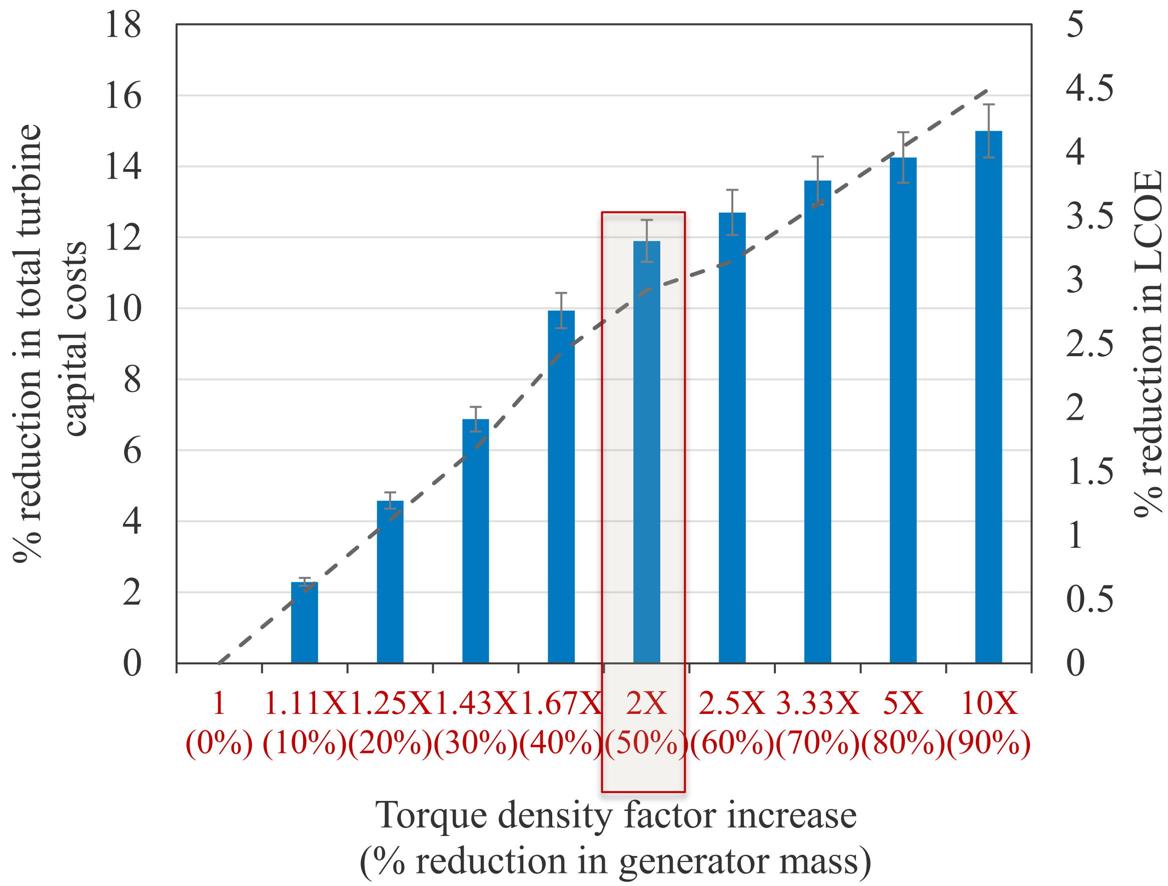
IEA 15 MW

Future

Day rate: >$200,000

Photo credits : *SGRE*, *GE*

The Quest for High-Torque Densities



Reduction in total capital costs when increasing the torque density for the International Energy Agency (IEA) 15-MW reference wind turbine[1]

Impact on levelized cost of energy (LCOE): 3%–3.5% improvement

There is a need for new approach

- Improving the torque densities by up to 2X can help reduce turbine capital costs by 12%.
- Up to 50% reduction in generator mass alone will be required
- **Is this achievable for a radial-flux permanent-magnet machine**?
  - **Design: two-dimensional assumptions on geometry** result in excessive use of magnetically active and inactive materials
  - **Materials:** High-grade neodymium-iron-boron (NdFeB) magnets - brittle with expensive critical rare-earth elements, such as dysprosium (Dy)
  - Lighter cores will necessitate lightweight alloys with high saturation flux densities and **better near-net shaping** and mechanical strength
  - **Manufacturing**: Prohibitively time- and labor-intensive

[1] Barter, G., Mendoza, N., Sethuraman L., Keller, J., Bennion, K., Kekelia, B., Cousineau, E., Feng, X., Kotecha, R., and Narumanchi, S. 2020. *Advanced next-generation high-efficiency lightweight wind turbine generator analysis*. National Renewable Energy Laboratory. NREL/TP-5000-77516.

Our Solution

MADE3D in USA

NREL Transforming ENERGY

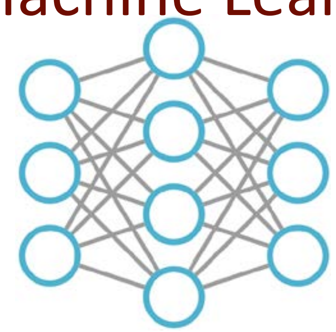
Manufacturing and **Additive Design** of **Electric** Machines enabled by **3-D**imensional printing (MADE3D) is a multiyear project sponsored by the U.S. Department of Energy (DOE) aimed at overcoming some of the challenges and kick-starting a new paradigm for on-site manufacturing of high-power-density electric machine designs.

MADE3D-AML leverages advanced multiphysics topology optimization and LCOE toolsets to produce 3D-printable, high-torque-density electric machines with low-cost, lightweight materials.

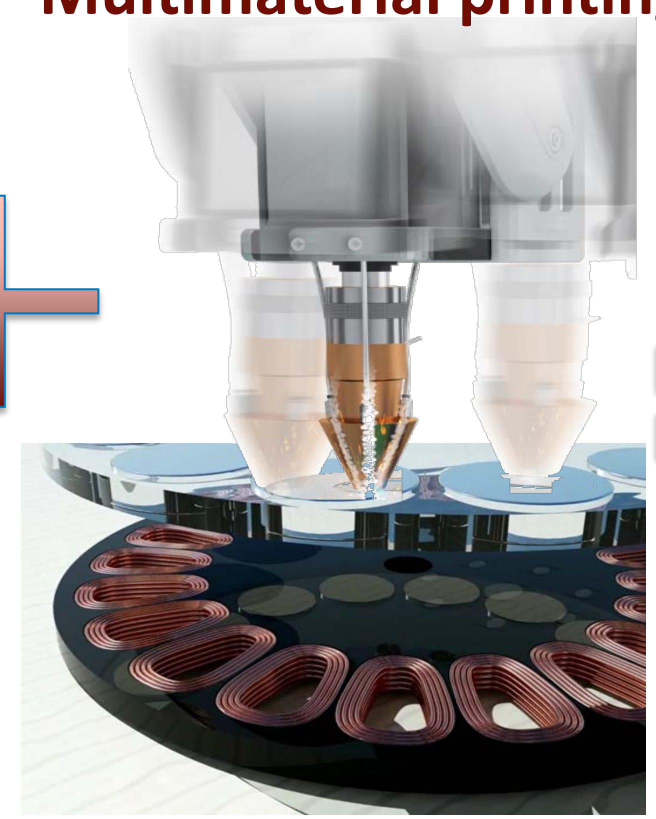
Additive Design

Topology Optimization

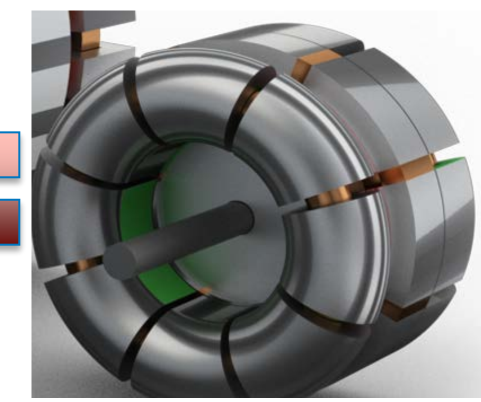
Machine Learning



Multimaterial printing



High-torque-dense designs enabled by additive manufacturing



Enables complexity and up to 50% weight reduction compared to traditional designs

Designs with 3D-printed stator cores

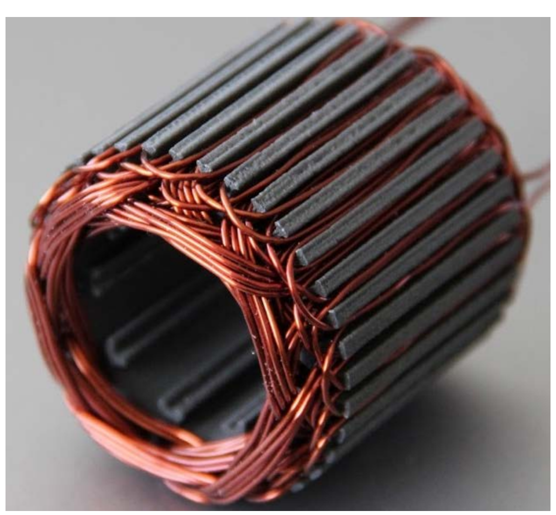
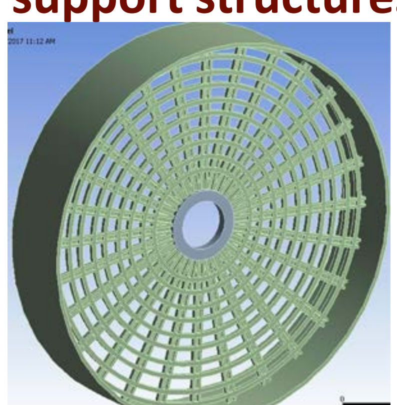


Photo credit : makeSEA

Designs with 3D-printed support structures



Designs with 3D-printed magnets

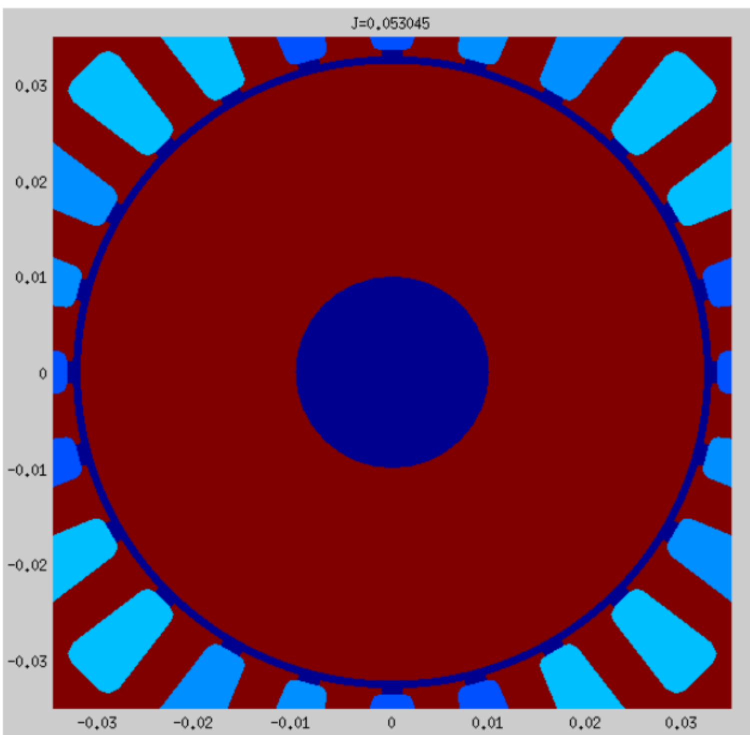
Photo credit : ORNL

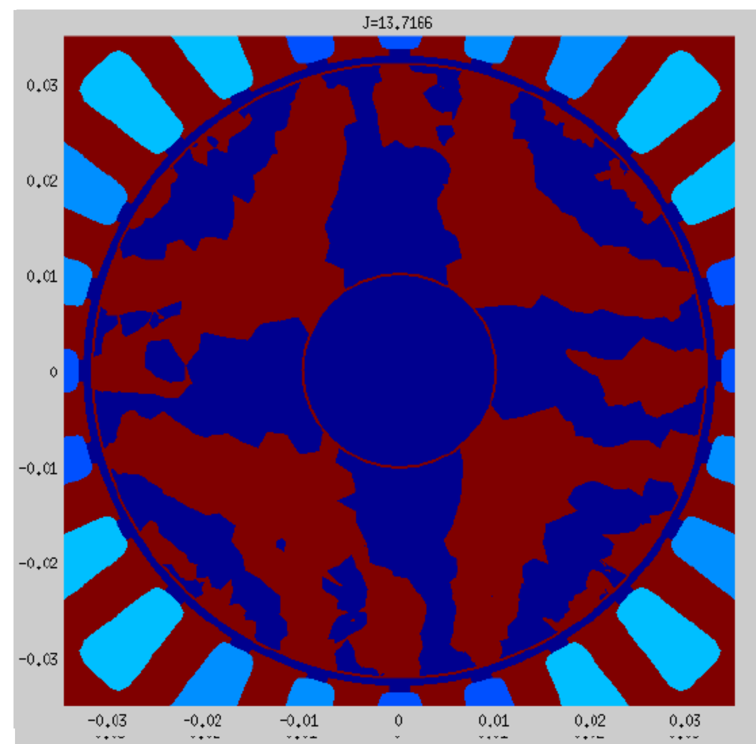
Enabling technologies include new materials and advanced printing processes including binder jet additive manufacturing and selective laser melting.

Photo credit : ExOne

Advanced Design: Topology Optimization

- **A technique** to control material distribution as well as geometrical boundaries
- > 50 design variables (each mesh element is a variable)



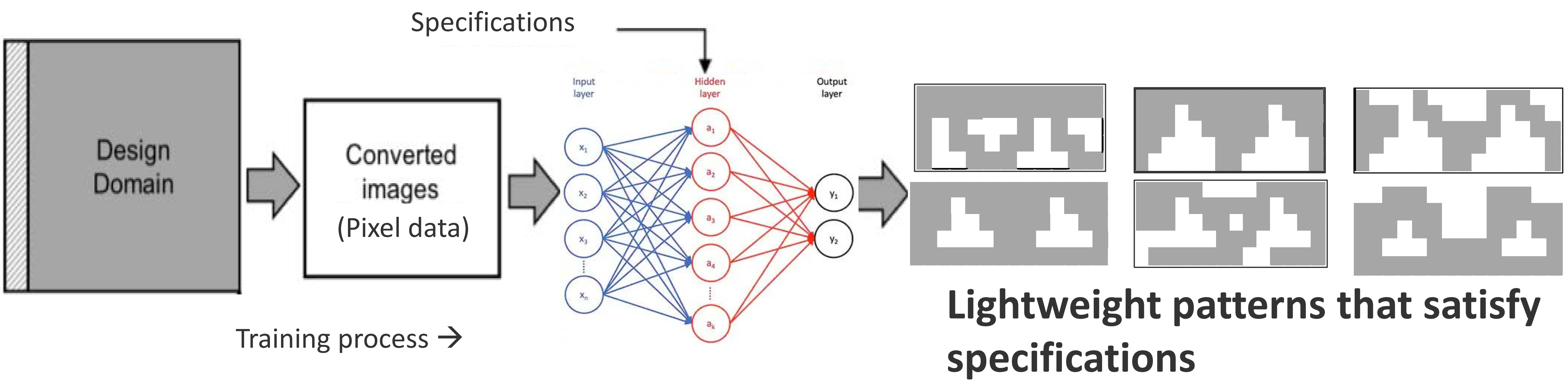


iter $= 0$, $\mathcal{J}(u) = 0.053$

Source: Gangl et al. 2016. "Sensitivity-Based Topology and Shape Optimization for Electrical Machines subject to Nonlinear Magnetostatics."

- Designs are too complex
- Largely focused on material removal
- **Computationally prohibitive** for large structures
  - A single optimization run can take a few days even when distributing over a high-performance-computing cluster with 50–100 nodes.

MADE3D-Advanced Machine Learning (AML) as the Accelerator

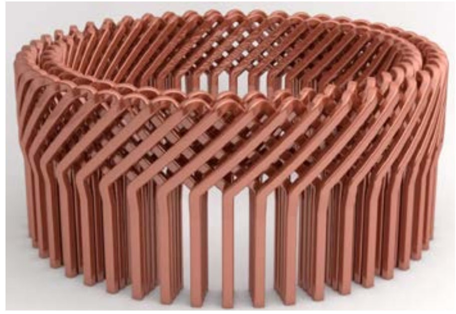


- MADE3D-AML is NREL's new proprietary software for performing multiphysics topology optimization (TO) of electric machines. This tool:
  - Employs deep generative machine learning algorithms
  - Has no limit on design variables
  - Has high robustness in image recognition
  - Can be trained to behave as surrogate models for regression relatively quickly, thereby greatly reducing computational costs
  - **Can identify multiple designs that satisfy a criteria.**

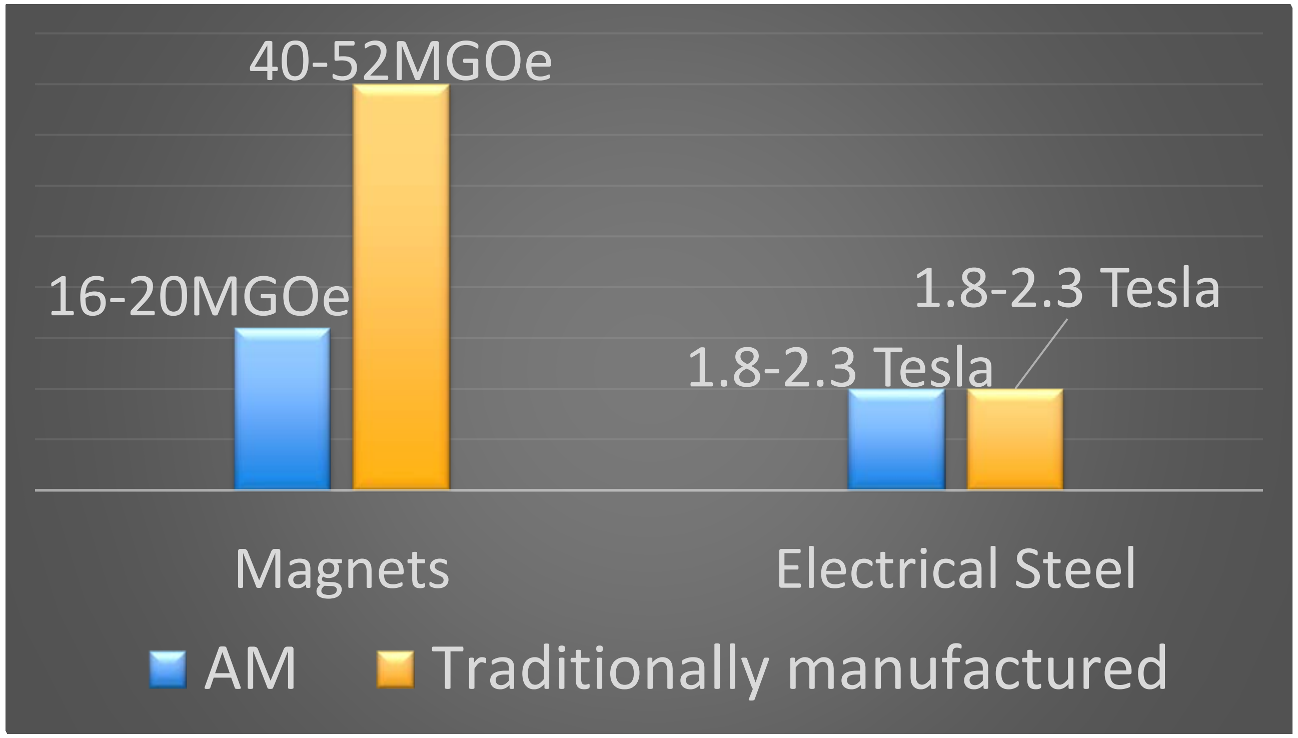
Additive Manufacturing Is Gaining Popularity for Small Motors

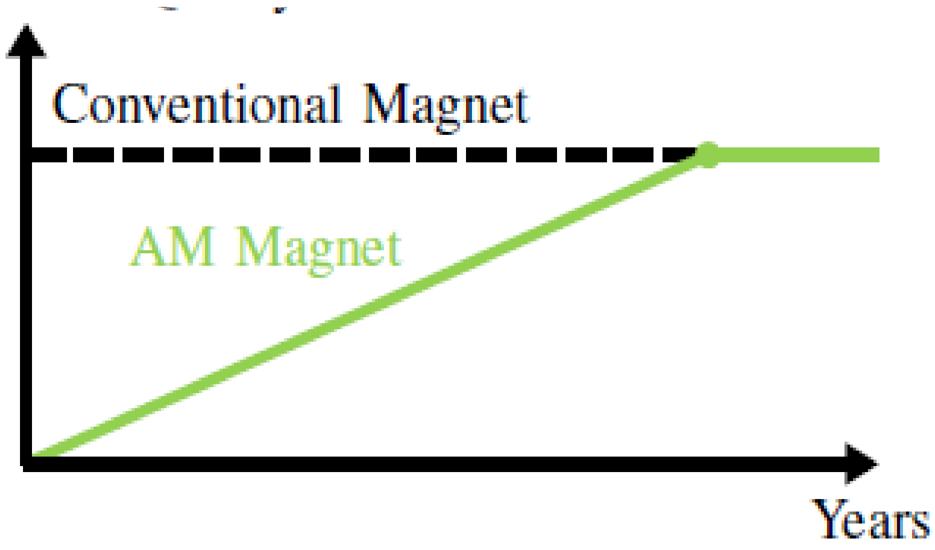
- Multimaterial processes for magnets, copper windings, and iron core are under development
- **Design for additive manufacturing** provides new opportunities with weaker magnets[2]

Equipmake's motor utilizing 3D-printed cooling channels and magnets



3D-printed windings by Additive Drives



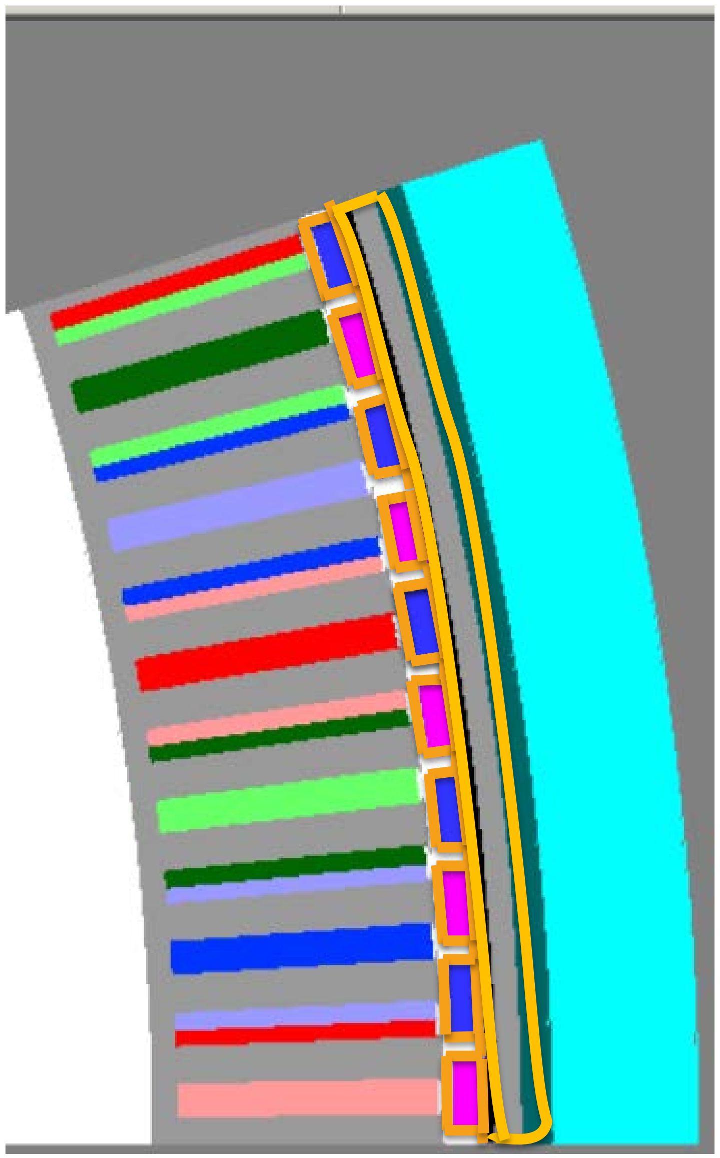


Additive manufacturing (AM) magnet material quality assumption[2]

[2] McGarry et al. 2019. *Optimization of Additively Manufactured Permanent Magnets for Wind Turbine Generators*. 2019 IEEE International Electric Machines & Drives Conference (IEMDC). IEEE International Electric Machines & Drives Conference.

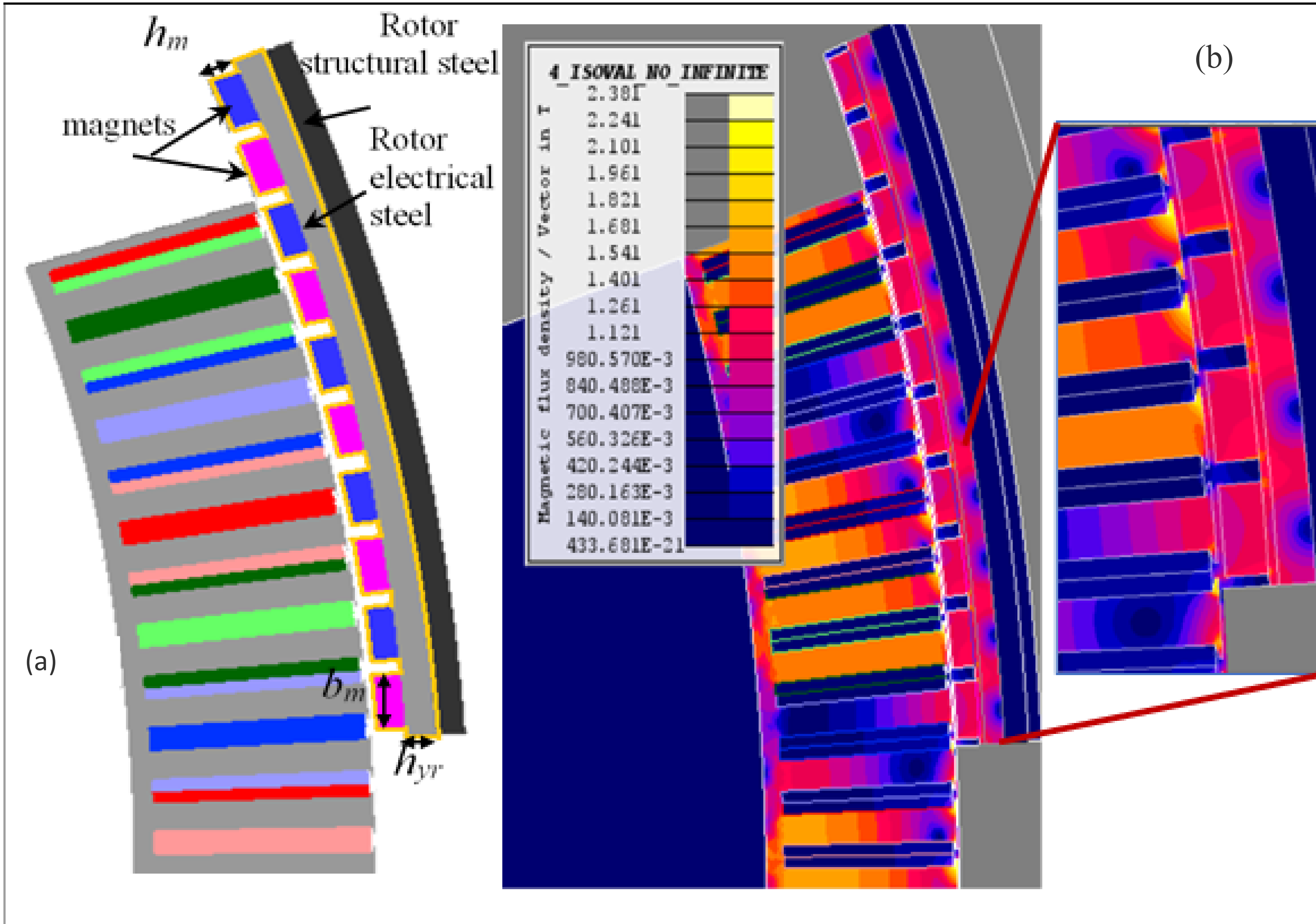
Objectives of the Present Work

Examine the magnetic optimization potential for the rotor of the IEA 15-MW reference wind turbine generator using additive manufacturing and topology optimization powered by conventional approach and the National Renewable Energy Laboratory's new software, MADE3D-AML.



- **Generator rotor active mass: ~58 tons**
- **Focus: Rotor active regions including the back iron and magnets**
- **Dimensions and masses**
  - **Rotor core thickness: 63.62 mm**
  - **$M_{rotorcore}$: 34.22 tons**
  - **Magnet thickness: 58.39 mm**
  - **M_{mag}: 24.08 tons**
  - **$T_{mean}/(M_{rotorcore} + M_{mag})$: 351.28 Nm/kg**
- **Optimization goal: maximize torque/rotor active mass**

Flux Contour at Rated Torque



Reference 15-MW generator sector (a) technology optimization design domain are bounded in yellow and (b) the magnetic flux density contour at rated torque conditions. The maximum rotor flux loading at rated torque condition was 1.35 Tesla.

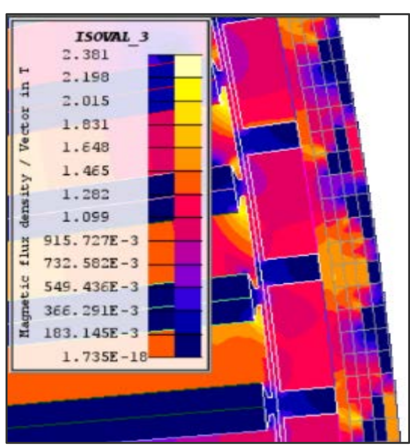
Approach

- Investigate **single-material TO** AND **multimaterial TO**

Material removal: single composition of magnets and steel for the rotor core

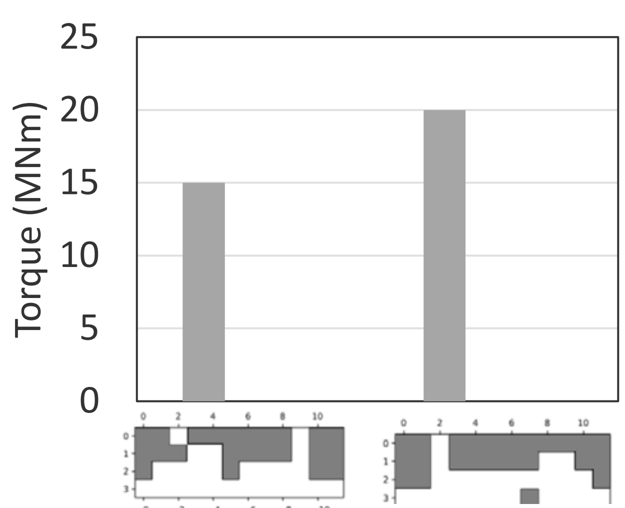
Material replacement: two different types of materials for both the magnets and rotor core

- **We use a four-step experimental design approach**

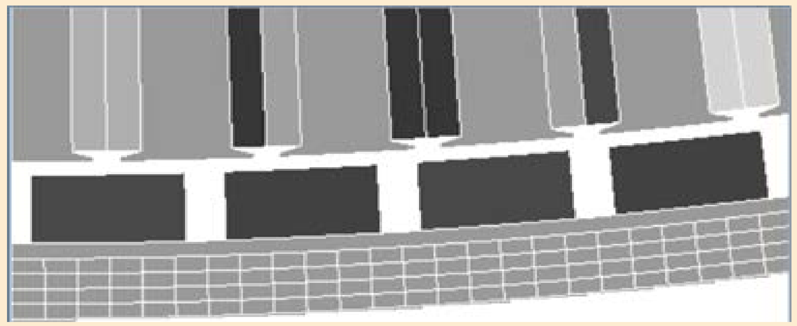
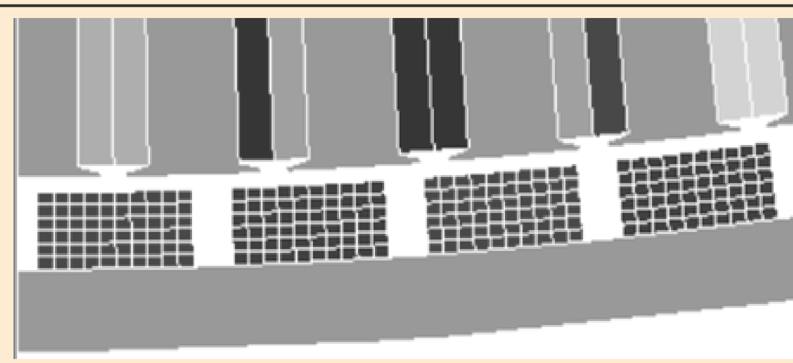
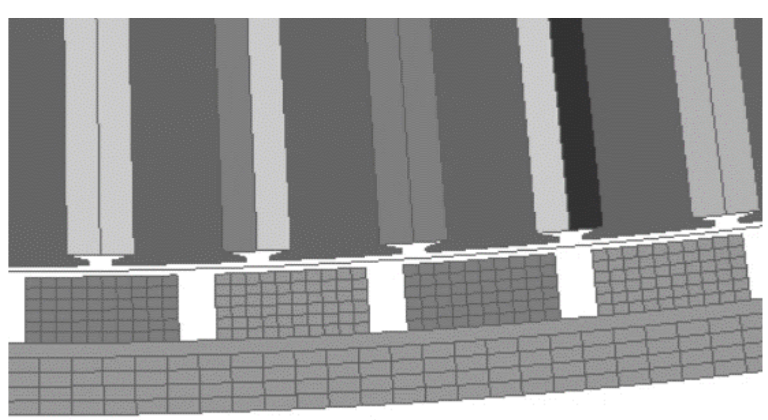


TRAINING DATA USING FINITE ELEMENT ANALYSIS (FEA)
- Design space definition
- Sampling
- Perform transient magnetic FEA
- Extract performance

→ **DEVELOP SURROGATE MODELS** → **PERFORM TOPOLOGY OPTMIZATION** → **VALIDATE AGAINST FINITE ELEMENT ANALYSIS**

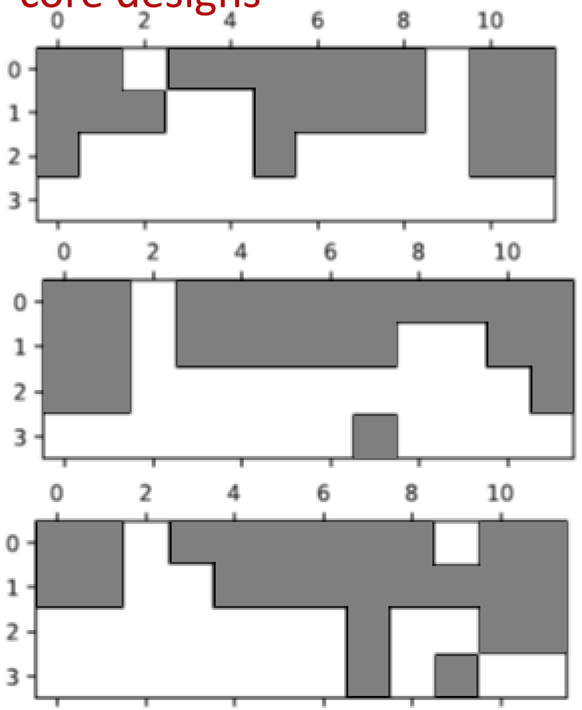


Design Space Definition and Scenarios

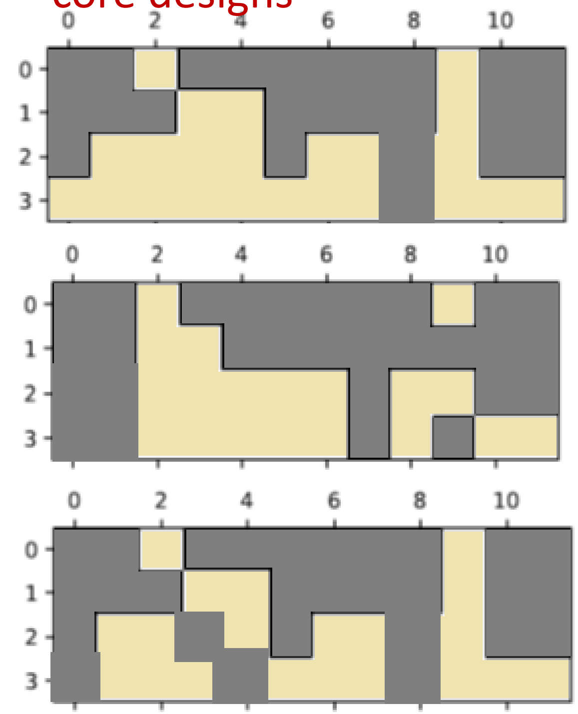
Case #	Mesh Region	Material 1	Material 2
1. Core only	 12-by-4 grid	Ferro-silicon alloy Fe-3.0Si	Air
			Soft magnetic composite (SMC)
2. Magnets only	 10-by-6 grid per pole	Sintered magnet (NdFeB)	Air
			Polymer bonded NdFeB magnet with zero dysprosium
3. Core and magnets	 12-by-4 grid for rotor core 10-by-6 grid per pole	Fe-3.0Si	Air/SMC
		Sintered magnet (NdFeB)	Air/polymer bonded NdFeB magnet with zero dysprosium

Data Generation

Sample single-material rotor core designs



Sample multimaterial rotor core designs

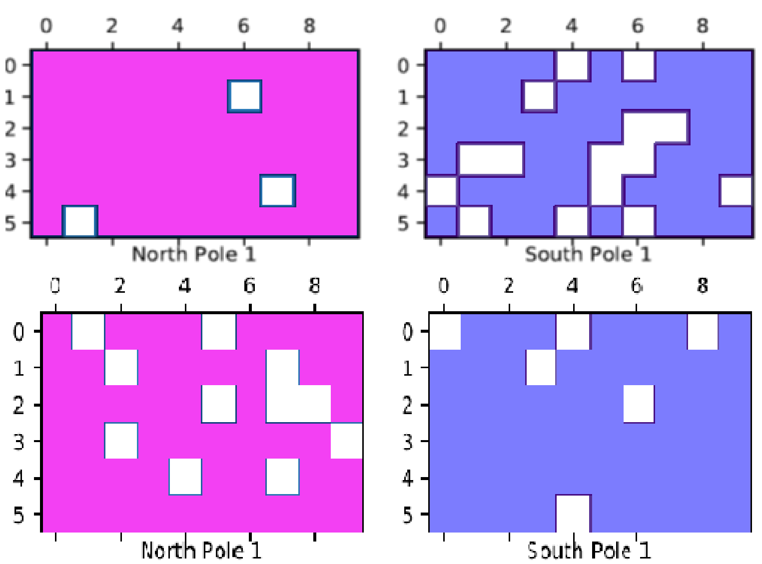


- Several patterns of single and multimaterial designs were generated using **Latin-hypercube sampling**. For N mesh elements, the total number of designs is:

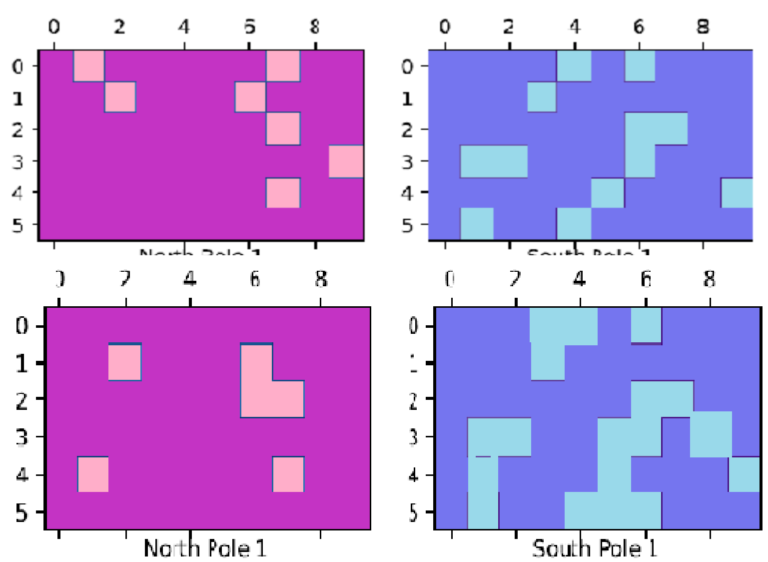
  $$1.1*(N+1)(N+2)/2$$

  - Rotor core: 1,348 designs
  - Magnet region: 8,120 designs

Sample single-material magnet designs

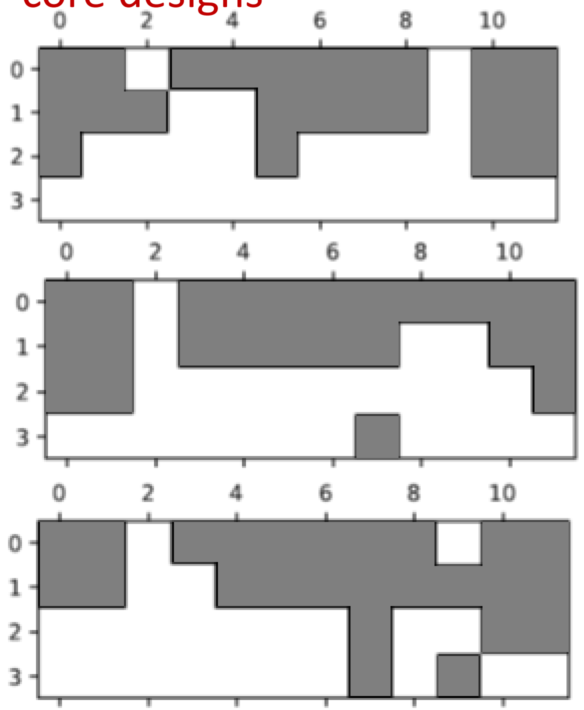


Sample multimaterial magnet designs

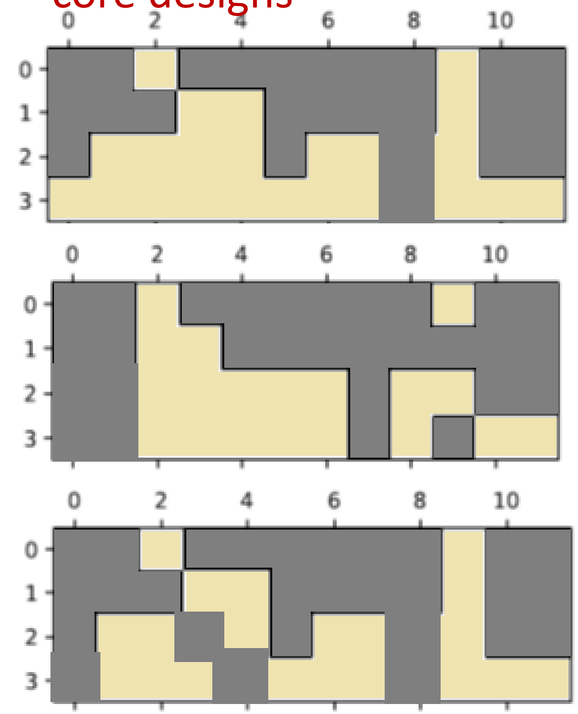


Data Generation

Sample single-material rotor core designs

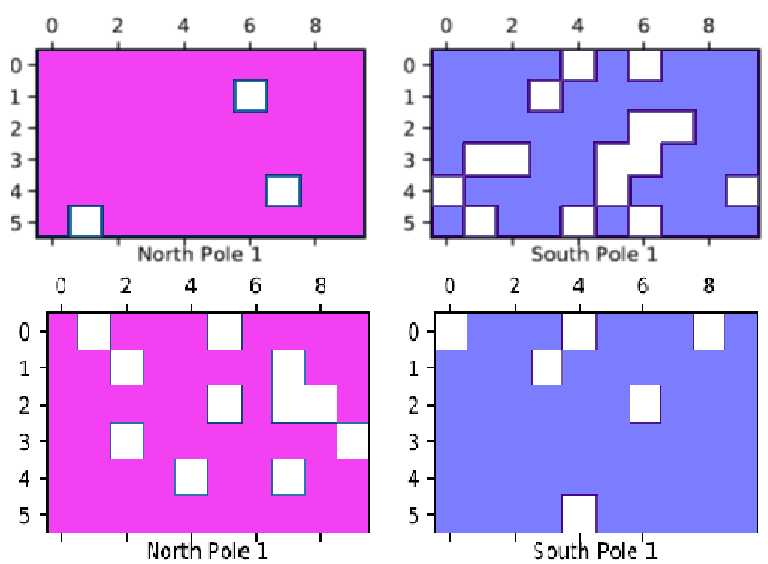


Sample multimaterial rotor core designs

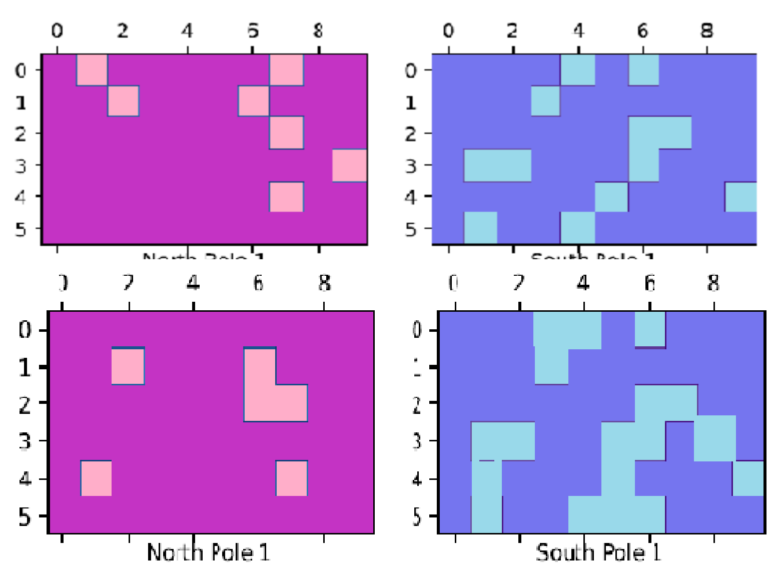


- Each design is evaluated by a transient magnetic FEA
- For rotor core evaluations, mean-air gap torque and rotor flux loading were extracted
- For magnet design evaluation, only mean air-gap torque was extracted

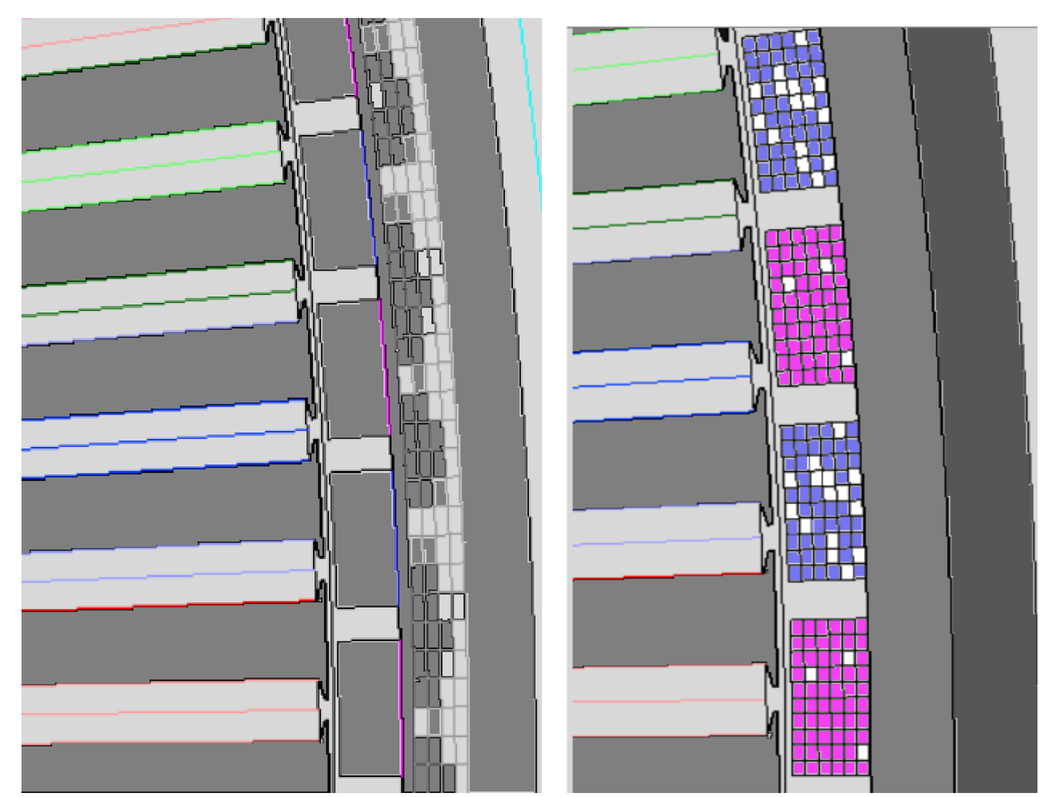
Sample single-material magnet designs



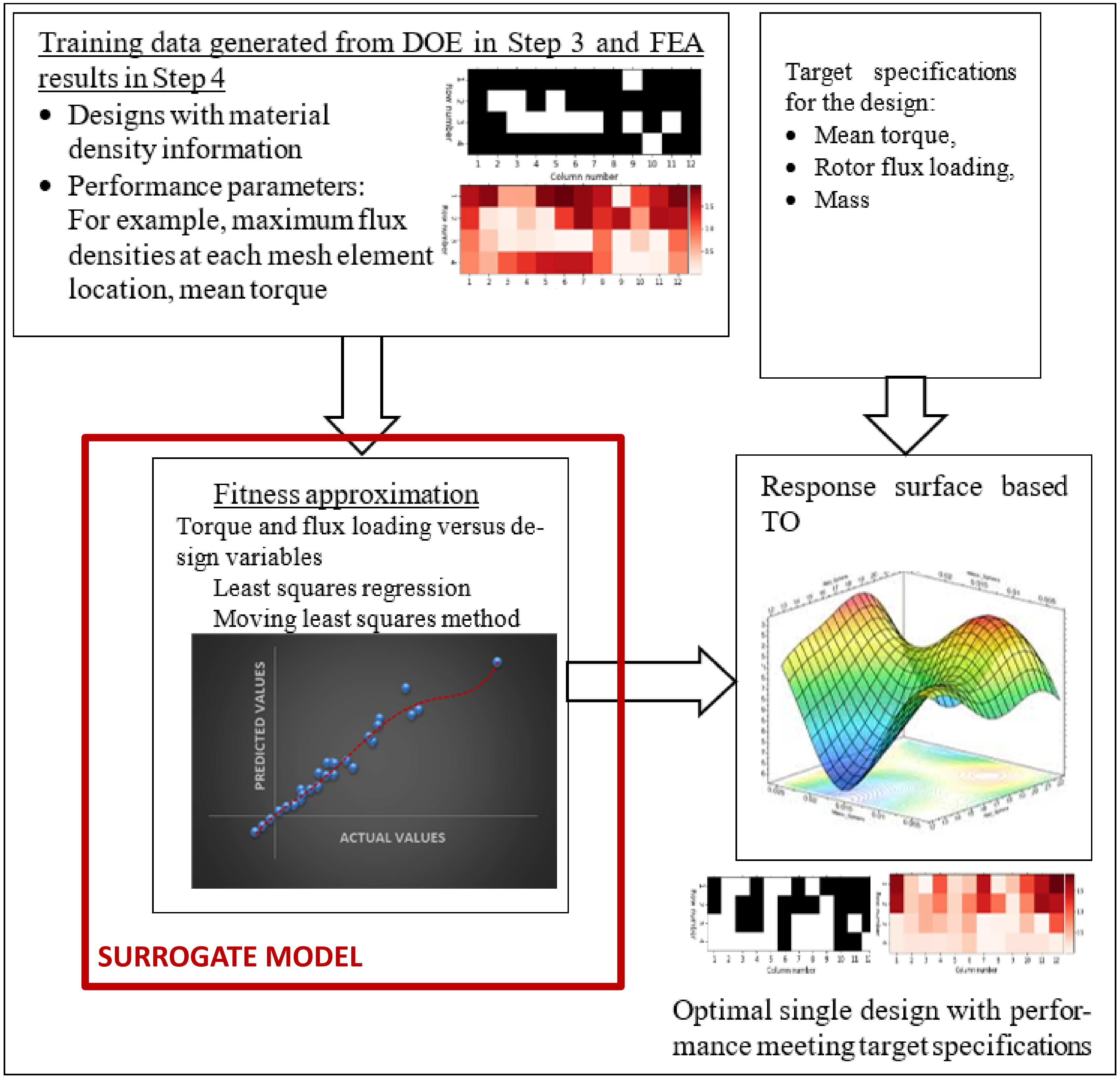
Sample multimaterial magnet designs



Pattern representation inside the machine

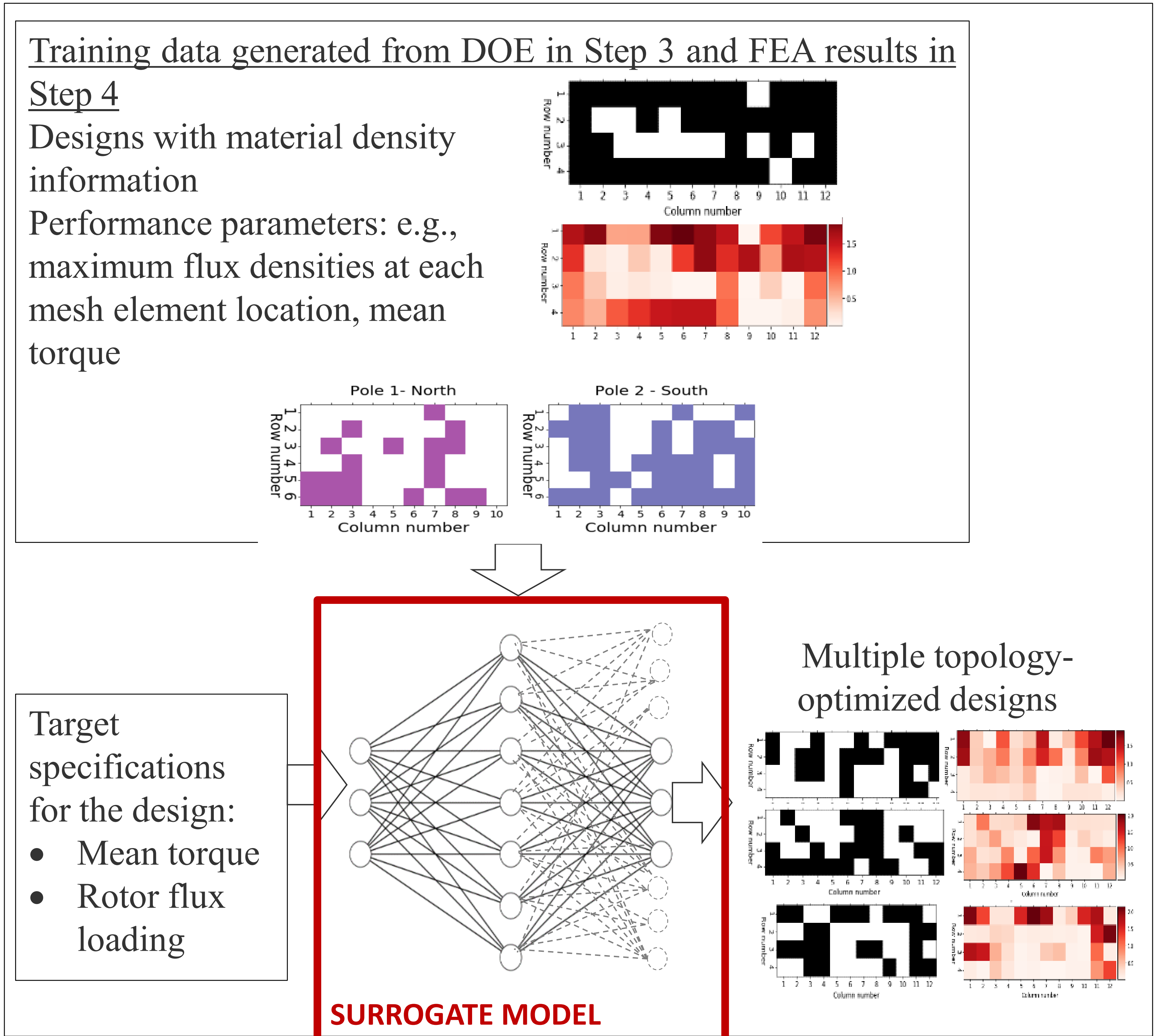


Conventional Topology Optimization Approach



- Training data: designs with mesh variables, torque, mass, rotor flux loading
- **Build surrogate model**: construct regression models to get best fitness between input and output
  - Define target torque, mass, and flux density constraints
  - Perform TO using response surface method

MADE3D-AML Topology Optimization Approach



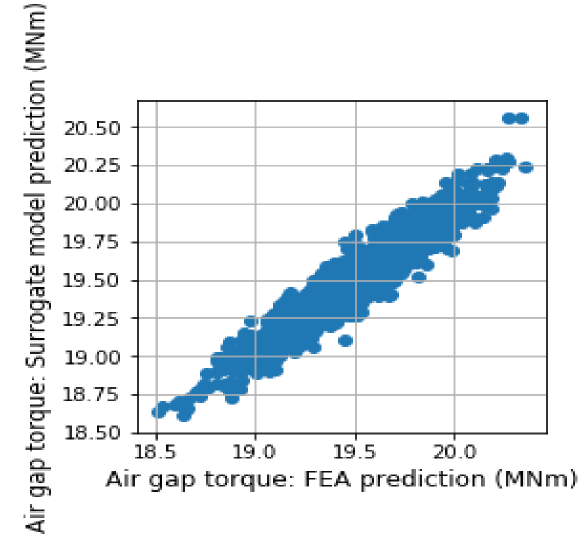
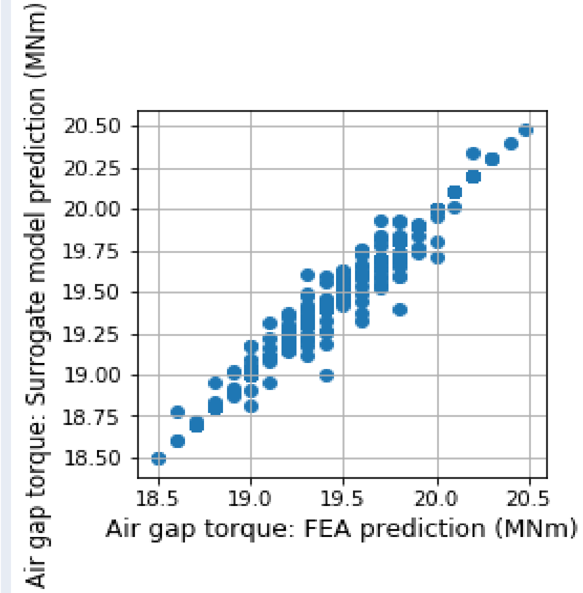
- Use same training data: designs with mesh variables, torque, mass, rotor flux loading
- **Build surrogate models:** update and optimize networks in MADE3D-AML and train
- Define target torque, mass, and flux density limits
- Perform topology optimization

Computational Efficiency Regression Model vs. MADE3D-AML

CASES	Conventional TO			TO using MADE3D-AML		
	Rotor Core TO		Magnet TO	Rotor Core TO		Magnet TO
	Single material	Multimaterial	Multimaterial	Single material	Multimaterial	Multimaterial
Total Training Size	1,348	1,348	8,120	1,348	1,348	8,120
DOE Data Generation	2 days	2 days	1 week	2 days	2 days	1 week
Training	1.5 hours	1.5 hours	>28 hours	**26 min**	**26 min**	**26 min**
Fitness Evaluation				**55 s**	**55 s**	**55 s**
Optimization	5 hours	17 hours	30 hours	**<5 min**	**<5 min**	**<5 min**

Time for training, fitness evaluation, and optimization is substantially lower with MADE3D-AML. Single-material magnet TO was not pursued because of limitations in training data.

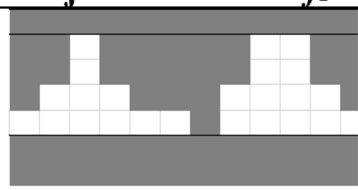
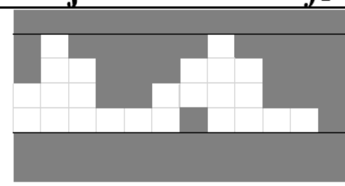
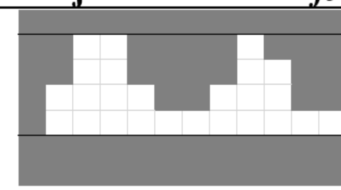
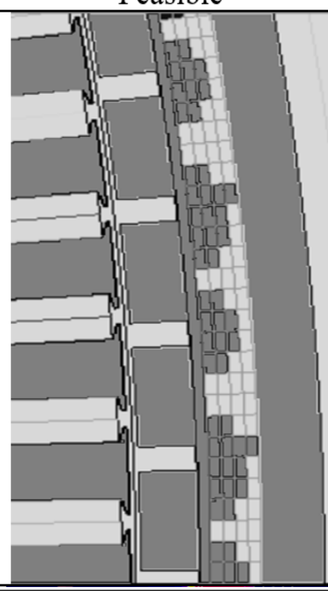
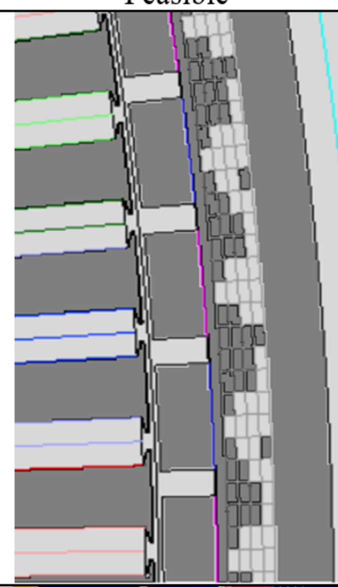
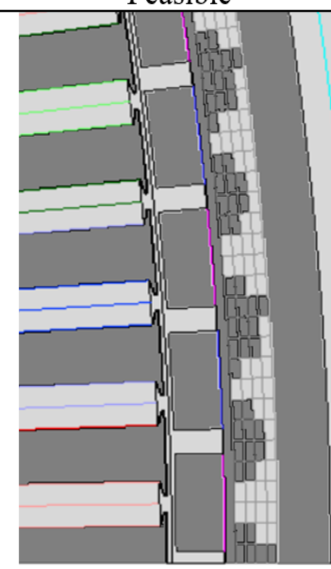
Surrogate Models: Accuracy in Predictions Regression Model vs. MADE3D-AML

CASES	Single material – rotor core: Torque RMSE as a percentage of mean				Torque Predictions
	Low Mass	High Mass	Median Mass	All cases	
Conventional Surrogate Model	0.513%	0.602%	0.527%	0.531%	
MADE3D-AML	**0.15%**	**0.24%**	**0.20%**	**0.202%**	

Root-mean-square error (RMSE) in torque predictions is halved with the MADE3D-AML model.

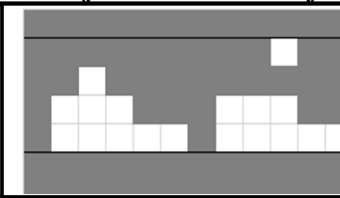
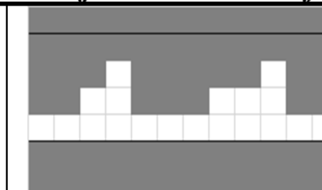
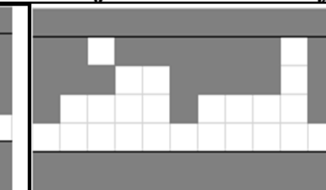
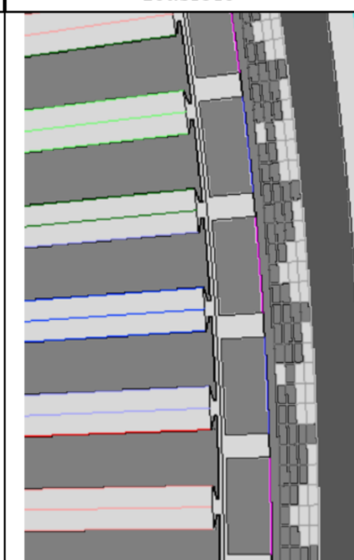
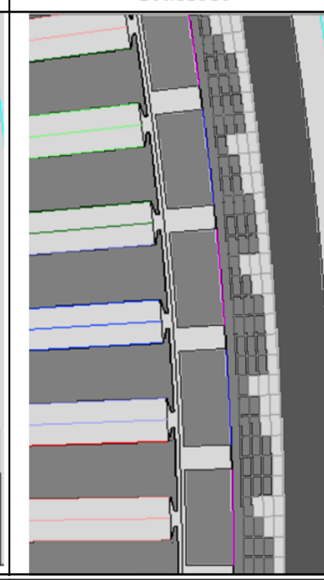
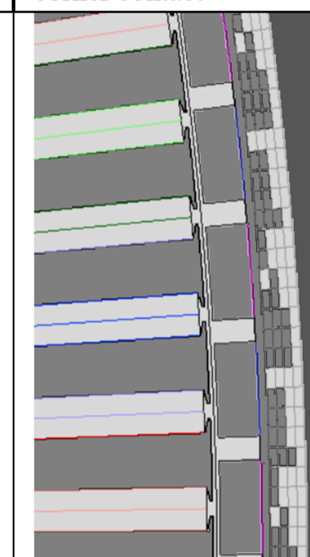
Results of TO: Single-Material Designs – Both Approaches Resulted in ~14-ton Weight Reduction

REGRESSION MODEL (RM)

	Objective function f_1	Objective function f_2	Objective function f_3
Pattern mat1 mat2 (air)			
Manufacturability	Feasible	Feasible	Feasible
Pattern representation inside the machine			

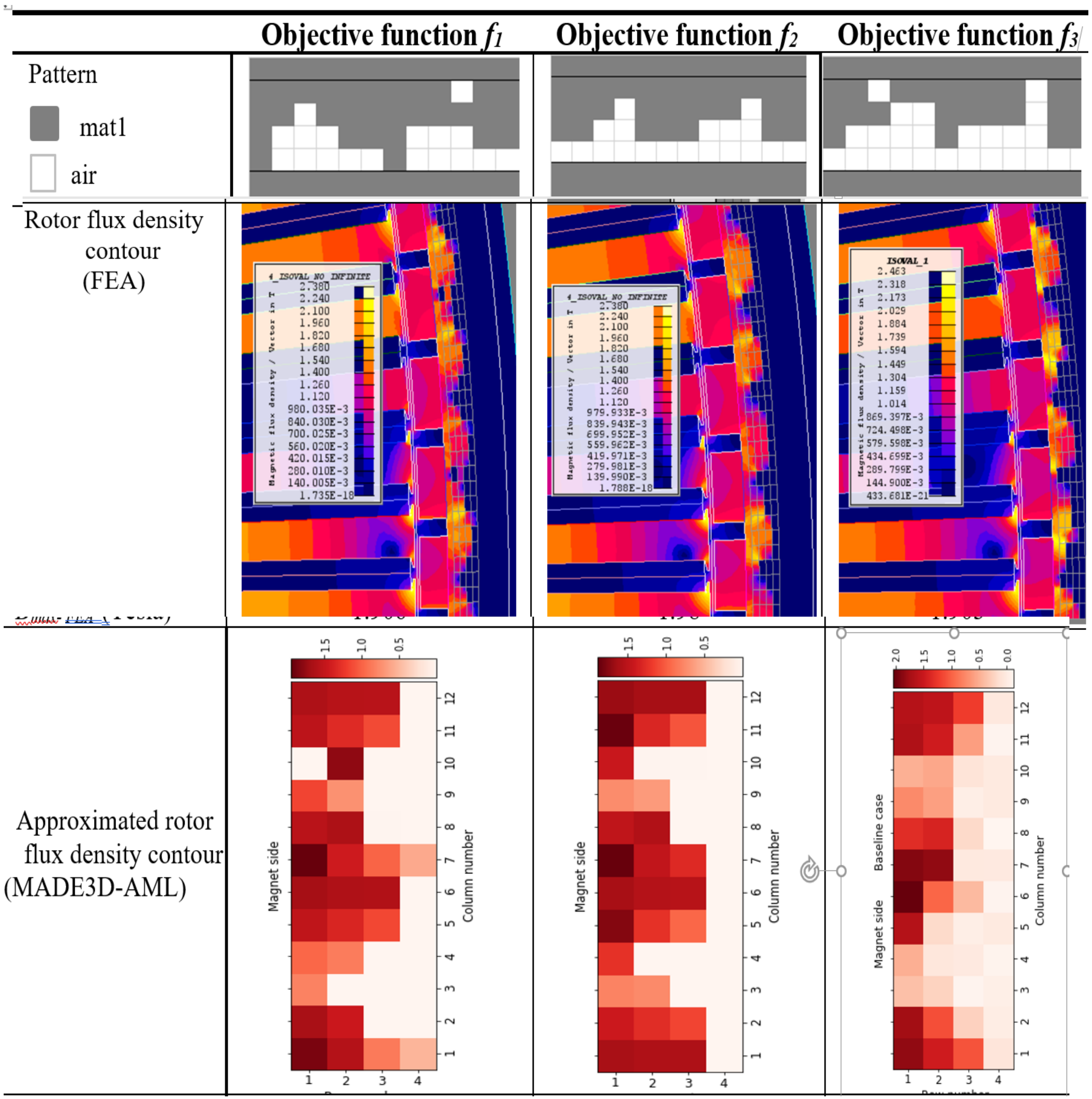
$M_{rotorcore}$ (tons)	20.527		20.527		19.95	
T_{mean} (MNm)	RM	FEA	RM	FEA	RM	FEA
	20.5	20.37	20.45	20.36	20.45	20.4
% increase in TD	29.17		29.05		30.84	
Wall time to optimization	5 hours		5 hours		5 hours	

MADE3D-AML

	Objective function f_1	Objective function f_2	Objective function f_3
Pattern mat1 air			
Manufacturability	feasible	feasible	corner contact
Pattern representation inside the machine			

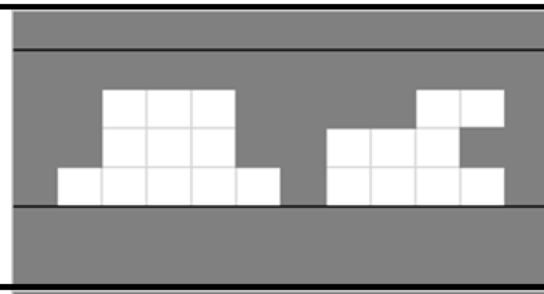
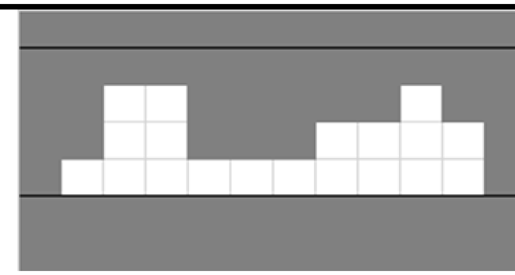
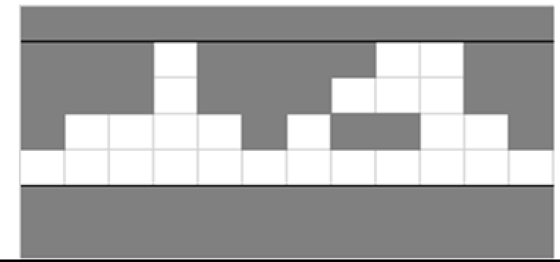
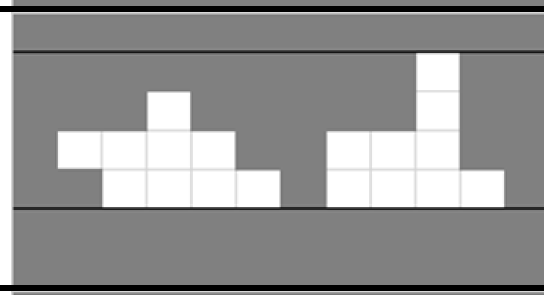
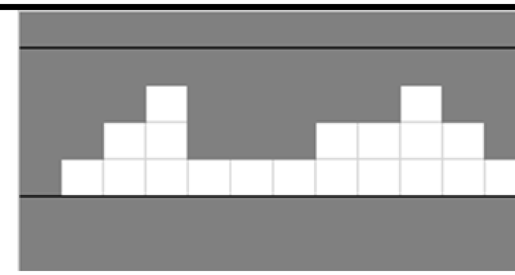
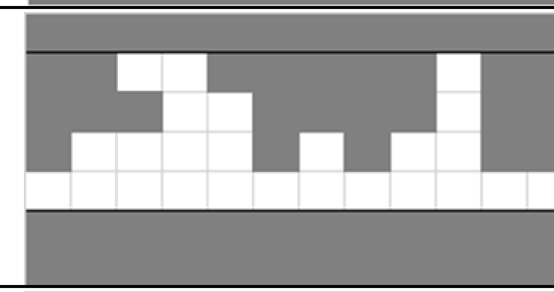
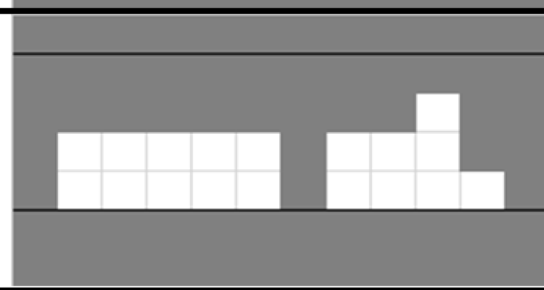
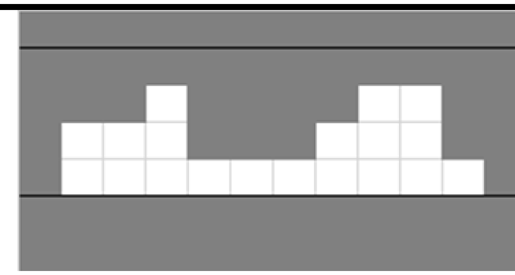
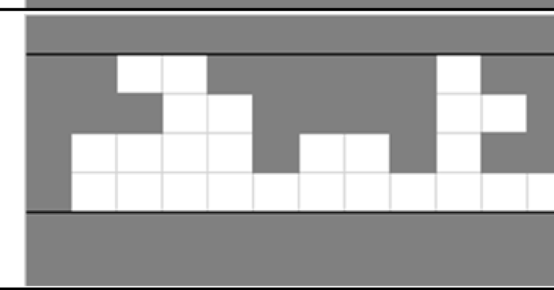
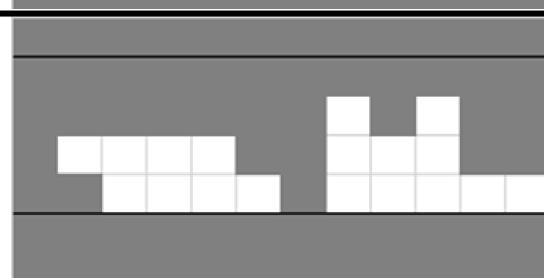
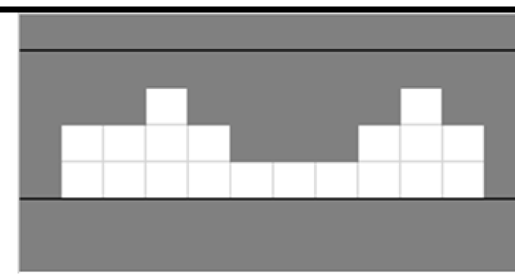
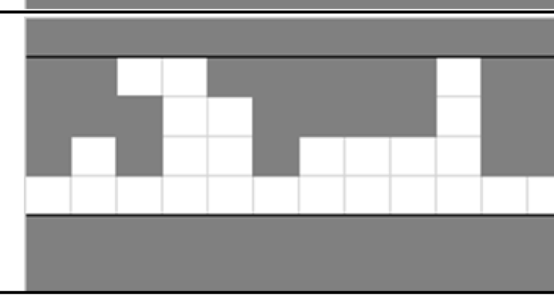
$M_{rotorcore}$ (tons)	23.95		22.81		19.95	
T_{mean} (MNm)	AML	FEA	AML	FEA	AML	FEA
	20.5	20.468	20.49	20.469	20.06	20.4
% increase in TD	21.3		24.3		31.3	
Wall time to optimization	**< 5 min**		**< 5 min**		**< 5 min**	

Results of TO: Single-Material Designs: FEA Validation



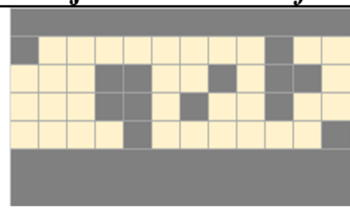
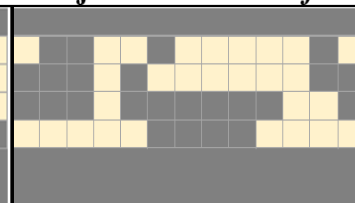
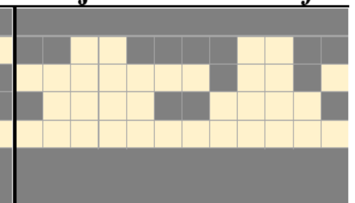
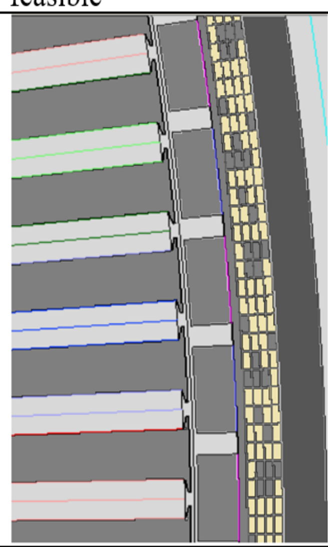
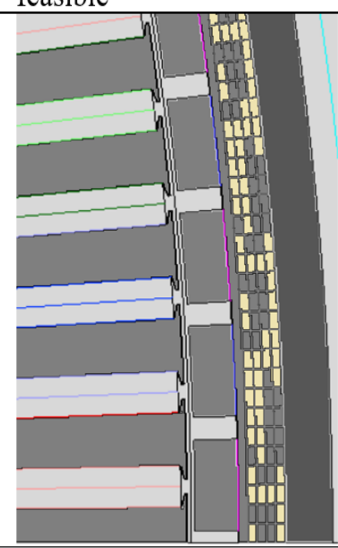
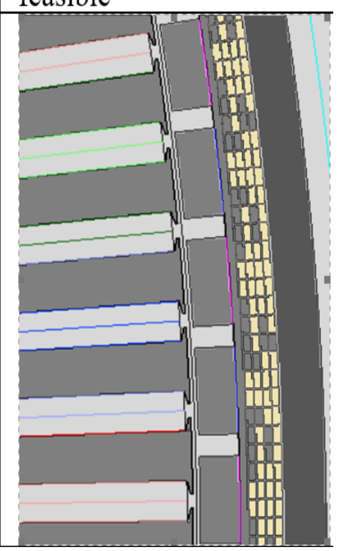
- AML predictions for rotor flux loading closely resemble FEA results

Results of TO: Few Additional Designs Identified by MADE3D-AML

Pattern	Objective function f_1	Objective function f_2	Objective function f_3
1			
2			
3			
4			
$M_{rotorcore}$ (tons)	23.95	22.81	19.95
Torque (MNm)	20.468	20.469	20.4
% increase in TD	21.3	24.3	31.3

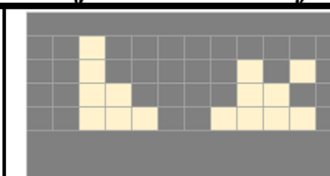
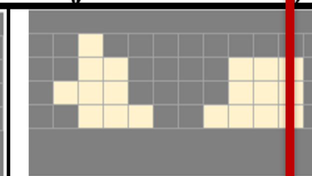
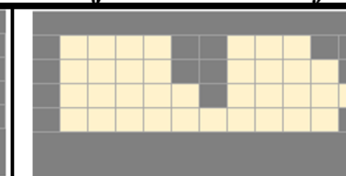
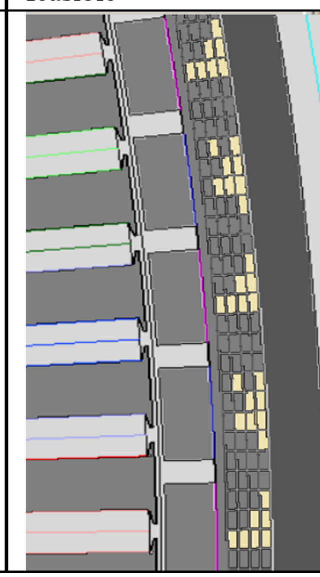
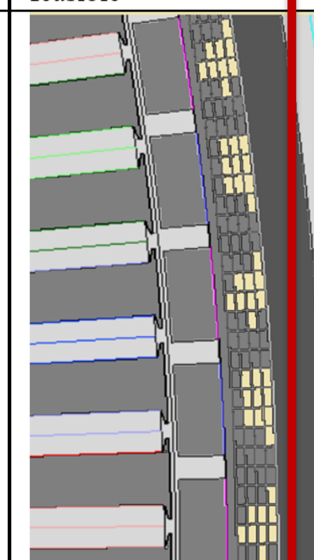
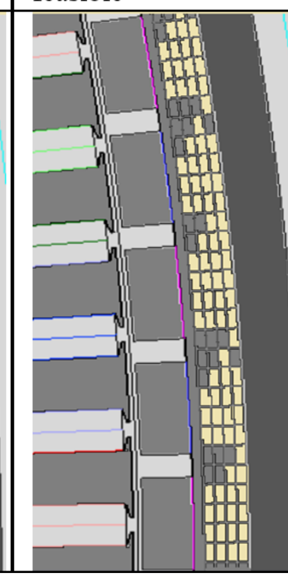
Multimaterial Designs for Rotor Core – ML Approach Replaced Material in Regions of Lower Magnetic Loading

REGRESSION MODEL (RM)

	Objective function f_1	Objective function f_2	Objective function f_3
Pattern mat1 mat2			
Manufacturability	feasible	feasible	feasible
Pattern representation inside the machine			

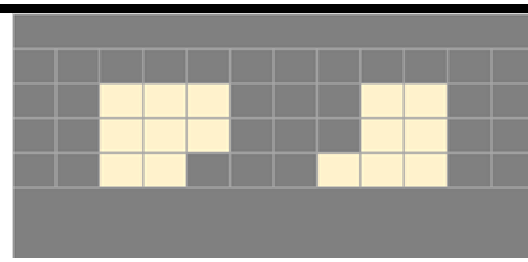
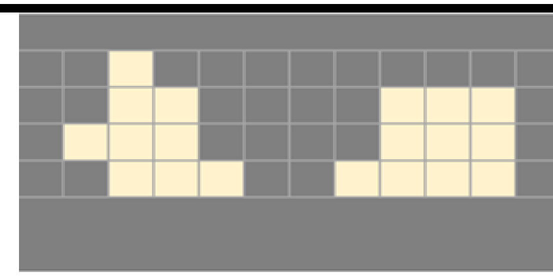
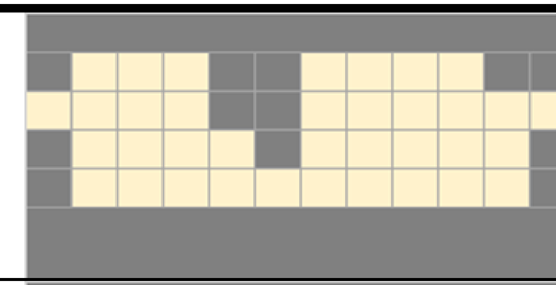
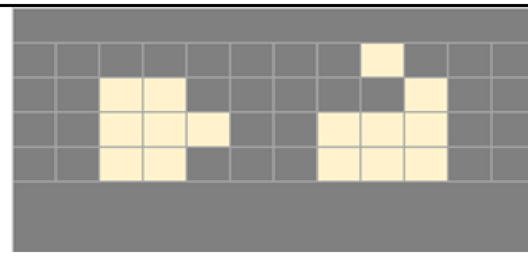
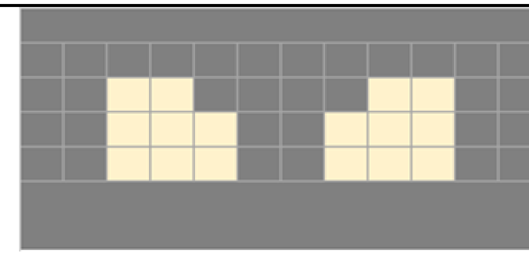
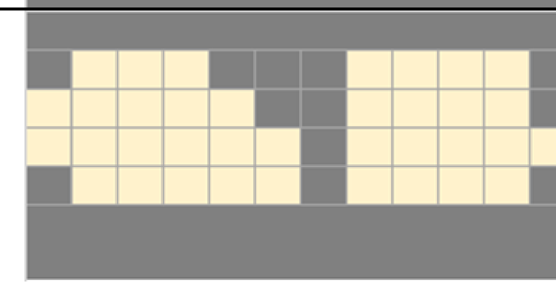
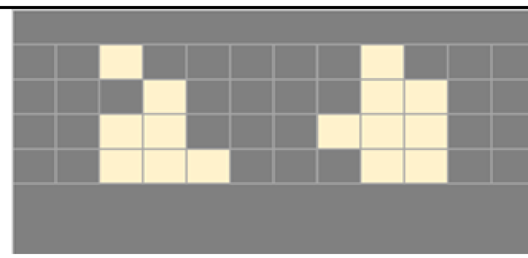
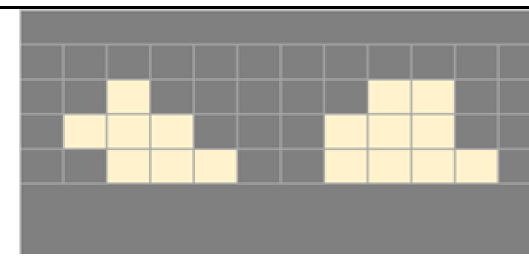
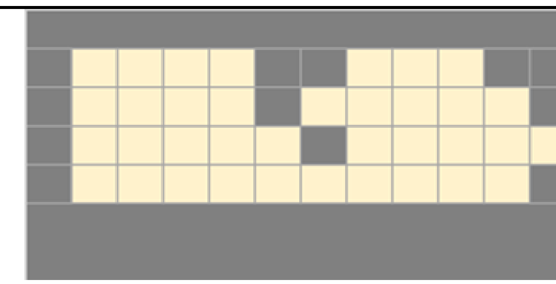
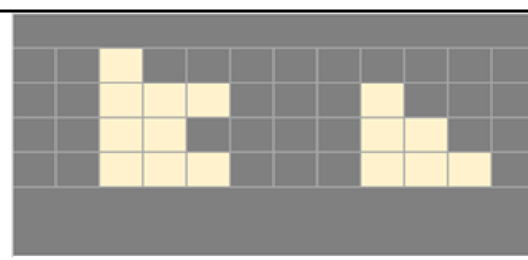
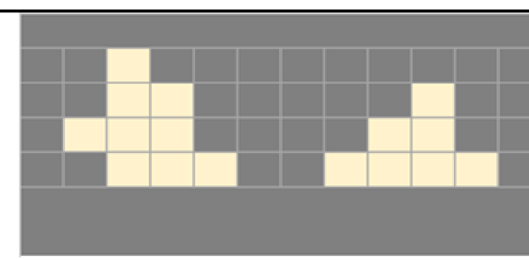
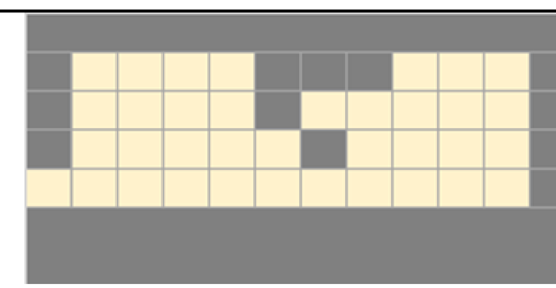
$M_{rotorcore}$ (tons)	32.007		32.517		32.07	
T_{mean} (MNm)	RM	FEA	RM	FEA	RM	FEA
	20.45	20.432	20.46	20.44	20.454	20.45
% increase in TD	3.70		2.82		3.69	
Time to optimization	16.4 hours		16.5 hours		17 hours	

MADE3D-AML

	Objective function f_1	Objective function f_2	Objective function f_3
Pattern mat1 mat2			
Manufacturability	feasible	feasible	feasible
Pattern representation inside the machine			

$M_{rotorcore}$ (tons)	33.28		33.21		**31.95**	
T_{mean} (MNm)	AML	FEA	AML	FEA	AML	FEA
	20.48	20.47	20.48	20.47	20.44	20.44
% increase in TD	1.62		1.74		3.84	
Wall time to optimization	**< 5 min**		**< 5 min**		**< 5 min**	

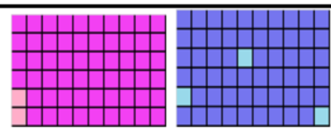
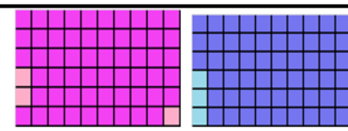
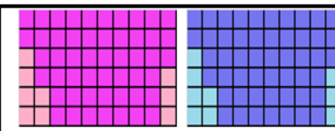
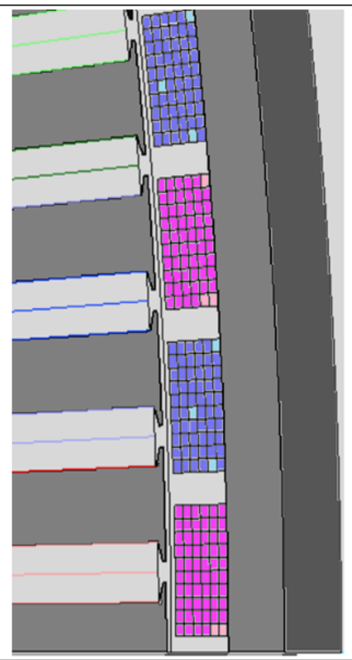
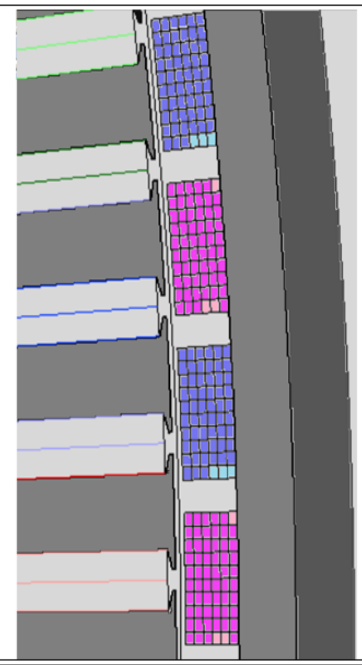
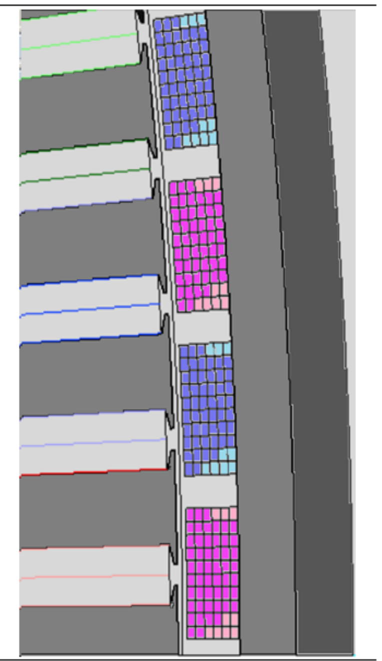
Results of TO: Few Additional Designs Identified by MADE3D-AML

Pattern	Objective function f_1	Objective function f_2	Objective function f_3
1			
2			
3			
4			

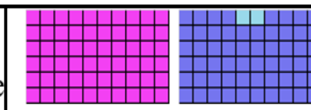
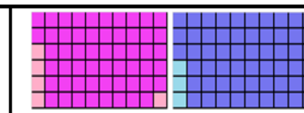
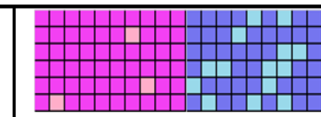
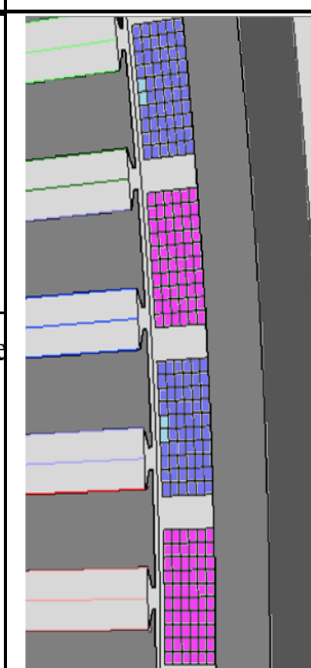
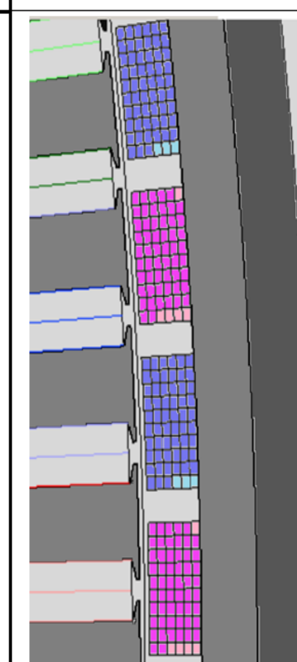
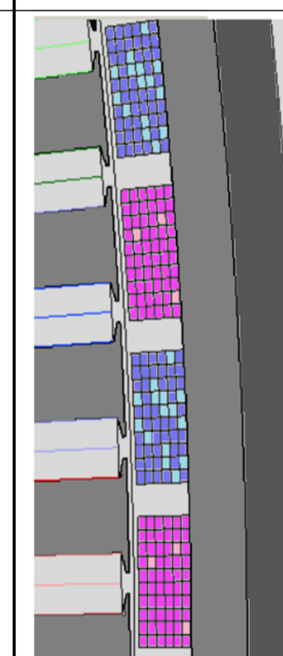
$M_{rotorcore}$ (tons)	33.28	33.21	31.95
Torque (MNm)	20.47	20.469	20.4
% increase in TD	1.68	1.74	3.84

Multimaterial Designs – Magnets: Up to 8.75% Savings in Costs

REGRESSION MODEL (RM)

	Objective function f_1		Objective function f_2		Objective function f_3	
Pattern mat1 'N' pole mat2 'N' pole mat1 'S' pole mat2 'S' pole						
Manufacturability	Feasible- FGM approach		Feasible- FGM approach		Feasible- FGM approach	
Pattern representation inside the machine						
M_{mag} (tons)	**23.77**		**23.71**		**22.98**	
$M_{mag\text{-}mat1}$ (tons)	23.06		22.8		20.46	
$M_{mag\text{-}mat2}$ (tons)	0.697		0.836		2.51	
Material cost savings (%)	2.49		3.23		8.75	
Torque estimates (MNm)	RM	FEA	RM	FEA	RM	FEA
	20.51	20.4	20.5	20.38	20.25	20.15
% increase in TD	0.184		0.2		0.67	
Time to optimization	32 hours		32.5 hours		32 hours	

MADE3D-AML

	Objective function f_1		Objective function f_2		Objective function f_3	
Pattern mat1 'N' pole mat2 'N' pole mat1 'S' pole mat2 'S' pole						
Manufacturability	Feasible-FGM approach		Feasible-FGM approach		Feasible-FGM approach	
Pattern representation inside the machine						
M_{mag} (tons)	**23.95**		**23.59**		**22.987**	
$M_{mag\text{-}mat1}$ (tons)	23.68		22.476		20.46	
$M_{mag\text{-}mat2}$ (tons)	0.278		1.115		2.51	
Material cost savings (%)	0.968		3.88		8.75	
Torque estimates (MNm)	AML	FEA	AML	FEA	AML	FEA
	20.5	20.37	20.5	20.37	19.9	19.7
% increase in TD	-0.314		0.3059		-1.9707	
Time to optimization	**< 5 min**		**< 5 min**		**< 5 min**	

Summary

Overall, a total mass reduction of 15.1 tons was possible from rotor active parts for the 15-MW generator.

- MADE3D-AML demonstrated a significant reduction in computational costs and increase in accuracy in performance predictions.
- Additionally, a wider selection of optimal 3D printable designs was identified.
- **Hybrid rotor core:** Fe-3.0Si and low-strength SMC present a new opportunity to realize a low-loss, high-strength rotor core.
- **Hybrid magnets:** The sintered magnet and dysprosium-free, polymer-bonded magnet showed potential to save magnet costs by up to 8.75%.
- We identified an improvement of more than 30% in torque/rotor active mass.
- **The results will inspire a new paradigm for design-driven manufacturing with novel material compositions and lightweight, low-cost, high-strength multimaterial geometries that were previously unexplored for direct-drive generators.**

Our Solution

MADE3D in USA

NREL Transforming ENERGY

Manufacturing and **Additive Design** of **Electric** Machines enabled by **3-D**imensional printing (MADE3D) is a multiyear project sponsored by the U.S. Department of Energy (DOE) aimed at overcoming some of the challenges and kick-starting a new paradigm for on-site manufacturing of high-power-density electric machine designs.

MADE3D-AML leverages advanced multiphysics

Additive Design
Topology Optimization

Multimaterial printing

High-torque-dense designs enabled by

Questions???

For partnership and licensing opportunities, please visit: https://www.labpartnering.org/lab-technologies/6ebf5c69-dc94-4393-a2e7-49042e16502d

Enables complexity and up to 50% weight reduction compared to traditional designs

Designs with 3D-printed stator cores

Designs with 3D-printed support structures

Designs with 3D-printed magnets

Enabling technologies include new materials and advanced printing processes including binder jet additive manufacturing and selective laser melting.

Thank you

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NREL/PR-5000-79384

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