Motor Design Limited

Optimization of a High Speed Copper Rotor Induction Motor for a Traction Application

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Overview

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5. Thermal Design
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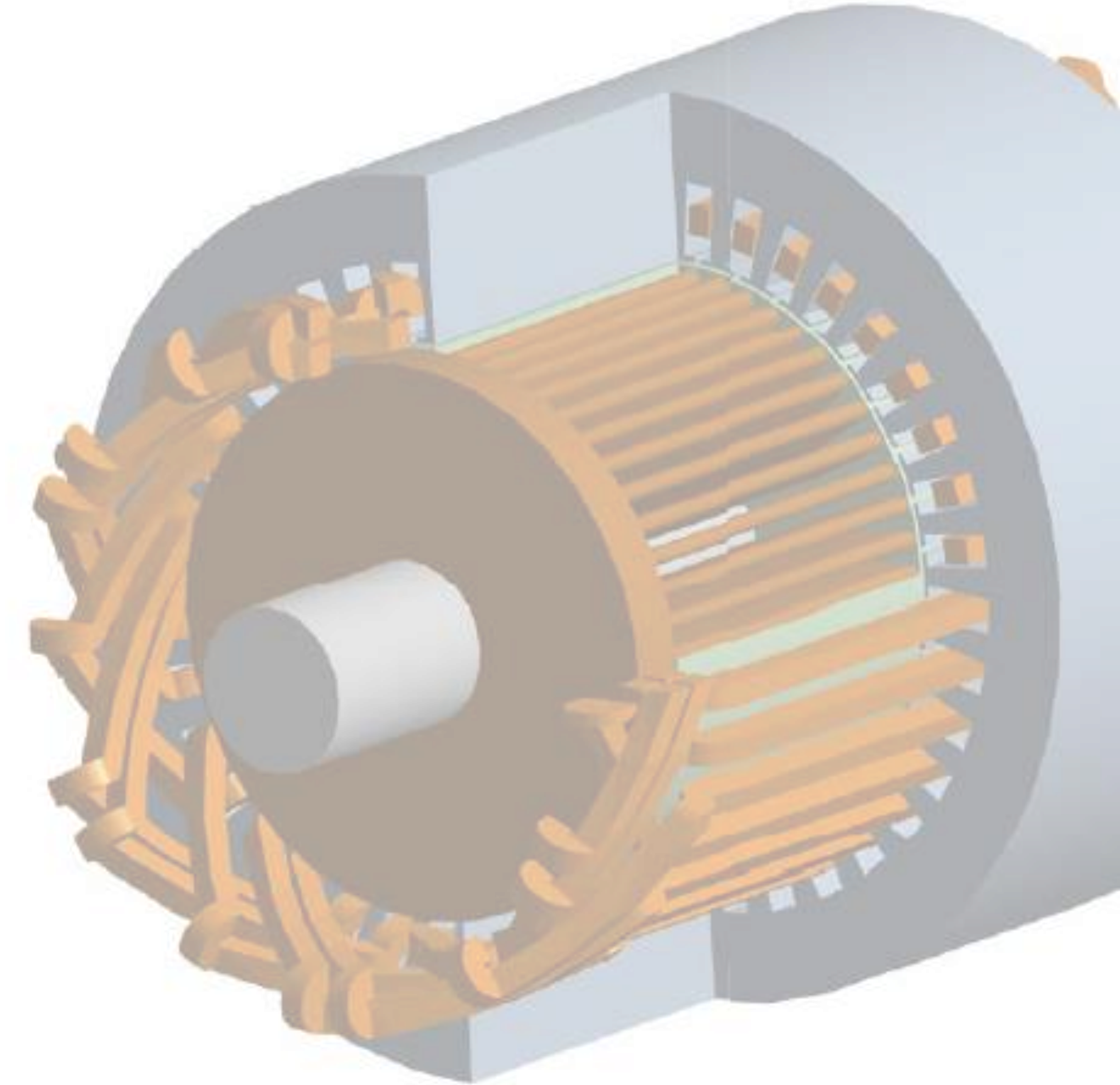


Introduction

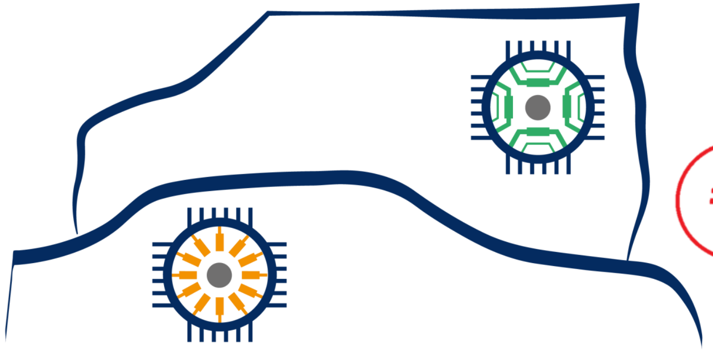
ReFreeDrive Project Overview

- Growing interest for EVs to support the transition to a climate-resilient, energy-efficient economy.
- Main expectations from car manufacturers to be addressed by electric motor designers are:
    1. Industrial feasibility
    2. Mass production
    3. High performance
    4. Low costs

Introduction

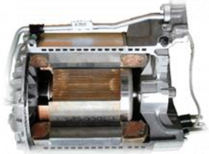
ReFreeDrive Project Overview

- Development of the next-gen of electric powertrains, focusing on rare-earth free traction motors
- Induction Motor (IM) technology considered a potential candidate.

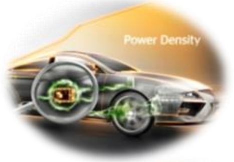


ReFreeDrive

- Copper rotor IM

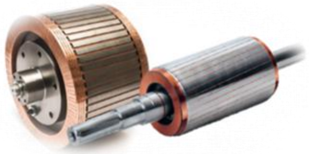


- High speed capability



- Low cost manufacturing

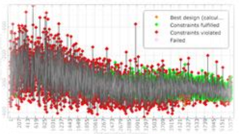
- Die-casted / Fabricated rotor



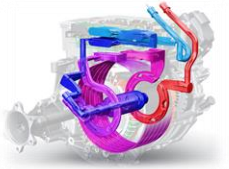
- Hairpin winding technology

- Low cost / loss materials

- Design optimization



- Rotor cooling



Specifications

Boundary Conditions

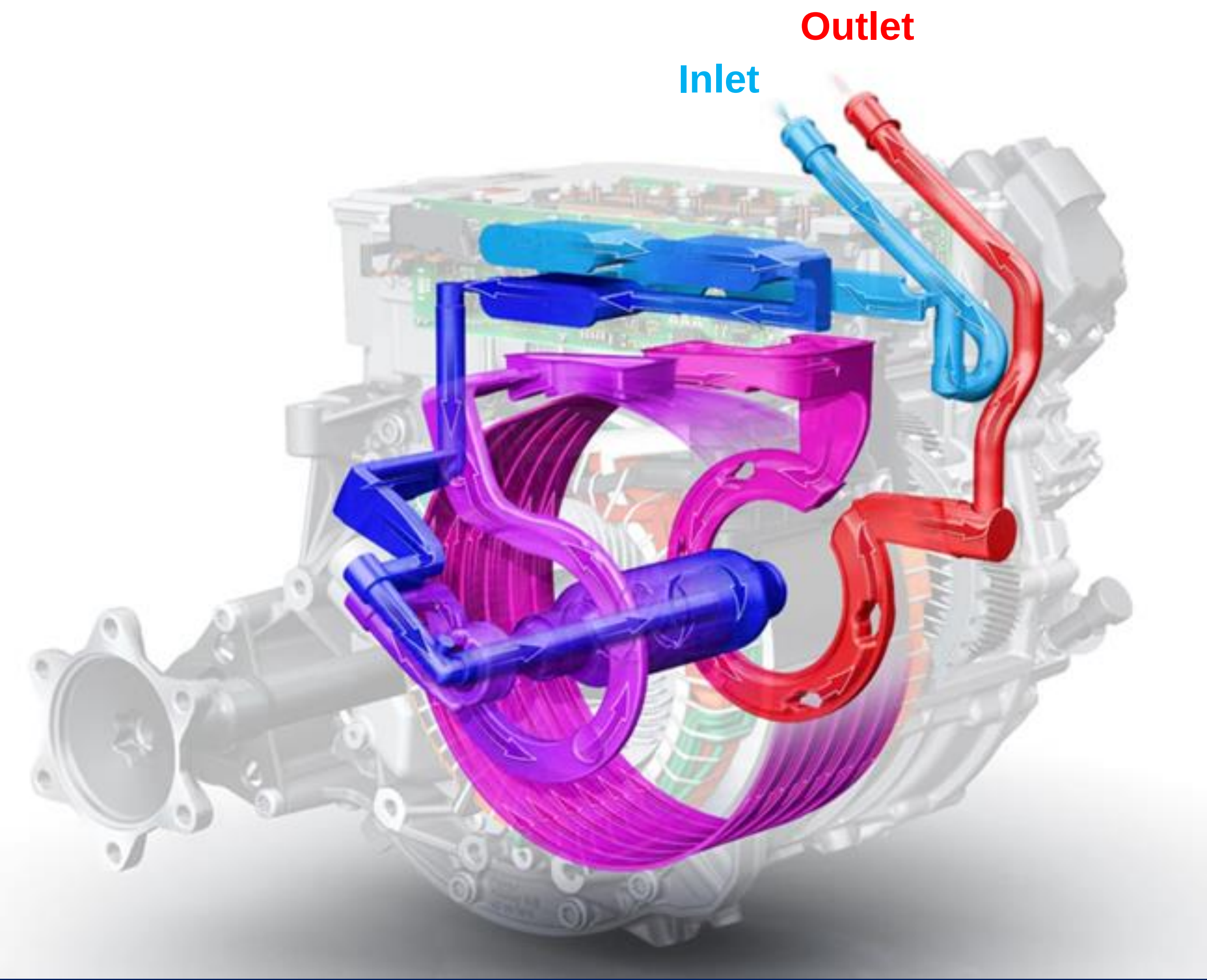
- Target vehicle: Jaguar XJMY21

	Requirement	Value	Unit
Performances	Peak torque @ Low speed	370	Nm
	Peak power @ Base speed	200	kW
	Cont. torque @ Low speed	152	Nm
	Cont. power @ Max. speed	70	kW
	Efficiency over WLTP3 cycle	≥ 94.5	%
	Operating speed	≤ 20000	rpm
Cooling	Stator cooling system	Water Jacket	-
	Rotor cooling system	Spiral	
	Coolant flow rate	≤ 10	l/min
	Cooling fluid type	EGW 50/50	
	Coolant temperature	≤ 90	°C
	Pressure drop (jacket only)	≤ 20	kPa
	Stator winding temperature	≤ 180	°C
	Rotor cage temperature	≤ 180	°C
PE	Inverter current	≤ 500	A_{rms}
	DC Link Voltage	720	Vdc
	Package size envelope	≤ Φ250 x L310	mm

Specifications

Boundary Conditions – Cooling System

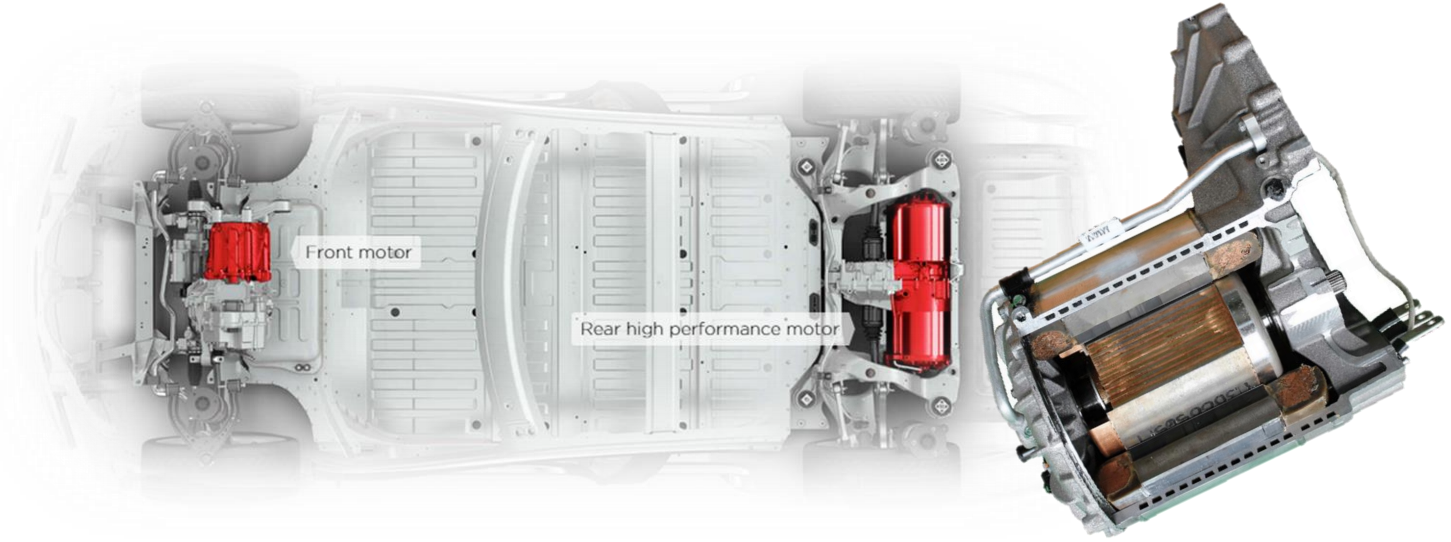
- Reference: Audi e-tron



Specifications

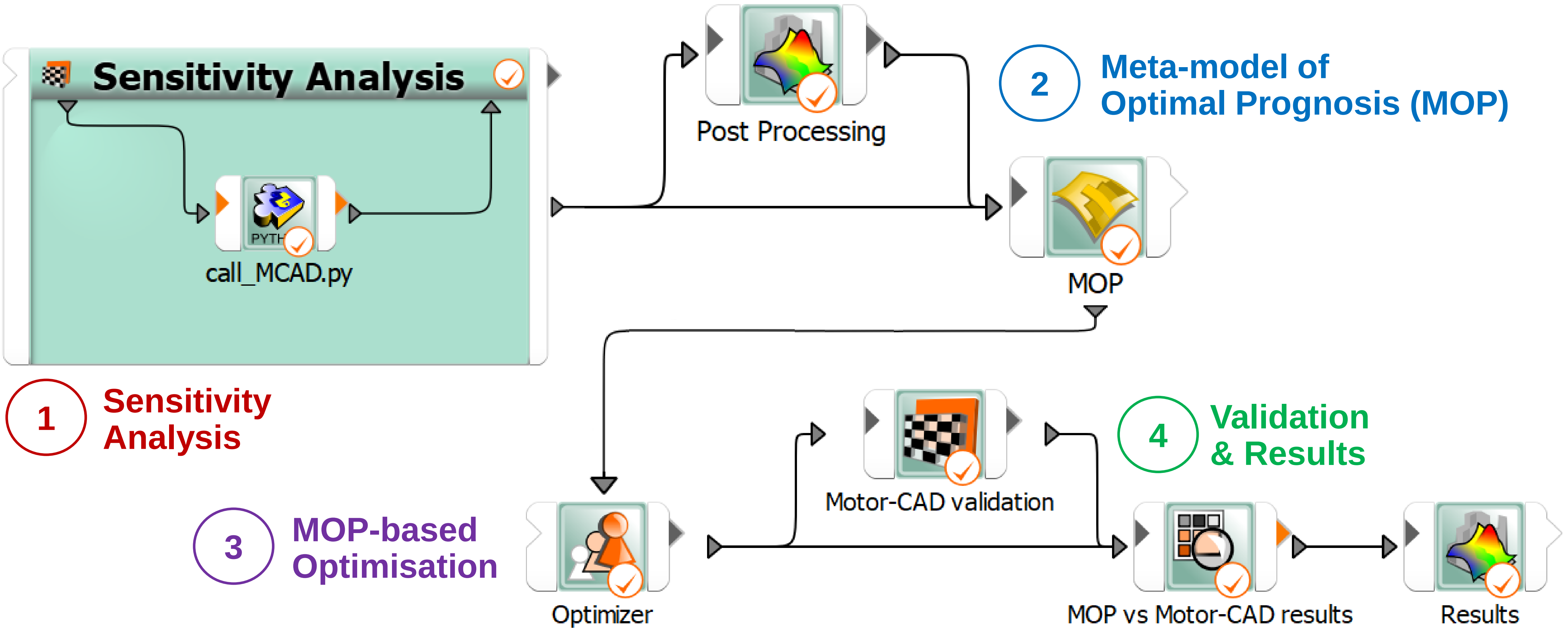
Key Performance Indicators (KPIs)

- Reference: Tesla 60S copper rotor induction motor.



Parameter	Tesla 60S	Target	Unit
Specific power	3.3	≥ 4.3	kW/kg
Power density	-	≥ 8.0	kW/l
Specific torque	6.3	≥ 8.2	Nm/kg
Torque density	-	≥ 15.4	Nm/l
Peak efficiency	93	≥ 96	%

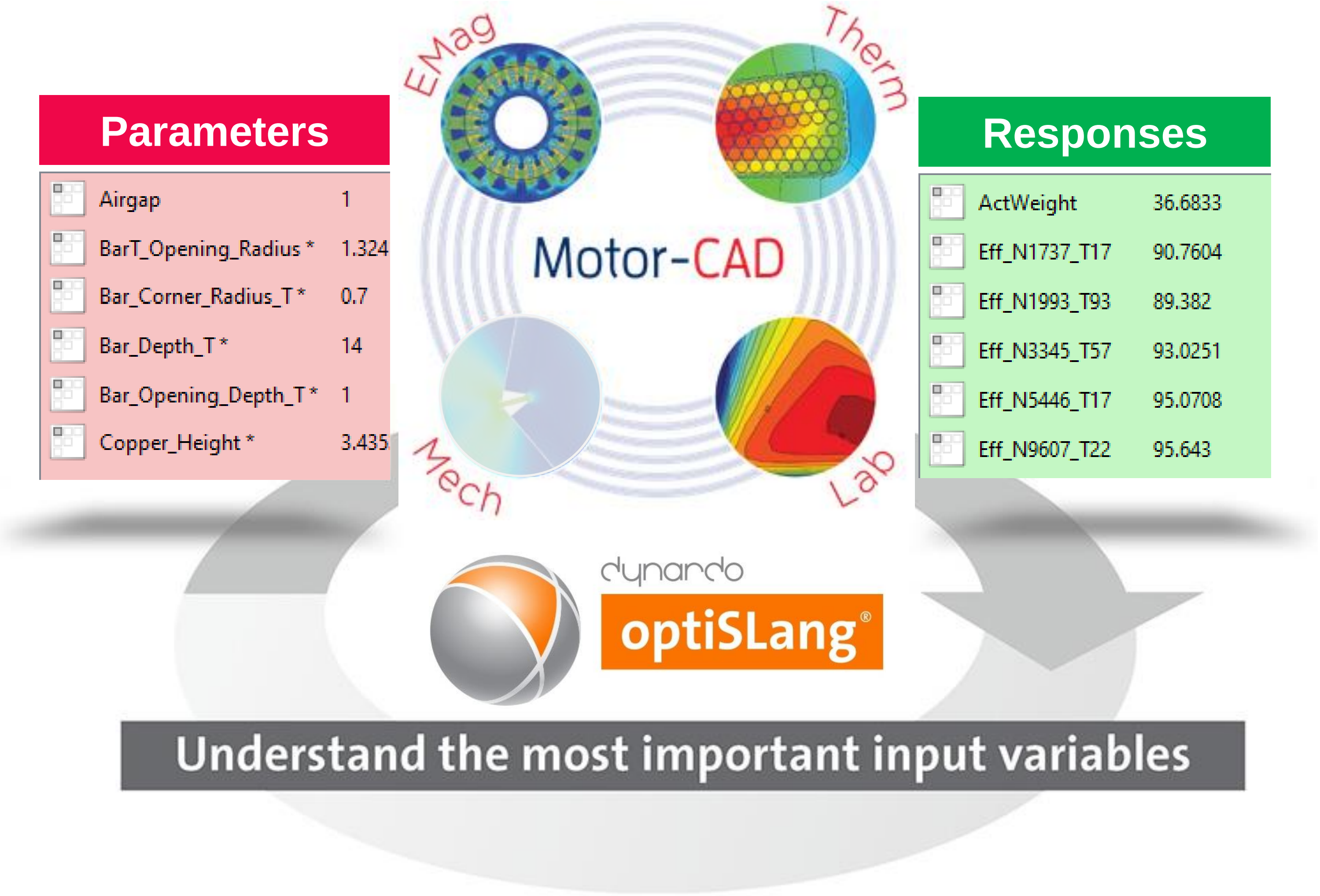
Analysis Workflow



Analysis Workflow

Objectives & Principles

- Motor-CAD & optiSLang coupled for a complete analysis:
  - ✔ Fast and effective optimisation over the full machine's operating speed range with good accuracy.
  - ✔ Comprehensive multi-physics analysis can be carried out.
  - ✔ Rigorous and traceable decisions for the design parameters.
- A meta-model based approach is set up in optiSLang software to optimize the machine.

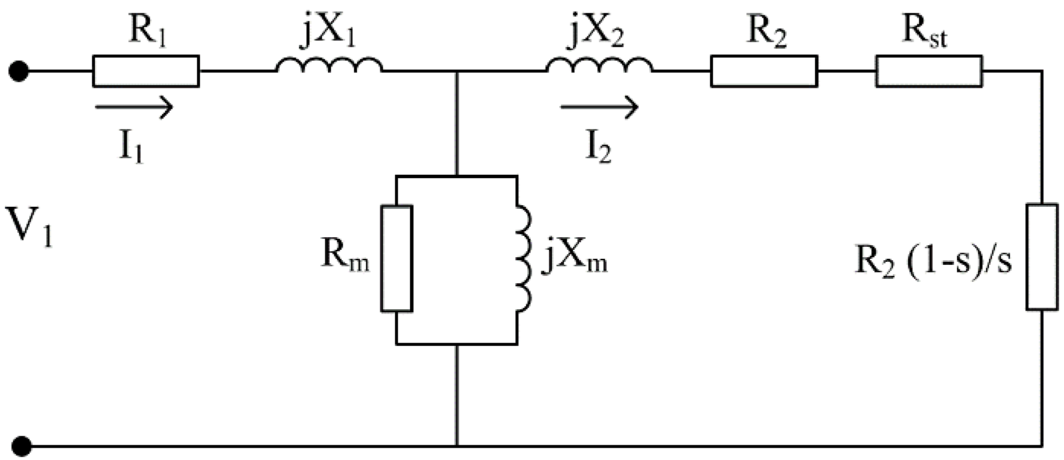


Analysis Workflow

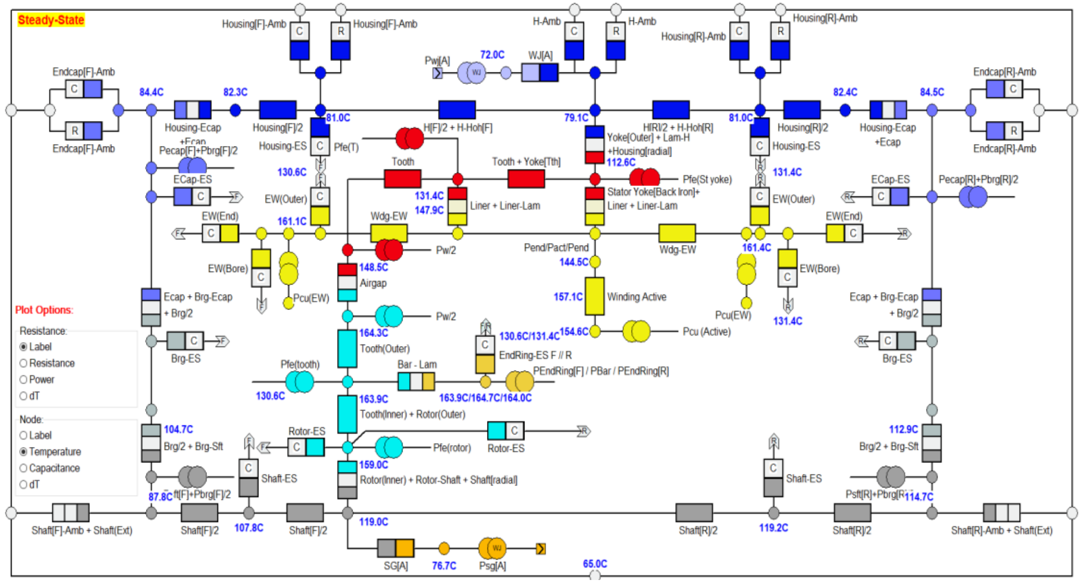
Performance Evaluation

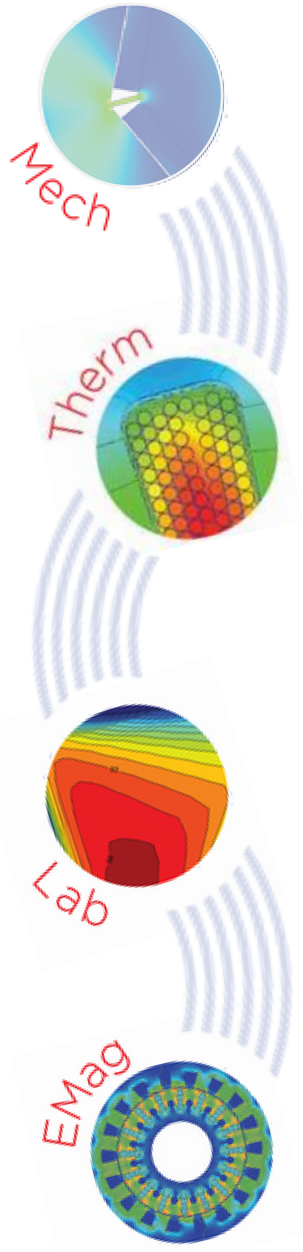
- A two-stage optimization process is adopted to split the design space in an effective way:
    1. Electromagnetic design
    2. Thermal design
- The machine's performance are calculated within its electrical and thermal limits.
- Each candidate solution takes approx. 10minutes to be computed in Motor-CAD software.

IM Analytical Magnetic Circuit



Lumped Parameter Thermal Network



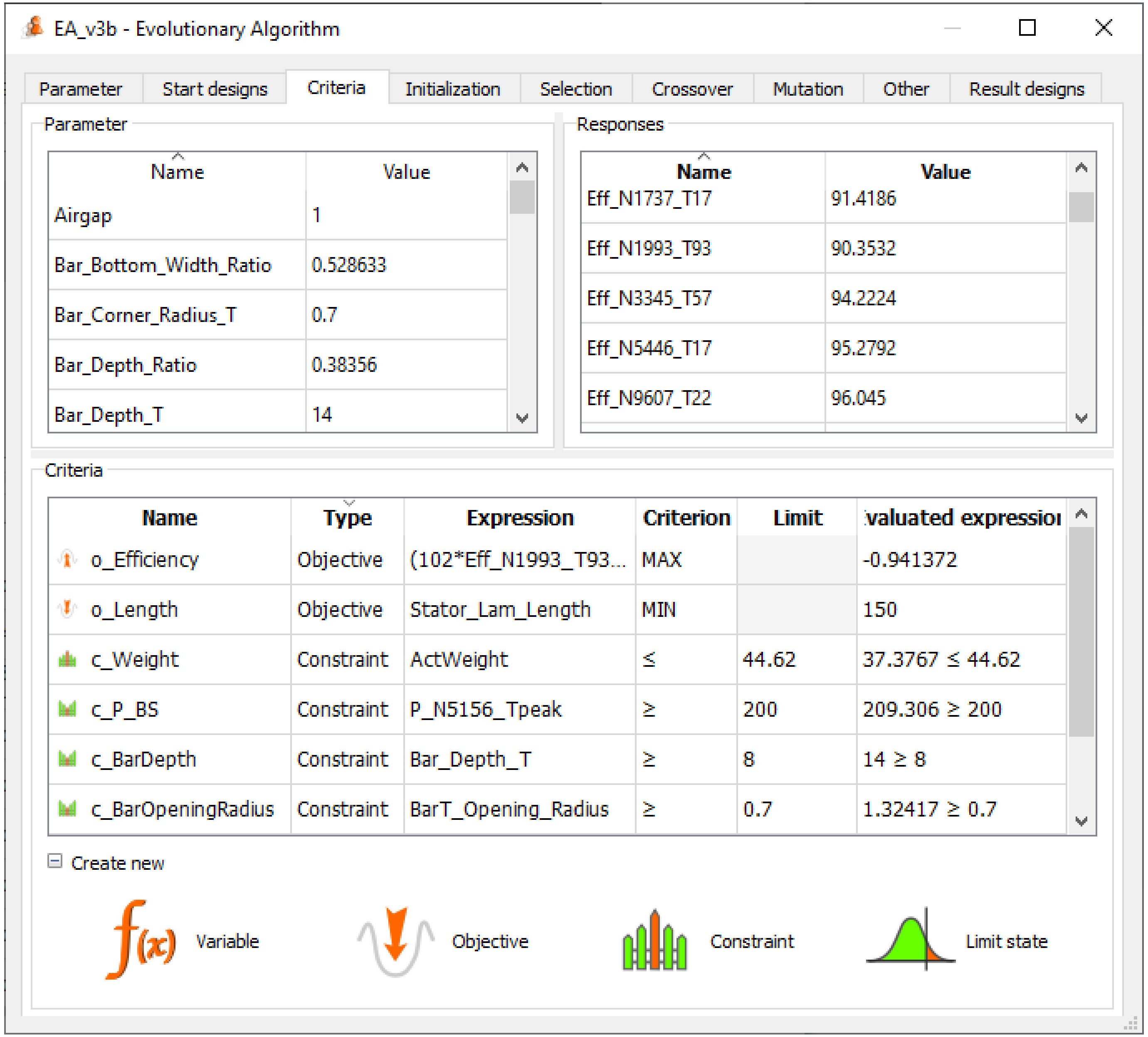


E-Mag Optimization

Objectives & Constraints

- **Objectives:**
  - ✓Max Efficiency (WLTP3)
  - ✓Min Active Length

- **Constraints:**
  - ✓Active Weight (kg) @ 44.6
  - ✓Power (kW) @ Base Speed ≥ 200
  - ✓Bar Depth (mm) ≥ 8
  - ✓Bar Opening Radius (mm) ≥ 0.7
  - ✓Bar Corner Radius (mm) ≥ 0.7

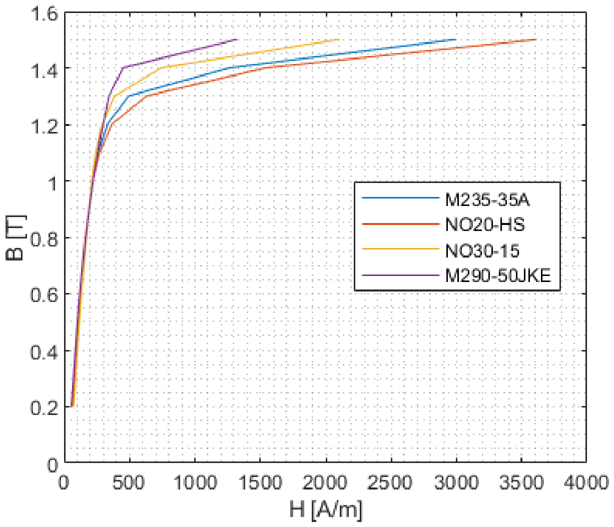


E-Mag Optimization

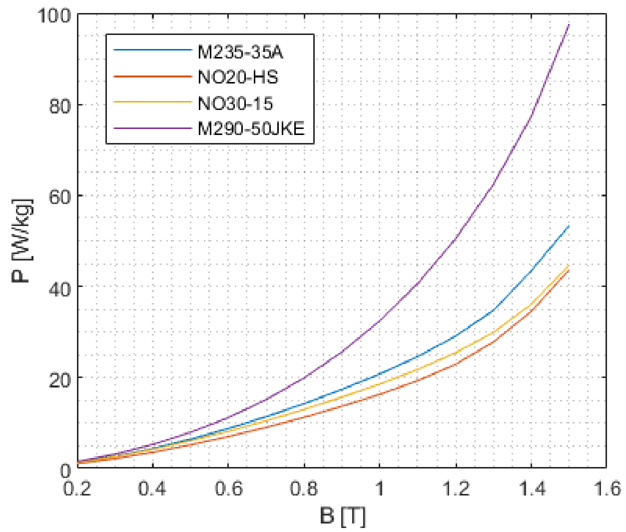
Fixed Parameters

- Machine topology:
  - 4-pole, 36-slot, 50-bar
- Geometry:
  - Stator outer diameter (mm) = 190
- Materials
  - M235-35A steel (rotor & stator)
  - CuAg0.04 (fabricated rotor cage)
  - Cu-ETP (die-casted rotor cage)
- Stator winding:
  - Turns / Phase = 12
  - Packing factor (%) = 73

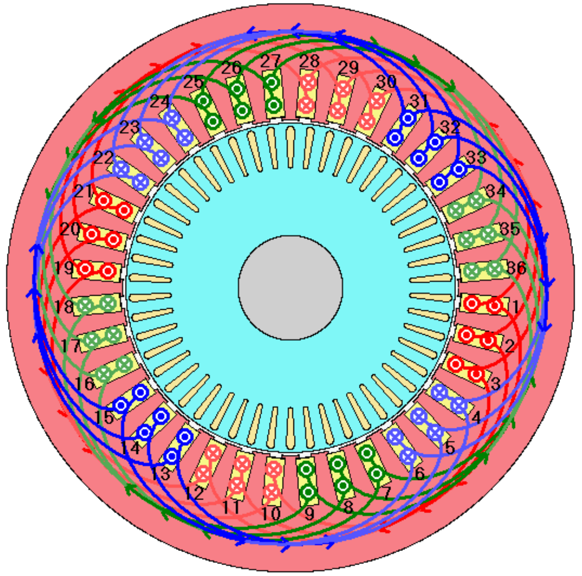
BH curves



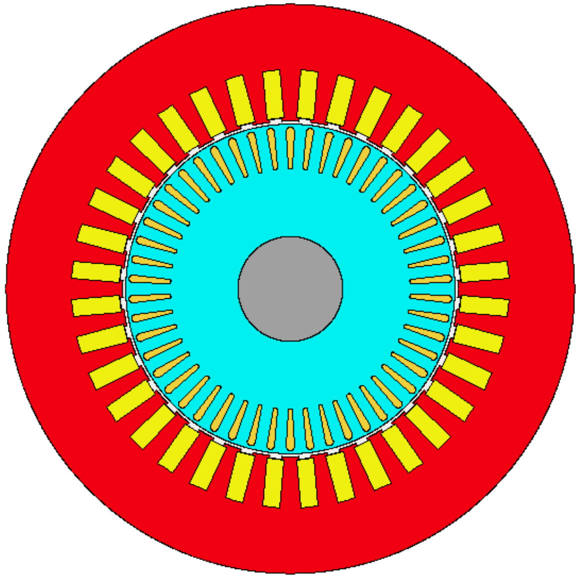
Specific Losses



Winding pattern



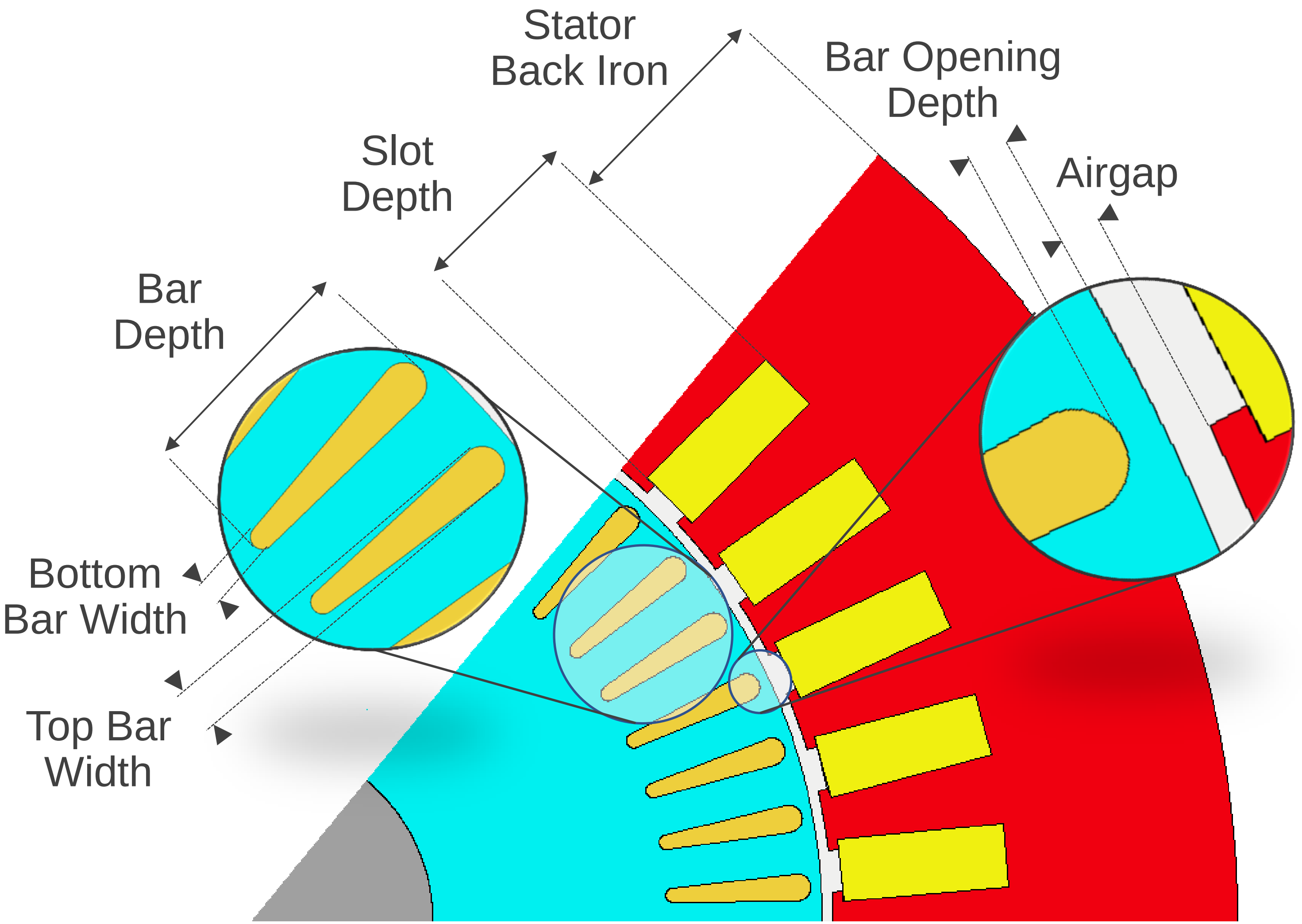
Radial Geometry



E-Mag Optimization

Variable Parameters

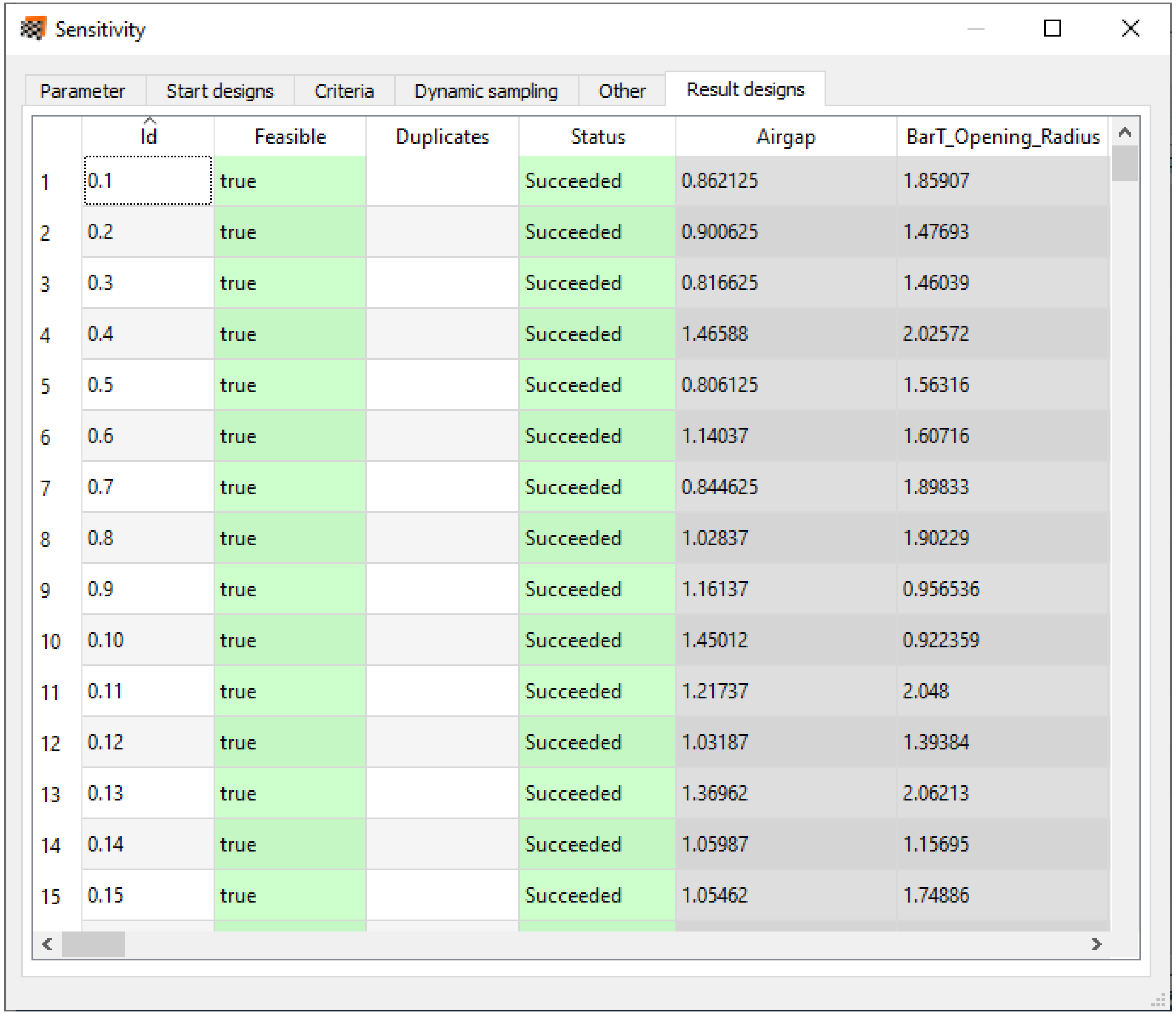
Parameter	Range	Unit
Active length	[100; 175]	mm
Mechanical airgap	[0.8; 1.5]	mm
Split ratio	[0.5; 0.7]	-
Slot depth ratio	[0.3; 0.6]	-
Slot width ratio	[0.4; 0.7]	-
Bar opening depth	[0.5; 1.2]	mm
Bar depth ratio	[0.5; 2.0]	-
Bottom bar width ratio	[0.2; 0.9]	-
Top bar width ratio	[0.3; 0.6]	-



E-Mag Optimization

Sensitivity Analysis

- Multi-core processing used in Motor-CAD calculations to build the saturation and loss models.
- One instance of Motor-CAD used – although parallelisation possible in optiSLang.
- Analysis completed in three days:
  - Generated designs: 400
  - Succeeded designs: 357
  - Failed designs: 43
  - Feasible designs: 0



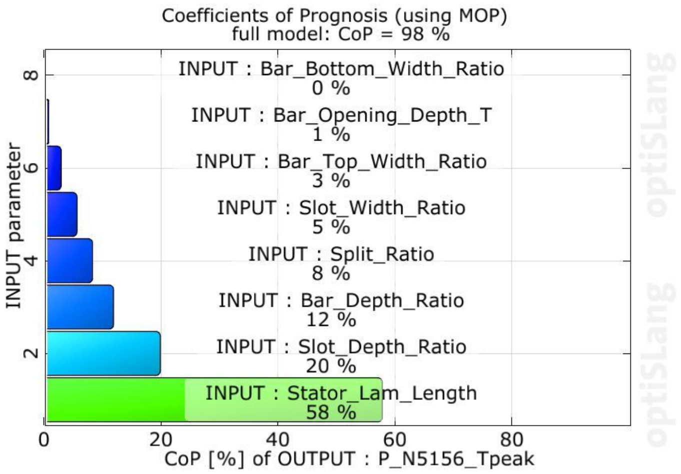
	Id	Feasible	Duplicates	Status	Airgap	BarT_Opening_Radius
1	0.1	true		Succeeded	0.862125	1.85907
2	0.2	true		Succeeded	0.900625	1.47693
3	0.3	true		Succeeded	0.816625	1.46039
4	0.4	true		Succeeded	1.46588	2.02572
5	0.5	true		Succeeded	0.806125	1.56316
6	0.6	true		Succeeded	1.14037	1.60716
7	0.7	true		Succeeded	0.844625	1.89833
8	0.8	true		Succeeded	1.02837	1.90229
9	0.9	true		Succeeded	1.16137	0.956536
10	0.10	true		Succeeded	1.45012	0.922359
11	0.11	true		Succeeded	1.21737	2.048
12	0.12	true		Succeeded	1.03187	1.39384
13	0.13	true		Succeeded	1.36962	2.06213
14	0.14	true		Succeeded	1.05987	1.15695
15	0.15	true		Succeeded	1.05462	1.74886

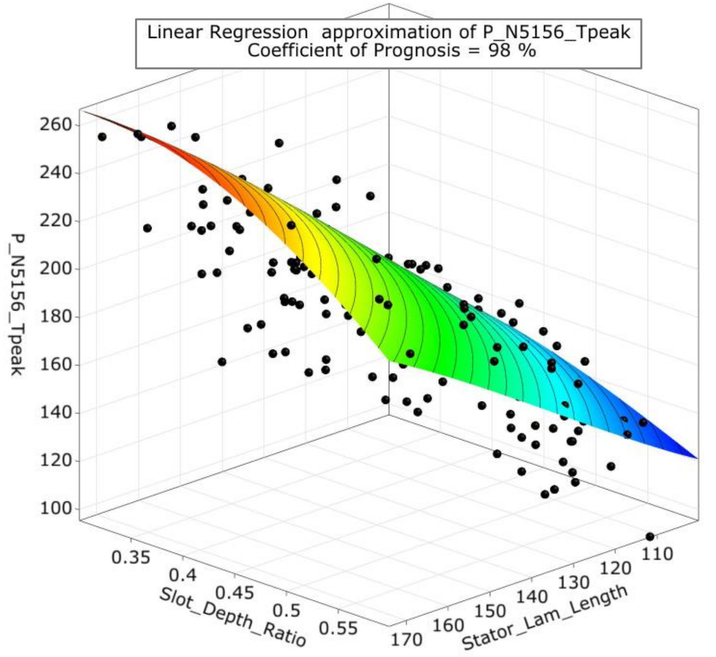
E-Mag Optimization

Metamodel of Optimal Prognosis (MOP)

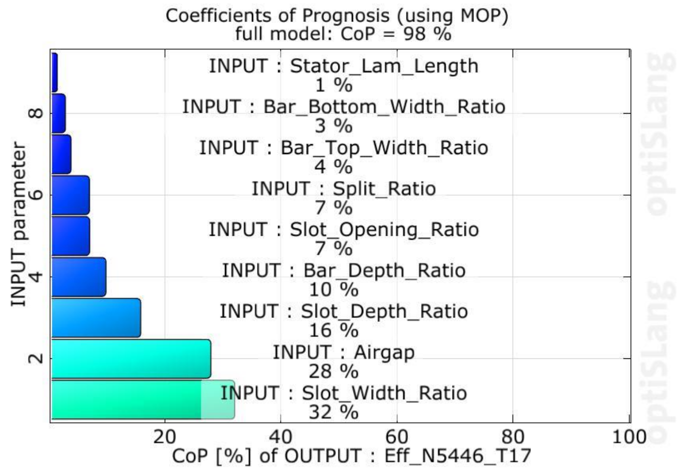
- The calculated MOPs show the optimal subspace for every output parameter of interest.
- The Coefficients of Prognosis, or CoPs, assess the quality of each MOP.
- Additional sampling data can be generated to improve the quality of each MOP..

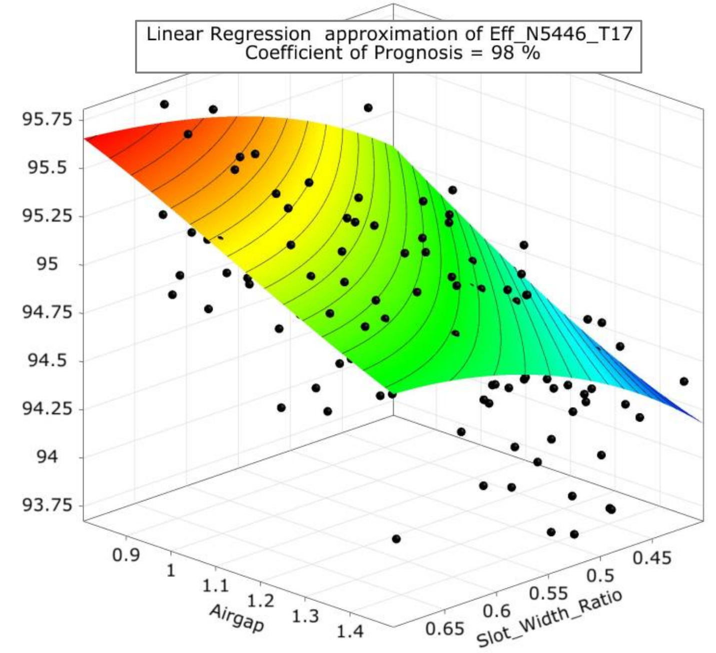
Peak Power @ Base Speed





Efficiency @ 17Nm, 5446rpm

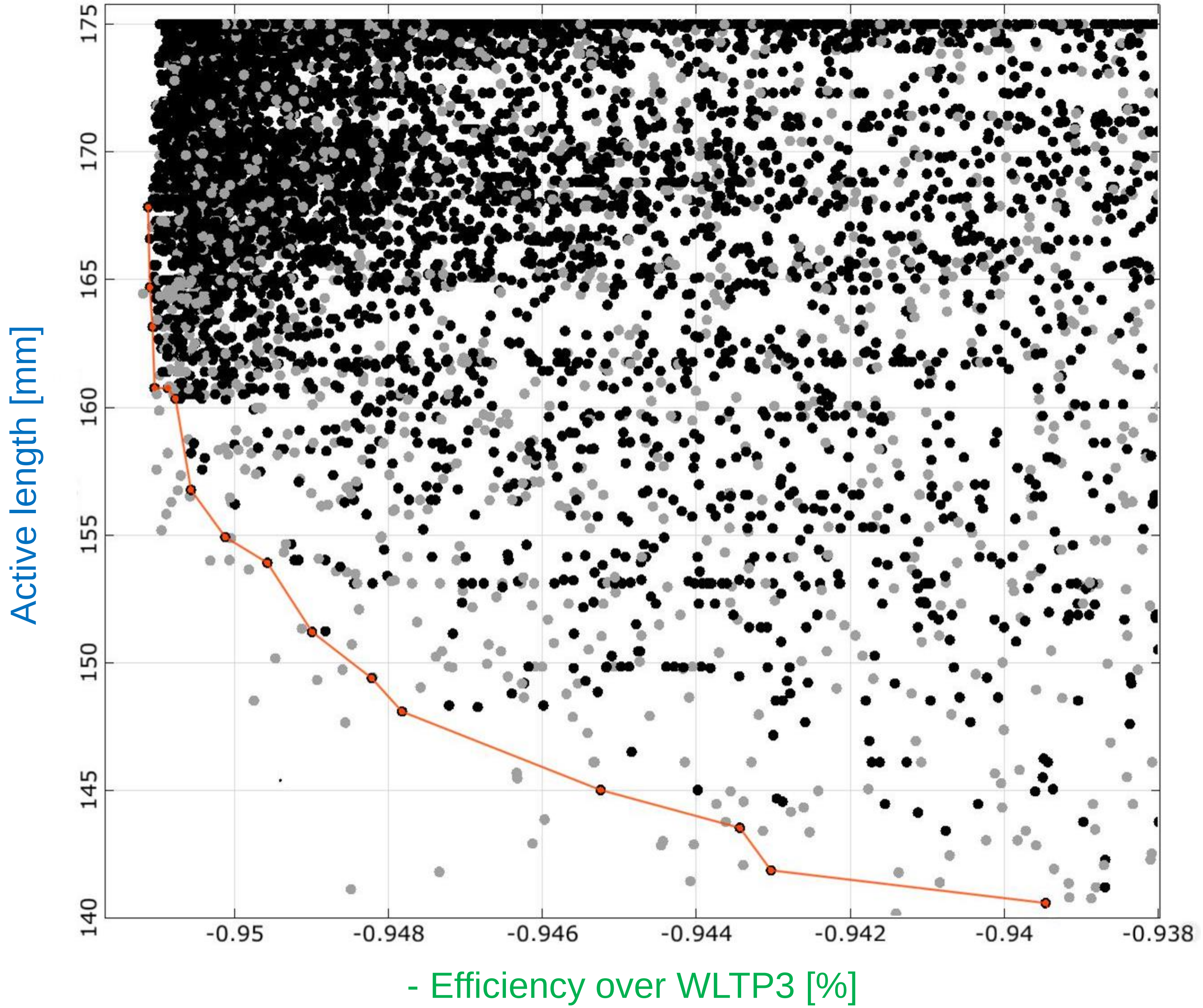




E-Mag Optimization

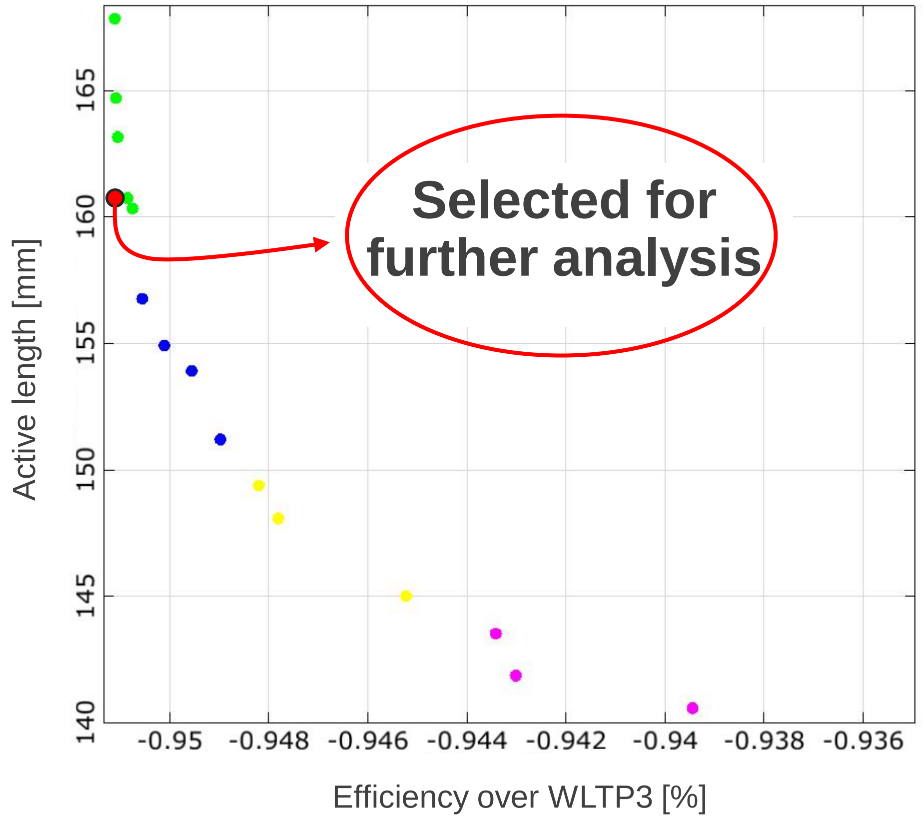
Pareto Frontier

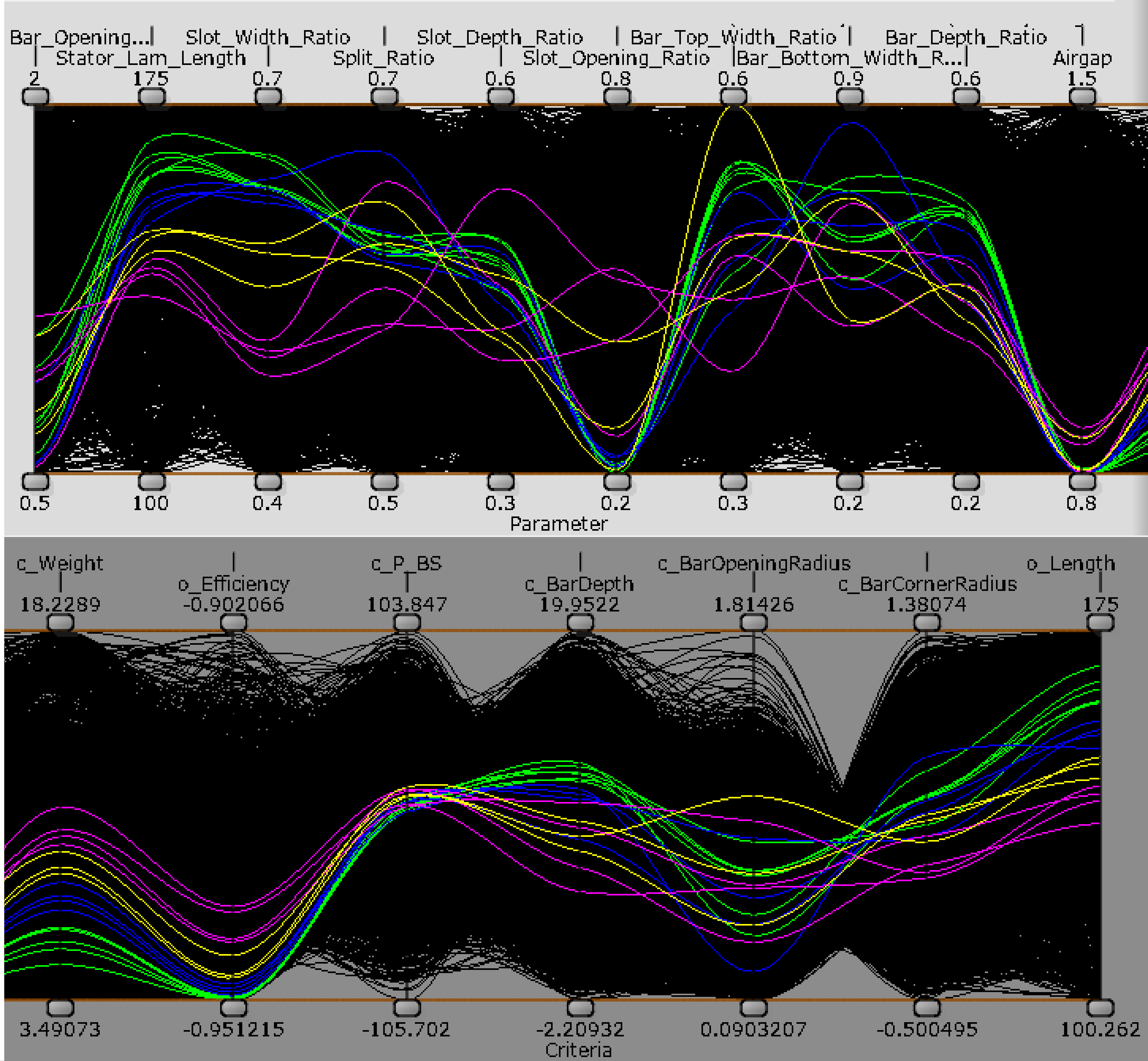
- Solution in which one can trade-off between Efficiency and Volume.
- Important features:
  - Algorithm used: evolutionary
  - Generated designs: 10900
  - Feasible designs: 7616
  - Front designs: 15
  - Simulation time: 10 minutes
- The same optimisation directly applied to Motor-CAD would have taken more than 100 days!



E-Mag Optimization

Parallel Coordinate Plot

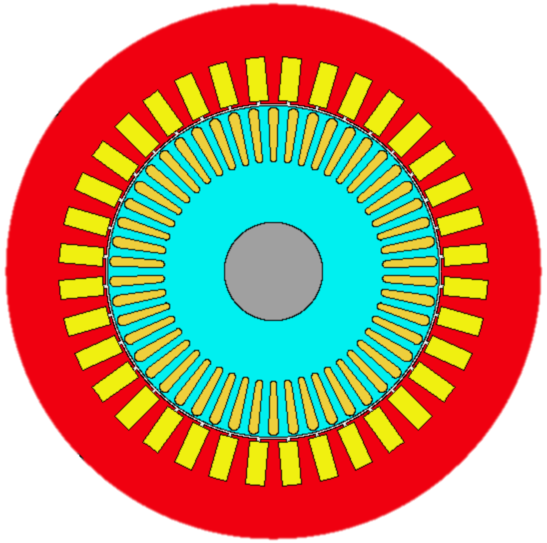


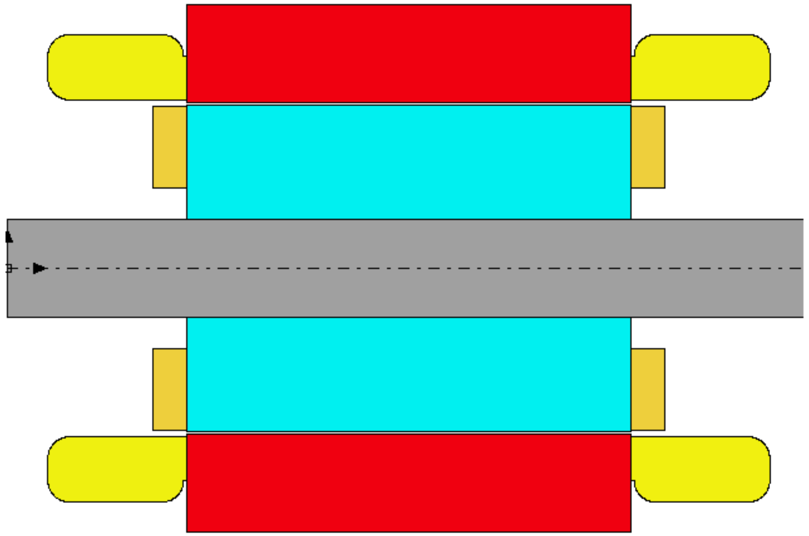


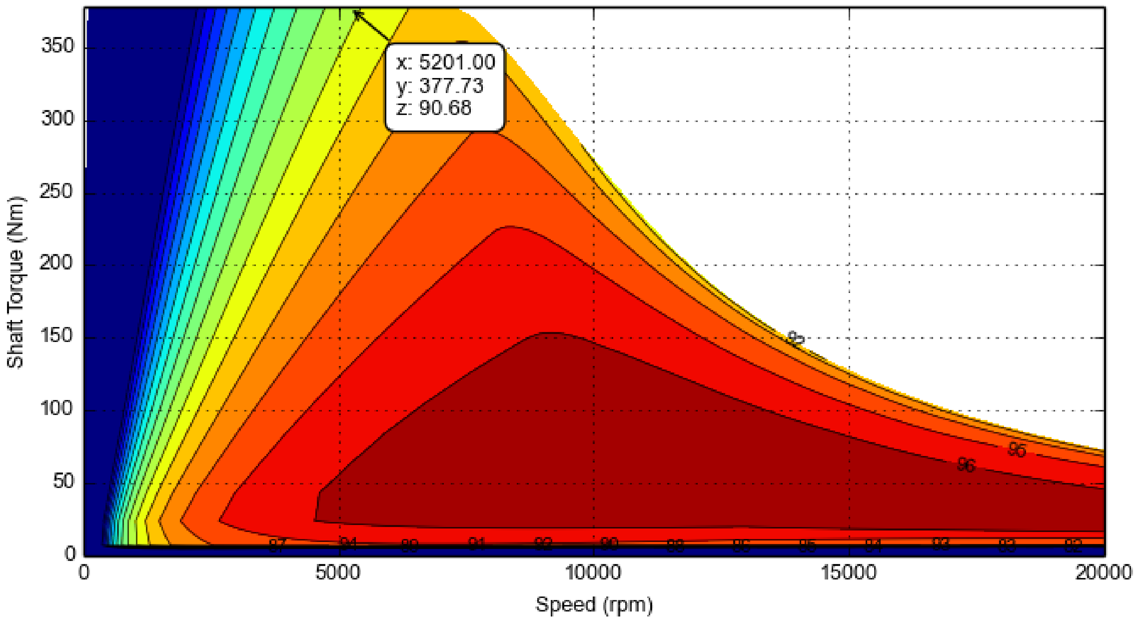
E-Mag Optimization

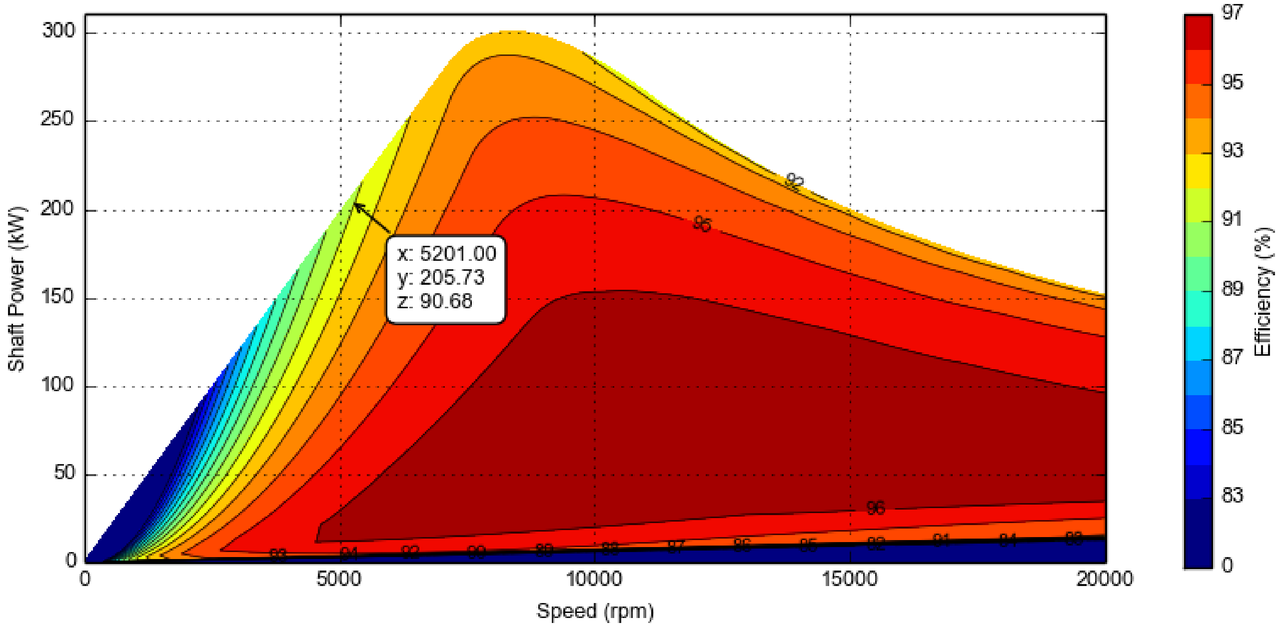
Validation in Motor-CAD

- Peak performance are met and the efficiency over the WLTP3 drive cycle is about 95.05% (motoring).





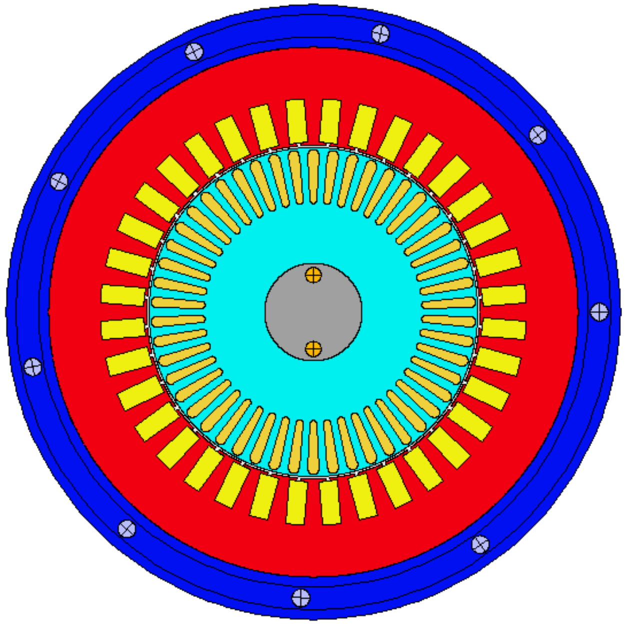


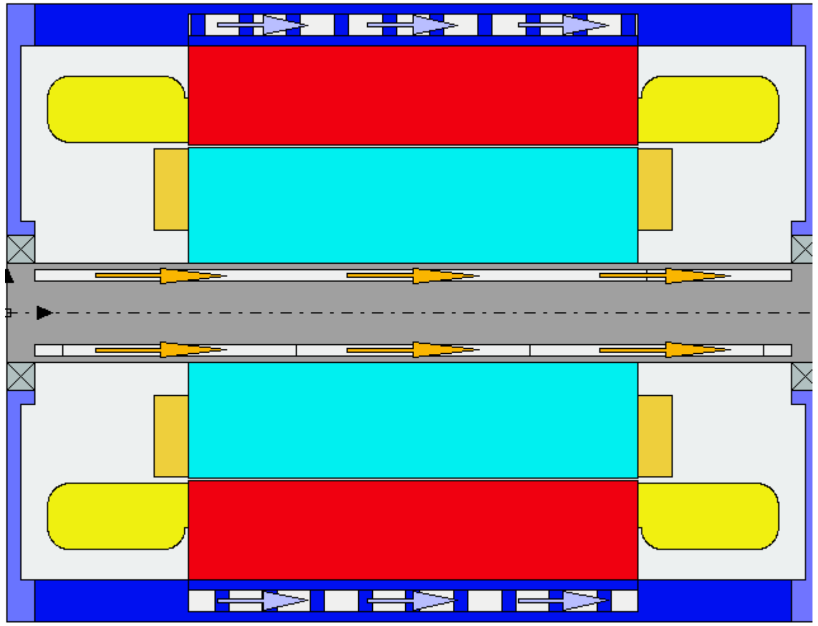


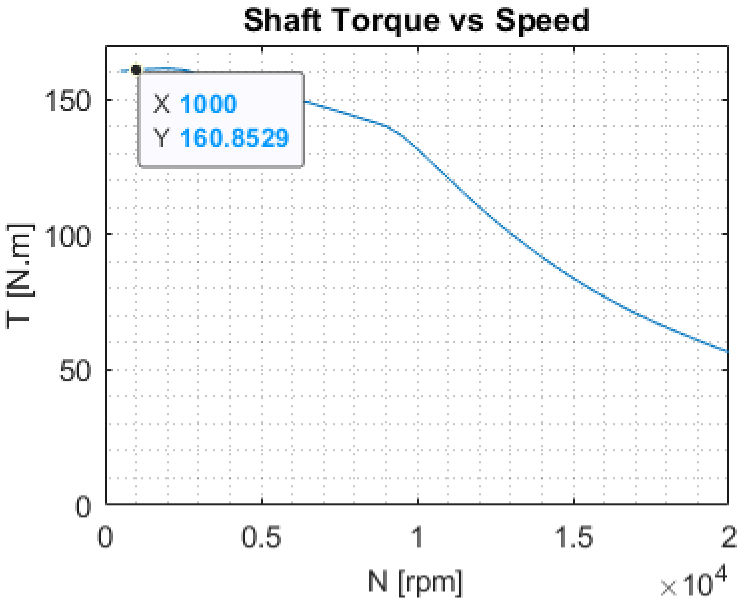
Thermal Design

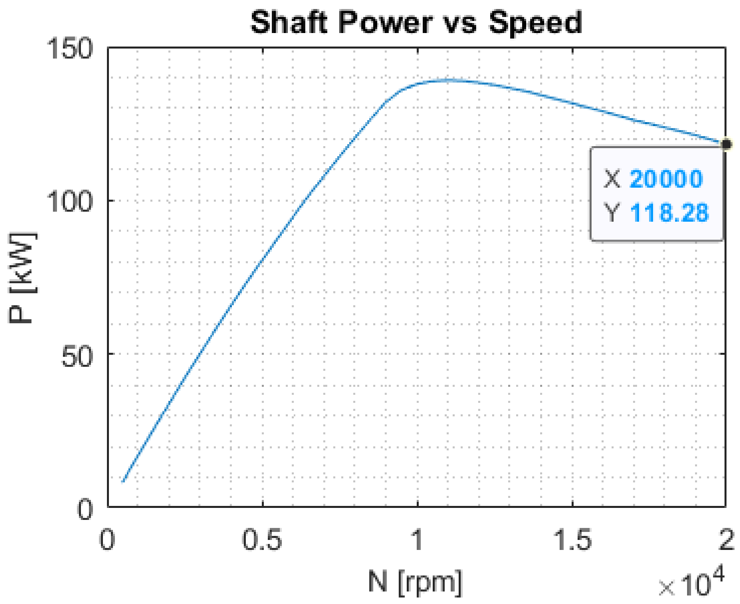
Housing WJ + Shaft Cooling Systems

- Same optimization approach used to design the cooling system.
- Variables include flow rates and the cooling channels' dimensions.
- Continuous performance are met with respect to the specification.









Conclusion

- The design of a 200kW, 20000rpm copper rotor induction motor for a traction application has been presented.
- The machine was optimized electromagnetically and thermally using Motor-CAD and optiSLang software.
- This combination is an incredibly powerful approach to optimise an electric machine for an automotive HEV/EV application.
- The optimized motor is currently being prototyped and will be tested next year. A scaled version will be then integrated on a vehicle powertrain for real performance testing.

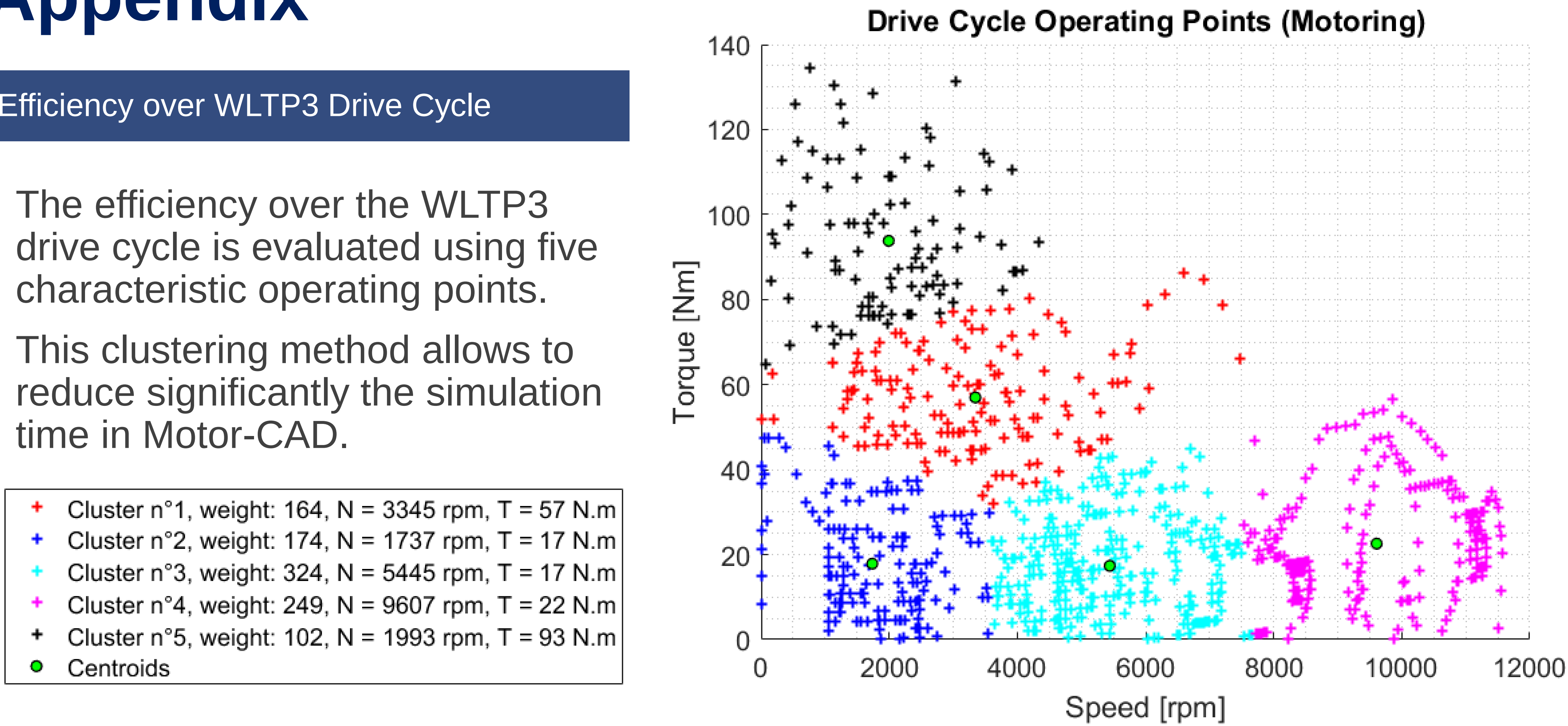
ReFreeDrive

Rare-Earth Free e-Drives feat. low cost manufacturing

Appendix

Efficiency over WLTP3 Drive Cycle

- The efficiency over the WLTP3 drive cycle is evaluated using five characteristic operating points.
- This clustering method allows to reduce significantly the simulation time in Motor-CAD.



Appendix

CoPs Matrix

- Matrix that shows the CoPs of all output parameters with respect to input parameters:
- The last column contains the full model CoPs of each response.