A progressive multiphysics optimisation approach to the design of an electric motor to meet vehicle-level performance targets

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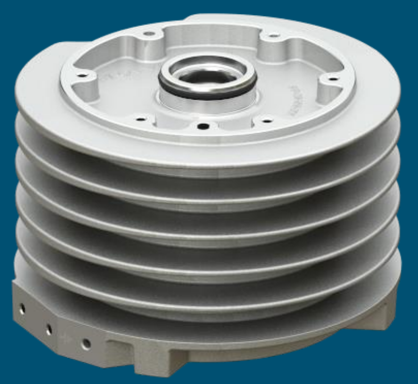
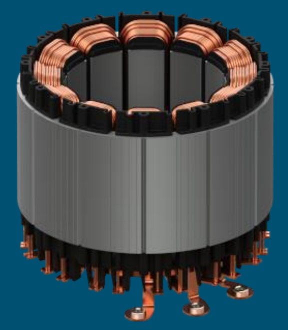
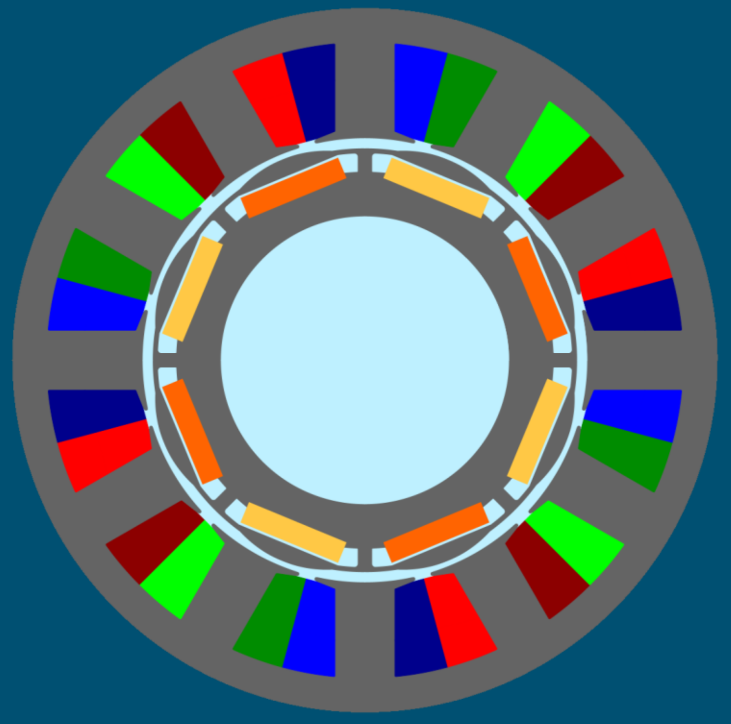
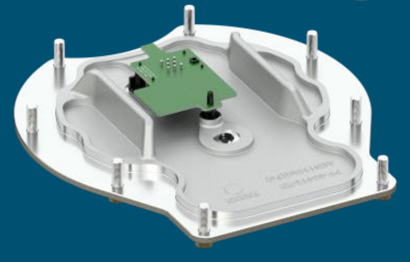
29 February 2024









ABOUT SAIETTA

AFT140i

AFT140i eDrive

RFT85-65 eDrive

VCU

Saietta Electric Drive

GLOBAL TECHNICAL CENTRE

Silverstone, United Kingdom

Saietta Sunderland Production

UK PRODUCTION FACILITY

Sunderland, United Kingdom

Saietta VNA

MAKE-IN-INDIA PRODUCTION FACILITY

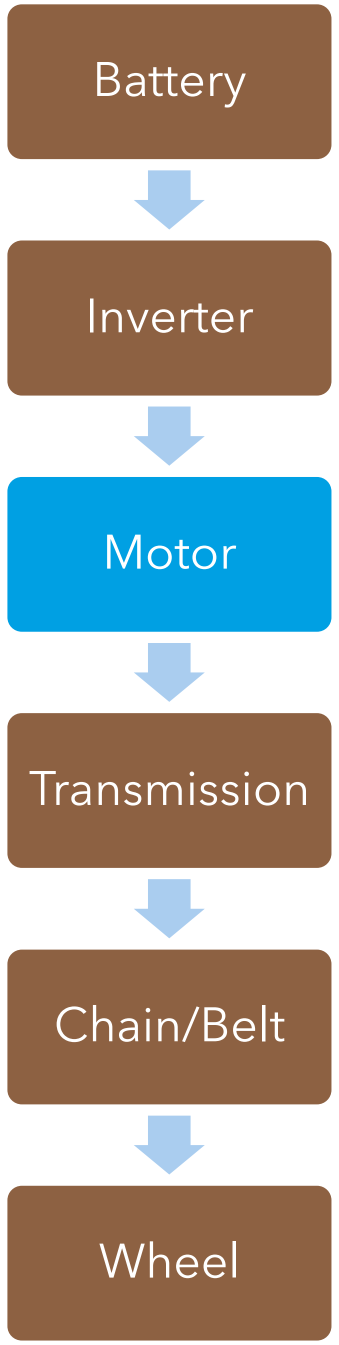
Manesar, New Delhi, India

SAIETTA ELECTRIC DRIVE

PROBLEM STATEMENT

Electric Motorcycle Requirements (Example Study)

- Space constraints
  - Maximum stator outer diameter – 175 mm
  - Maximum stator length (including end windings) – 100 mm
- Transmission
  - Feasible overall ratios (including chain/belt ratio) – 10:1 | 12:1
- Battery / Inverter
  - Nominal DC voltage – 48 V
  - Maximum phase current – 240 Arms/ph
- Performance
  - Peak wheel torque - 320 Nm for 10 s
  - Wheel torque knee point – 250 rpm
  - Peak power – 9 kW for 10 s
  - Continuous power - 6 kW @ 300 rpm @ 50 °C ambient (190 Nm @ wheel)
  - Specific wheel operating point – 200 Nm @ 350 rpm for 60 s @ 50 °C ambient
  - Peak wheel torque @ maximum wheel speed – 80 Nm @ 850 rpm
  - Cogging torque limit – 3%
  - Torque ripple limit – 25%
- Range optimisation
  - World Motorcycle Test Cycle (WMTC)

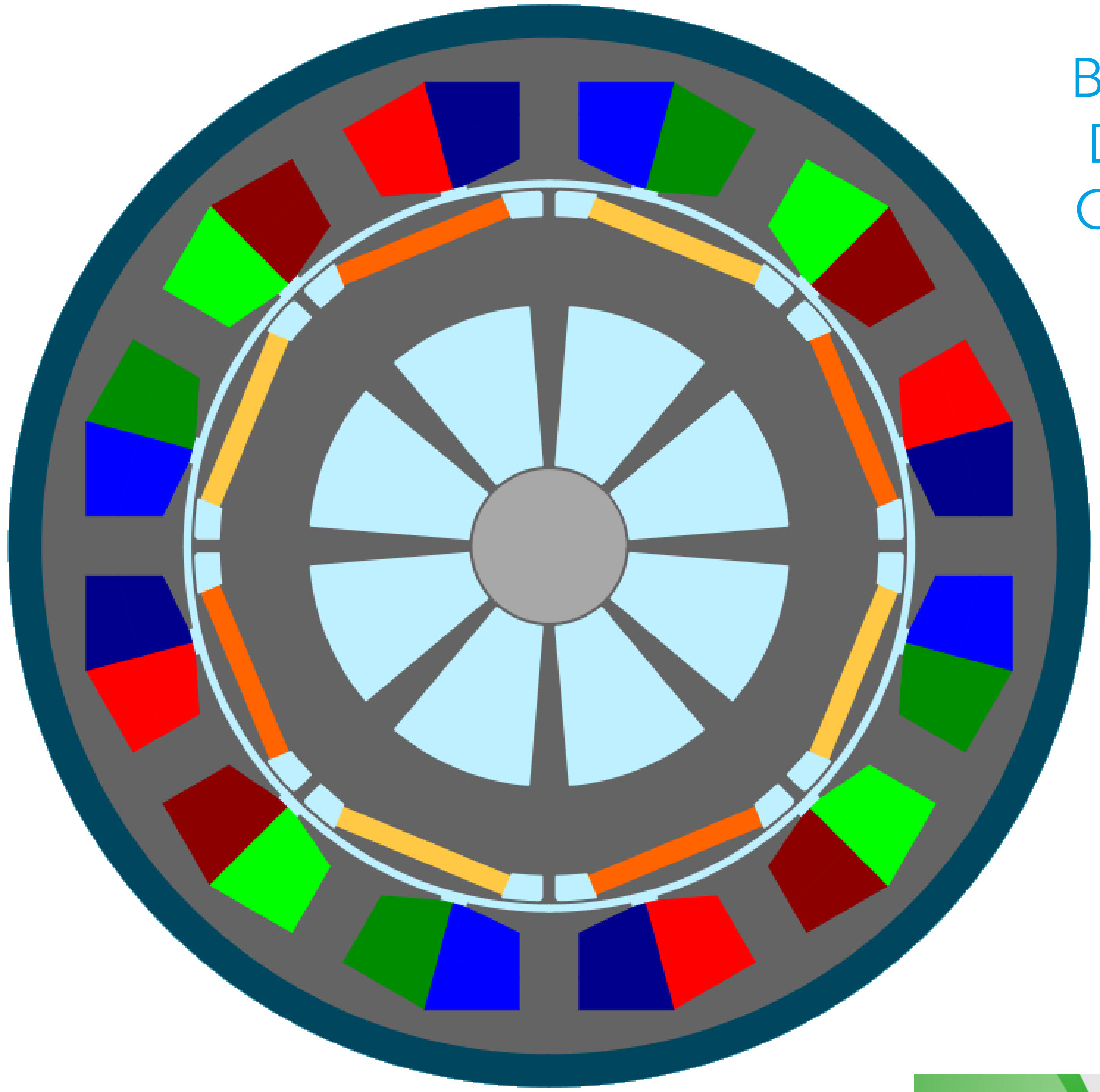


Optimum motor solution is that which delivers the performance at the lowest cost for a chosen drive cycle efficiency

GEOMETRY PARAMETRISATION

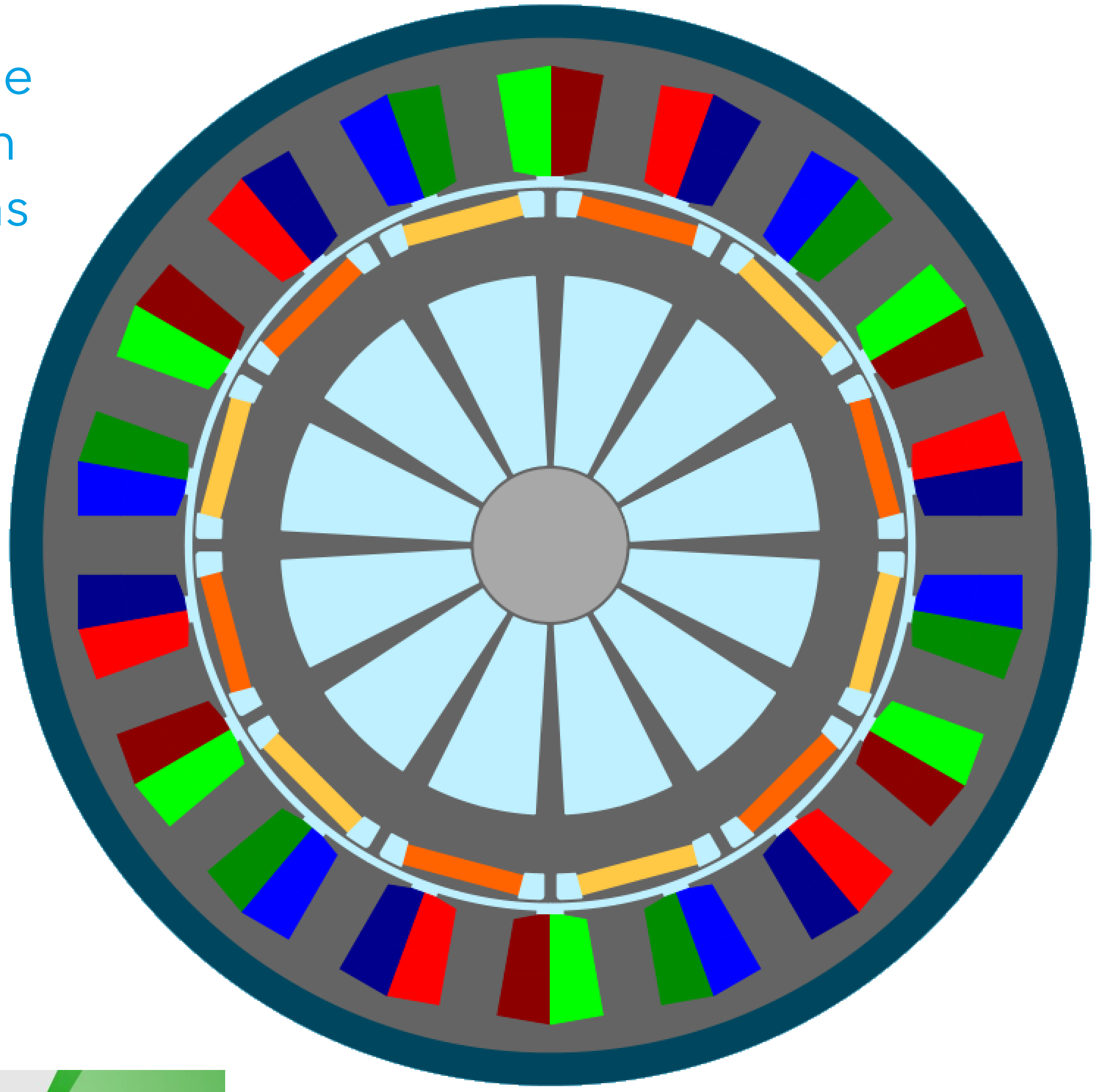
Machine Topology & Transmission Ratio

- Radial Flux Machine
  - Interior Permanent Magnet (IPM) rotor (single magnet per pole)
  - Segmented-stator (bobbin wound = parallel tooth)



8 pole / 12 slot

Baseline Design Options

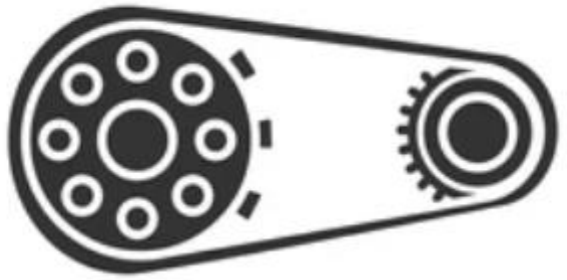


12 pole / 18 slot

Altair® FluxMotor®
MotorFactory

Parallel-shaft reducer on motor

+



Belt / chain drive to wheel

Parameters
Number of Poles
Number of Slots
Stator Outer Diameter (OD)
Split Ratio (Airgap Diameter to Stator OD)
Airgap (mm)
Active Length (mm)
Overall Transmission Ratio (Motor to Wheel)

Acknowledgement: Close collaboration with Altair's e-Motor Director Team, who have been incredibly supportive to enable us to get the most from their software toolchain

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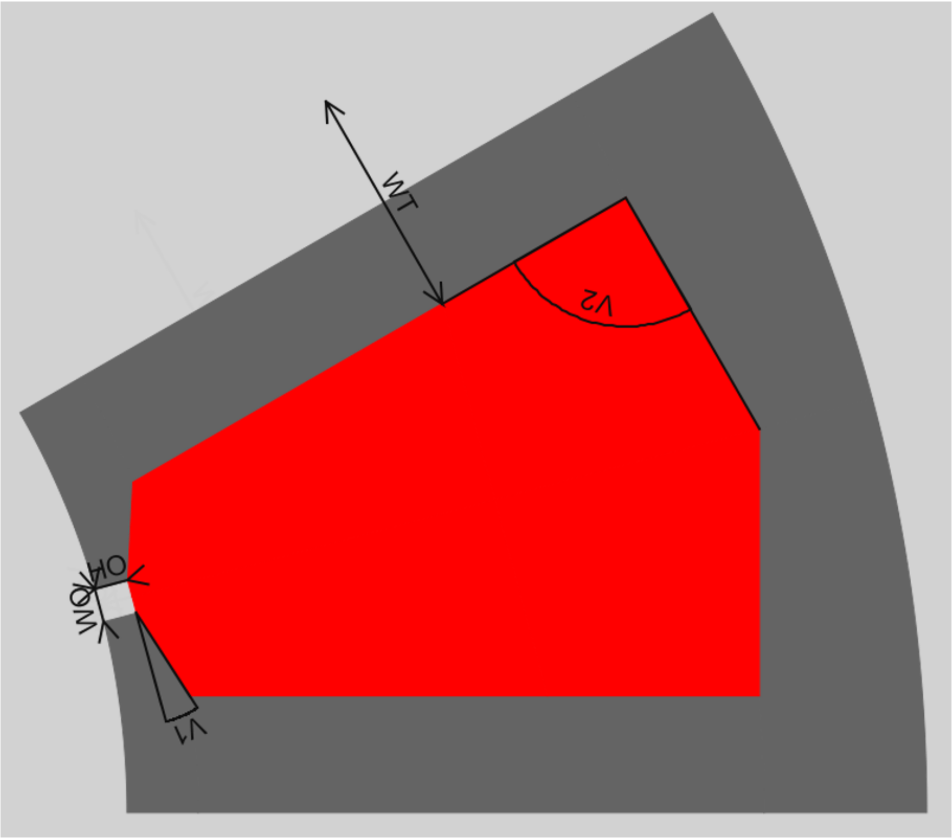
GEOMETRY PARAMETRISATION

Stator



Parameters
Tooth Width (WT)
Slot Opening (WO)
Slot Opening Height (HO)
Tooth Tip Angle (V1)
Slot Corner Radii (R1,R2,R3)
Slot Bottom Angle (V2)

- Yoke thickness driven by tooth width
- Tooth width driven by Slot Width : Tooth Width ratio

Representative geometry templates for demo purposes only

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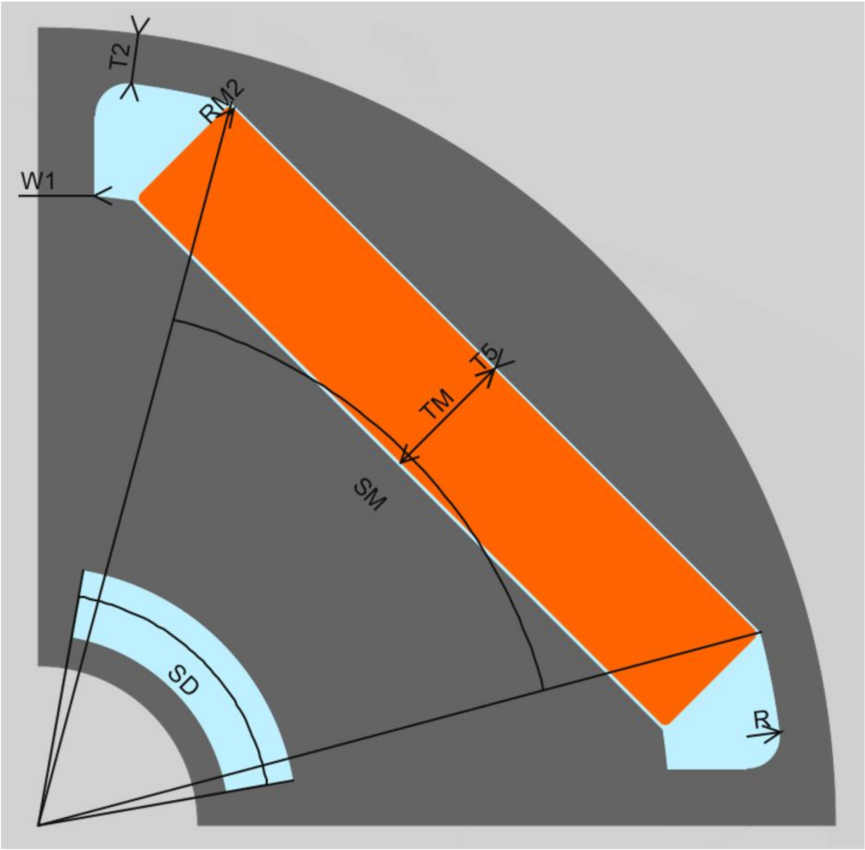
Rotor

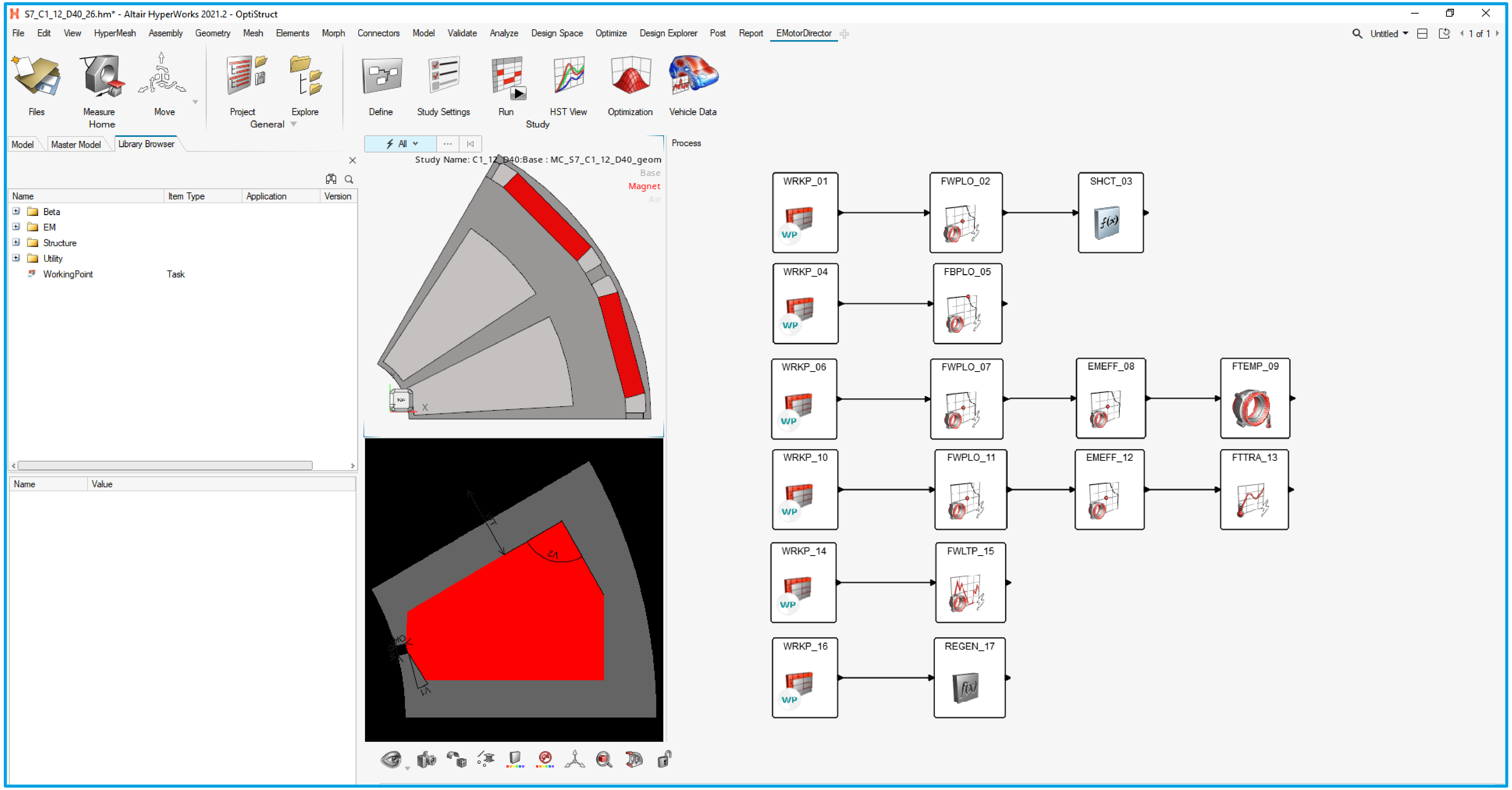


Parameters
Magnet Span (SM)
Magnet Thickness (TM)
Magnet Corner Radii (RM2)
Web Width (W1)
Bridge Thickness (T2)
Pocket Radii (R)
Pocket Tolerance (T5)
Duct Span (SD)

DESIGN OF EXPERIMENTS (DOE)

Altair® e-Motor Director™

ALTAIR



- Efficiently establish relationship between multiple input variables and key output responses
- Responses gathered from various electromagnetic, thermal, and structural analysis tasks
- Easy interface to define the analysis tasks that are run for each experiment

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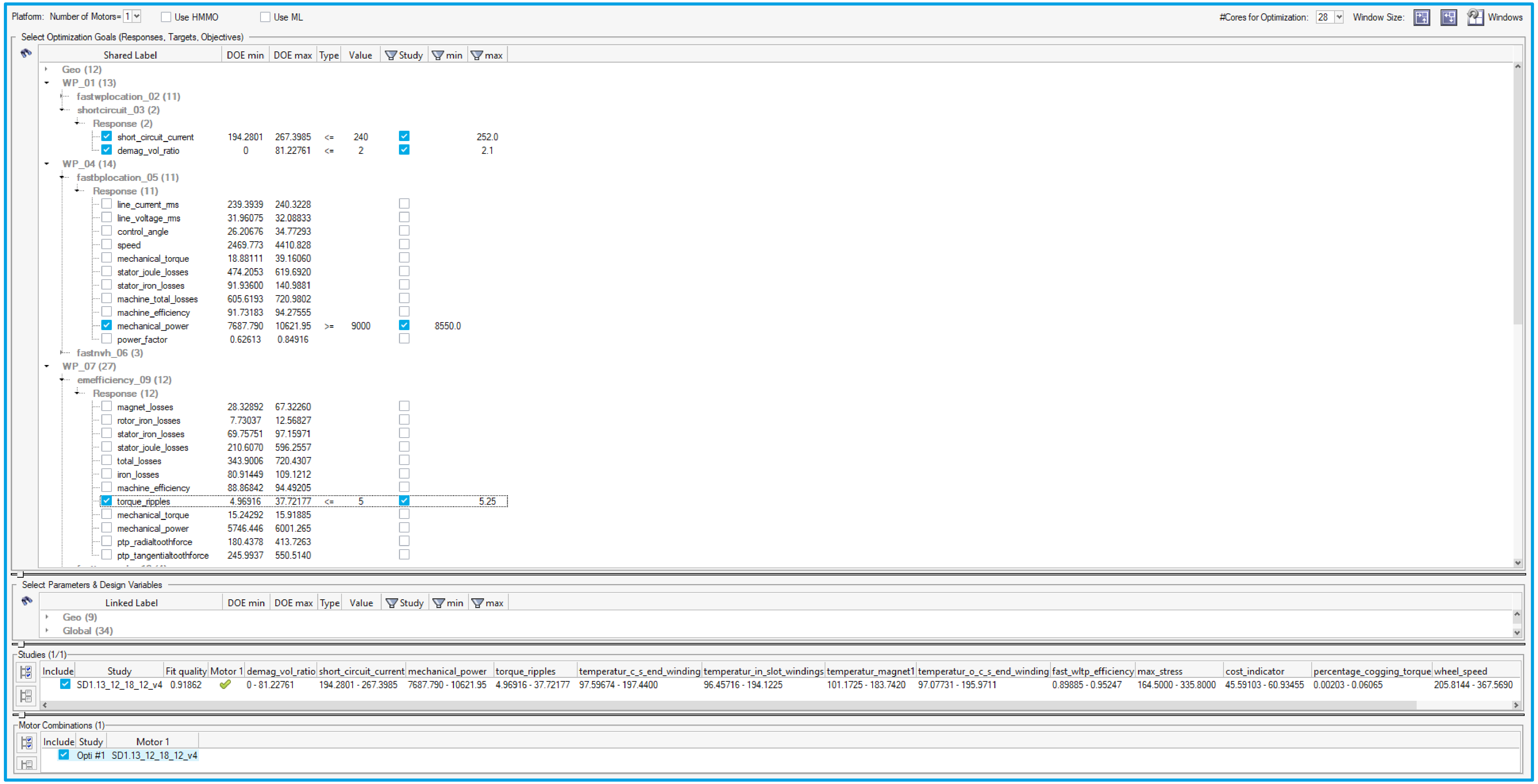
OPTIMISATION

Altair® e-Motor Director™



- Response Surface methodology
- Uses a "fit" (mathematical model) established from the DoE
- Optimisation on response surfaces using GRSM or HMMO
- Allows for AI based optimisation

OPTIMISATION

The Challenge

Let's just create a DoE for all possible parameter variations and all responses of interest and let the optimisation process spit out the best design

Unfortunately, it's not so straightforward:

- Lots of parameters = high computational cost

- Some parameters have very low impact on overall motor performance (e.g. the torque / speed characteristics)
  - End up exploring a very high proportion of infeasible designs
  - Influence of some parameters can get "lost in the noise"

- Discrete parameters such as the gear ratio or the number of turns per coil cause discontinuities in the response surface leading to challenging/unreliable optimisation

Segment the Design Space

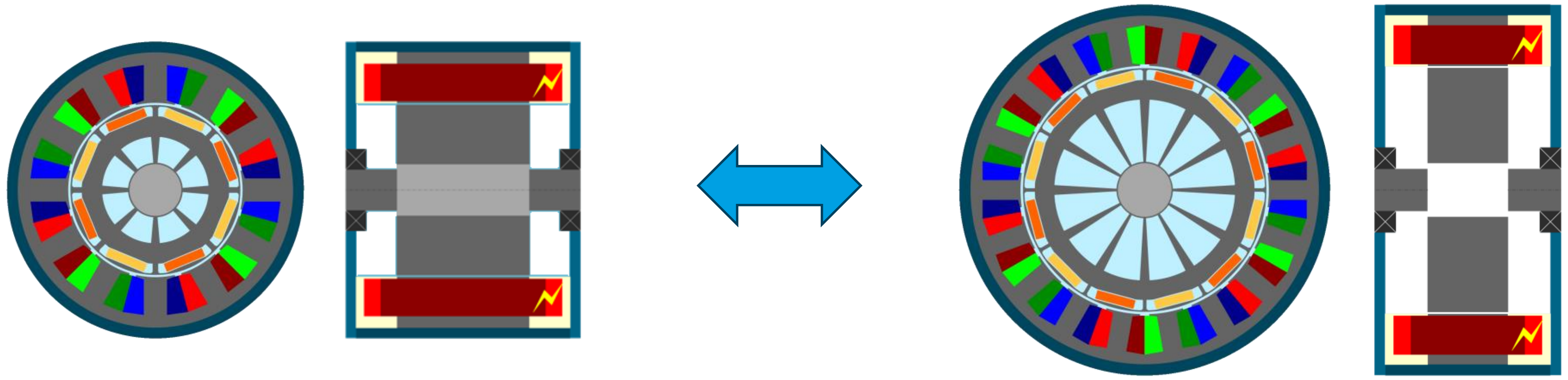
OPTIMISATION

A Phased Approach

CONCEPT PHASE

› Find best overall motor proportions for each distinct configuration (e.g. slot / pole combination and gear ratio)

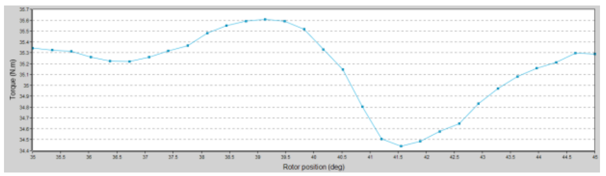
Large variation allowed for a low number of design variables



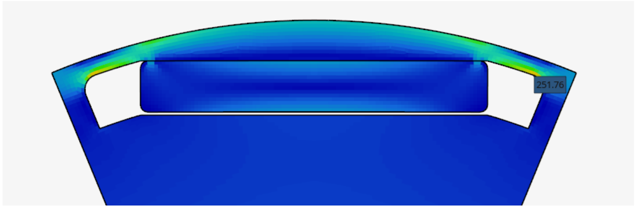
DETAILED PHASE

› Use optimal outputs from Concept Phase as baseline
  › Set a manufacturable stator/winding geometry (wire size, slot height, etc)
  › Refine each design configuration, including some additional constraints

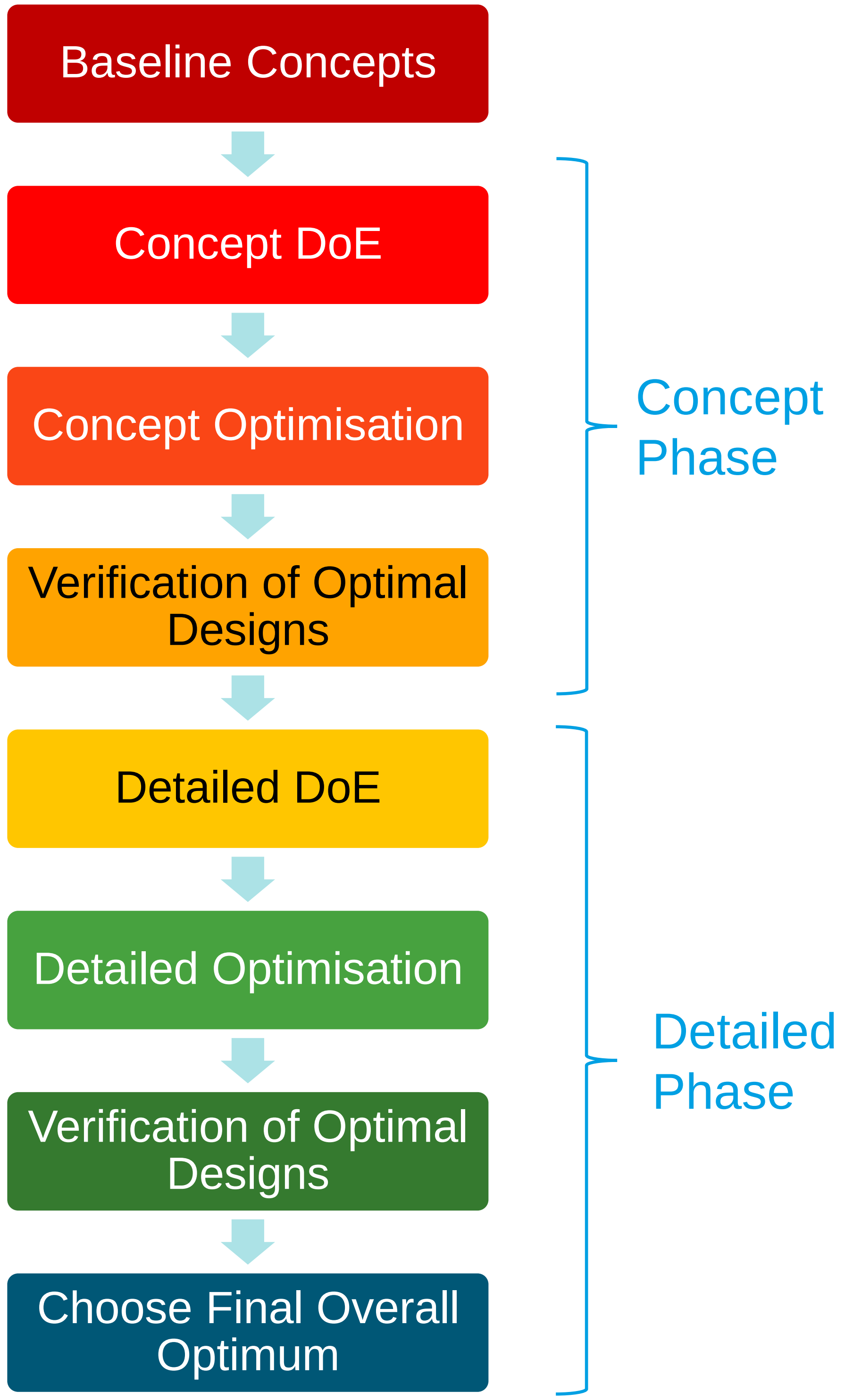
Small variation allowed for a greater number of design variables



e.g. Torque Ripple



e.g. Rotor Stress



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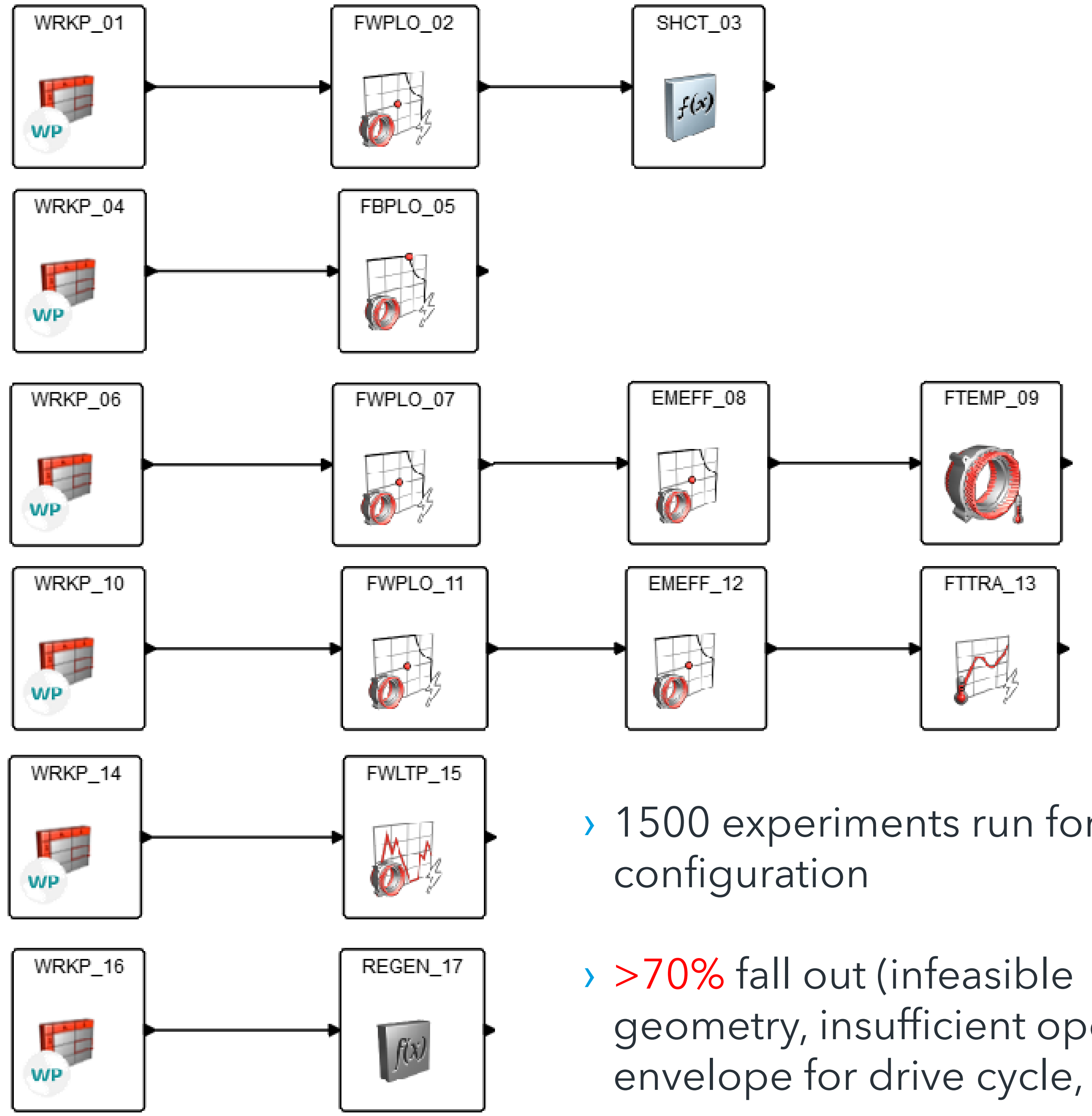
CONCEPT PHASE

Design of Experiments (DoE) & Optimisation

Design Variable	Lower Limit	Upper Limit
Maximum Phase Current (Arms/ph)	200	260
Active Length (mm)	35	80
Stator Outer Diameter (mm)	115	190
Split Ratio (Airgap Diameter to Stator OD)	0.5	0.9
Number of Turns per Coil	15	22
Wire Diameter (mm)	(calculated to give 60% slot fill)	
Magnet Thickness (mm)	2.0	6.0
Magnet Span (elec. deg)	95	145
Web Width (mm)	0.5	4.5

Response	Optimisation
Maximum Phase Current (Arms/ph)	<= 240
Peak Power (kW)	>= 9
Peak Wheel Torque (Nm)	>= 350 (some margin for next phase)
Wheel Torque Knee Point (rpm)	>= 250
Short-Circuit Current (Arms/ph)	<= 240
Demagnetisation Volume (%)	<= 2 (to avoid discontinuity at 0)
Magnet Temperature (°C)	<= 140
Winding Temperature (°C)	<= 165
Drive Cycle Efficiency (%)	Maximise
Cost Function	Minimise

RESPONSE GENERATION (11 tasks)



- 1500 experiments run for each configuration
- >70% fall out (infeasible geometry, insufficient operating envelope for drive cycle, etc)

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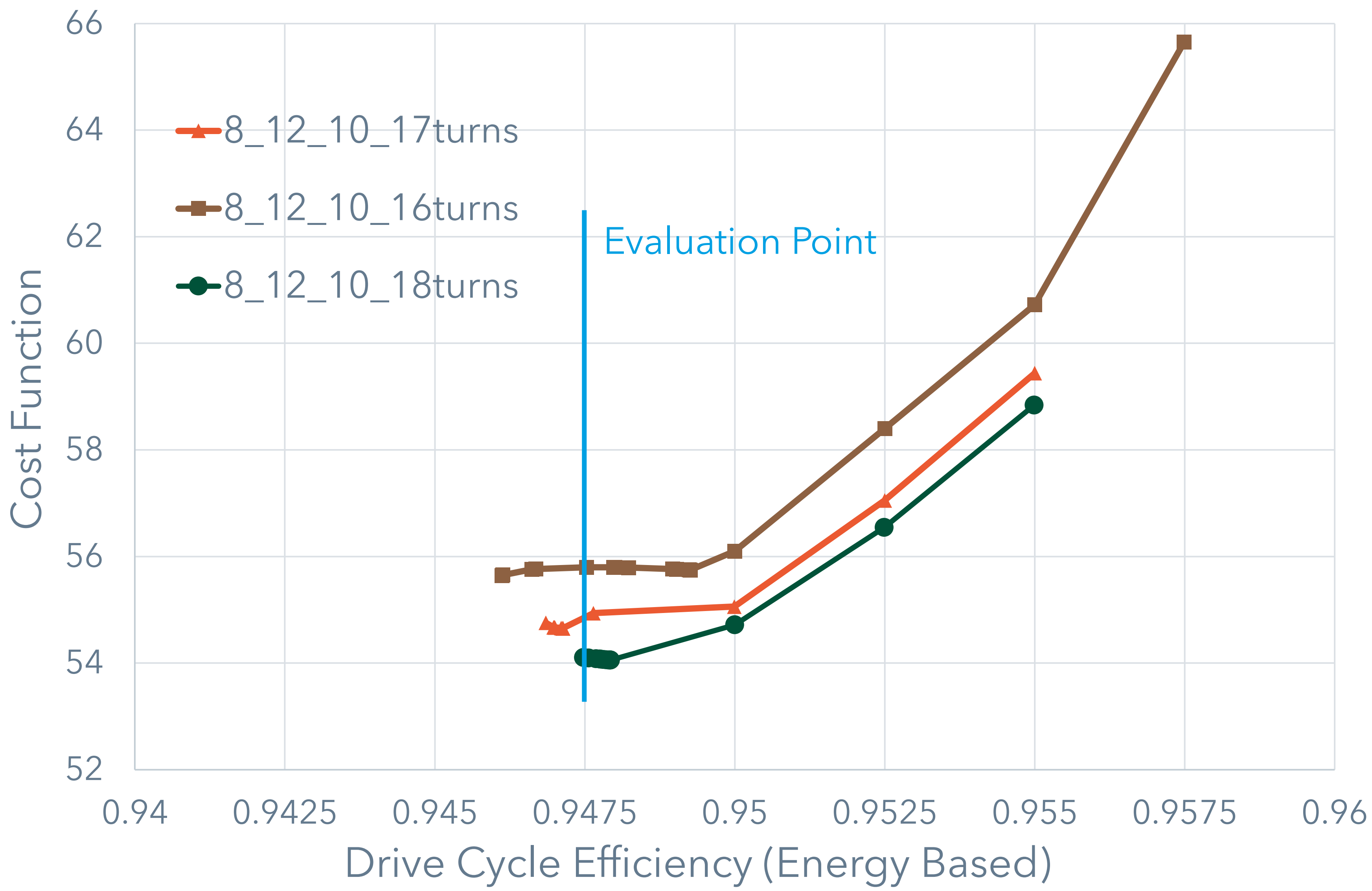
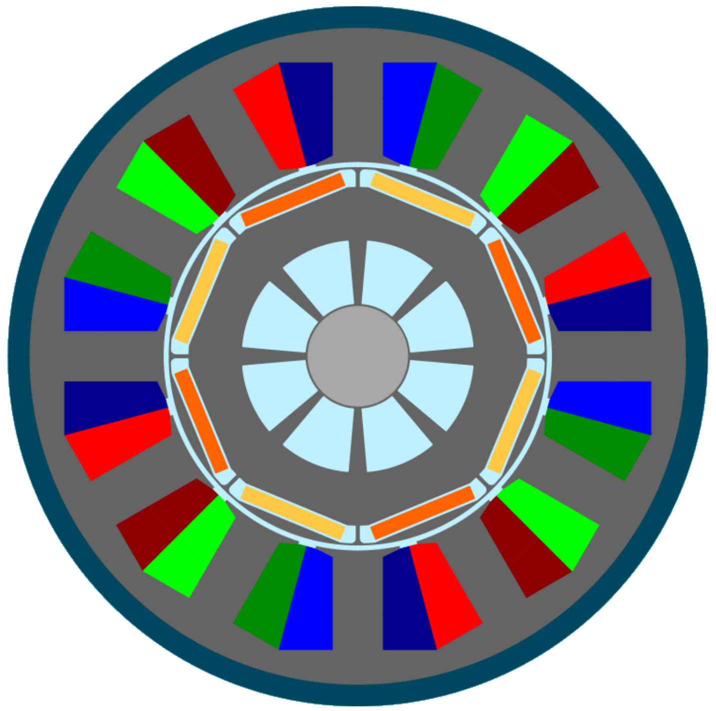
CONCEPT PHASE

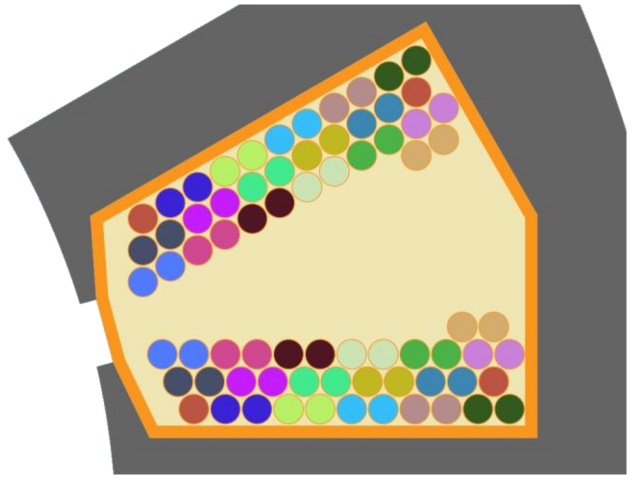
Pareto Front – e.g. 8 pole / 12 slot / 10:1 gear ratio configuration

- Cost Function represents raw material cost of active materials
- Motor efficiency and active material volume/cost are conflicting requirements
  ⟶ a pareto optimisation problem
- Pareto fronts emerge for each discrete variable (such as number of coil turns)



Response	Optimum
Maximum Phase Current (Arms/ph)	240
Active Length (mm)	42.5
Stator Outer Diameter (mm)	167
Split Ratio (Airgap Diameter to Stator OD)	0.59
Tooth Width (mm)	13
Number of Turns per Coil	18
Magnet Thickness (mm)	4.1
Magnet Span (elec. deg)	138
Web Width (mm)	1.5
Wire Diameter (mm)	1.7





SAIETTA ELECTRIC DRIVE

DETAILED PHASE

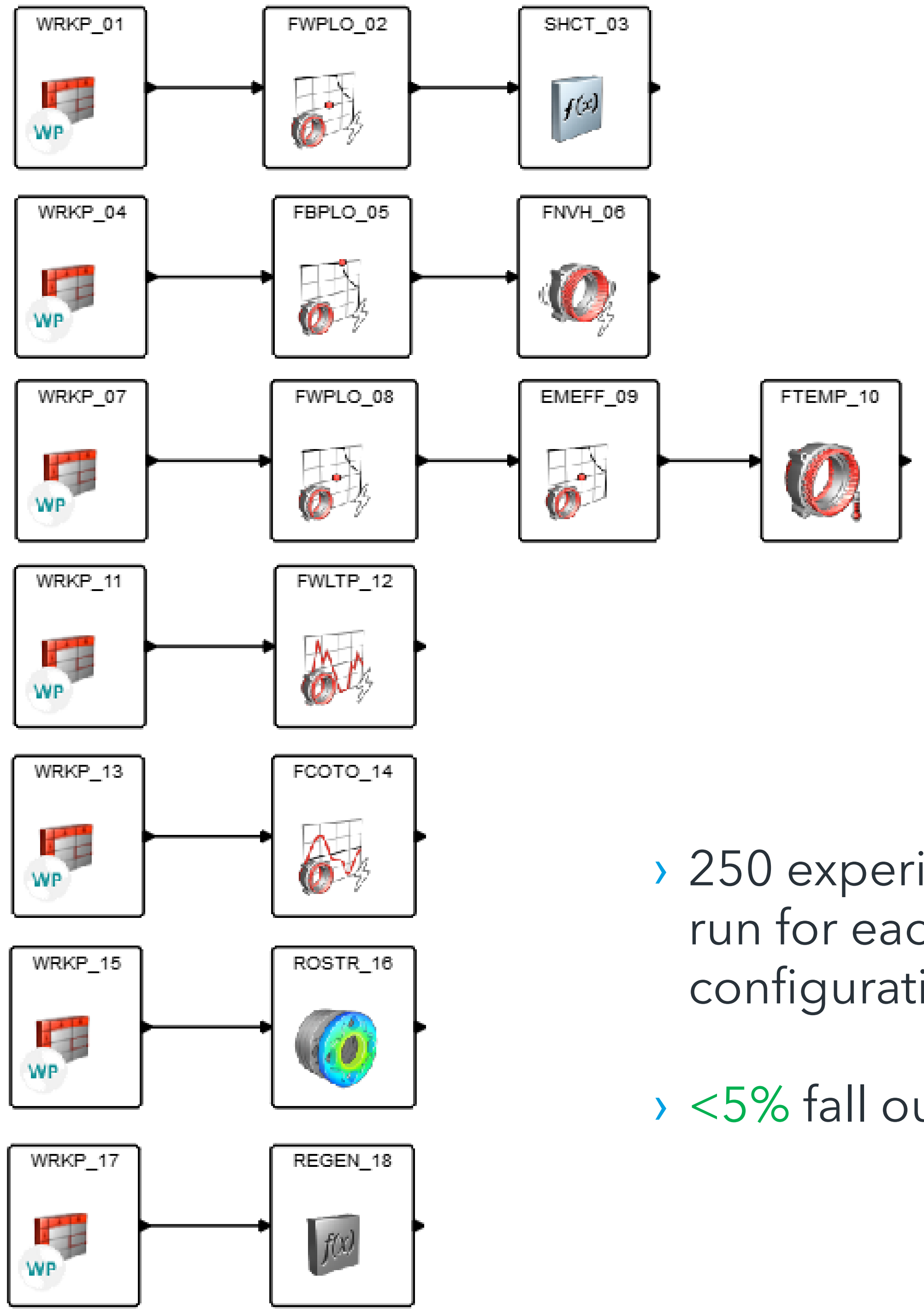
Design of Experiments (DoE) & Optimisation

Design Variable
Active Length (mm)
Airgap (mm)
Slot Opening Width (mm)
Magnet Span (elec. deg)
Magnet Thickness (mm)
Bridge Thickness (mm)
Web Width (mm)
Magnet Pocket Radii (mm)

- ± 25% variation for DoE
- ± 20% variation for Optimisation (avoid DoE borders where fit is less reliable)
- Distinct ranges for each configuration in this phase

Response	Optimisation
Peak Power (kW)	>= 9
Peak Wheel Torque (Nm)	>= 320
Wheel Torque Knee Point (rpm)	>= 250
Short-Circuit Current (Arms/ph)	<= 240
Demagnetisation Volume (%)	<= 2
Magnet Temperature (°C)	<= 140
Winding Temperature (°C)	<= 165
Maximum Rotor Stress (MPa)	<= 250
Cogging Torque (%)	<= 3
Torque Ripple (%)	<= 22
Cost Function	Minimise

RESPONSE GENERATION (11 tasks)



- 250 experiments run for each configuration
- <5% fall out

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DETAILED PHASE

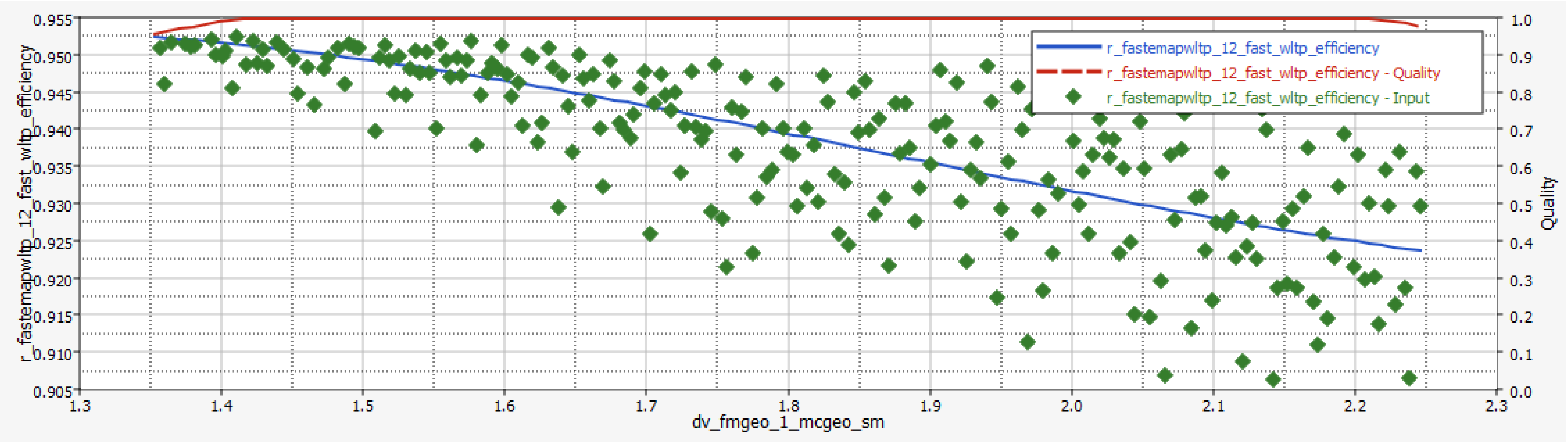
Fit Quality

CORRELATION TABLE EXTRACT

Label	Fit Type	Fit Specifics	X R^2
r_shortcircuit_03_demag_vol_ratio	RBF	linear - Multiquadric - 6.7869684	0.9379034
r_fastbplocation_05_line_voltage_rms	LSR	Custom	0.7488873
r_fastbplocation_05_control_angle	RBF	constant - CS21 - 3.9150742	0.9667478
r_fastbplocation_05_speed	RBF	linear - Multiquadric - 10.000000	0.9992056
r_fastbplocation_05_mechanical_torque	RBF	constant - CS21 - 7.2759667	0.9994831
r_fastbplocation_05_stator_joule_losses	LSR	Custom	0.9997674
r_fastbplocation_05_stator_iron_losses	RBF	constant - CS21 - 8.8650202	0.9960373
r_fastbplocation_05_machine_total_losses	RBF	constant - CS21 - 8.8650202	0.9990771
r_fastbplocation_05_machine_efficiency	RBF	linear - Multiquadric - 8.9490598	0.9987195
r_fastbplocation_05_mechanical_power	RBF	constant - CS21 - 8.8650202	0.9993449
r_fastbplocation_05_power_factor	RBF	constant - CS21 - 8.8650202	0.9993107
r_fastnvh_06_nvh_overall_sound_power_level	RBF	constant - Multiquadric - 1.0000000	0.8292369
r_fastnvh_06_nvh_overall_sound_power_level_dba	RBF	constant - Multiquadric - 1.0000000	0.8225759
r_fastnvh_06_nvh_reference_pressure_for_0db	RBF	constant - CS21 - 4.5337882	0.9959594
r_fastwplocation_08_line_current_rms	RBF	constant - CS21 - 4.6181632	0.9961006
r_fastwplocation_08_line_voltage_rms	LSR	Custom	0.9712581
r_fastwplocation_08_control_angle	RBF	constant - CS21 - 1.0000000	0.8991670
r_fastwplocation_08_stator_joule_losses	RBF	constant - CS21 - 4.6041097	0.9837144
r_fastwplocation_08_stator_iron_losses	RBF	constant - CS21 - 8.8650202	0.9248549
r_fastwplocation_08_machine_total_losses	RBF	constant - CS21 - 8.4079979	0.9851342
r_fastwplocation_08_machine_efficiency	RBF	constant - CS21 - 7.4025382	0.9854917
r_fastwplocation_08_power_factor	RBF	constant - CS21 - 8.8650202	0.9985704
r_emefficiency_09_magnet_losses	RBF	constant - CS21 - 2.7513843	0.9616562

TRADE-OFF EXAMPLE

Magnet Span vs Drive Cycle Efficiency



Simulation results
Correlation
Fit quality (1 = perfect fit quality)

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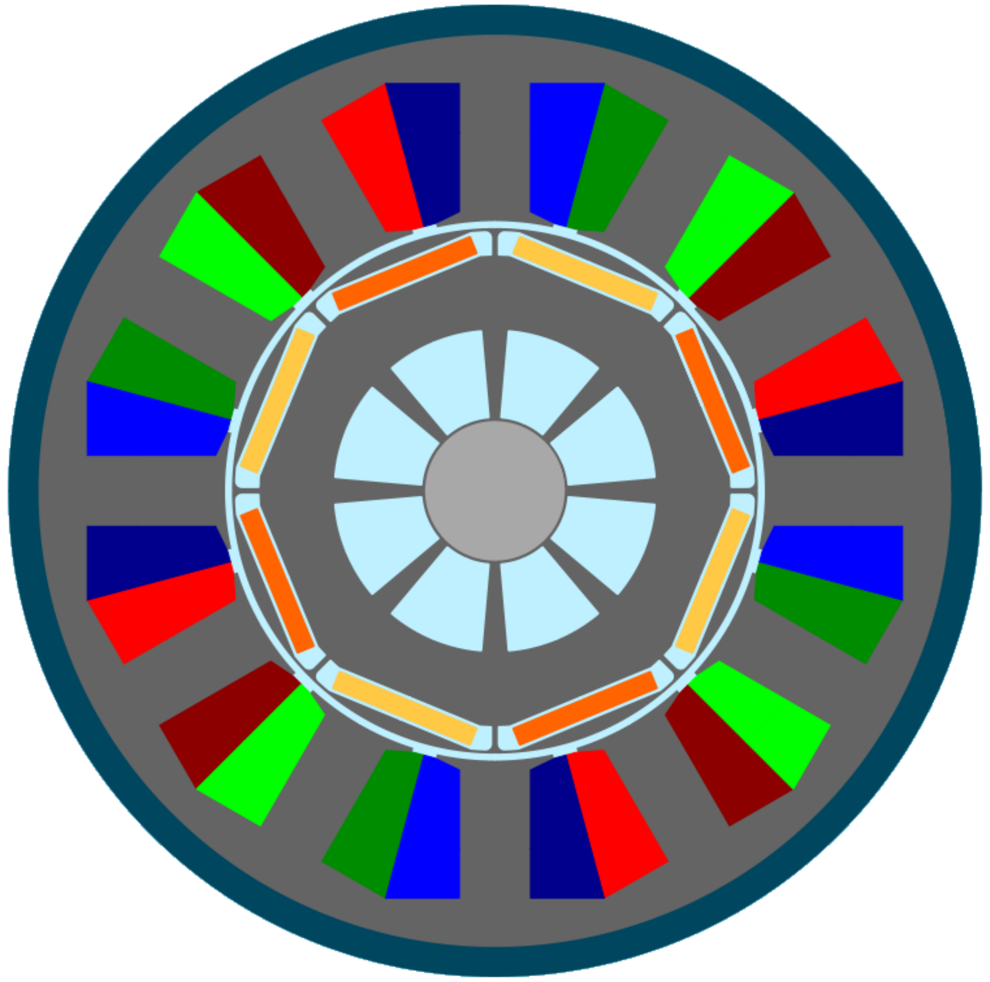
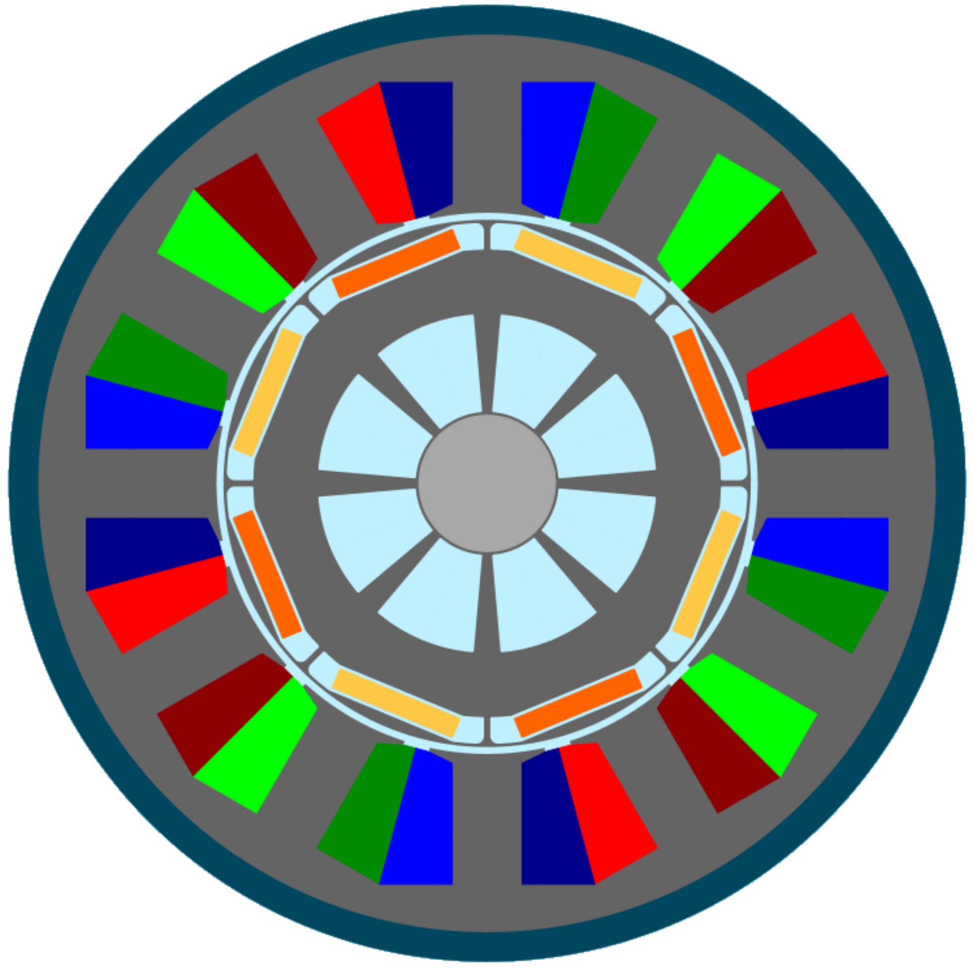
DETAILED PHASE

Optimisation (Refinement from Concept Phase)

Example configuration:
8 pole / 12 slot
10:1 gear ratio

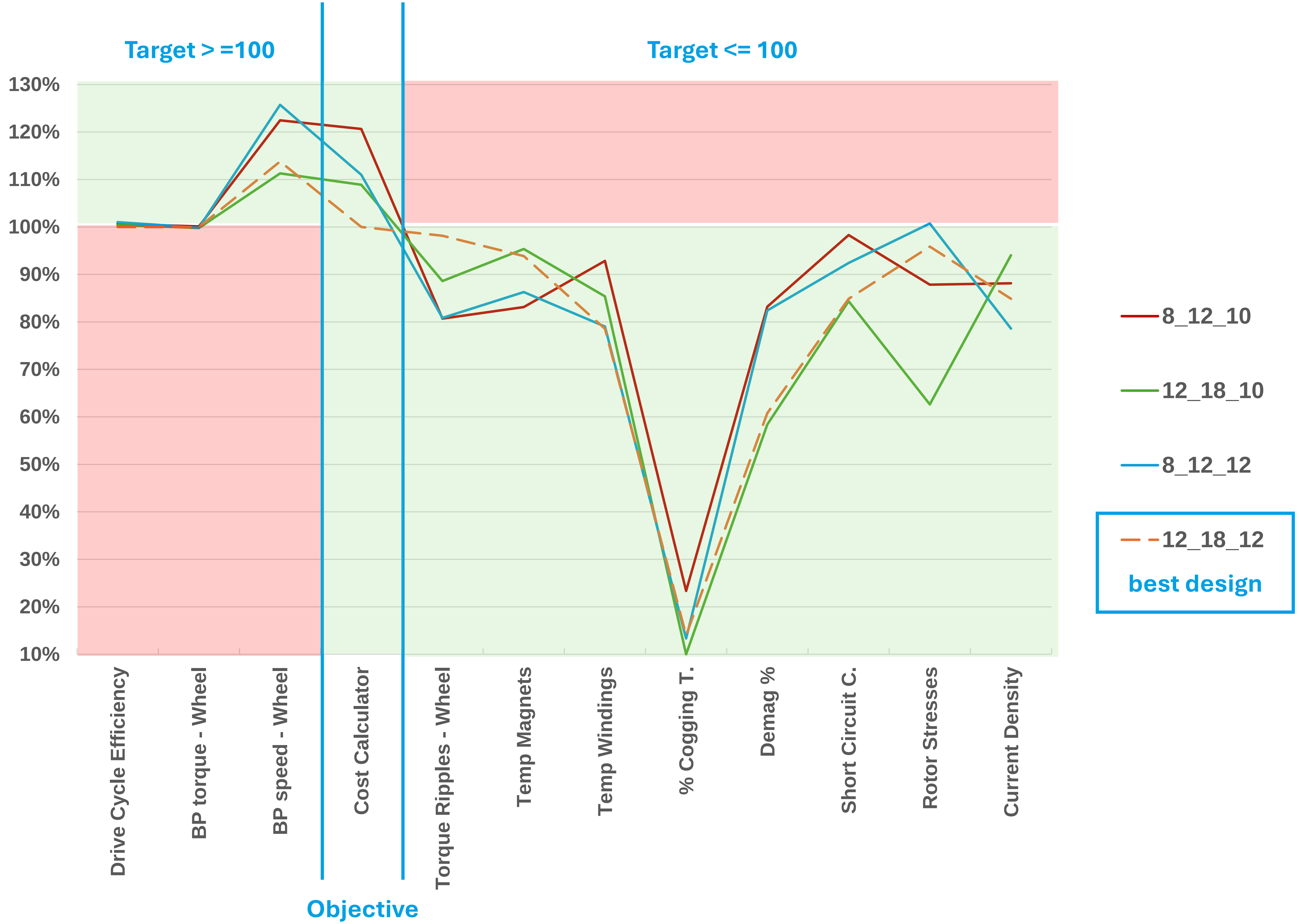




Parameter	Concept Phase	Detailed Phase
Magnet Span (elec. deg)	138	120
Magnet Thickness (mm)	4.05	4.46
Bridge Thickness (mm)	1.00	1.07
Web Width (mm)	1.50	1.65
Slot Opening (mm)	4.00	4.41
Airgap (mm)	0.80	0.89
Active Length (mm)	42.5	48.2

OVERALL OPTIMUM DESIGN

Snake Plot



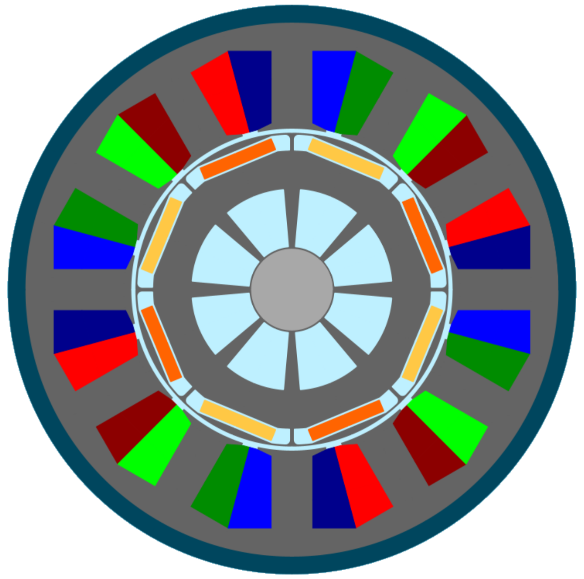
FOR EXAMPLE

- **Rotor stress**: 8p-12s (12:1) optimum design is limited by this constraint, whereas the 12p-18s (10:1) design is far removed
- **Cogging torque**: Constraint is having no influence on the optimum design for any of the configurations

OVERALL OPTIMUM DESIGN

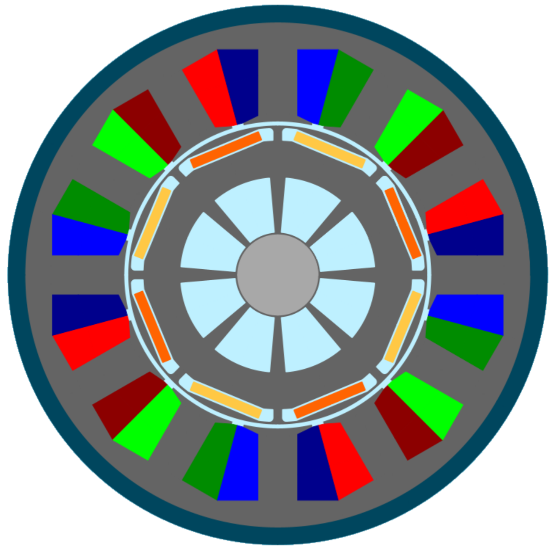
Validation & Final Selection

- All final design options are validated (full simulations run to generate responses, rather than taking the response surface output)



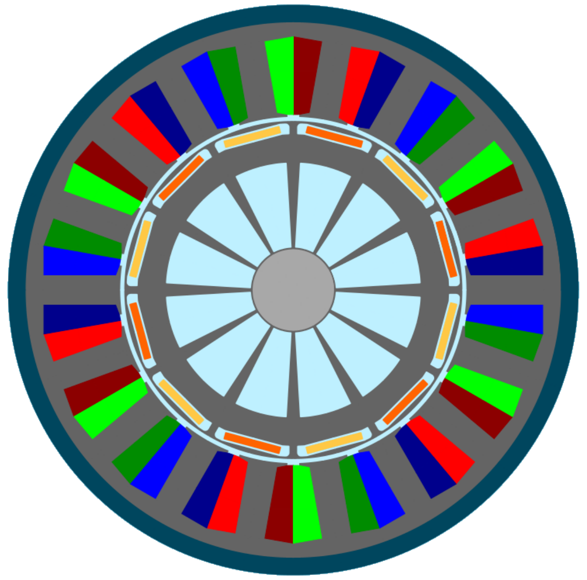
8p-12s (10:1)

Outer Diameter = 167 mm
Active Length = 48.2 mm
Cost Function = 60.6
Drive Cycle Eff. = 94.2%



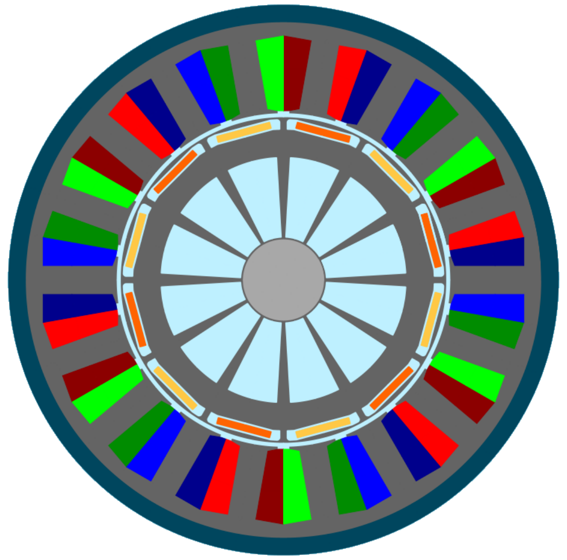
8p-12s (12:1)

Outer Diameter = 159 mm
Active Length = 50.9 mm
Cost Function = 55.8
Drive Cycle Eff. = 94.6%



12p-18s (10:1)

Outer Diameter = 168 mm
Active Length = 46.7 mm
Cost Function = 54.7
Drive Cycle Eff. = 94.0%



12p-18s (12:1)

Outer Diameter = 162 mm
Active Length = 42.9 mm
Cost Function = 50.2
Drive Cycle Eff. = 93.6%

Decreasing component cost

- Increasing assembly complexity / cost with decreasing component cost (Look to include an assembly cost metric in Cost Function?)
- Should other performance factors (such as NVH) also be considered to make a final decision?
- These designs can be further tuned for additional aspects

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ELECTRIC DRIVE

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