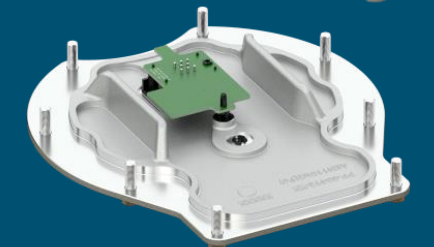
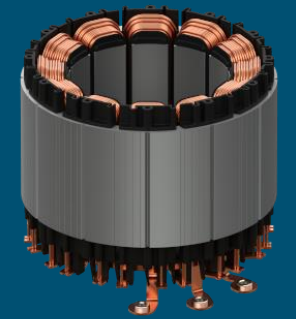
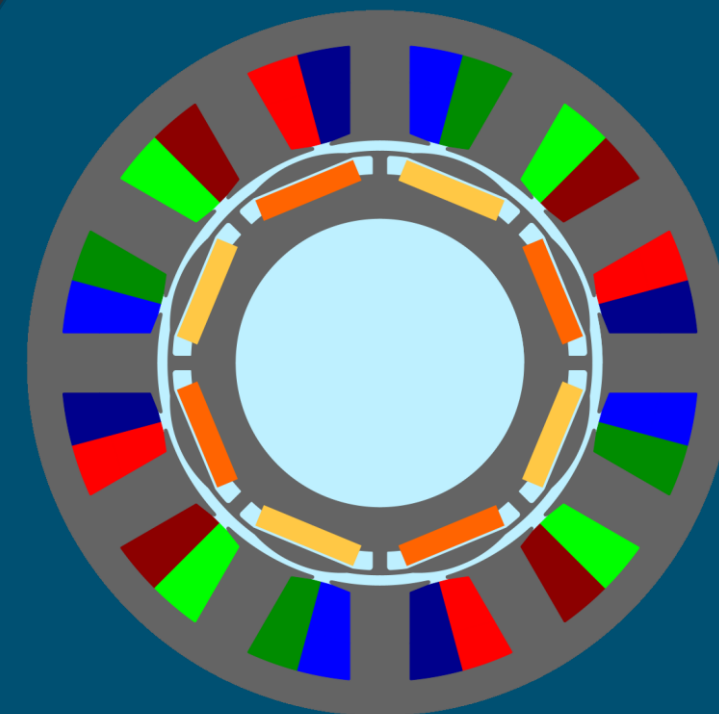


# A progressive multiphysics optimisation approach to the design of an electric motor to meet vehicle-level performance targets

Dr Chris Lines (Head of R&D)

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



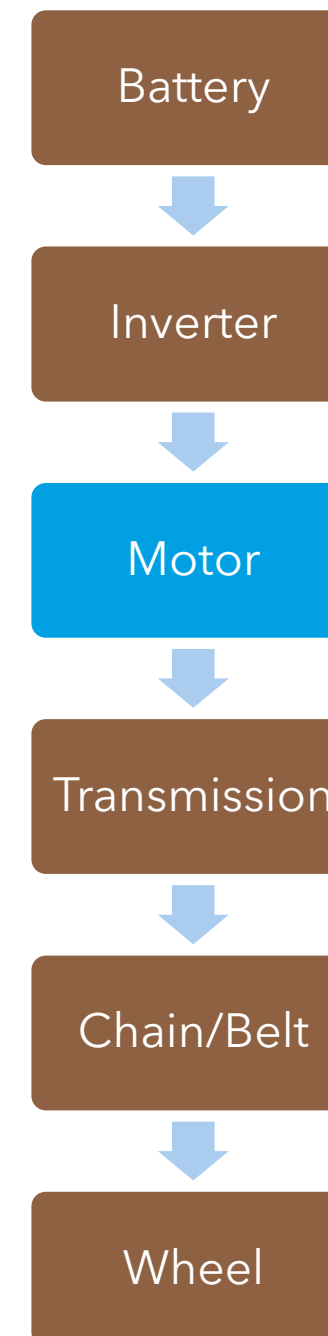
*Manesar, New Delhi, India*



# 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)



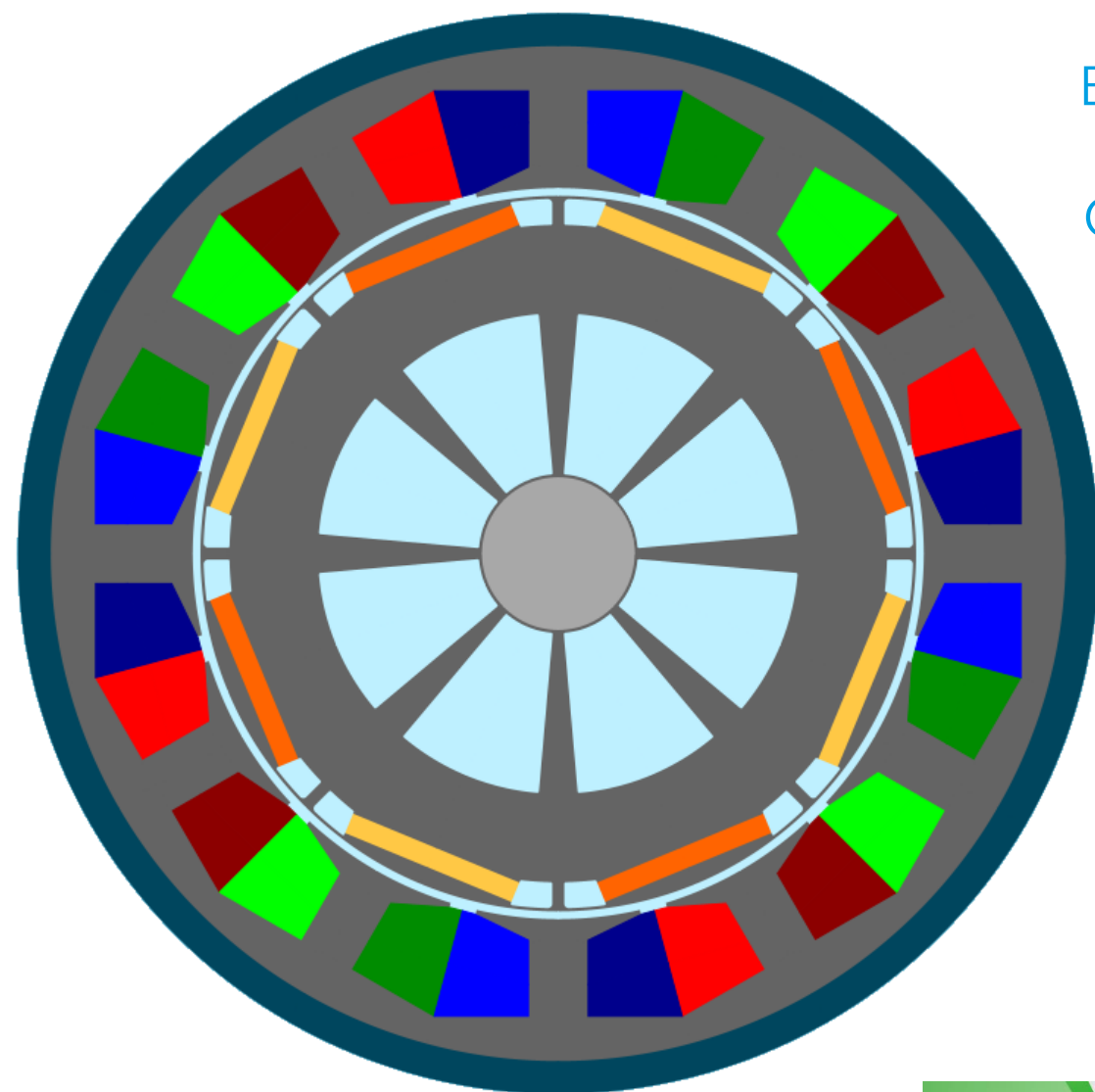
**Optimum motor solution is that which delivers the performance at the lowest cost for a chosen drive cycle efficiency**

# GEOMETRY PARAMETRISATION

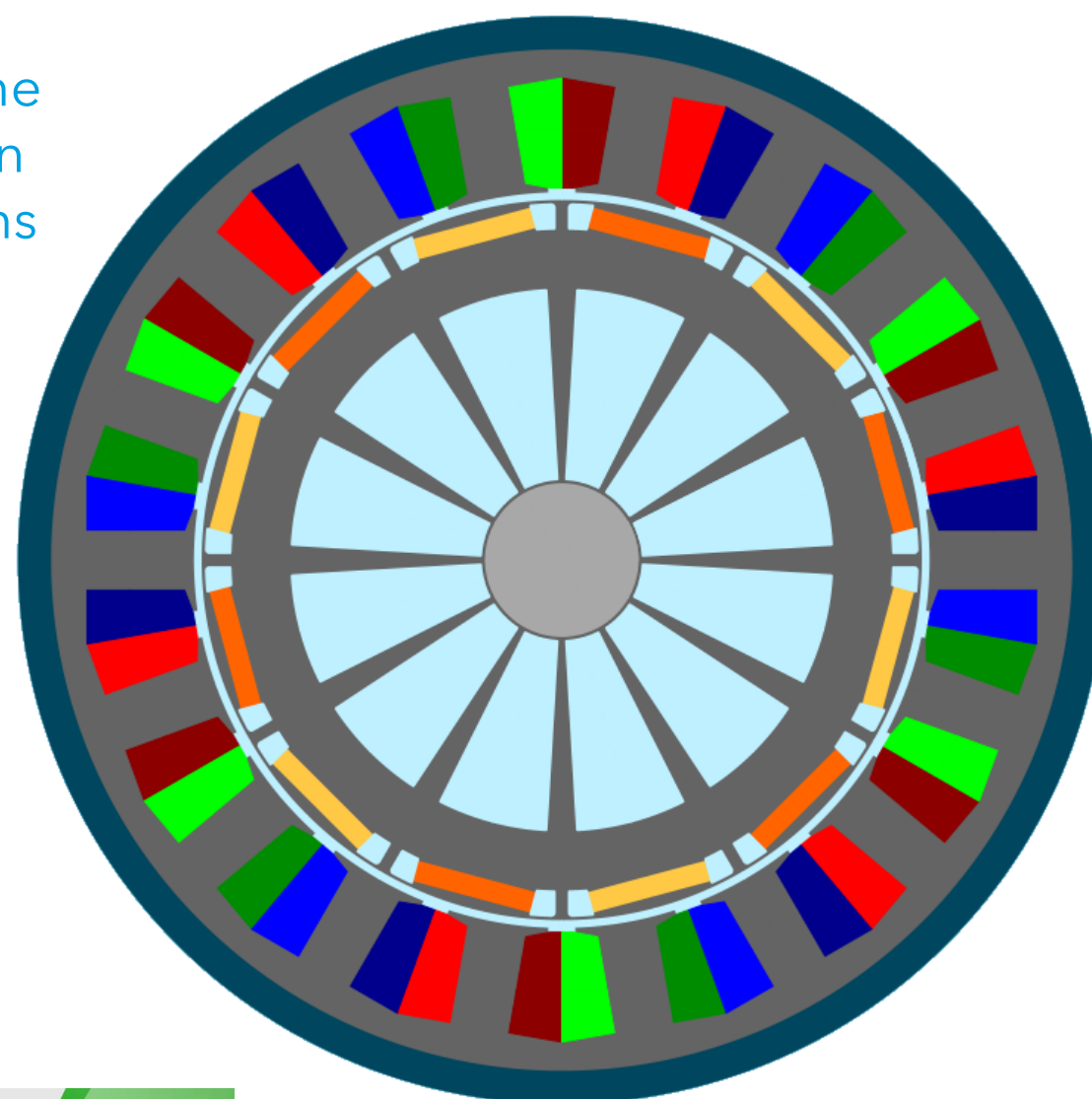
## Machine Topology & Transmission Ratio

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

Baseline  
Design  
Options



8 pole / 12 slot



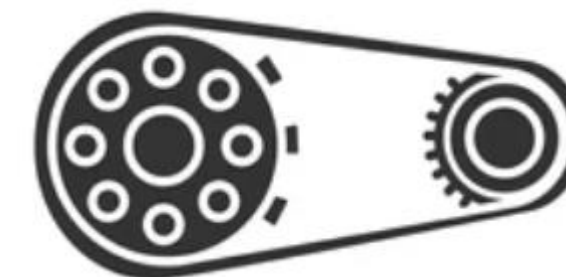
12 pole / 18 slot



Altair® FluxMotor®  
MotorFactory



Parallel-shaft  
reducer on  
motor



Belt / chain  
drive to wheel



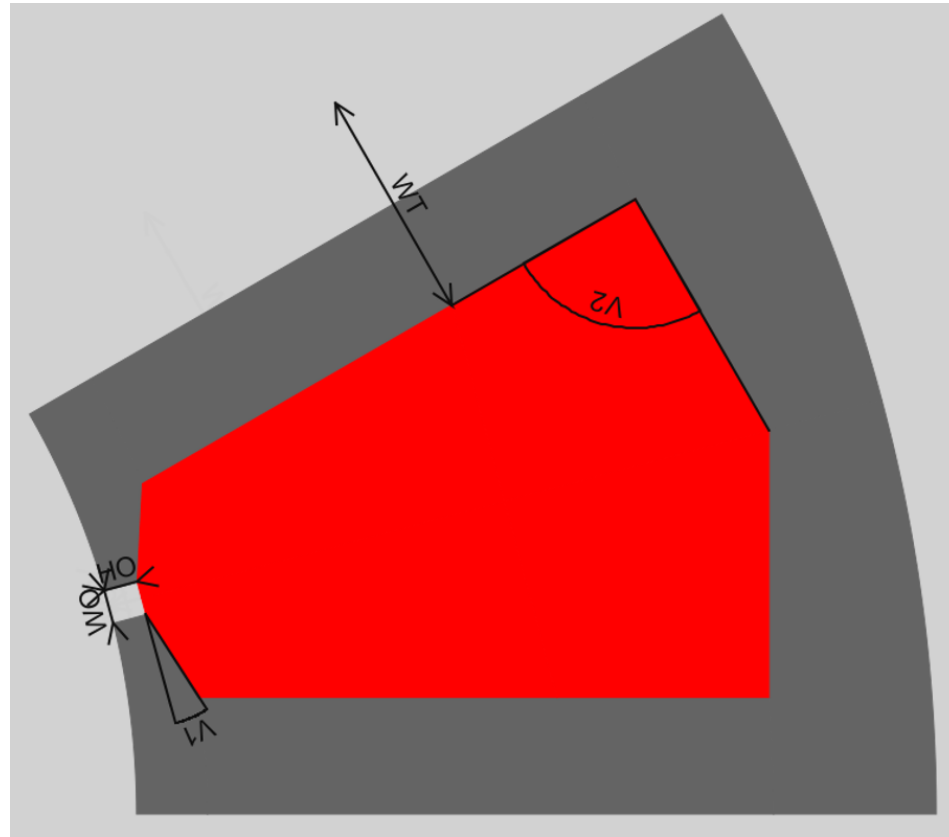
### Parameters

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

# GEOMETRY PARAMETRISATION

## Stator

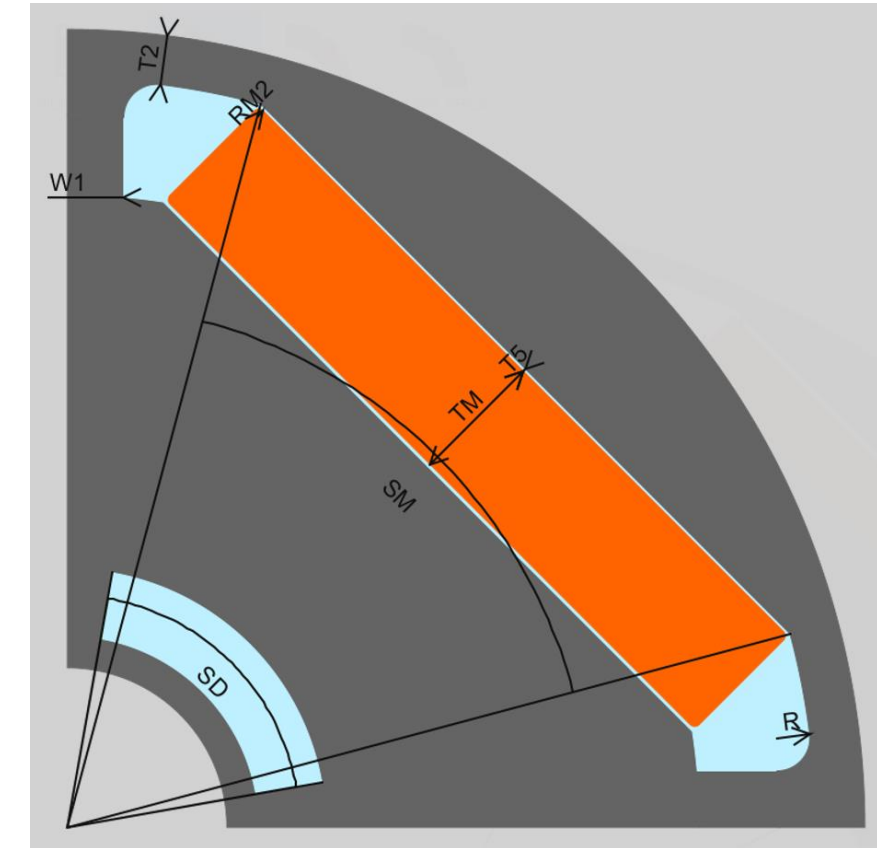


### Parameters

- 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

## 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)

Representative geometry templates for demo purposes only



Altair FluxMotor  
MotorFactory



# DESIGN OF EXPERIMENTS (DOE)

Altair® e-Motor Director™



The screenshot displays the Altair HyperWorks 2021.2 - OptiStruct interface. The top menu bar includes File, Edit, View, HyperMesh, Assembly, Geometry, Mesh, Elements, Morph, Connectors, Model, Validate, Analyze, Design Space, Optimize, Design Explorer, Post, Report, and EMotorDirector. The toolbar contains icons for Files, Measure Home, Move, Project General, Explore, Define, Study Settings, Run, HST View, Optimization, and Vehicle Data. The library browser on the left shows a tree structure with folders for Beta, EM, Structure, Utility, and WorkingPoint. The main workspace shows a 3D model of a motor component with a red highlighted area. Below the model is a table with columns for Name and Value. The process flow diagram on the right shows a sequence of tasks: WRKP\_01, WRKP\_04, WRKP\_06, WRKP\_10, WRKP\_14, WRKP\_16, FWPLO\_02, FBPLO\_05, FWPLO\_07, FWPLO\_11, FWLTP\_15, SHCT\_03, EMEFF\_08, EMEFF\_12, FTEMP\_09, and FTTRA\_13. The tasks are connected by arrows indicating the flow of the DOE process.

- › 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

# OPTIMISATION

Altair® e-Motor Director™



Platform: Number of Motors= 1  Use HMMO  Use ML #Cores for Optimization: 28 Window Size: [Icons] Windows

Select Optimization Goals (Responses, Targets, Objectives)

Shared Label	DOE min	DOE max	Type	Value	Study	min	max
Geo (12)							
WP_01 (13)							
fastwplocation_02 (11)							
shortcircuit_03 (2)							
Response (2)							
<input checked="" type="checkbox"/> short_circuit_current	194.2801	267.3985	<=	240	<input checked="" type="checkbox"/>		252.0
<input checked="" type="checkbox"/> demag_vol_ratio	0	81.22761	<=	2	<input checked="" type="checkbox"/>		2.1
WP_04 (14)							
fastbplocation_05 (11)							
Response (11)							
<input type="checkbox"/> line_current_ms	239.3939	240.3228			<input type="checkbox"/>		
<input type="checkbox"/> line_voltage_ms	31.96075	32.08833			<input type="checkbox"/>		
<input type="checkbox"/> control_angle	26.20676	34.77293			<input type="checkbox"/>		
<input type="checkbox"/> speed	2469.773	4410.828			<input type="checkbox"/>		
<input type="checkbox"/> mechanical_torque	18.88111	39.16060			<input type="checkbox"/>		
<input type="checkbox"/> stator_joule_losses	474.2053	619.6920			<input type="checkbox"/>		
<input type="checkbox"/> stator_iron_losses	91.93600	140.9881			<input type="checkbox"/>		
<input type="checkbox"/> machine_total_losses	605.6193	720.9802			<input type="checkbox"/>		
<input type="checkbox"/> machine_efficiency	91.73183	94.27555			<input type="checkbox"/>		
<input checked="" type="checkbox"/> mechanical_power	7687.790	10621.95	>=	9000	<input checked="" type="checkbox"/>		8550.0
<input type="checkbox"/> power_factor	0.62613	0.84916			<input type="checkbox"/>		
fastnvh_06 (3)							
WP_07 (27)							
emefficiency_09 (12)							
Response (12)							
<input type="checkbox"/> magnet_losses	28.32892	67.32260			<input type="checkbox"/>		
<input type="checkbox"/> rotor_iron_losses	7.73037	12.56827			<input type="checkbox"/>		
<input type="checkbox"/> stator_iron_losses	69.75751	97.15971			<input type="checkbox"/>		
<input type="checkbox"/> stator_joule_losses	210.6070	596.2557			<input type="checkbox"/>		
<input type="checkbox"/> total_losses	343.9006	720.4307			<input type="checkbox"/>		
<input type="checkbox"/> iron_losses	80.91449	109.1212			<input type="checkbox"/>		
<input type="checkbox"/> machine_efficiency	88.86842	94.49205			<input type="checkbox"/>		
<input checked="" type="checkbox"/> torque_ripples	4.96916	37.72177	<=	5	<input checked="" type="checkbox"/>		5.25
<input type="checkbox"/> mechanical_torque	15.24292	15.91885			<input type="checkbox"/>		
<input type="checkbox"/> mechanical_power	5746.446	6001.265			<input type="checkbox"/>		
<input type="checkbox"/> ptp_radialtoothforce	180.4378	413.7263			<input type="checkbox"/>		
<input type="checkbox"/> ptp_tangentialtoothforce	245.9937	550.5140			<input type="checkbox"/>		

Select Parameters & Design Variables

Linked Label	DOE min	DOE max	Type	Value	Study	min	max
Geo (9)							
Global (34)							

Studies (1/1)

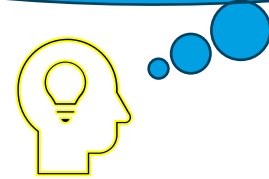
Include	Study	Fit quality	Motor 1	demag_vol_ratio	short_circuit_current	mechanical_power	torque_ripples	temperatur_c_s_end_winding	temperatur_in_slot_windings	temperatur_magnet1	temperatur_o_c_s_end_winding	fast_wltp_efficiency	max_stress	cost_indicator	percentage_cogging_torque	wheel_speed
<input checked="" type="checkbox"/>	SD1.13_12_18_12_v4	0.91862	<input checked="" type="checkbox"/>	0 - 81.22761	194.2801 - 267.3985	7687.790 - 10621.95	4.96916 - 37.72177	97.59674 - 197.4400	96.45716 - 194.1225	101.1725 - 183.7420	97.07731 - 195.9711	0.89885 - 0.95247	164.5000 - 335.8000	45.59103 - 60.93455	0.00203 - 0.06065	205.8144 - 367.5690

Motor Combinations (1)

Include	Study	Motor 1
<input checked="" type="checkbox"/>	Opti #1	SD1.13_12_18_12_v4

- › 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

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



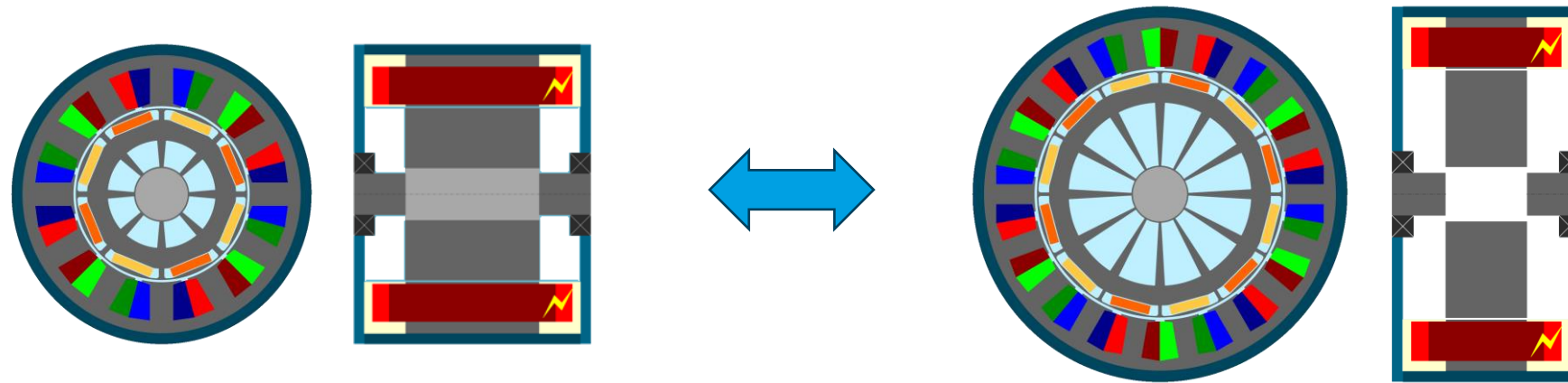
# OPTIMISATION

## A Phased Approach

### CONCEPT PHASE

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

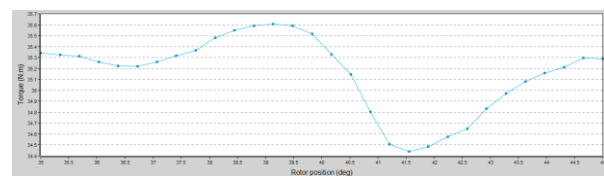
**Large variation allowed for a low number of design variables**



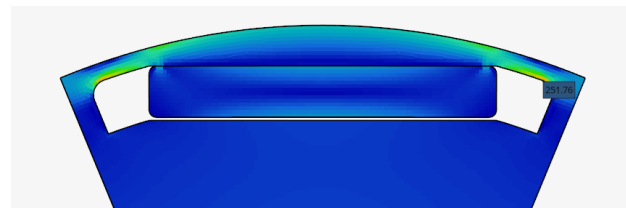
### DETAILED PHASE

- › 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

Baseline Concepts

Concept DoE

Concept Optimisation

Verification of Optimal Designs

Detailed DoE

Detailed Optimisation

Verification of Optimal Designs

Choose Final Overall Optimum

Concept Phase

Detailed Phase

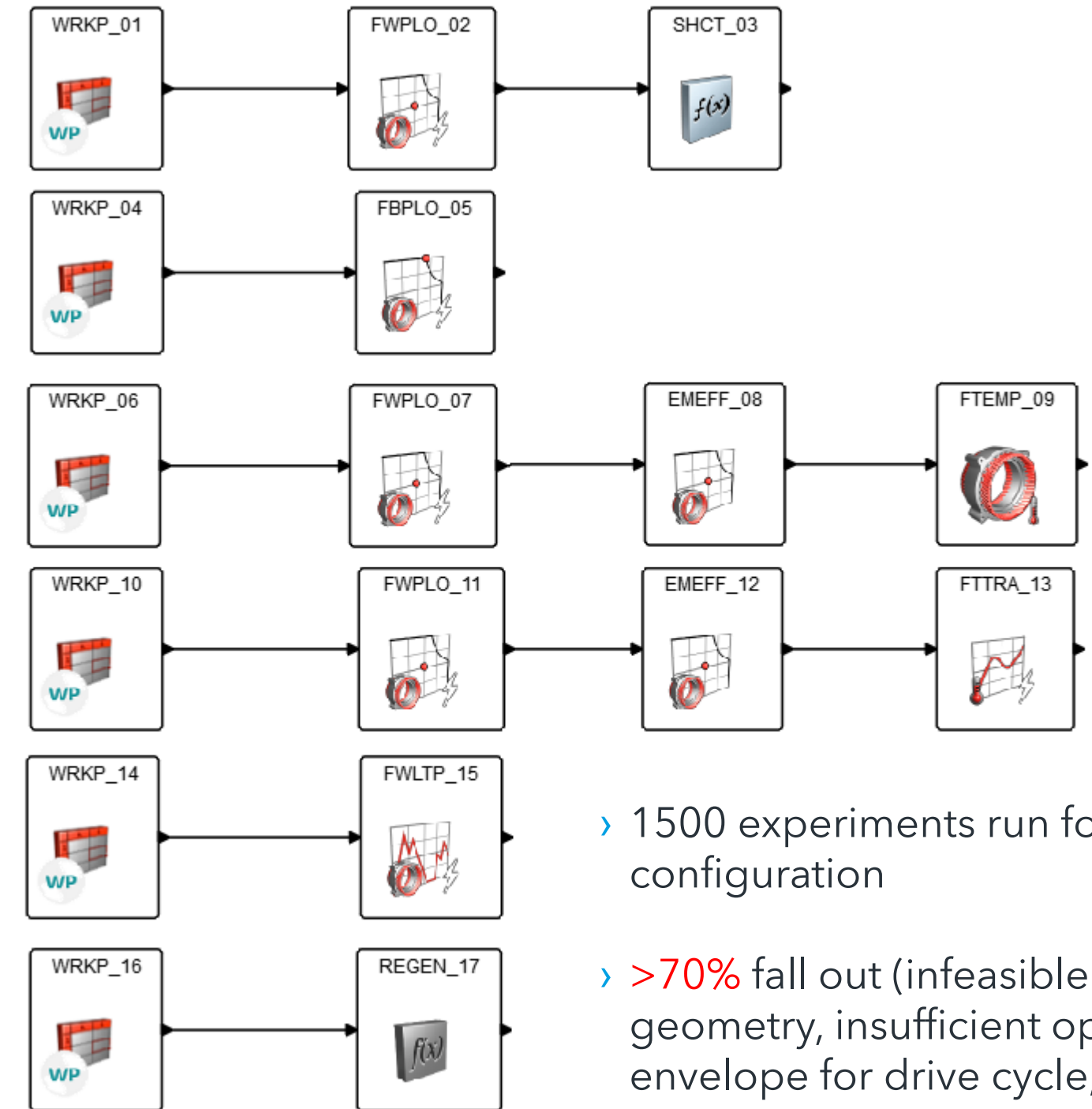
# CONCEPT PHASE

## 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)	$\leq 240$
Peak Power (kW)	$\geq 9$
Peak Wheel Torque (Nm)	$\geq 350$ (some margin for next phase)
Wheel Torque Knee Point (rpm)	$\geq 250$
Short-Circuit Current (Arms/ph)	$\leq 240$
Demagnetisation Volume (%)	$\leq 2$ (to avoid discontinuity at 0)
Magnet Temperature ( $^{\circ}\text{C}$ )	$\leq 140$
Winding Temperature ( $^{\circ}\text{C}$ )	$\leq 165$
Drive Cycle Efficiency (%)	Maximise
Cost Function	Minimise

## RESPONSE GENERATION (11 tasks)



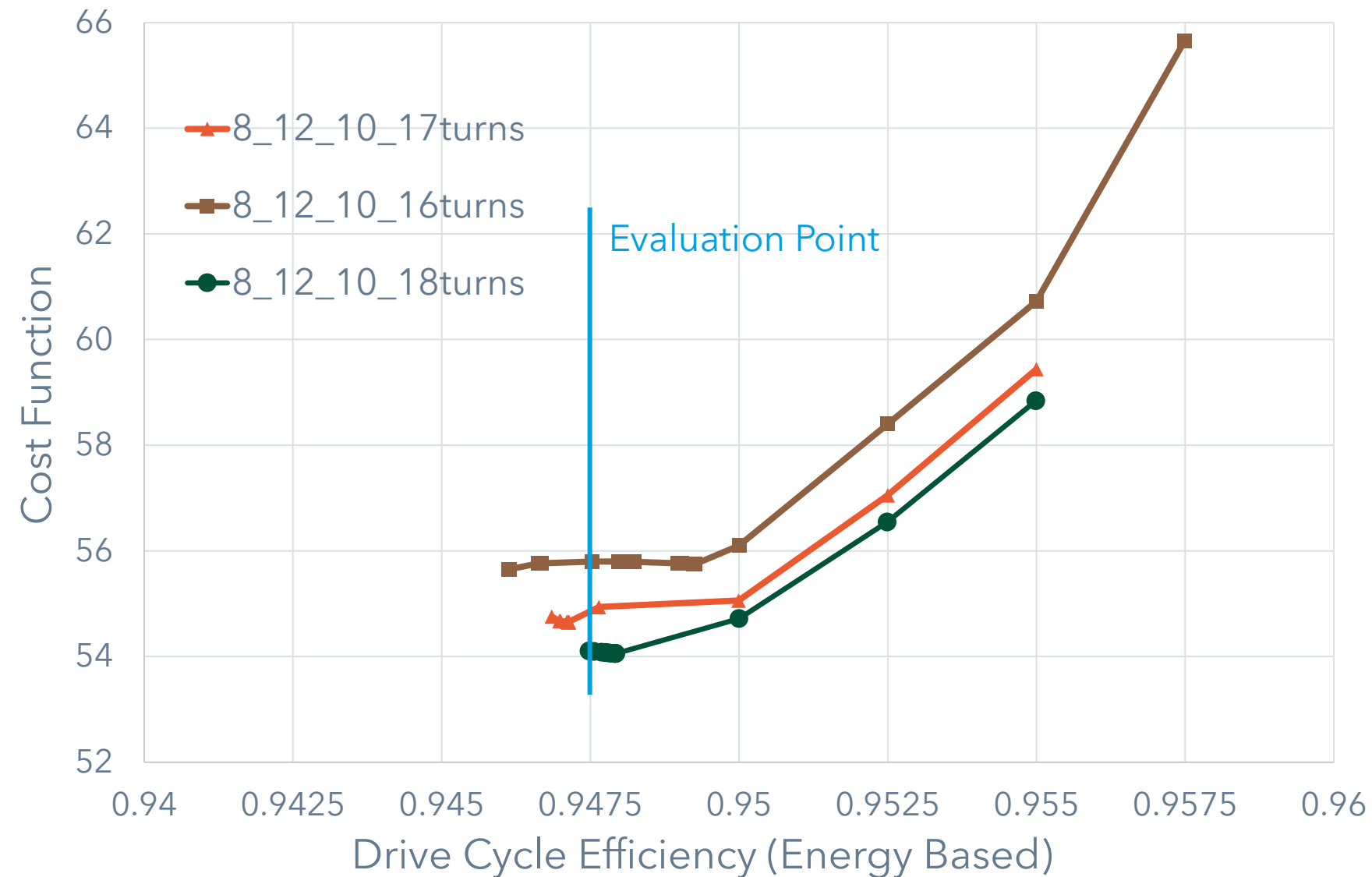
- > 1500 experiments run for each configuration
- > **>70%** fall out (infeasible geometry, insufficient operating envelope for drive cycle, etc)



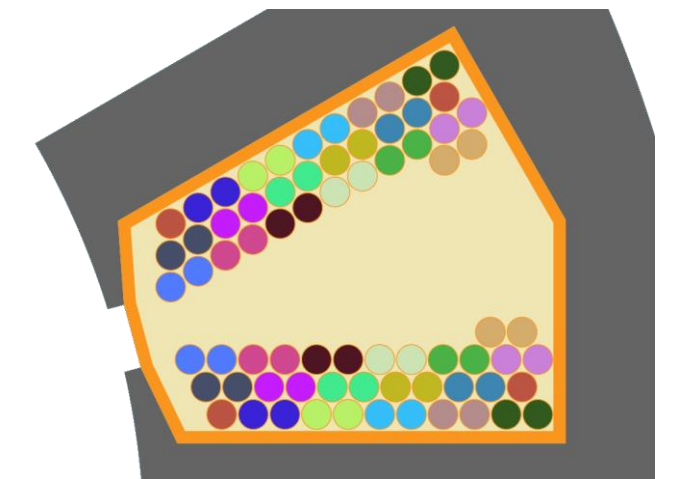
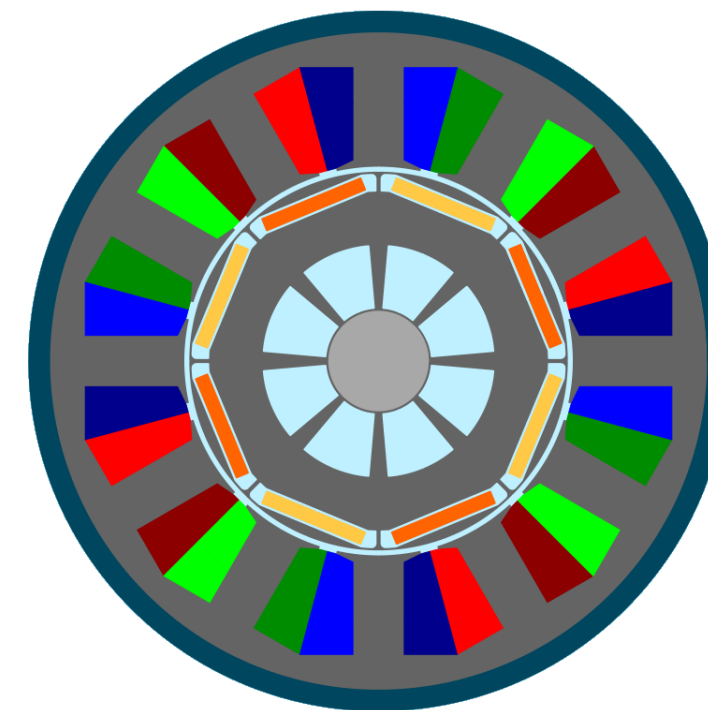
# CONCEPT PHASE

## 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



# 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)

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

### Response

Peak Power (kW)

Peak Wheel Torque (Nm)

Wheel Torque Knee Point (rpm)

Short-Circuit Current ( $A_{rms}/ph$ )

Demagnetisation Volume (%)

Magnet Temperature ( $^{\circ}C$ )

Winding Temperature ( $^{\circ}C$ )

Maximum Rotor Stress (MPa)

Cogging Torque (%)

Torque Ripple (%)

Cost Function

### Optimisation

$\geq 9$

$\geq 320$

$\geq 250$

$\leq 240$

$\leq 2$

$\leq 140$

$\leq 165$

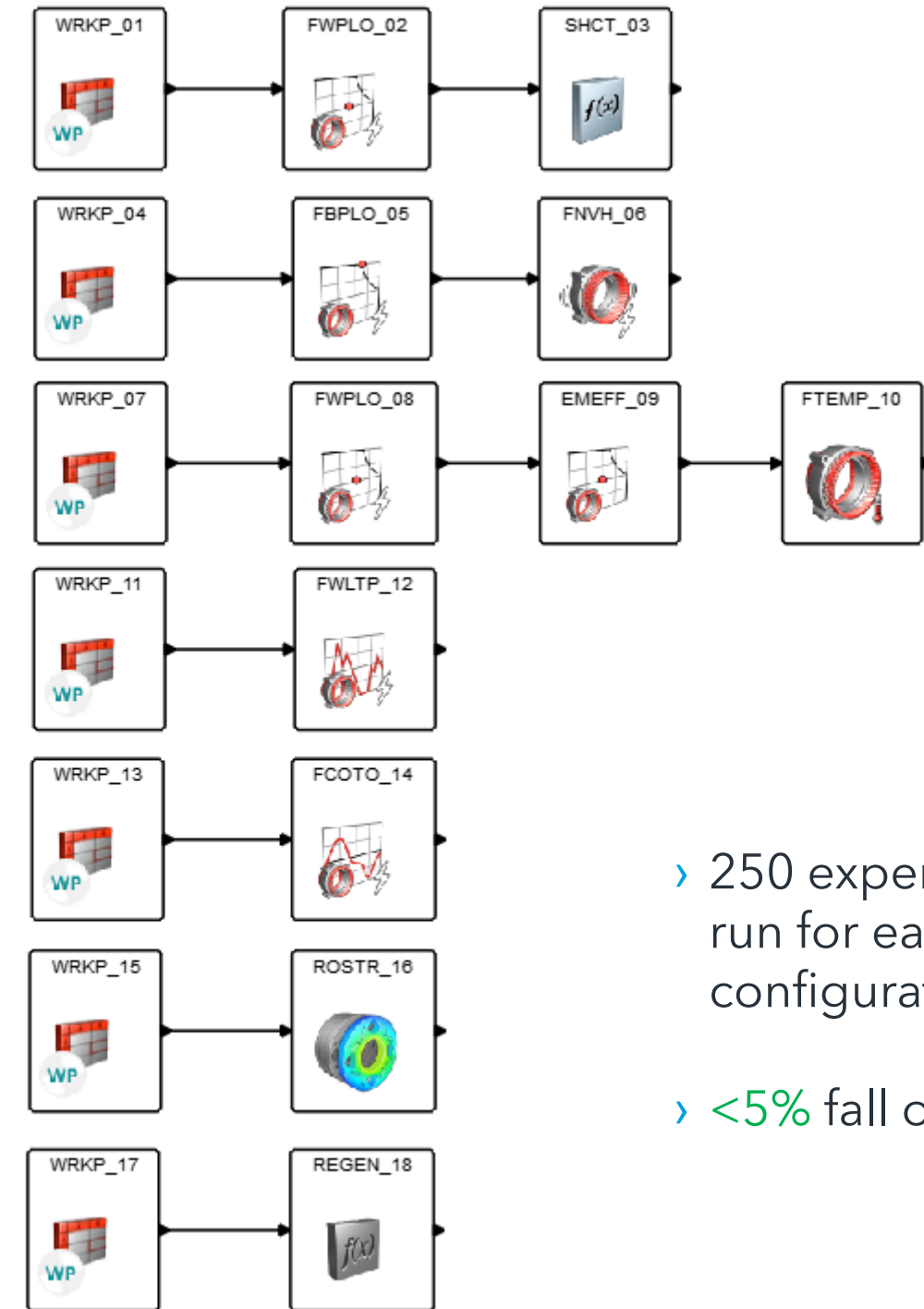
$\leq 250$

$\leq 3$

$\leq 22$

Minimise

## RESPONSE GENERATION (11 tasks)



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



# DETAILED PHASE

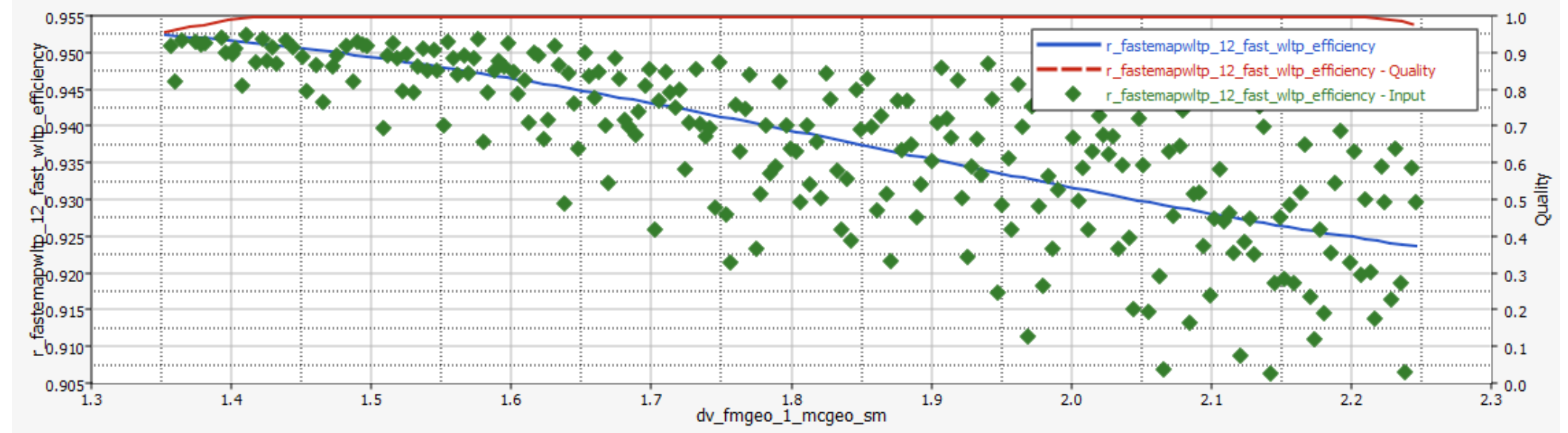
## Fit Quality

### CORRELATION TABLE EXTRACT

Label	Fit Type	Fit Specifics	X	R <sup>2</sup>
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_nvnh_overall_sound_power_level	RBF	constant - Multiquadric - 1.0000000	0.8292369	
r_fastnvh_06_nvnh_overall_sound_power_level_dba	RBF	constant - Multiquadric - 1.0000000	0.8225759	
r_fastnvh_06_nvnh_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	
r_emefficiency_09_stator_iron_losses	RBF	constant - CS21 - 1.5217000	0.9553704	

### TRADE-OFF EXAMPLE

Magnet Span vs Drive Cycle Efficiency



Simulation results

Correlation

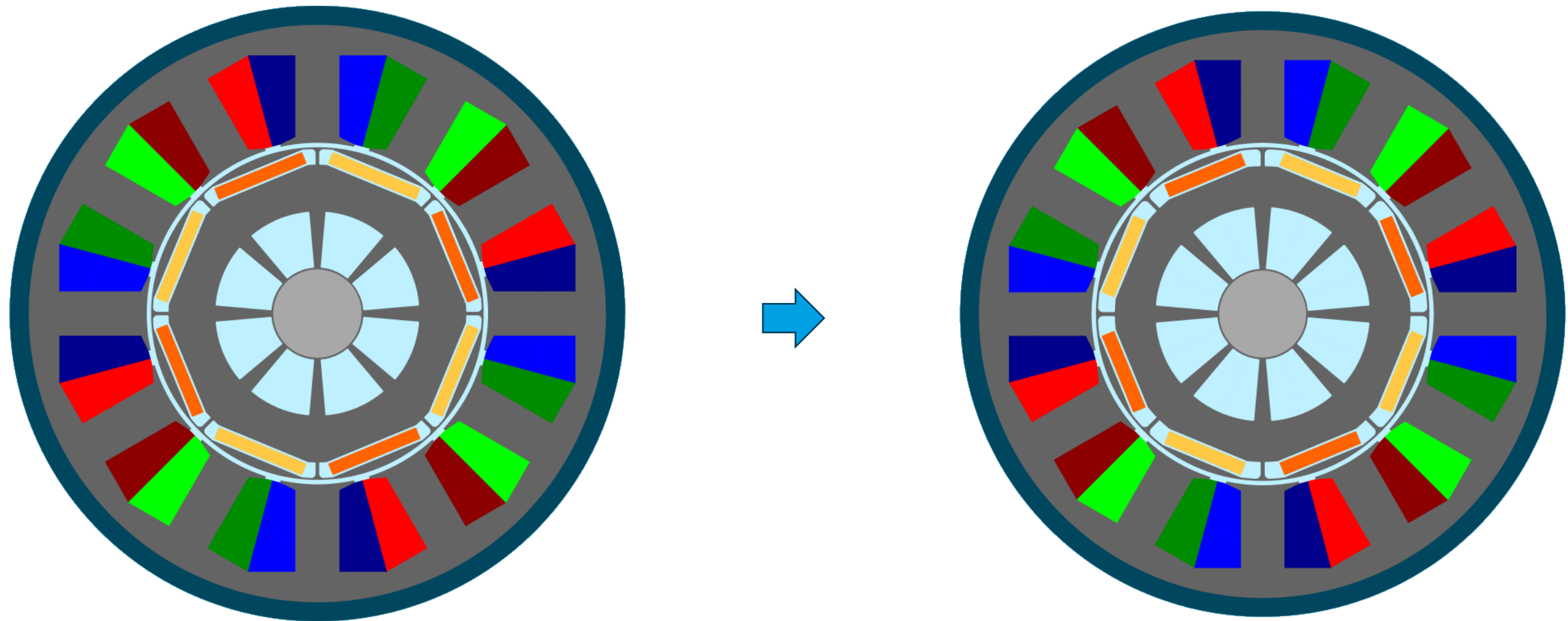
Fit quality (1 = perfect fit quality)

# DETAILED PHASE

## Optimisation (Refinement from Concept Phase)

### Example configuration:

8 pole / 12 slot  
10:1 gear ratio

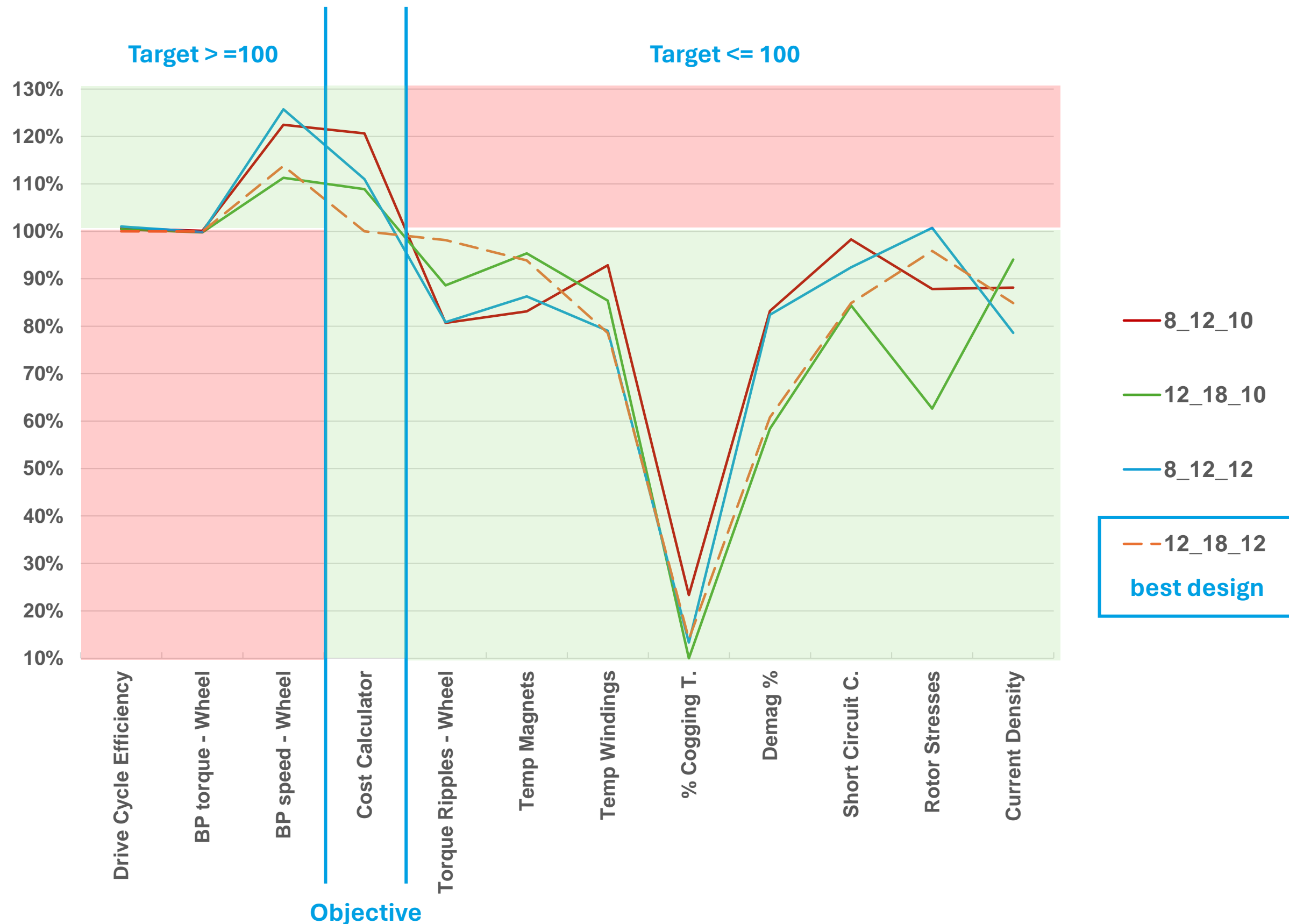


Parameter	Concept Phase	Detailed Phase
Magnet Span (elec. deg)	138	120
Magnet Thickness (mm)	4.05	4.46
Bridge Thickness (mm)	1.00	1.07
Web Width (mm)	1.50	1.65
Slot Opening (mm)	4.00	4.41
Airgap (mm)	0.80	0.89
Active Length (mm)	42.5	48.2



# OVERALL OPTIMUM DESIGN

## Snake Plot



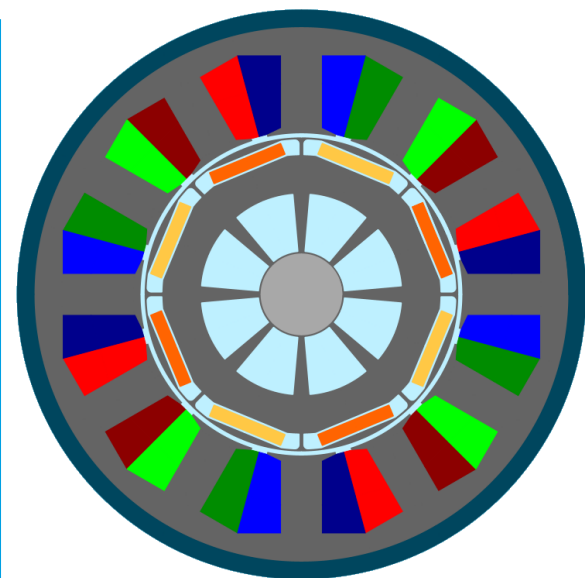
## FOR EXAMPLE

- › **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

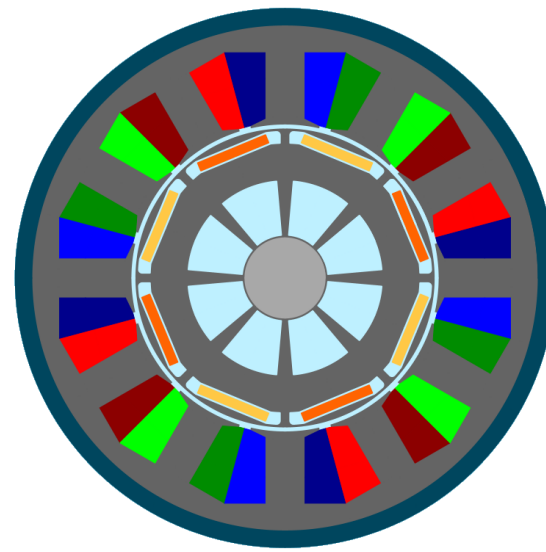
## Validation & Final Selection

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



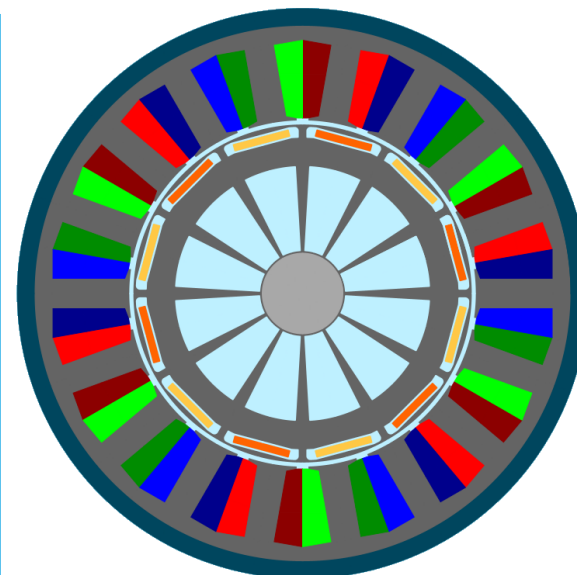
**8p-12s (10:1)**

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



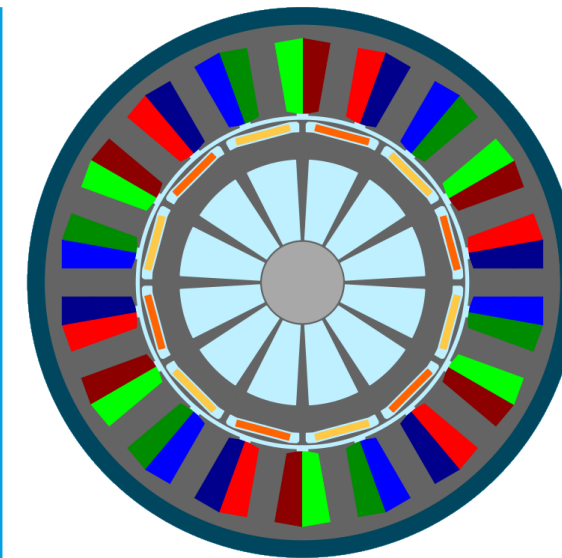
**8p-12s (12:1)**

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%

- › 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

Decreasing component cost



At Saietta, we're forging a new way: a new generation of ultra high-efficiency, high power-to-weight, compact, lightweight electric motors and controllers specifically designed to propel a broad range of vehicles into a new era.

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