Workshop: Optimization of Electric Drives

Melanie Michon, Motor Design Limited
Sebastiano DiFraia, Ansys Incorporated
Markus Stokmaier, Dynardo GmbH

17th Weimar Optimization and Stochastic Days 2020
June 25 – 26, 2020
Virtual Conference

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Optimization of Electric Drives – Workshop Agenda

Electric machine design challenges in automotive (S. DiFraia)

AEDT & Motor-CAD integration technology (M. Stokmaier)

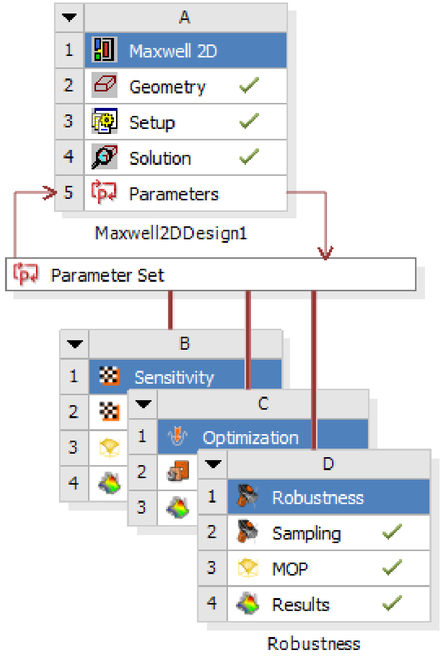
- Plugin-based solver integration for AEDT & Motor-CAD
- Python-based solver integration

Optimization of electric drives (M. Michon, M. Stokmaier)

- A challenging P2HEV traction motor application
- Evaluation routine for design variations
- MOP-based multi-objective optimization

Discussions

optiSLang integrations for Motor-CAD and AEDT

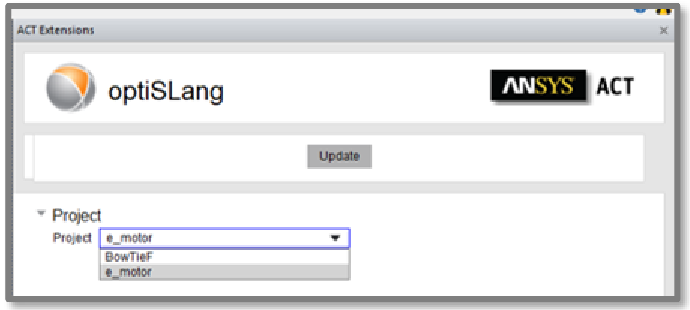


AEDT

MotorCAD_solve

AEDT_advanced (Beta)

Python



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Simulation in Electromagnetics and Beyond

Physics

- electro-statics & low frequency
- high frequency & waves
- circuits & signals

Methods

- analytics & numerics
- reduced models & fully resolved fields
  i.a. lumped, FEM, BEM, ray tracing, ...

Focus on today's challenges

- electric motors → type → setup → drive U,I → optimal design
- simulation workflow & design variation
  → leverage algorithmic power
  → make best design decisions consciously on a sound basis

Best Practice

- different for every discipline
- different for every application
- different for every team

programmed workflow
= codified best practice

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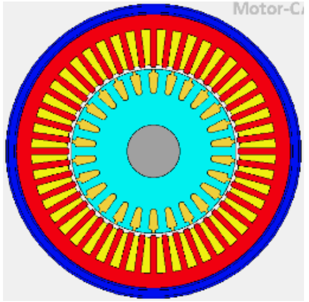
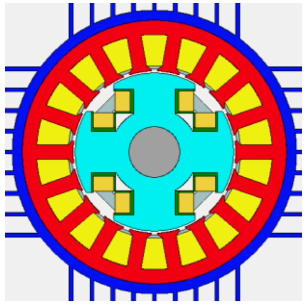
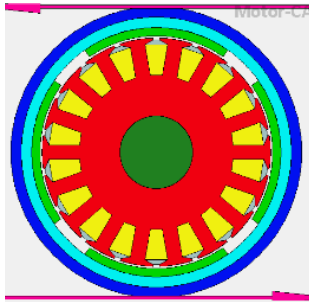
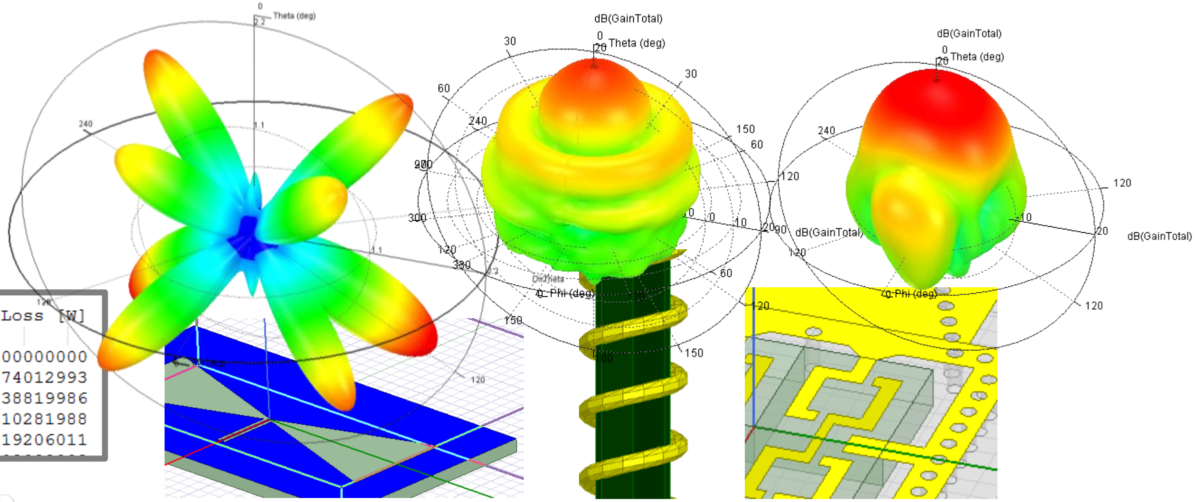
Simulation in Electromagnetics and Beyond

Developments
- Electrification, IoT, 5G,...
- virtual development
- connected automated control

Challenges
- design space: topology & parametric
- goal conflicts due to multi-physics
- goal conflicts at system level

Needs
- manoeuverability in design spaces
  → human & algorithmic decisions
- workflow automation
- communicating component data
  → specs, CAD, maps, tolerances/scatter



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69444.444444444394321	204.953701038819986
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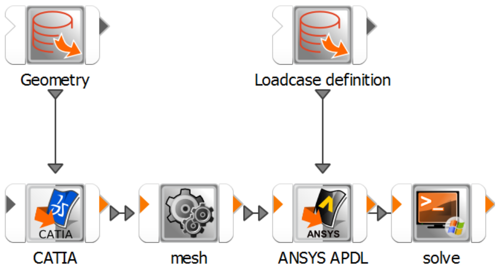
138888.888888888992369	179.225461219206011



The team with the quickest workflow work-trough speed ...

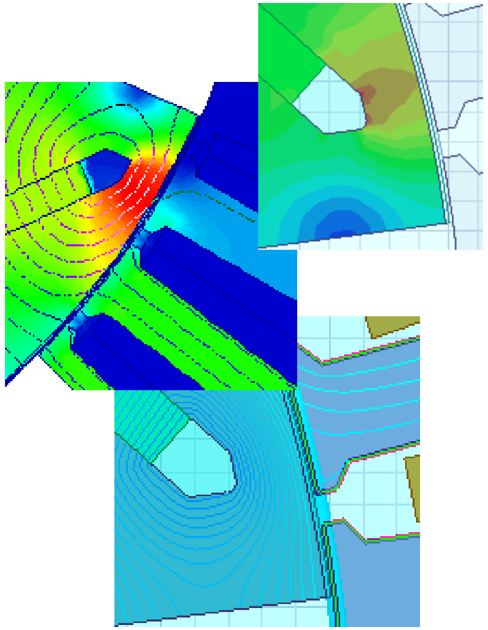
... can base decisions on objective comparisons
... can place the best innovate solutions

Getting value from simulation

The ideal team masters:

Balance & Practicality & Speed
& Long-Lasting Effect

Geek Extremism

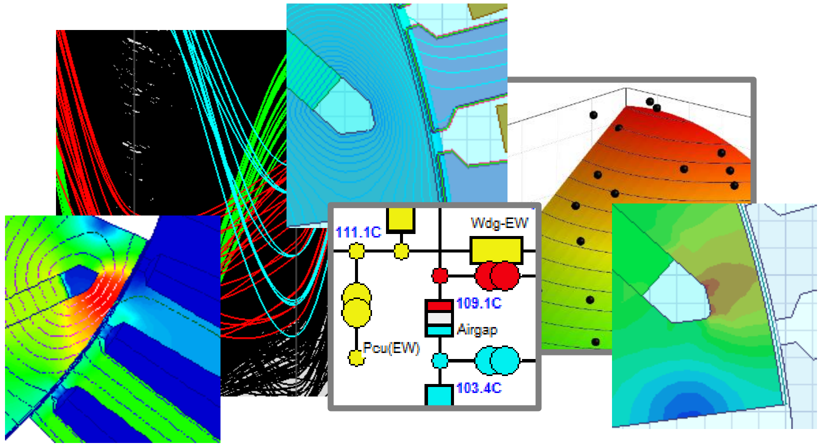


I know exactly where the torque ripples are coming from.

What should we do against them?

Well, good question, there are plenty of ideas ...

- know when to seek causality in details
- know when to seek system understanding
- know when to go algorithmic
- roll out successful best practice & workflows

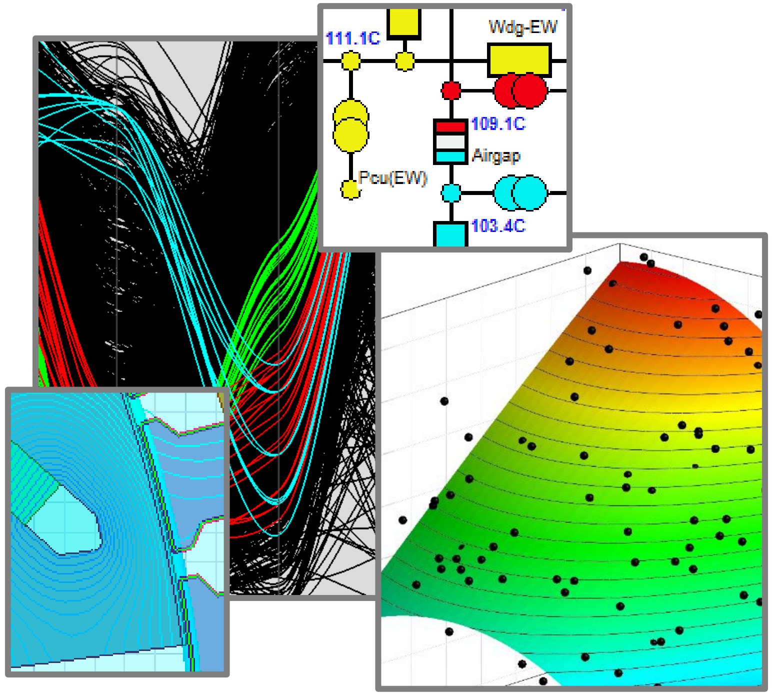


Tool Extremism

lazy application of black-box algorithms to black-box problems

Getting value from simulation

Spectrum of tool usage



investigative research
→ gain insight & understanding

fully automatic

pre-calculation
optimize:
slots, poles, winding
optimize:
peak torque + thermal
optimize:
multiple load cases / map
optimize:
NVH, 3D, losses

establish workflows
→ benefit from your (codified) competence

Combining Motor-CAD & Electronics Desktop & optiSLang
you have the entire spectrum at your fingertip every day

Ansys

Thanks for your interest, attention & discussion
Enjoy WOSD!

Ansys / DYNARDO | presented at the 17th Weimar Optimization and Stochastic Days 2020 | Source: www.dynardo.de/en/library

Electric Machine Design Challenges in Automotive

June 26th, 2020

Ansys

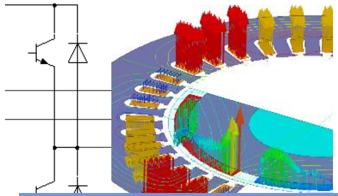
Electrical Machines – Product and *Design* Challenges

Summary

- **Power density, torque, performance**
- **Efficiency (wide speed range)**
- **Reliability, safety, lifetime**
- **System (harmonics, drivecycle, HiL, ROM)**
- **Demagnetization, breakdowns**
  - **Insulation, thermal, …**
- **Costs, cycle time**
  - **Development, manufacturing**
- **Material, size, space, weight**

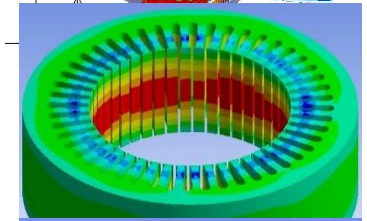
- **Fast and accurate**
- **All physical disciplines**

- **Transient magnetics**



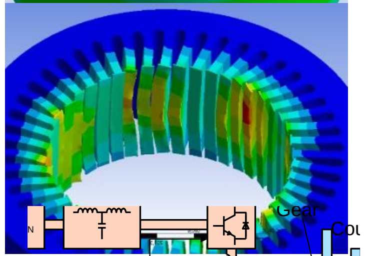
coupled with

- **Cooling**



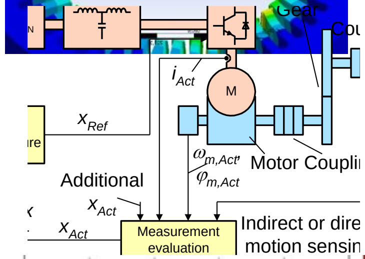
coupled with

- **Noise, vibration, harshness**



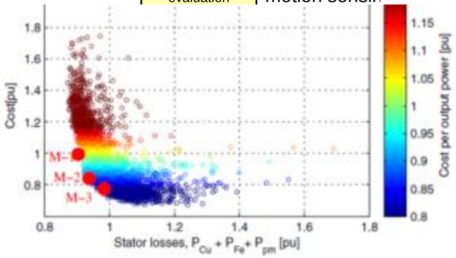
coupled with

- **System performance**

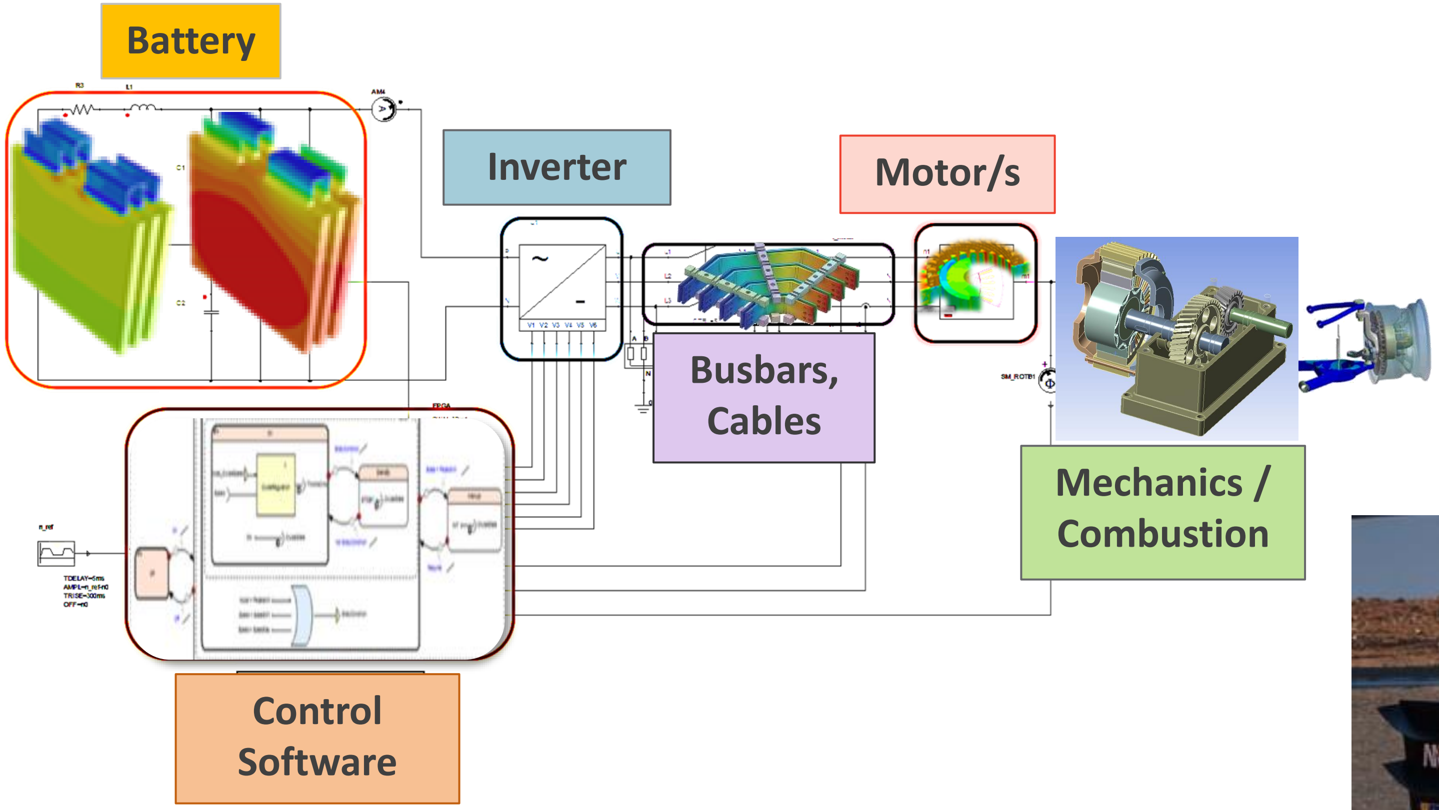


combined with

- **Fast calculations, optimization**



Electric Powertrain *System* Approach



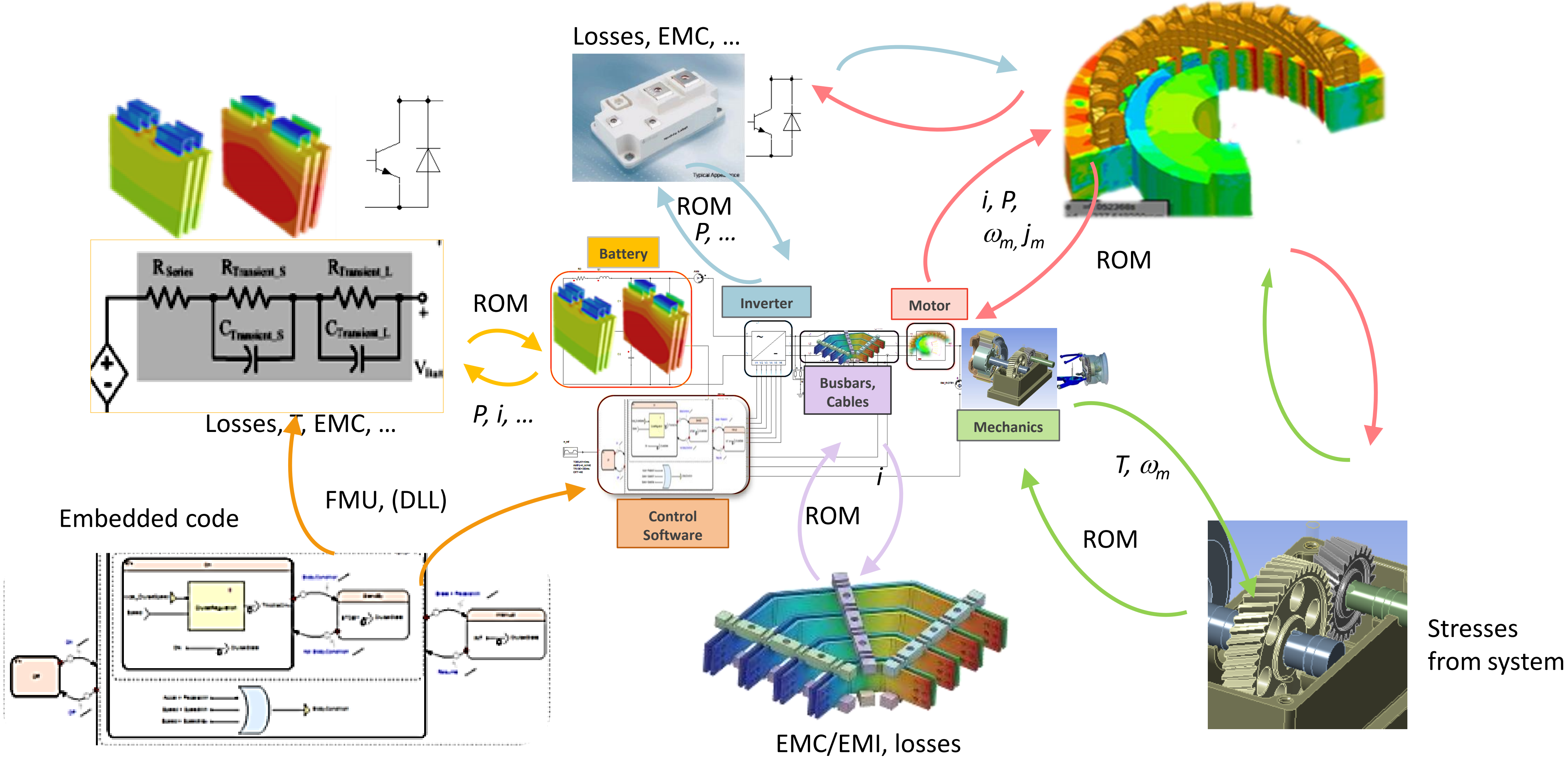
Increase efficiency and performance of electric powertrain

OEM = Original Equipment Manufacturer

- **OEMs are VW, Toyota, Ford, Renault, etc.**

Tier1 companies are direct suppliers of OEMs

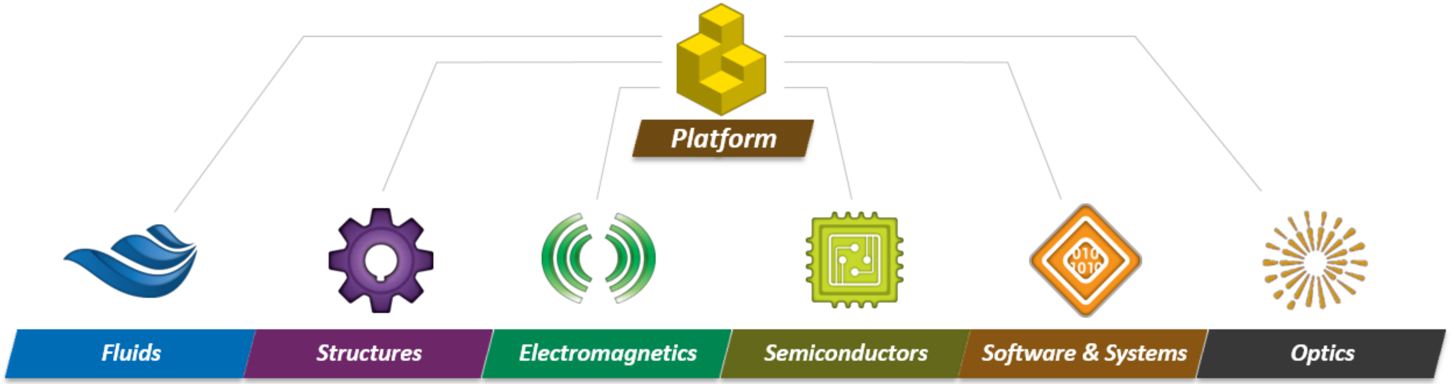
Electric Powertrain – System of Components

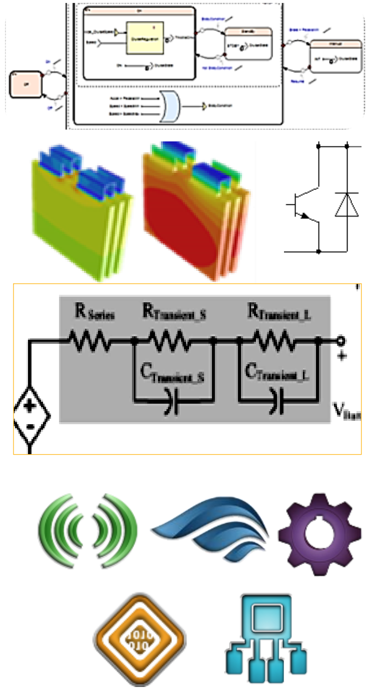


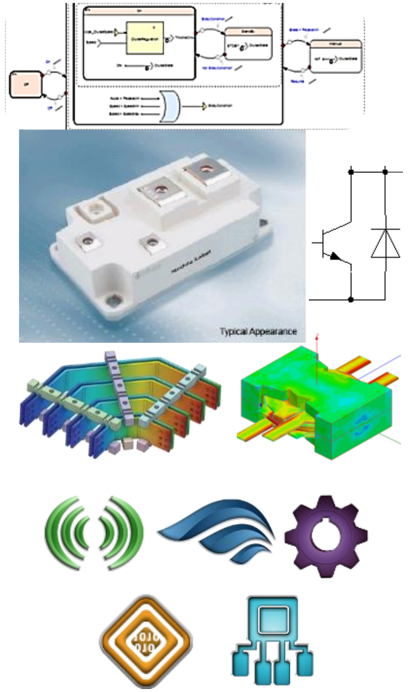
Adapt system and components for best powertrain performance

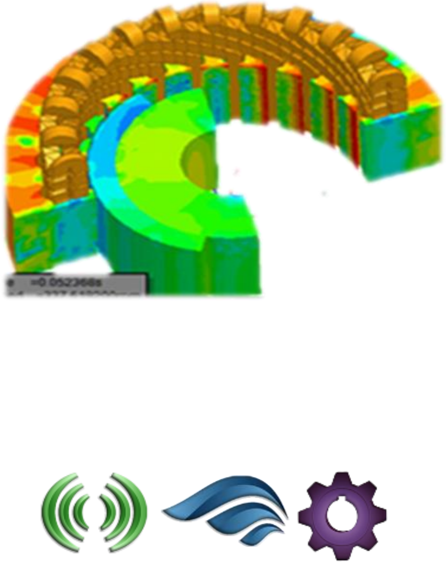
Electric Powertrain – *Component* Validation and Design

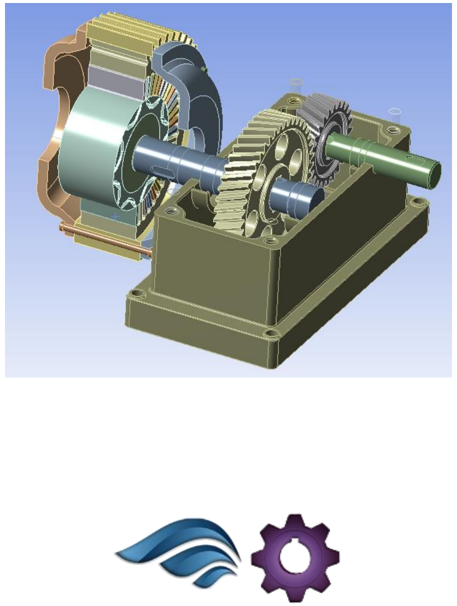
- **Best component**
- **Very accurate ROM**







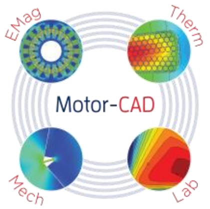


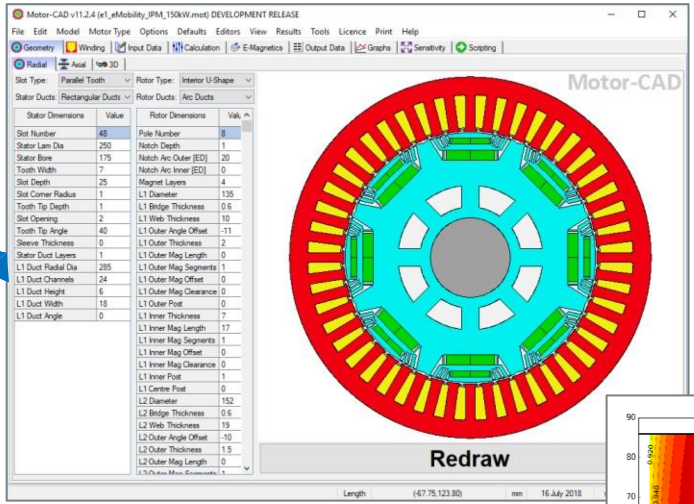


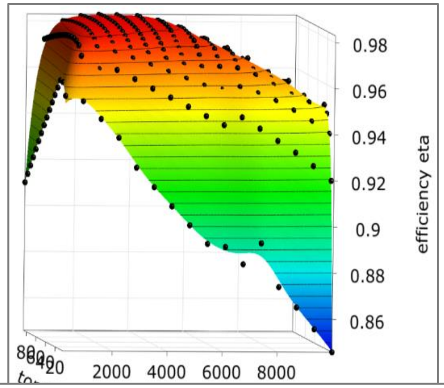
Motor Design Workflows
Two Common Examples

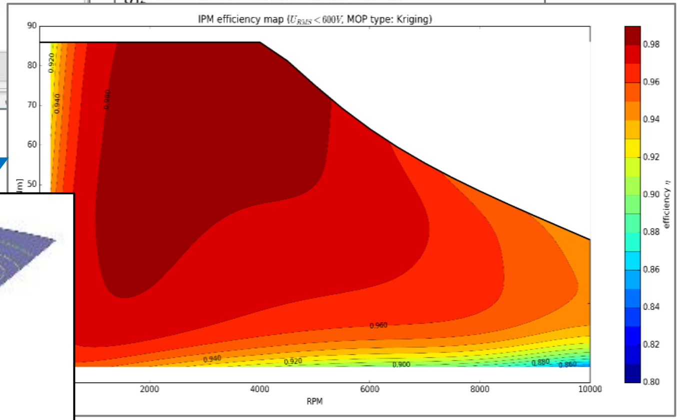
- Short Bidding Cycle
  - **Derive new motor from old**
  - **Only 2 … 4 h for bidding**
  - **Motor-CAD for design**
  - **Maxwell Transient for verification**
  - **Detailed analysis for improving**

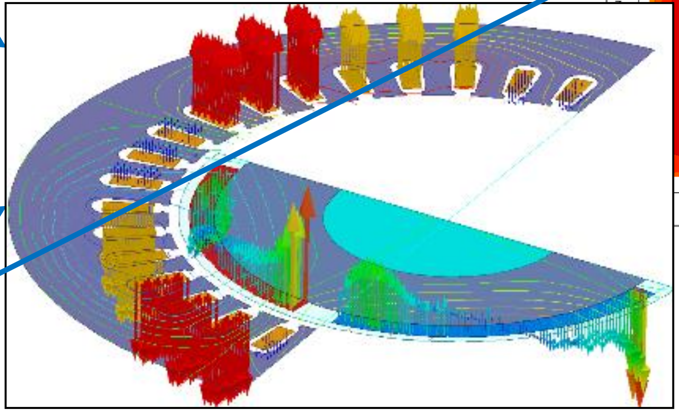
- Incoming Motor Validation
  - **Get motor from tier without data**
  - **Run calibration to make a model**
  - **Motor-CAD + field simulation + optiSLang**
  - **Get Reduced Order Model (ROM)**









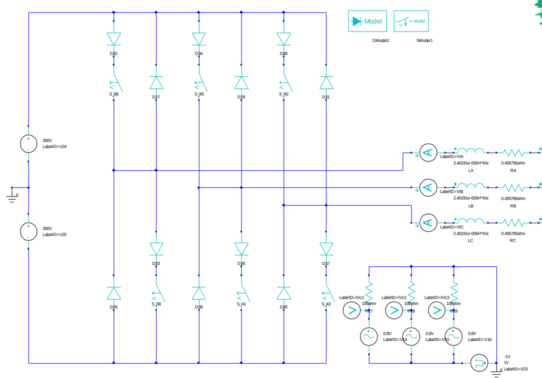
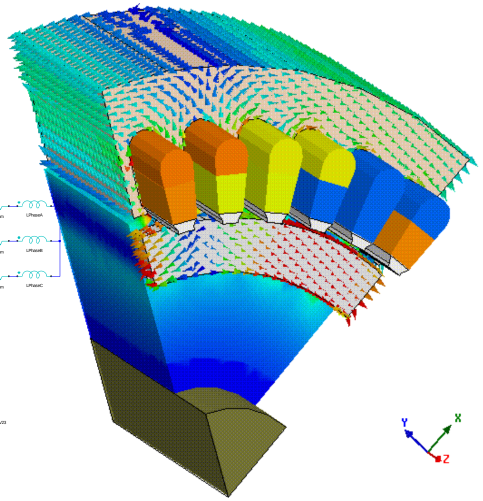
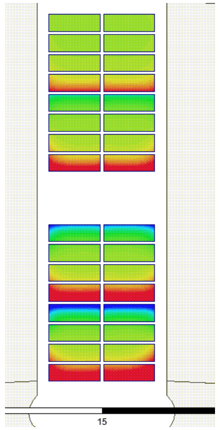
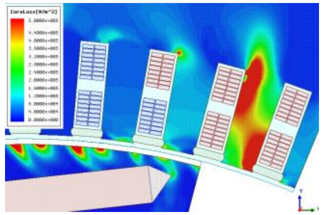
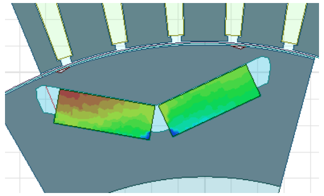


Ansys / OPTISLANG

Ansys

Electromagnetic Solution
Transient 2D/3D

- dB/dt transients – fully integrated solution
  - **Power electronics switched excitation**
  - **Large motion**
- Comprehensive loss schemes
  - **Windings**
  - **Lamination, ferrites**
  - **Solids and magnets**
- Effects
  - **Nonlinear, anisotropic, laminated**
  - **Magnetostriction, de-/magnetization, hysteresis**
- Comprehensive results, reports
  - **Integral q(t), density Q(x, t)**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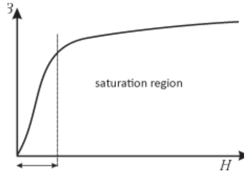
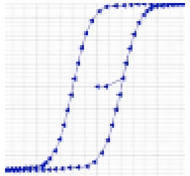
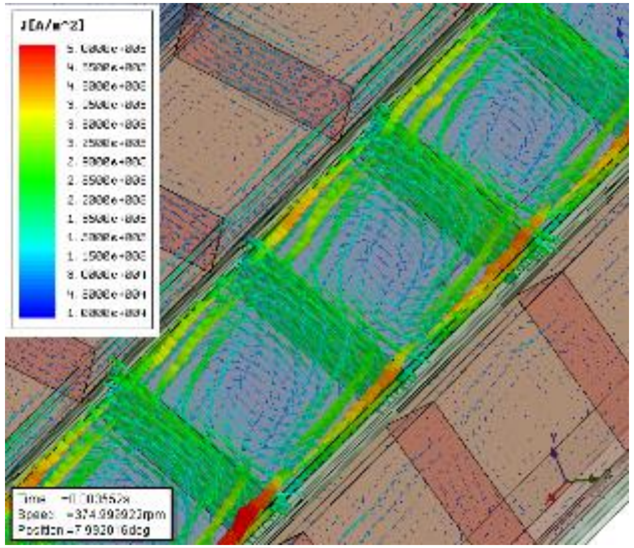
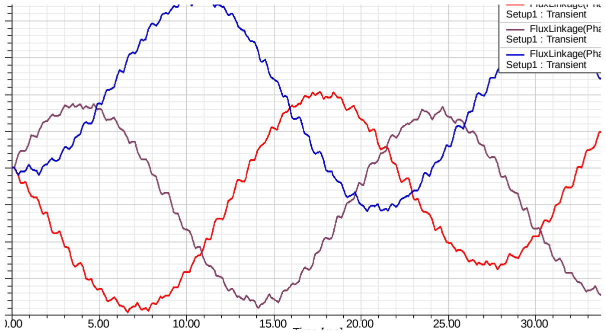


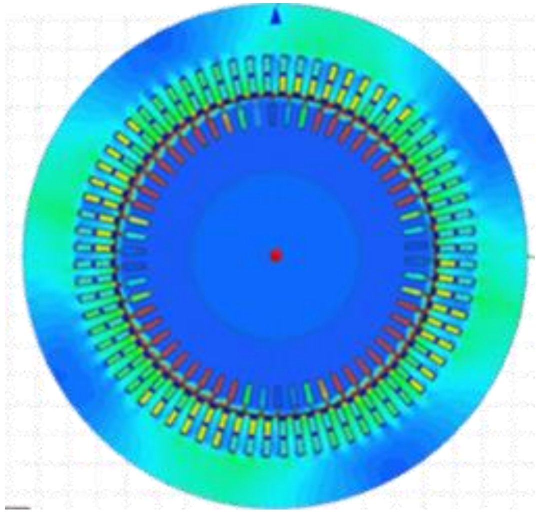





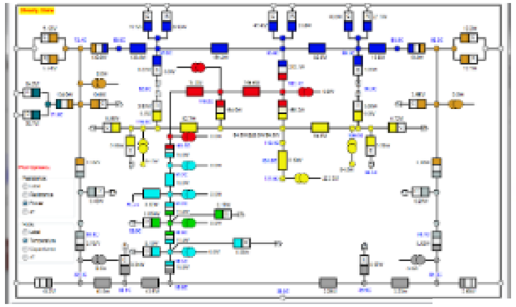
Thermal management

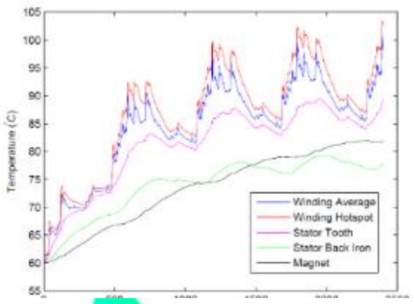
- Calculation speed vs. accuracy
- *Convection in airgap* is key for rotor cooling

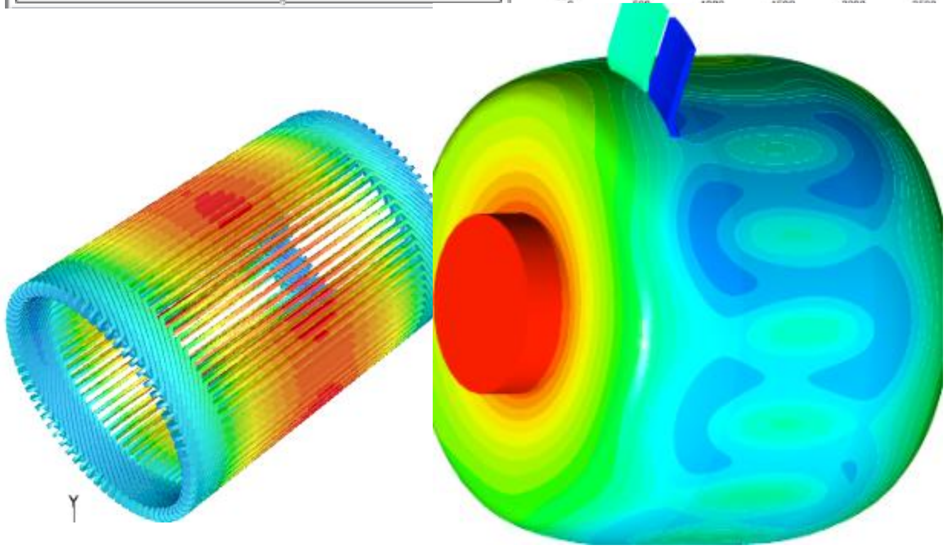
Electromagnetic
Motor-CAD, Maxwell

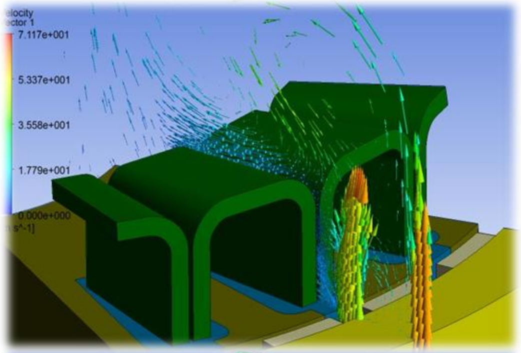


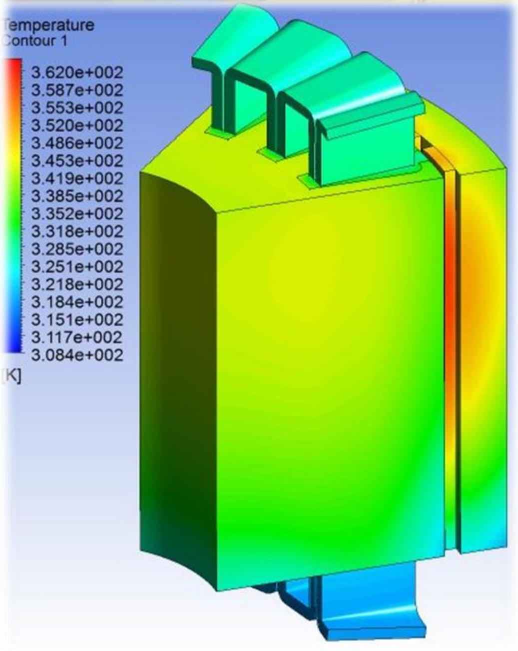
Thermal
Motor-CAD, Mechanical, CFD



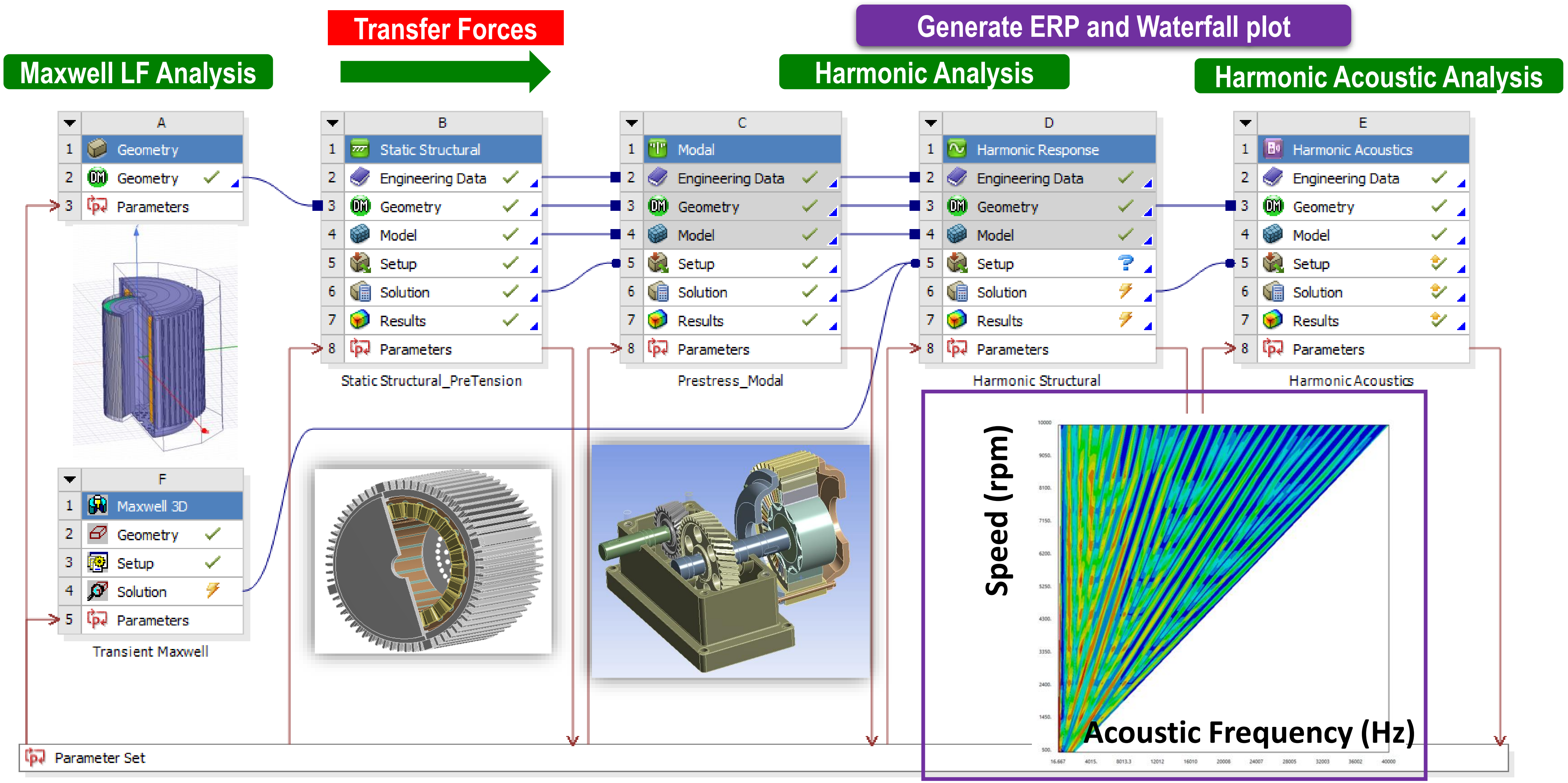






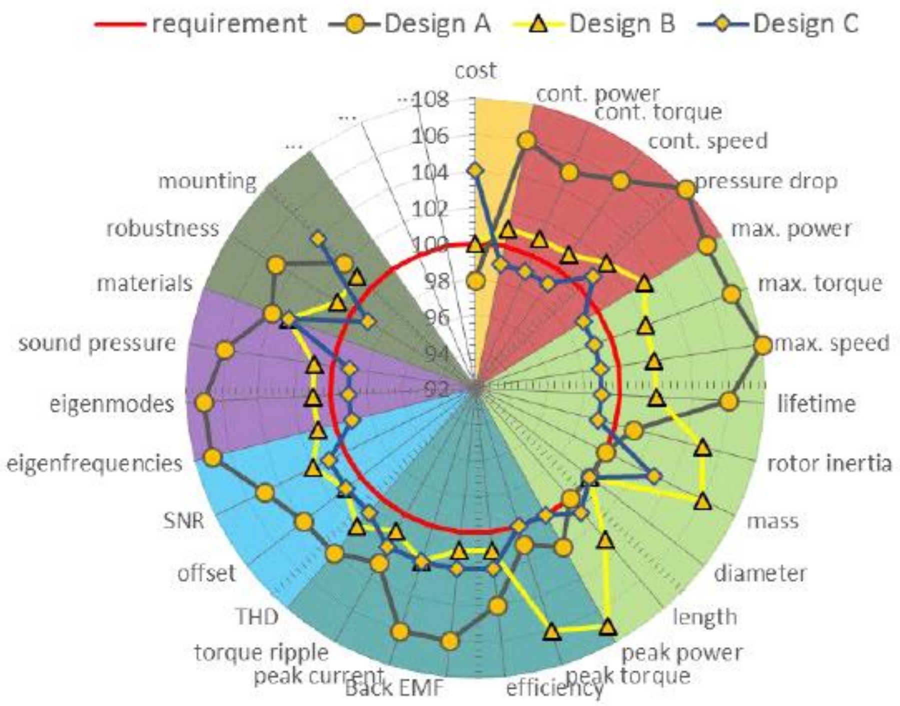


Noise-Vibration and Acoustic Modeling for Electrical Machines



Comparison of different designs – “All in one chart”

- Postprocessing with evaluation of performance „at a glance“
- Requirements and performance indicators in different domains
  - Cost
  - Thermal
  - Mechanical
  - EMAG
  - Control
  - NVH
  - Environment
  - tbc



- Radar chart
  - Dimensionless representation
  - Requirements as 100 % reference (outside red circle = requirement fulfilled)
  - All information in one single chart
  - Easy comparison of several designs

EM-motive GmbH / DBEM/EEP4-Brück / slide 12 WOST 2017, June 1 – 2, 2017, congress centrum neue weimarhalle, Weimar

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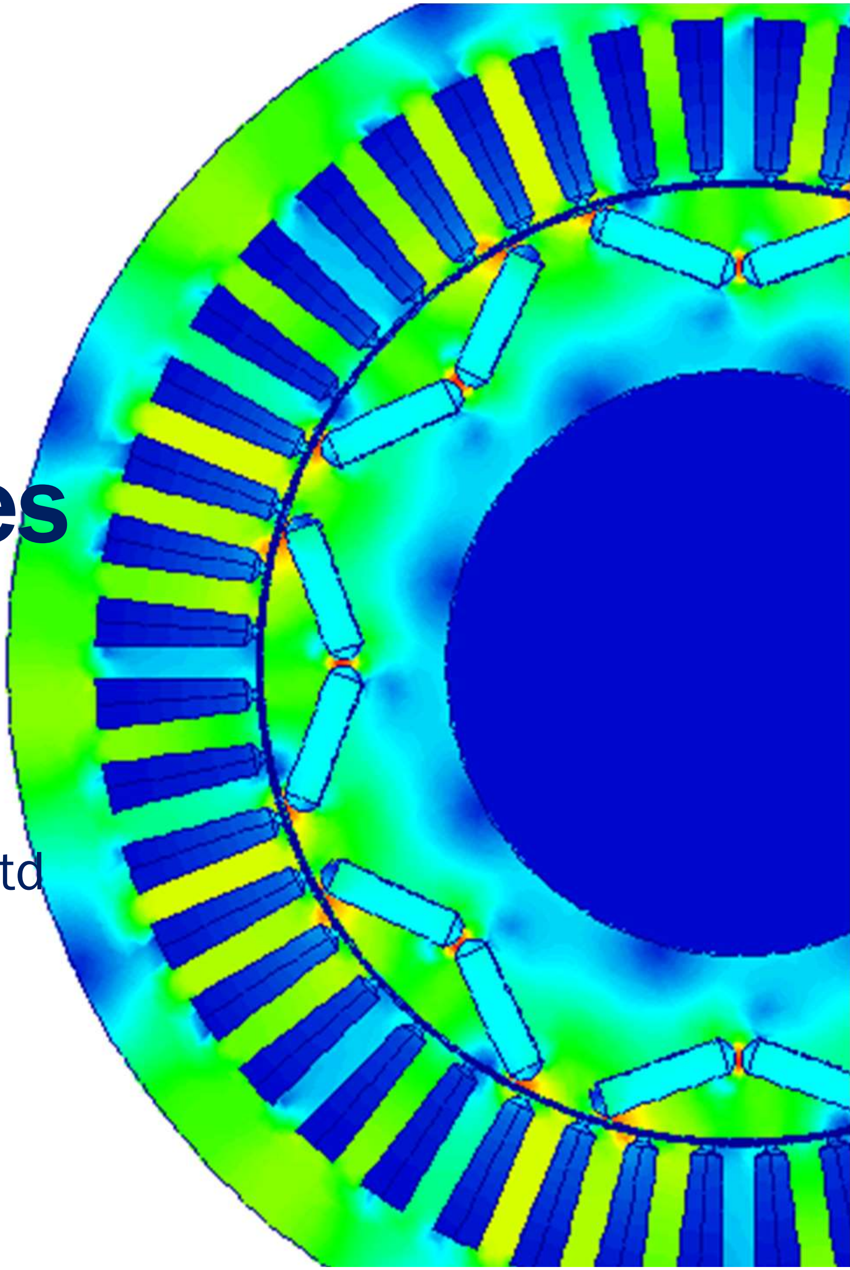
Motor Design Limited

Optimisation of Electric Drives



Dr. Melanie Michon, Head of Engineering, Motor Design Ltd

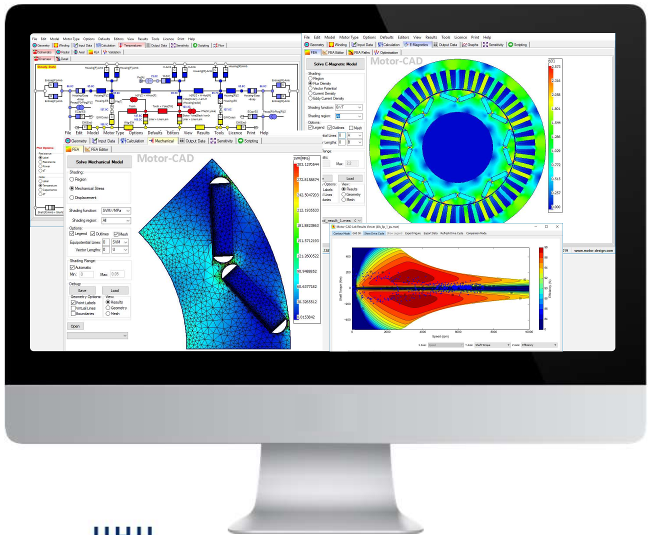
26th June 2020

Content

- Motor Design Ltd. (MDL)
- E-machine design: trends and challenges
- Optimization workflow
- IPM traction motor example
- Demo
- Summary

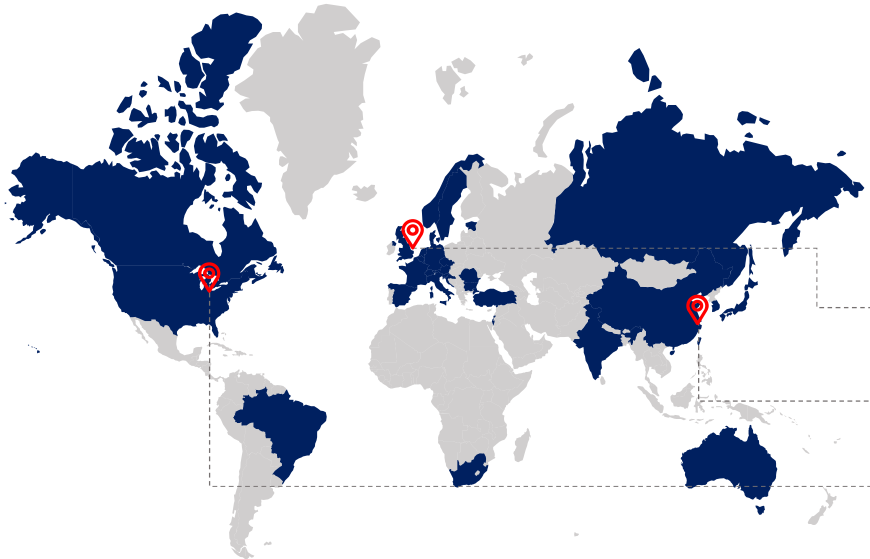
About Motor Design Ltd

- Software developers: Ansys Motor-CAD
  - Developers of Ansys Motor-CAD – world-leading tool for the design and analysis of electric motors.
  - High level of customer support and engineering know-how.
  - Developed with expert electric machine designers.
- Consultancy
  - Design, analysis & training.
  - Led by motor design experts with significant industry and academic experience.
- Research
  - Involved in collaborative government/EU-funded research projects.
  - Collaborate with Universities worldwide to develop electric machine modelling techniques and create validation data.



Motor-CAD
MOTOR DESIGN SOFTWARE BY MOTOR DESIGN ENGINEERS

About Motor Design Ltd



Worldwide Customers

Customers in 33 countries and over 470 companies worldwide.

MDL Headquarters
Wrexham, UK

MDL Asia
Shanghai, China

MDL USA
Ohio, USA

Customers across 6 industry sectors
Automotive, aerospace, rail, renewables, industrial & appliances.

43% of the team are design engineers

30% of the team are software developers

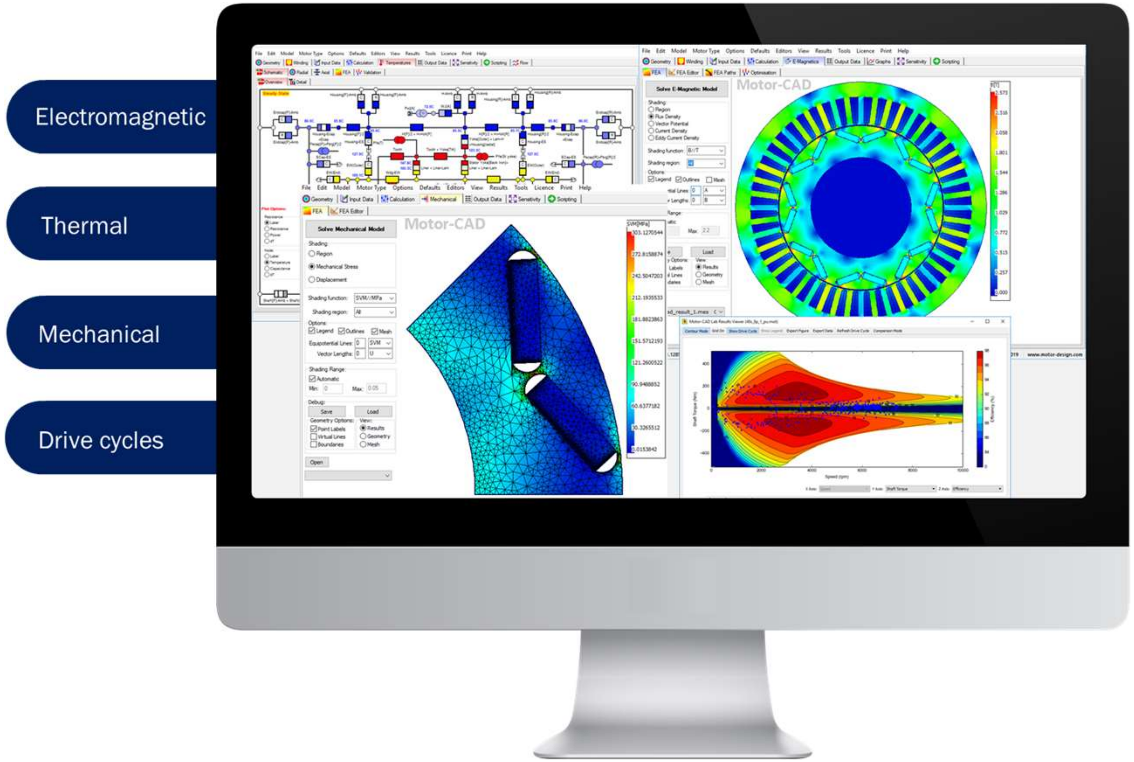
47% of the team have a PhD

Developing Motor-CAD software since **1998**

MDL has OEM software partnership with Ansys

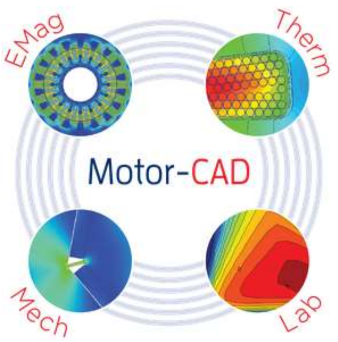
Motor-CAD software
Integrated multiphysics design tool

- Market leading tool for the design and analysis of radial flux electric motors.
- Combines analytical and FE methods for fast and accurate performance prediction.
- Enables multiphysics simulation across the full operating range:
  - Peak performance characteristics
  - Transient thermal analysis
  - Continuous performance envelope
  - Efficiency maps
  - Energy consumption over driving conditions
  - Mechanical stress pattern



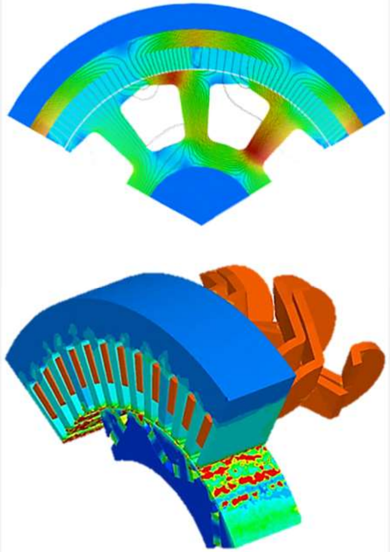
End-to-End Workflow with Motor-CAD and Ansys tools

Motor-CAD
Rapid Multiphysics Electric Motor Design

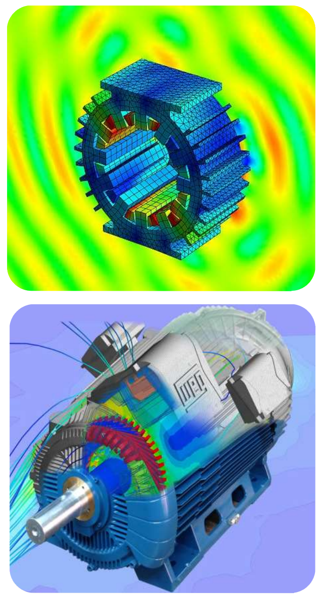


Iterative Design Space Exploration Toolkit

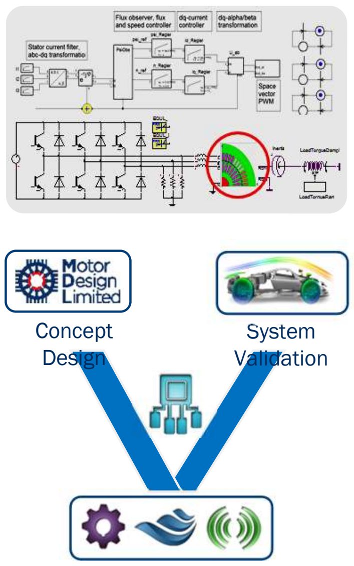
Maxwell 2D & 3D
Advanced Magnetics Modelling



Mechanical & CFD
NVH, Cooling



System Validation
Control Logic, Software



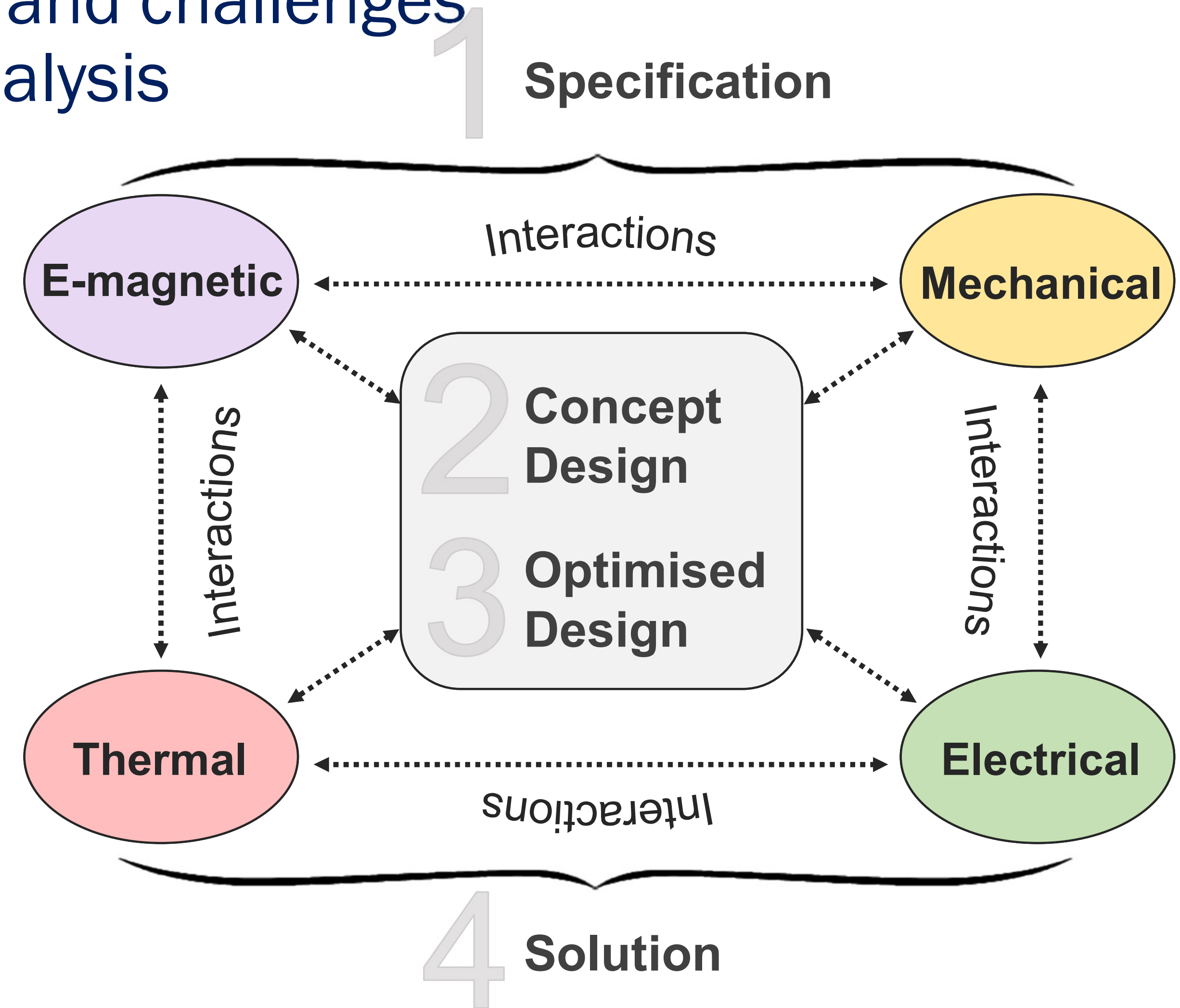
DESIGN → ANALYSIS → OPERATION

E-Machine design: trends and challenges
Need for multi-criteria design process

- Higher efficiency
- Increased torque and power density
- Reduced costs
- Increasing volumes and mass production
- Increased integration
- Shorter development cycles

E-Machine design: trend and challenges
Need for Multiphysics analysis

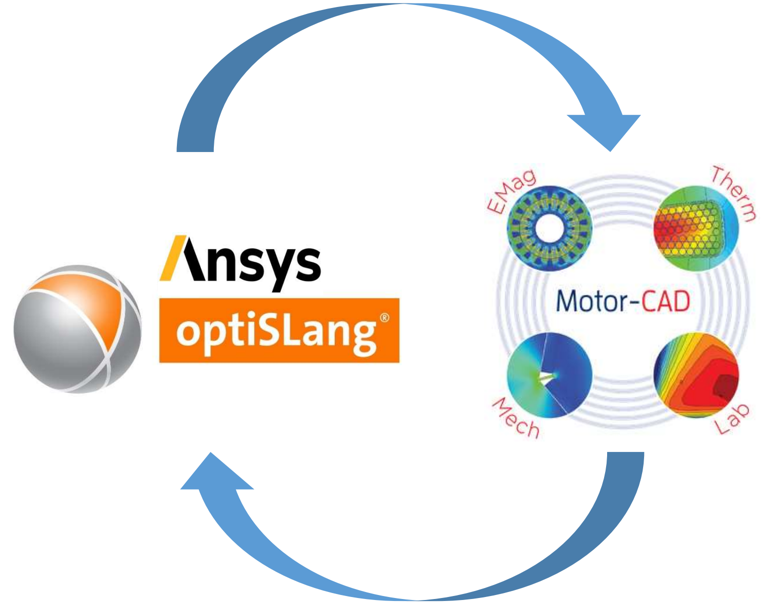
- Design optimisation of e-motors is multidisciplinary by nature:
  - Mechanical: NVH, stress, fatigue, manufacturing quality, …
  - Thermal: steady state / transient performance, cooling system, …
  - Electromagnetic: power density, torque ripples, efficiency, …
  - Electrical: voltage limit, maximum input current, …
- Interactions between the different physical domains often lead to conflicting performance criteria



E-Machine design: trend and challenges
Need for efficient optimisation strategies

- Electric machine design space is large with complex interactions.
- Designers seek for design optimization processes that enable:
  - Efficient multi-objective design optimization
  - Rapid design trade-offs
  - Traceability on design decisions
  - Fast response to changing requirements
  - Robust design insights

Can be achieved by using **Motor-CAD and optiSlang**



Data-driven exploration of the design space utilizing multiphysics simulation

Optimisation Workflow Step by Step

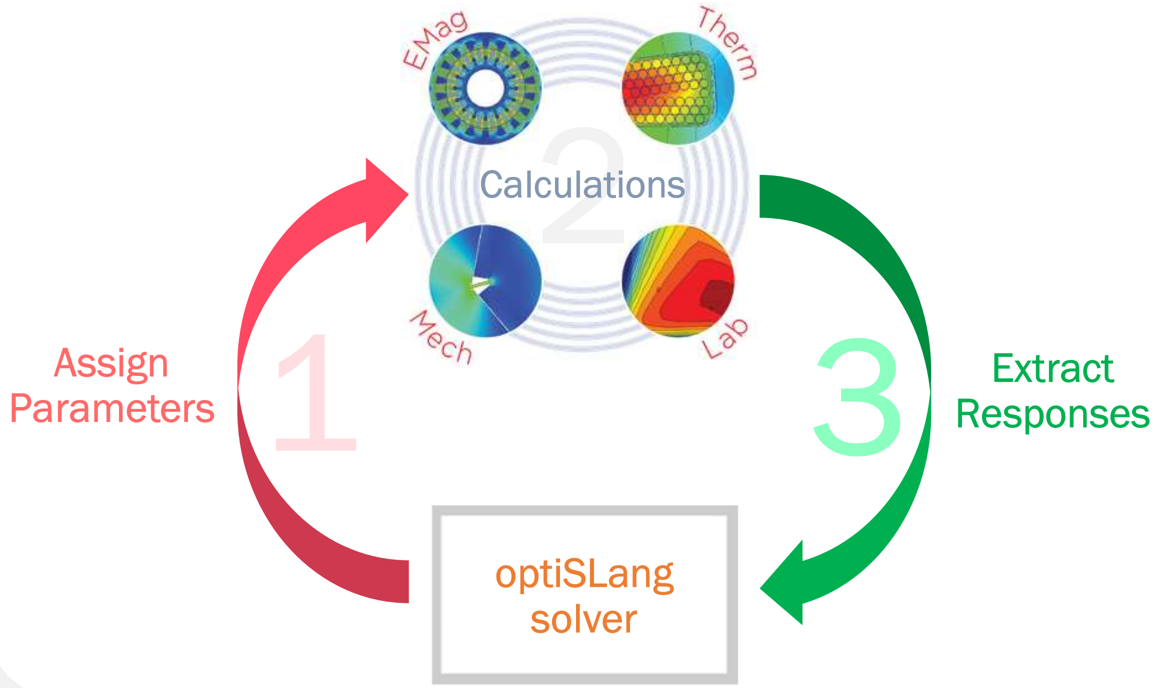
1 Sensitivity Analysis

2 Meta-modelling

3 Optimization

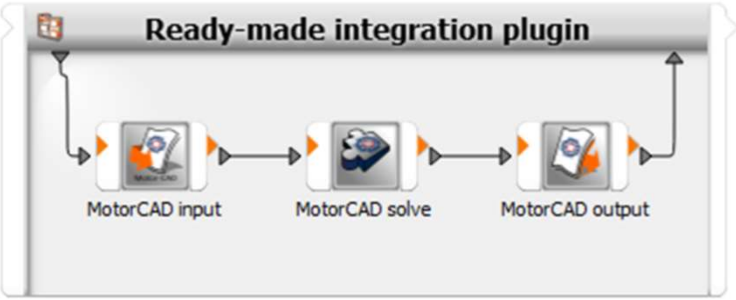
4 Validation

- Motor-CAD is driven by optiSLang in order to assign variables, run calculations and extract output parameters of interest



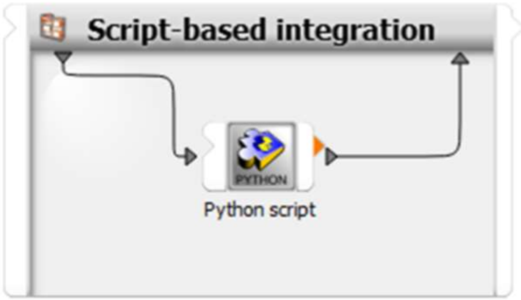
Optimization workflow
Motor-CAD integration

- Ready-made plugin:



✔ Easy integration
✔ Motor-CAD sequences automatically defined
✔ Parameter lists automatically generated.
✖ Low DOF problems with narrow ranges
✖ Limited number of inputs / outputs

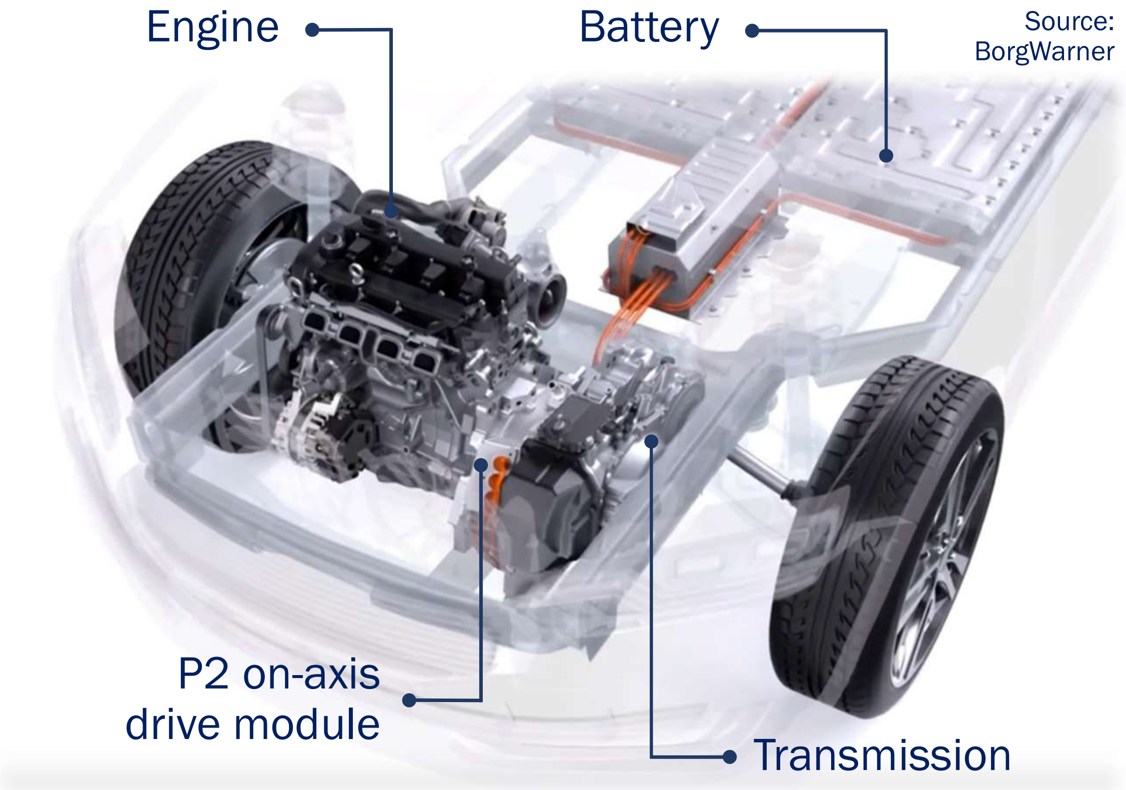
- Customized Python scripts:



✔ Complete control over the analysis
✔ No particular Python skills required
✔ Access to any Motor-CAD parameter
✔ Large design space with high DOFs problems
✖ More effort required (e.g. parameterization)

IPM traction motor example
Specification

- P2 PHEV Application

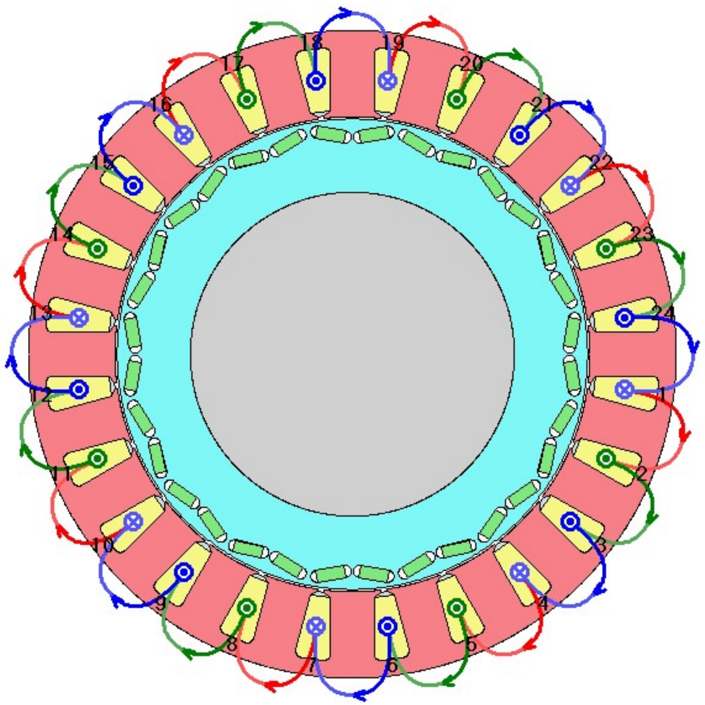


Requirement	Value	Unit
Peak torque	400	Nm
Peak power @ 3krpm	120	kW
Peak power @ 6krpm	100	kW
Cont. torque @ 1krpm	300	Nm
Cont. torque @ 5krpm	124	Nm
Maximum speed	7000	Rpm
Cooling system	WJ	
Coolant flow rate	≤ 6.5	l/min
Coolant fluid type	EWG	
Coolant inlet temperature	65	°C
Line current	≤ 500	A_{rms}
DC bus voltage	350	V
Machine diameter	330	mm
Machine length	≤ 220	mm

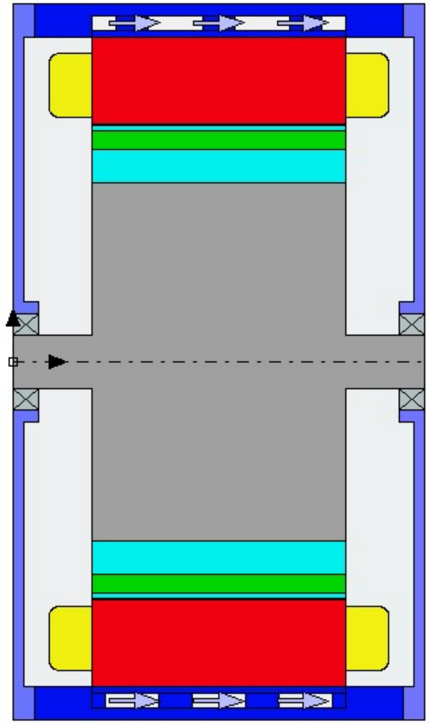
IPM traction motor example
Preliminary design

- Topology:
  - Stator slots = 24
  - Rotor poles = 16
  - V-shaped magnets
- Materials:
  - Magnets: N38UH
  - M235-35A
- Stator winding:
  - Concentrated, double-layer
  - Parallel paths per phase = 8
- Geometry:
  - Stator OD (mm) = 300
  - Mechanical airgap (mm) = 1

Winding pattern



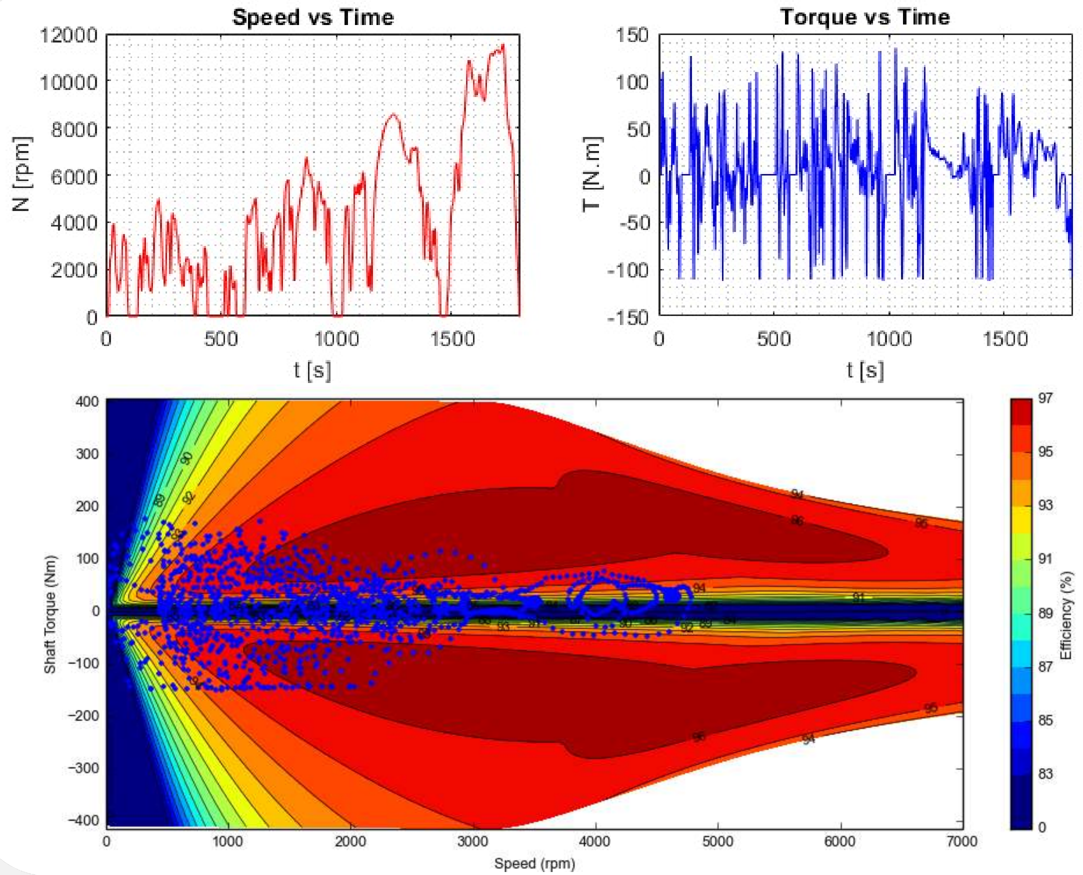
Cooling system



IPM traction motor example
Optimization scenario

- Multi-objective:
  - ❑ Maxi efficiency over WLTP-3
  - ❑ Min active volume
  - ❑ Min material cost
- Multi-constraints:
  - ❑ Cont. Torque (Nm) @ 1krpm ≥ 300
  - ❑ Cont. Torque (Nm) @ 5krpm ≥ 124
  - ❑ Peak Power (kW) @ 3krpm ≥ 120
  - ❑ Peak Power (kW) @ 6krpm ≥ 100
  - ❑ Torque Ripple (%) @ 0.5krpm ≤ 10
  - ❑ Max. Stress ≤ 0.5 x Yield Strength

WLTP-3 Drive Cycle



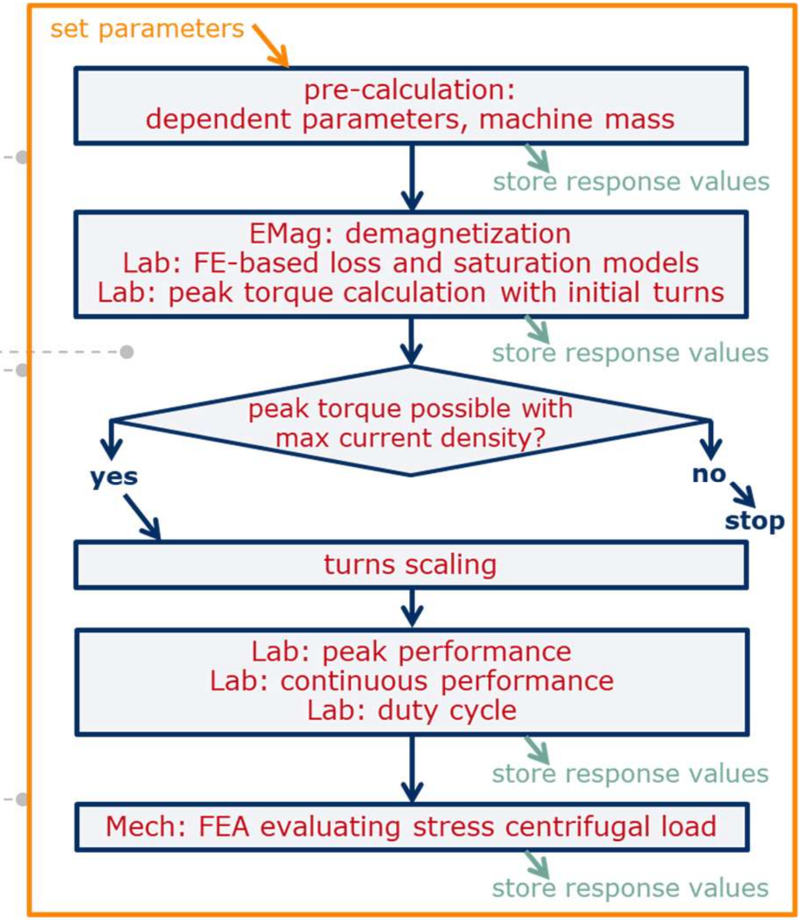
IPM Optimisation Workflow

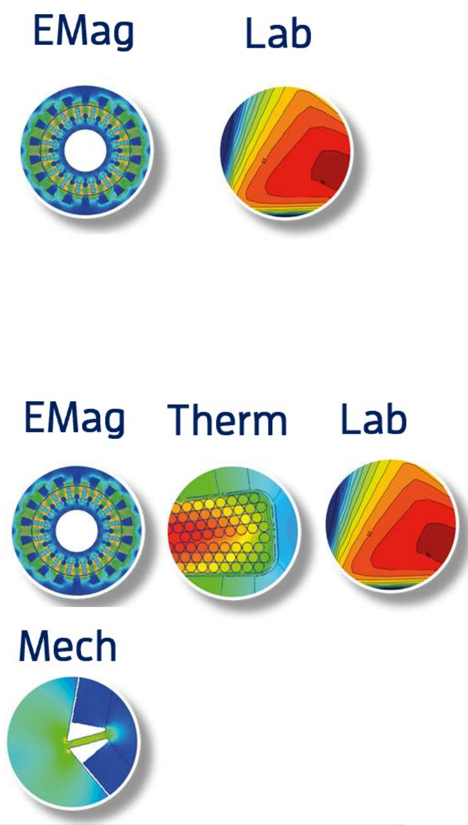
1 Sensitivity Analysis

2 Meta-modelling

3 Optimization

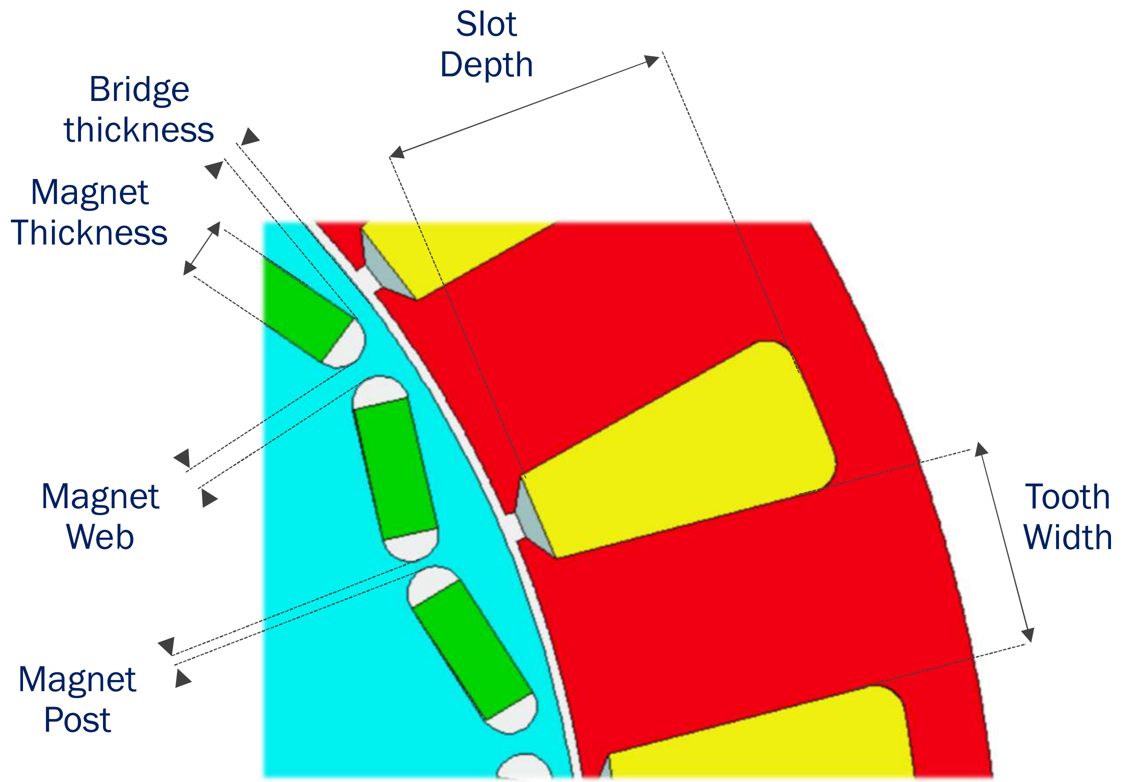
4 Validation





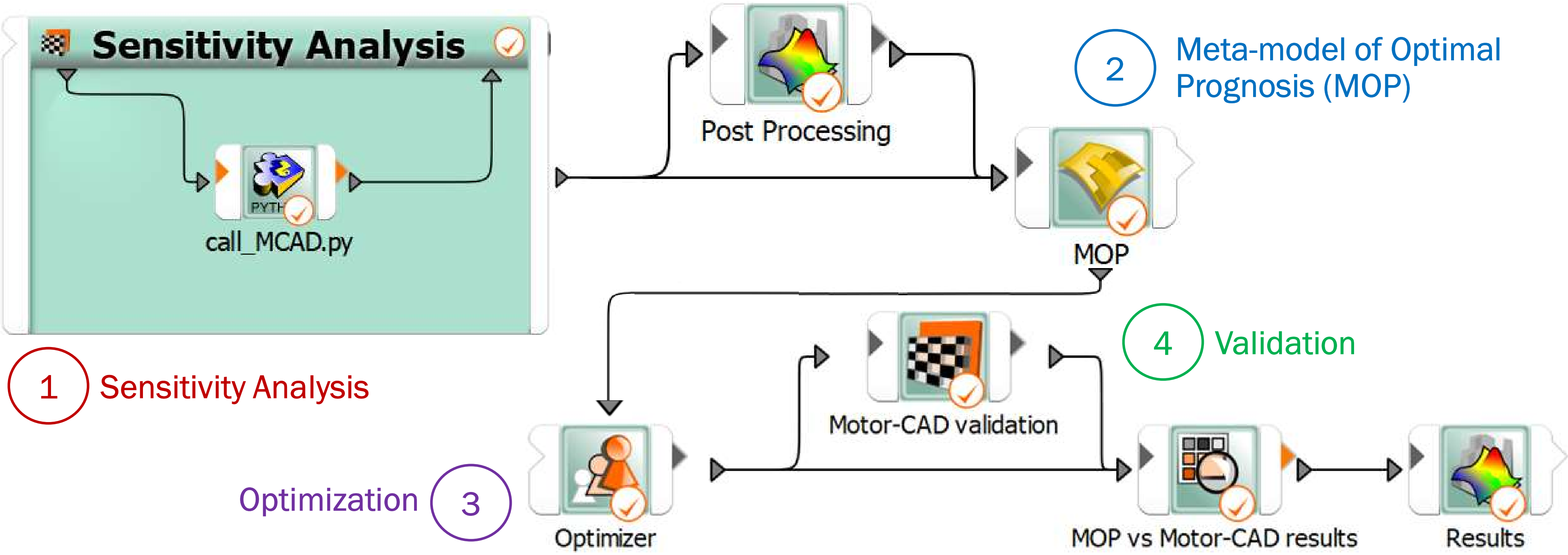
IPM traction motor example
Design space

Parameter	lb	ub	Unit
Active length	100	150	mm
Rotor bridge thickness	0.4	1.5	mm
Magnet pole angle	95	160	°
Magnet post thickness	0.4	2.5	mm
Magnet thickness	4	8	mm
Magnet web thickness	0.8	8	mm
Slot depth ratio[1]	0.6	0.8	
Slot width ratio[2]	0.25	0.5	
Split ratio[3]	0.65	0.85	

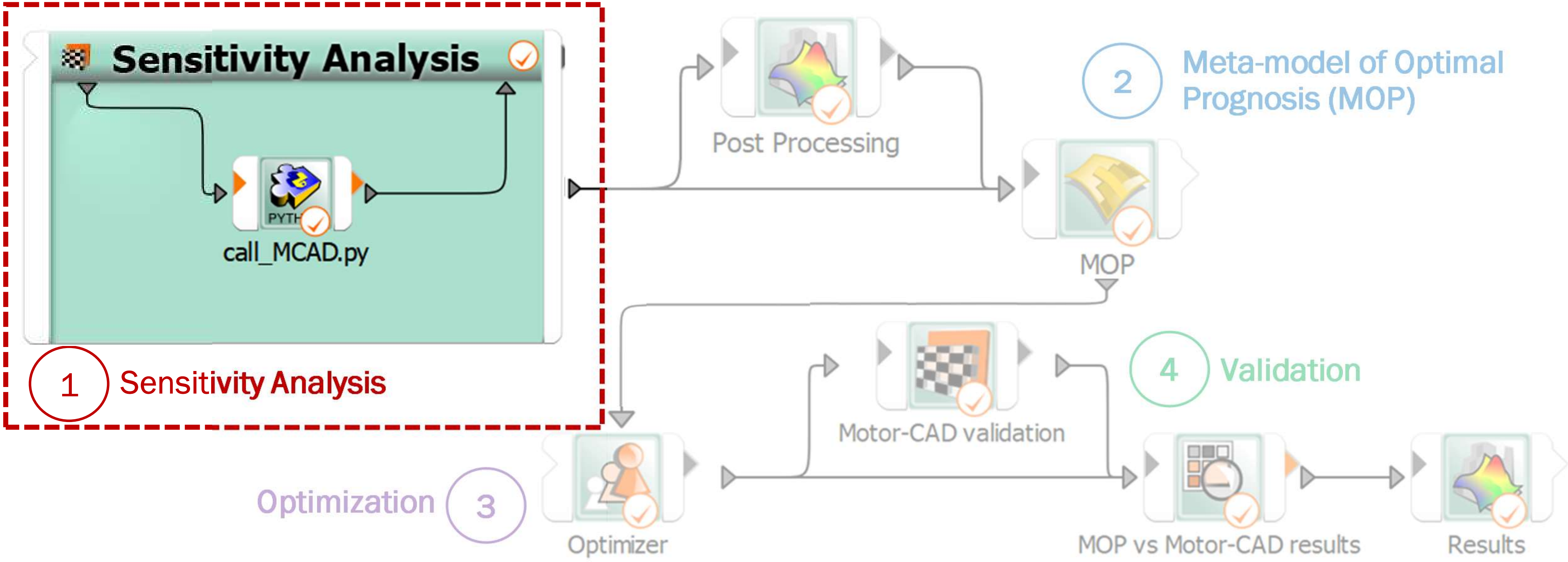


[1] Slot Depth / (Slot Depth + Stator Back Iron Thickness)
[2] Slot Width / (Slot Width + Stator Tooth Width)
[3] Stator Inner Diameter/ Stator Outer Diameter

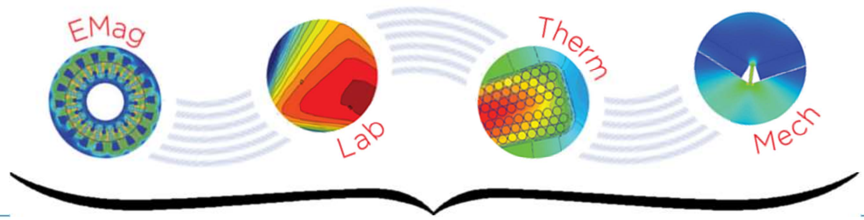
IPM traction motor example
Workflow in optiSLang



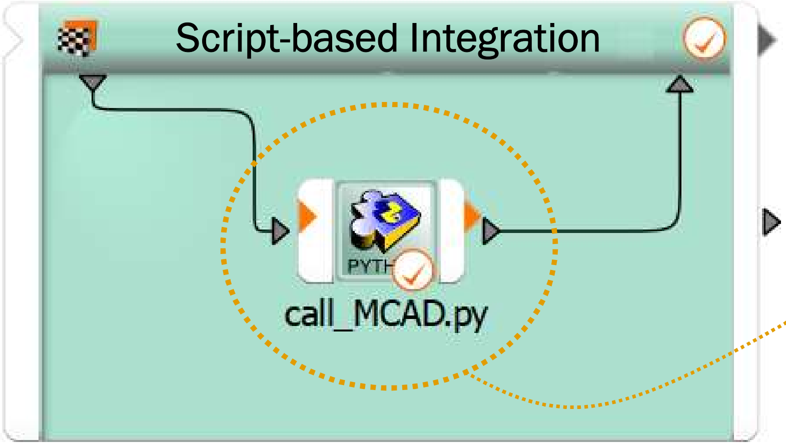
IPM traction motor example
Step 1: Sensitivity Analysis

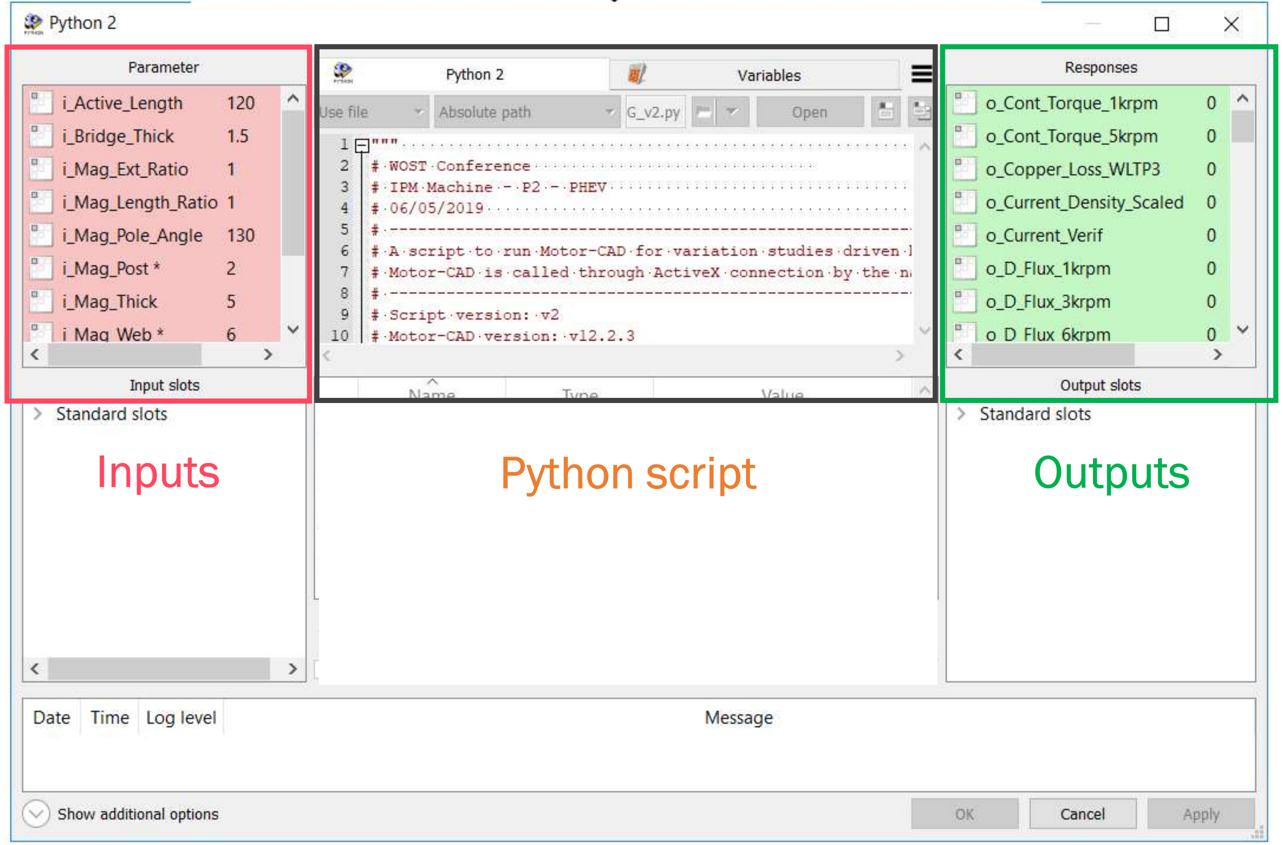


IPM traction motor example
Step 1: Sensitivity Analysis



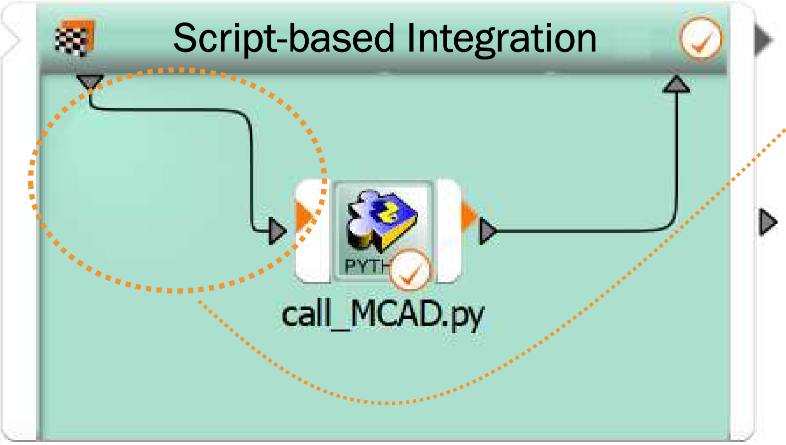
- Interface that is used with the script based integration method to initialize Inputs and Outputs.
- Custom Python script used to:
  - Assign parameters
  - Run calculations
  - Collect responses





IPM traction motor example
Step 1: Sensitivity Analysis

- After inputs/outputs initialization, the design space should is to be defined for each variable.
- It will be used by the optiSLang solver to generate samples for the sensitivity analysis.



Sensitivity

Parameter | Start designs | Criteria | Dynamic sampling | Other | Result designs

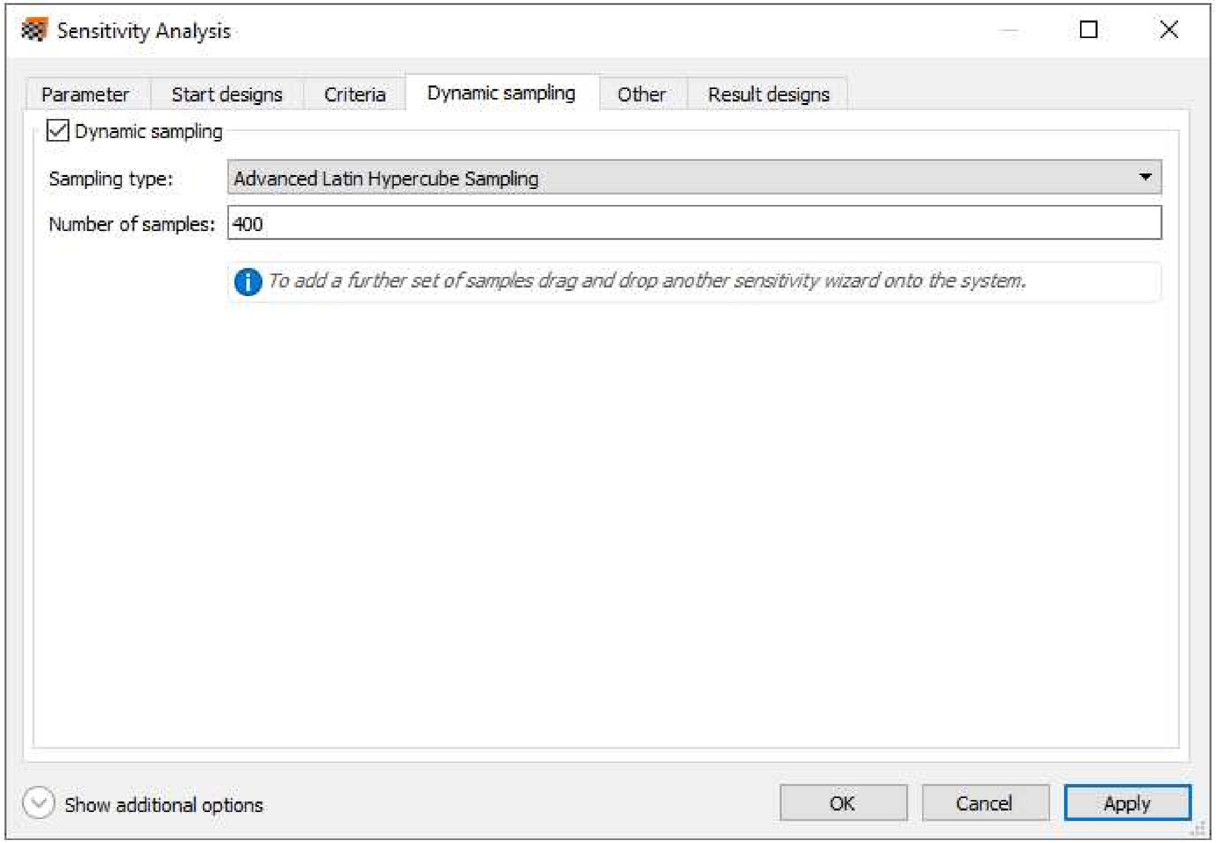
	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot
1	i_Active_Length	Optimization	120	☐	REAL	Continuous	100	150	
2	i_Bridge_Thick	Optimization	1.5	☐	REAL	Continuous	0.8	2	
3	i_Mag_Pole_Angle	Optimization	130	☐	REAL	Continuous	95	165	
4	i_Mag_Post	Optimization	2	☐	REAL	Continuous	0.8	3.5	
5	i_Mag_Thick	Optimization	5	☐	REAL	Continuous	3	8	
6	i_Mag_Web	Optimization	6	☐	REAL	Continuous	3	10	
7	i_Slot_Depth_Ratio	Optimization	0.7	☐	REAL	Continuous	0.6	0.8	
8	i_Slot_Width_Ratio	Optimization	0.35	☐	REAL	Continuous	0.25	0.5	
9	i_Split_Ratio	Optimization	0.75	☐	REAL	Continuous	0.68	0.85	
10	i_Mag_Ext_Ratio	Optimization	1	☑	REAL	Continuous	0.9	1.1	
11	i_Mag_Length_Ratio	Optimization	1	☑	REAL	Continuous	0.9	1.1	

Parameter merging: Prefer defined | Import parameter

Show additional options | OK | Cancel | Apply

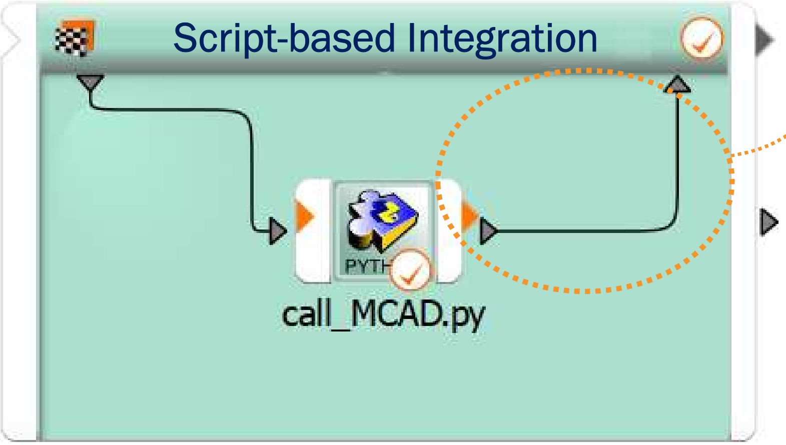
IPM traction motor example
Step 1: Sensitivity Analysis

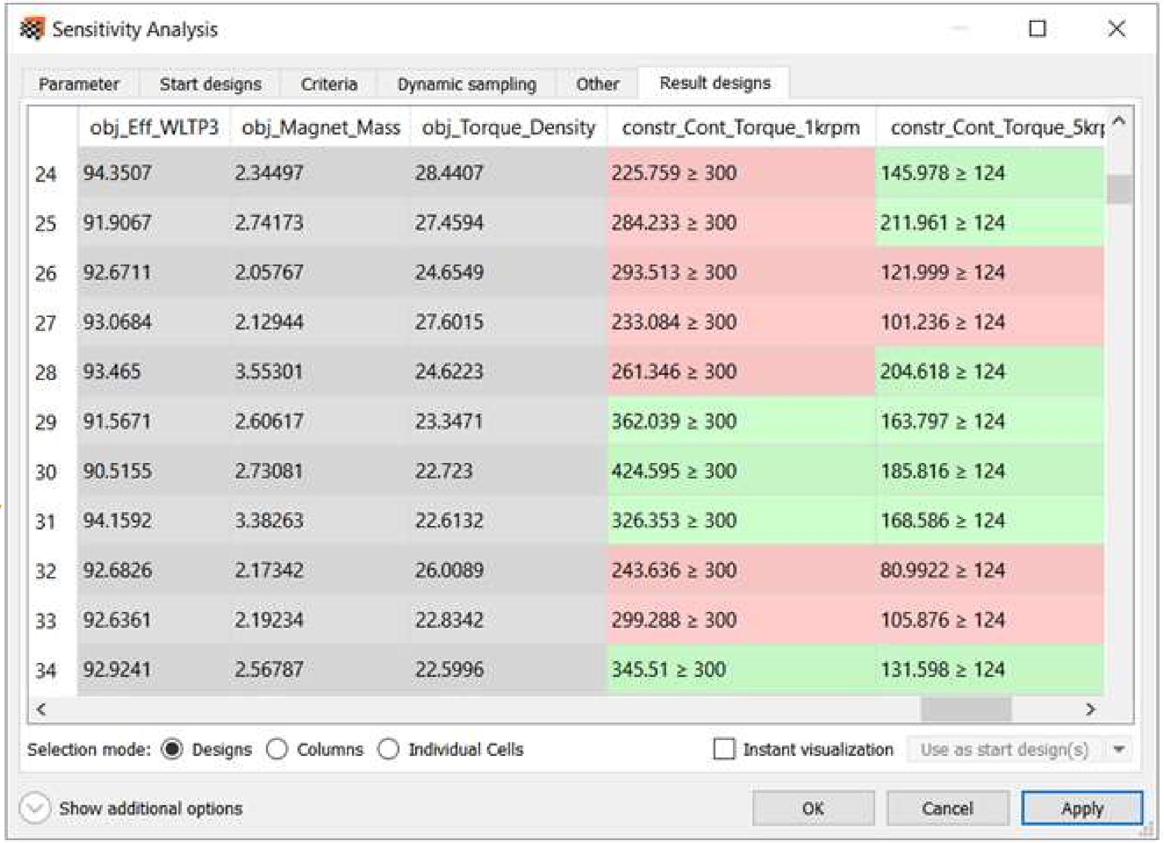
- OptiSLang automatically detects the best sampling method to be used.
- In this case, the Advanced Latin Hypercube Sampling (ALHS) method has been selected.
- The calculation settings used are as follows:
  - 400 samples
  - 2-core processor
  - 3 instances of Motor-CAD in parallel



IPM traction motor example
Step 1: Sensitivity Analysis

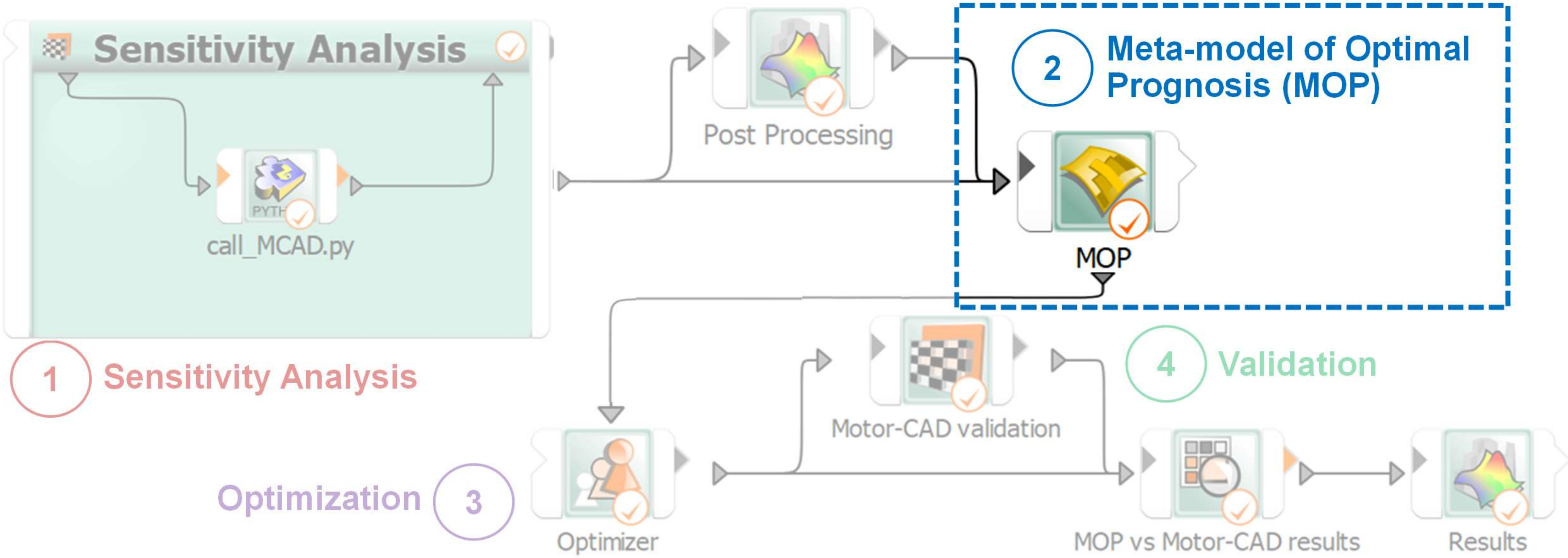
- Performance data sets are collected from every simulated design in Motor-CAD.
- At this stage it is already possible to visualize potential solutions with respect to given constraints.





	obj_Eff_WLTP3	obj_Magnet_Mass	obj_Torque_Density	constr_Cont_Torque_1krpm	constr_Cont_Torque_5krp
24	94.3507	2.34497	28.4407	225.759 ≥ 300	145.978 ≥ 124
25	91.9067	2.74173	27.4594	284.233 ≥ 300	211.961 ≥ 124
26	92.6711	2.05767	24.6549	293.513 ≥ 300	121.999 ≥ 124
27	93.0684	2.12944	27.6015	233.084 ≥ 300	101.236 ≥ 124
28	93.465	3.55301	24.6223	261.346 ≥ 300	204.618 ≥ 124
29	91.5671	2.60617	23.3471	362.039 ≥ 300	163.797 ≥ 124
30	90.5155	2.73081	22.723	424.595 ≥ 300	185.816 ≥ 124
31	94.1592	3.38263	22.6132	326.353 ≥ 300	168.586 ≥ 124
32	92.6826	2.17342	26.0089	243.636 ≥ 300	80.9922 ≥ 124
33	92.6361	2.19234	22.8342	299.288 ≥ 300	105.876 ≥ 124
34	92.9241	2.56787	22.5996	345.51 ≥ 300	131.598 ≥ 124

IPM traction motor example
Metamodel of Optimal Prognosis (MOP)



IPM traction motor example
Coefficient of Prognosis

- Matrix that shows the CoPs of all output parameters with respect to input parameters:
  - **Single CoP:** variance-based measure used to quantify the variable importance.
  - **Full model CoP** (last column): objective measure used to assess for the forecast quality of the MOP.
- Here, the high full model CoPs indicate an almost perfect prediction quality of the MOPs.

	i_Active_Length	i_Bridge_Thick	i_Mag_Pole_Angle	i_Mag_Post	i_Mag_Thick	i_Mag_Web	i_Slot_Depth_Ratio	i_Slot_Width_Ratio	i_Split_Ratio	Total
o_Wdg_Mass	6.9 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	15.8 %	18.5 %	61.5 %	100.0 %
o_Torque_Ripple	3.8 %	5.2 %	12.5 %	12.6 %	4.3 %	21.6 %	16.4 %	2.1 %	32.5 %	93.3 %
o_Torque_Density	100.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	100.0 %
o_Stress_Safety	0.0 %	13.0 %	35.0 %	0.3 %	0.2 %	4.6 %	0.0 %	0.0 %	48.4 %	97.6 %
o_Stator_Core_Mass	26.8 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	3.0 %	9.5 %	63.5 %	100.0 %
o_Rotor_Core_Mass	32.5 %	0.0 %	0.9 %	0.2 %	4.0 %	1.1 %	0.0 %	0.0 %	61.1 %	100.0 %
o_Peak_Power_Max	5.9 %	4.4 %	9.9 %	6.9 %	0.0 %	5.8 %	7.7 %	0.1 %	61.5 %	99.4 %
o_Peak_Power_6krpm	6.4 %	5.0 %	11.3 %	8.7 %	0.0 %	7.7 %	7.2 %	0.2 %	58.1 %	99.2 %
o_Magnet_Mass	24.9 %	0.0 %	13.1 %	1.1 %	19.5 %	15.2 %	0.0 %	0.0 %	33.5 %	100.0 %
o_Eff_WLTP3	9.6 %	3.3 %	18.4 %	12.0 %	8.6 %	12.6 %	22.3 %	8.9 %	24.4 %	98.3 %
o_Cont_Torque_5krpm	7.4 %	3.1 %	13.5 %	6.5 %	0.0 %	16.1 %	8.1 %	0.3 %	49.9 %	98.9 %
o_Cont_Torque_1krpm	45.8 %	5.4 %	15.5 %	7.9 %	2.9 %	7.4 %	1.3 %	1.7 %	14.0 %	98.2 %

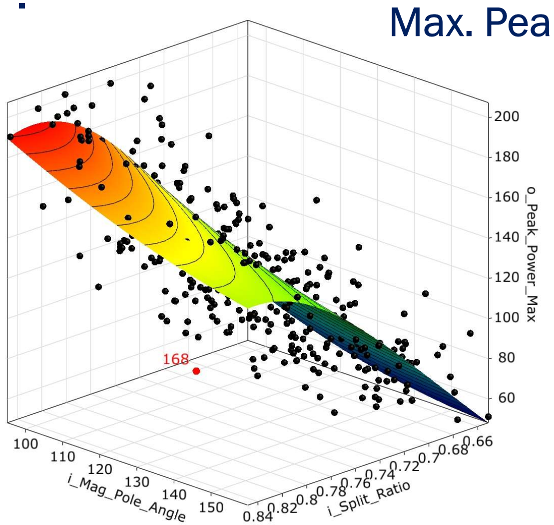
IPM traction motor examp
MOPs

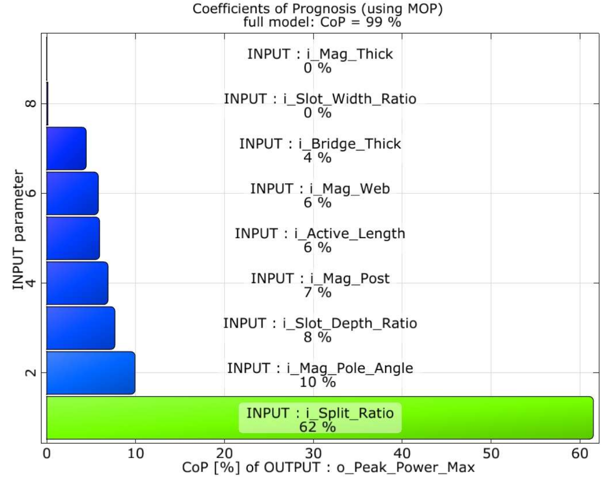
- The metamodels of the maximum peak power and continuous torque are shown as an example.

- One can visualize their optimal subspace along with sensitivities to design variables.

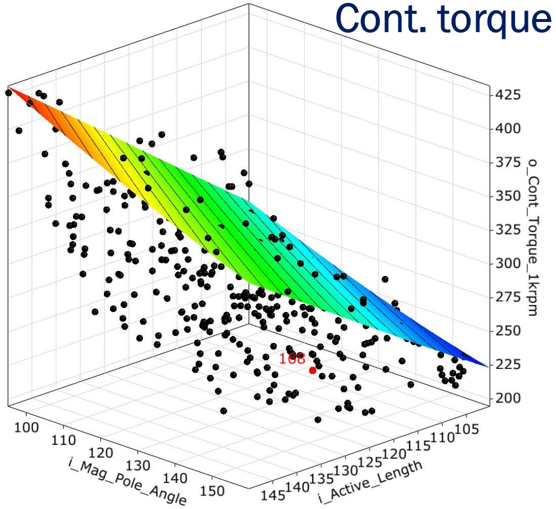
- Additional sampling data (black dots on the graph) can be used to improve the MOP's quality.

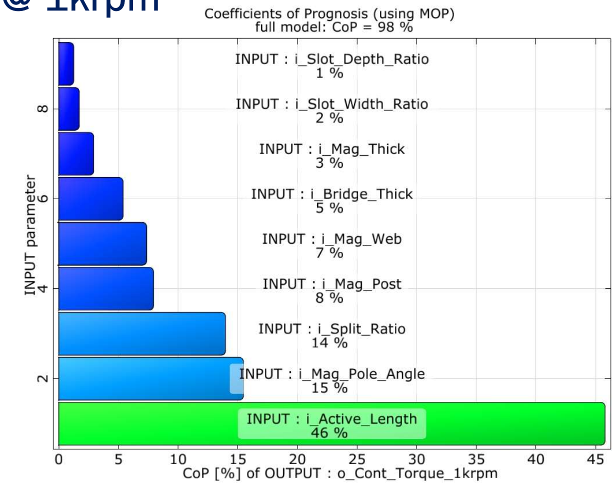
Max. Peak Power





Cont. torque @ 1krpm





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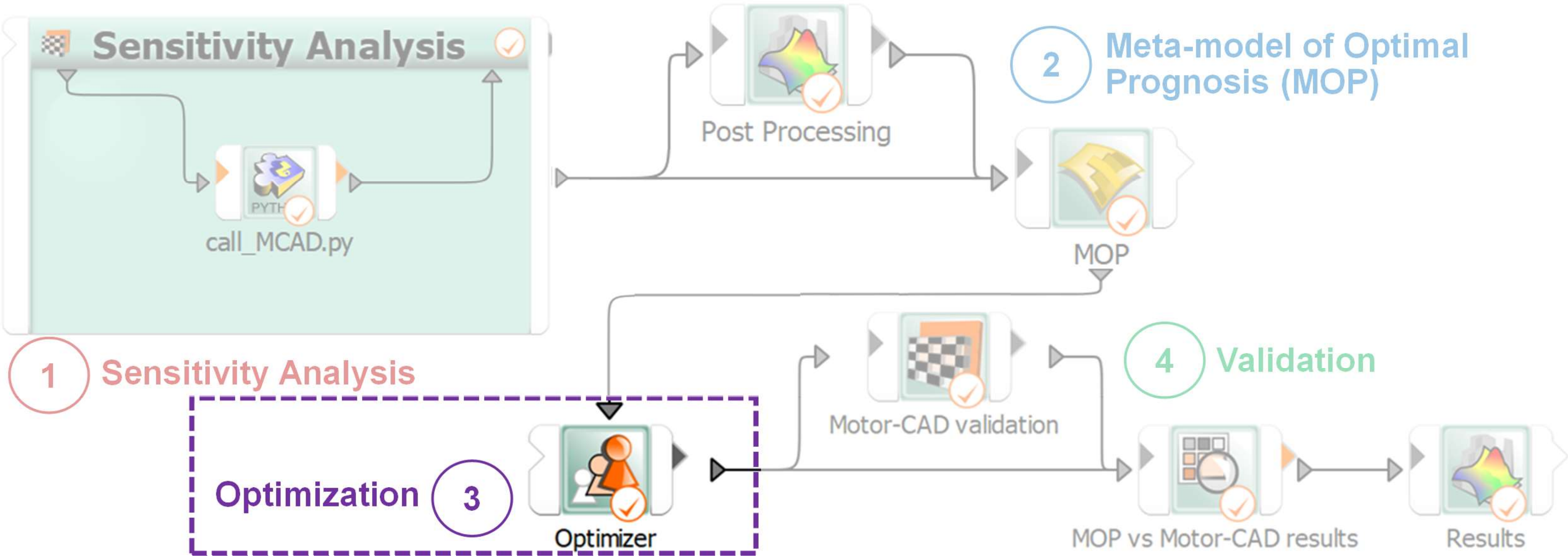
IPM traction motor example
Optimization



IPM traction motor example
Optimization setup

- Constraints and objectives are set up by simply drag and drop parameters of interest.
- Weighing coefficients have been assigned to each active material in the cost function:
  - Rare-earth material: 80£/kg
  - Steel material: 1.04£/kg
  - Copper material: 8£/kg
- An Evolutionary Algorithm (EA) was recommended for multi objective optimization (MOO)

Evolutionary Algorithm

Parameter | Start designs | Criteria | Initialization | Selection | Crossover | Mutation | Other | Result designs

Parameter

Name	Value

Responses

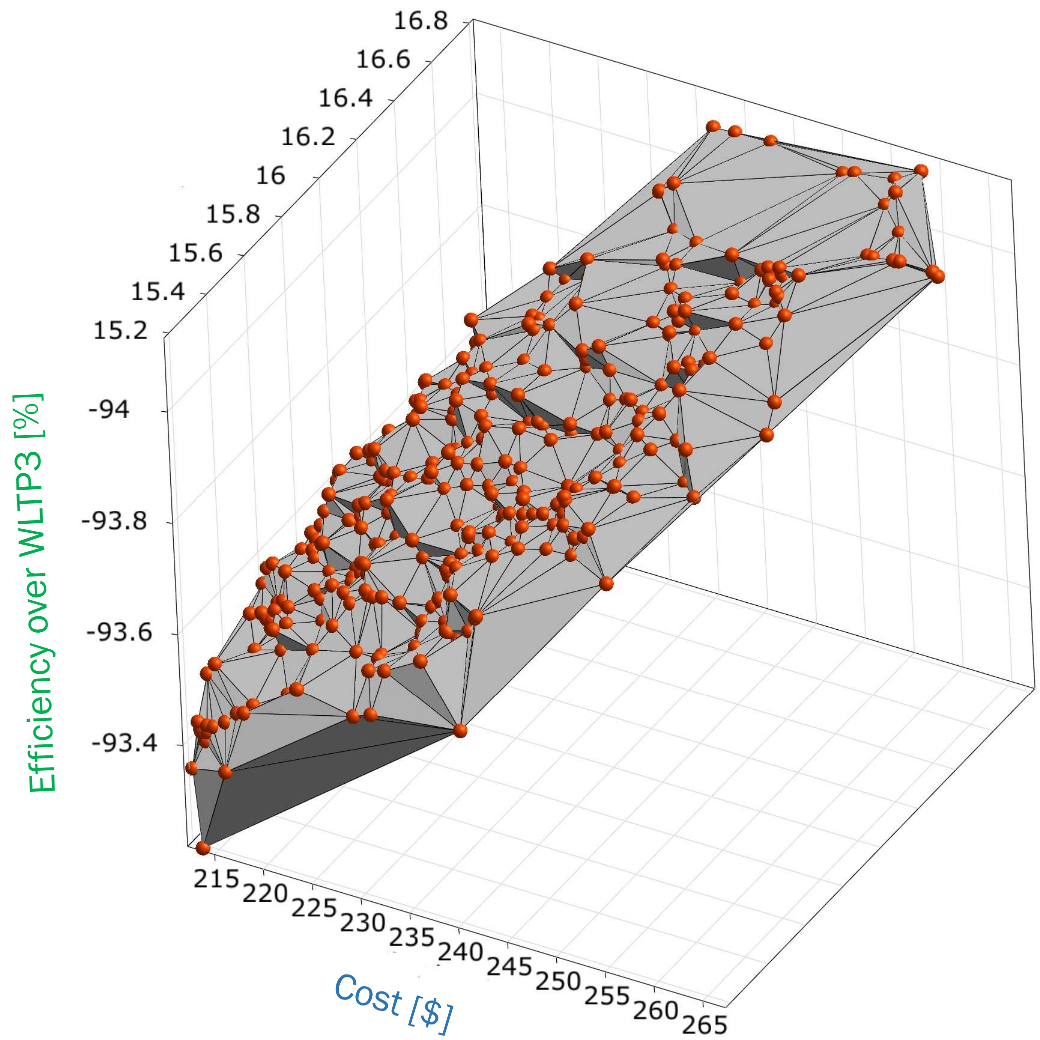
Name	Value

Criteria

Name	Type	Expression	Criterion	Limit
obj_Efficiency_WLTP3	Objective	o_Eff_WLTP3	MAX	
obj_Active_Volume	Objective	400/o_Torque_Density	MIN	
obj_Material_Cost	Objective	8*o_Wdg_Mass +80*o_Magnet_Mass+1.04*...	MIN	
constr_Cont_Torque_1krpm	Constraint	o_Cont_Torque_1krpm	≥	300
constr_Cont_Torque_5krpm	Constraint	o_Cont_Torque_5krpm	≥	124
constr_Peak_Power_Max	Constraint	o_Peak_Power_Max	≥	120
constr_Peak_Power_6krpm	Constraint	o_Peak_Power_6krpm	≥	100
constr_Stress_Safety	Constraint	o_Stress_Safety	≥	1.5
constr_Torque_Ripple_500rpm	Constraint	o_Torque_Ripple_500rpm	≤	10

IPM traction motor example
MOO results: 3D Pareto plot

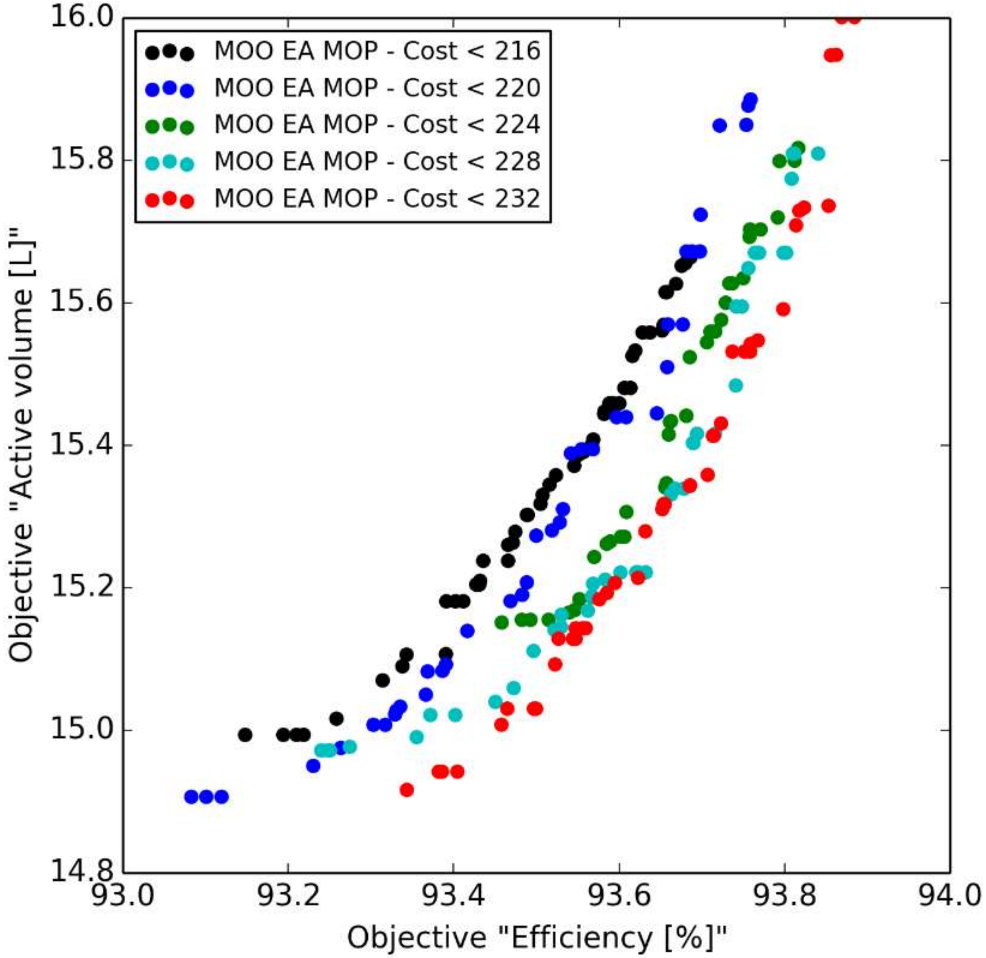
- Solution in which one can trade-off between efficiency, and volume and cost against each other.
- Important figures:
  - Evolutionary Algorithm (EA)
  - Generated designs: 18820
  - Feasible designs: 7789
  - Front designs: 333
  - Simulation time: 30 minutes
- Performing a direct optimisation would have taken more than 80 days!



IPM traction motor example
MOO results: 2D Pareto plot

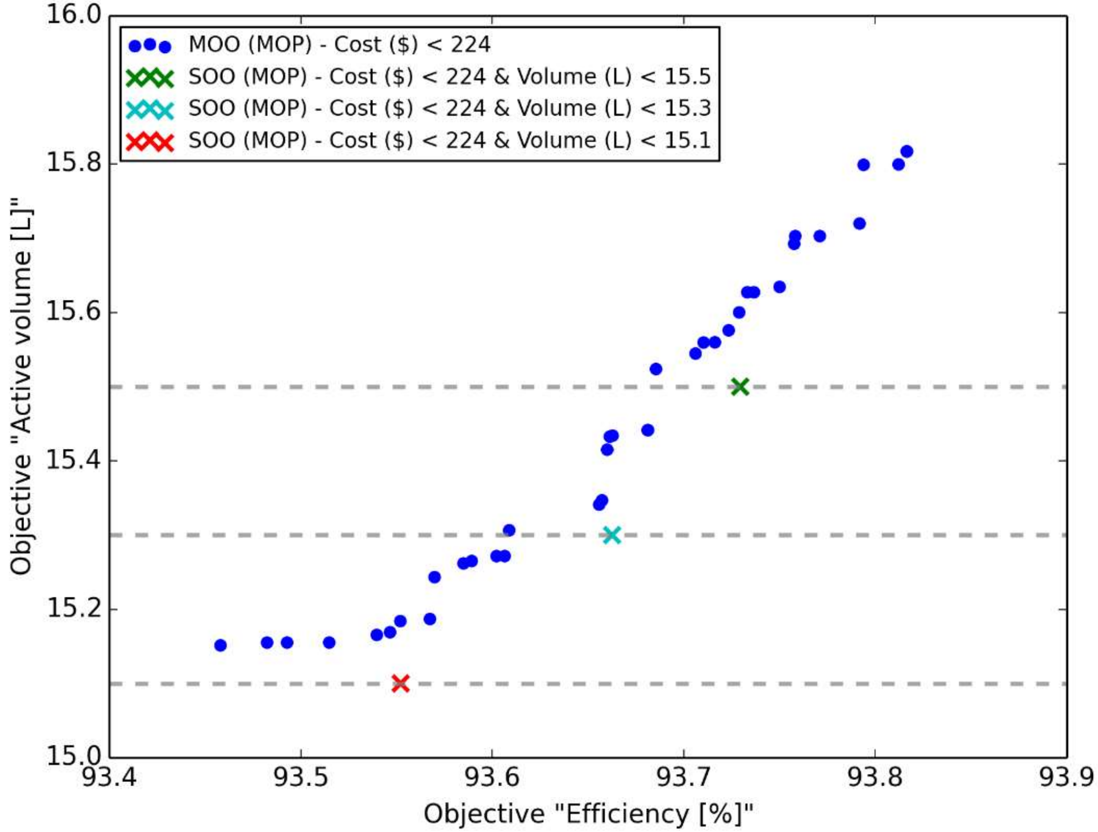
- Solution in which one can trade-off between efficiency and volume, with cost set up as a constraint:
  1. Material cost (£) < 216 (●)
  2. Material cost (£) < 220 (●)
  3. Material cost (£) < 224 (●)
  4. Material cost (£) < 230 (●)
  5. Material cost (£) < 232 (●)

- Highest efficient machine topologies are those with higher volume and higher material cost.

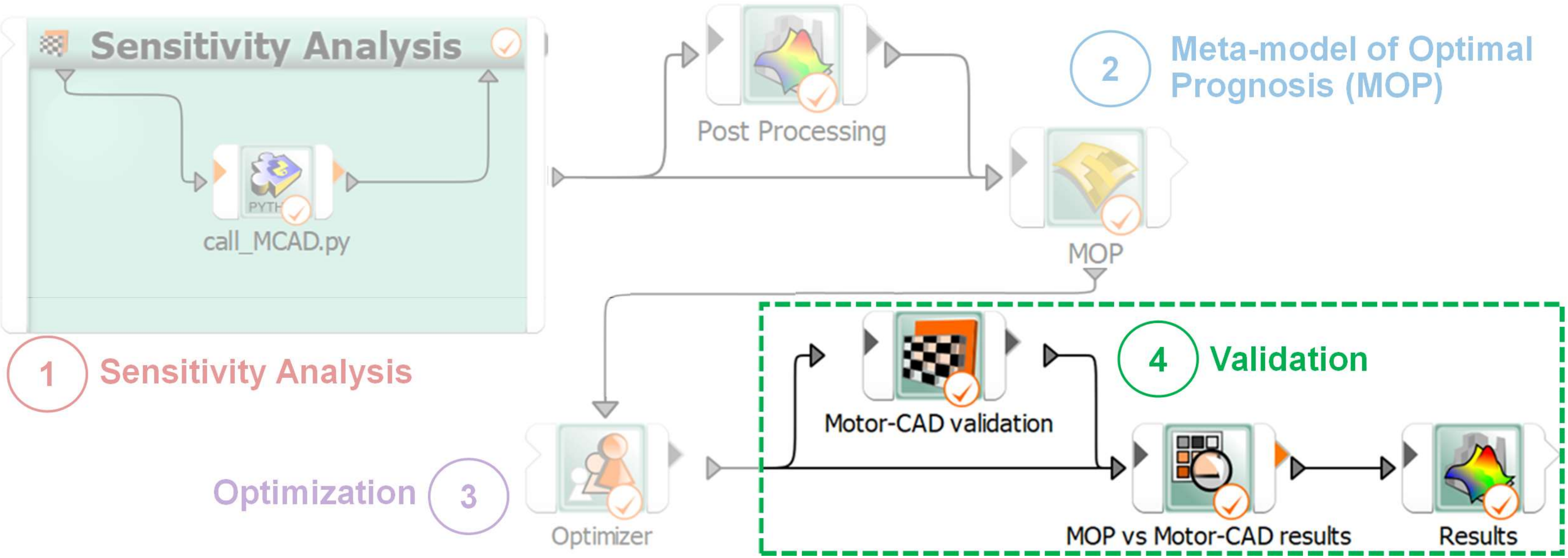


IPM traction motor example
SOO results

- One can optimize the motor efficiency further by performing relevant single objective optimizations:
  - ❑ Cost (£) < 224 and Volume (L) < 15.5 (x)
  - ❑ Cost (£) < 224 and Volume (L) < 15.3 (x)
  - ❑ Cost (£) < 224 and Volume (L) < 15.1 (x)
- SOO results are overlaid to the 2D pareto plot calculated for a material cost lower than 224£ (●).

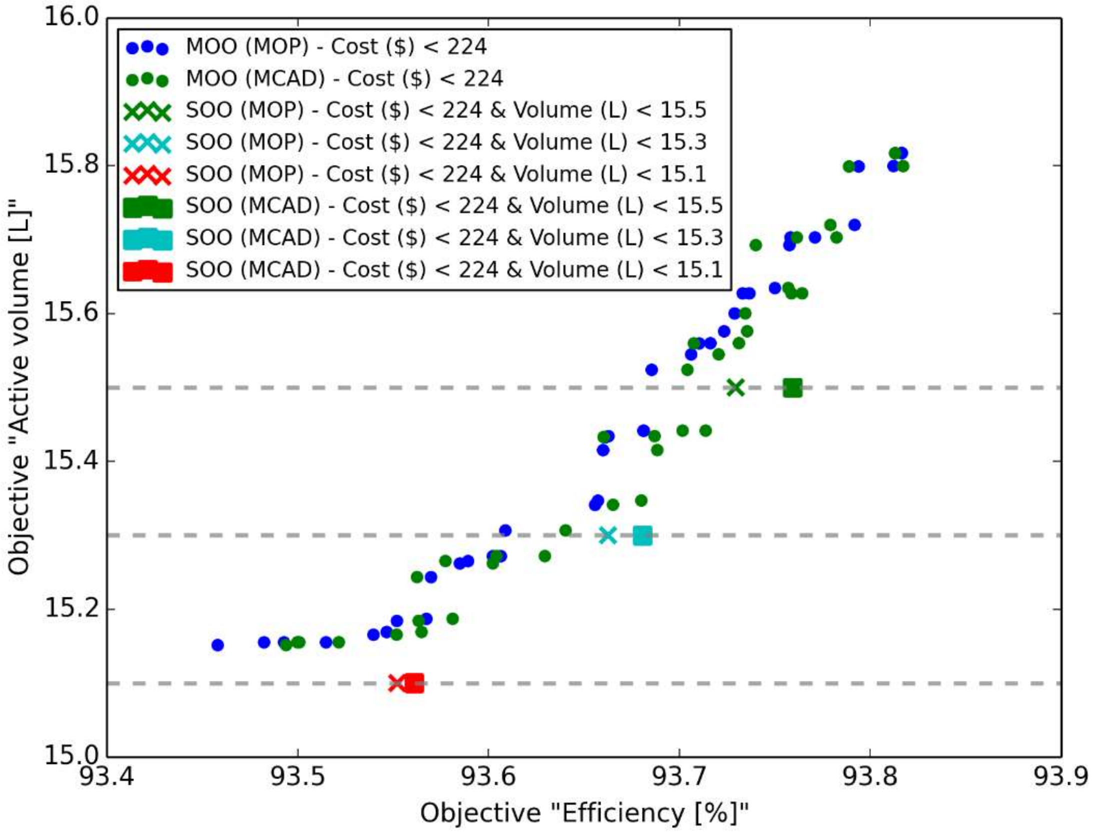


IPM traction motor example
Validation



IPM traction motor example
Validation with Motor-CAD

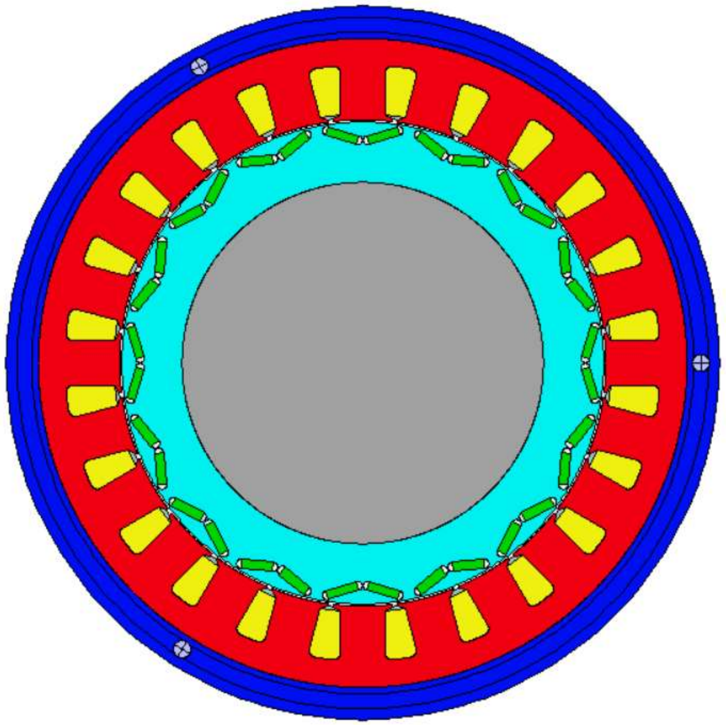
- Very good agreement between MOP based and validated results for both MOO and SOO studies.
- Performance of the design highlighted with a green square are shown in next slides for illustration.



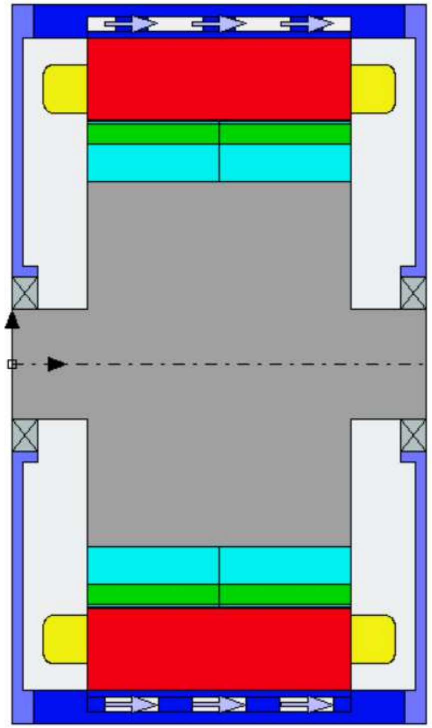
IPM traction motor example
Validation with Motor-CAD

Parameter	Value	Unit
Active length	121.1	mm
Rotor bridge thickness	0.7	mm
Magnet pole angle	145.7	°
Magnet post thickness	0.4	mm
Magnet thickness	4.3	mm
Magnet web thickness	5.5	mm
Slot depth ratio	0.68	
Slot width ratio	0.31	
Split ratio	0.75	

Radial cross section

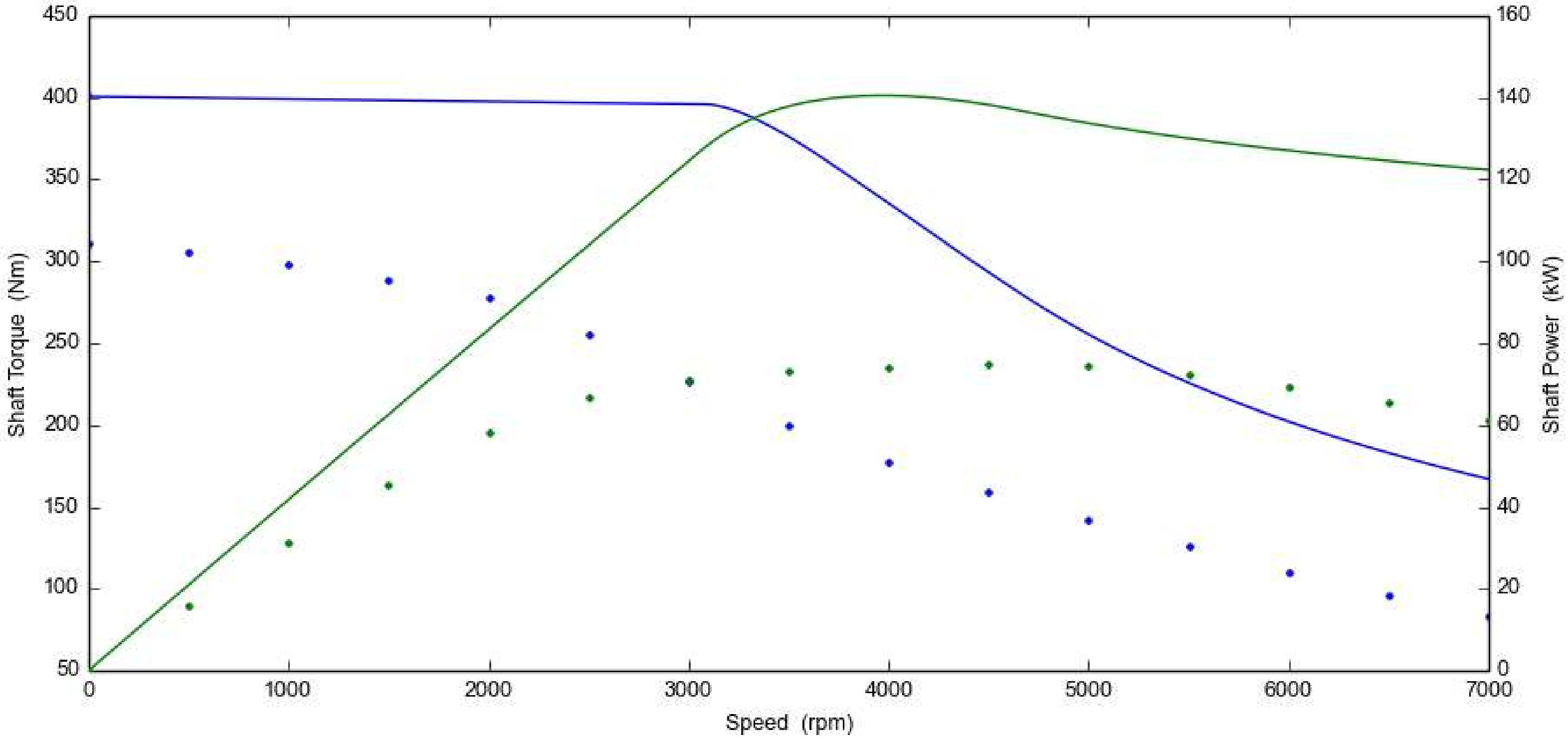


Axial cross section



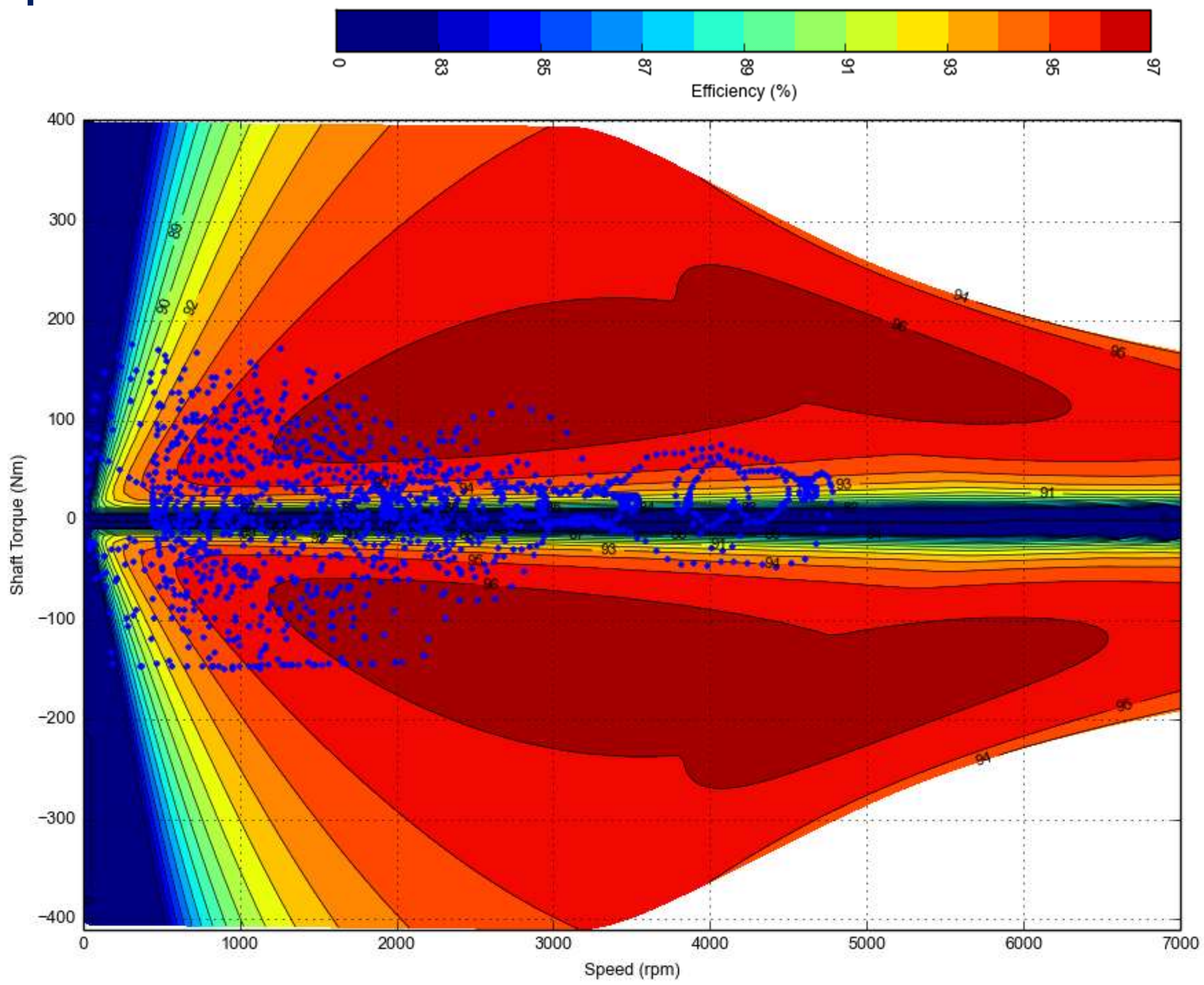
IPM traction motor example
Validation with Motor-CAD

- Peak (lines) and continuous (dots) performance requirements are met.



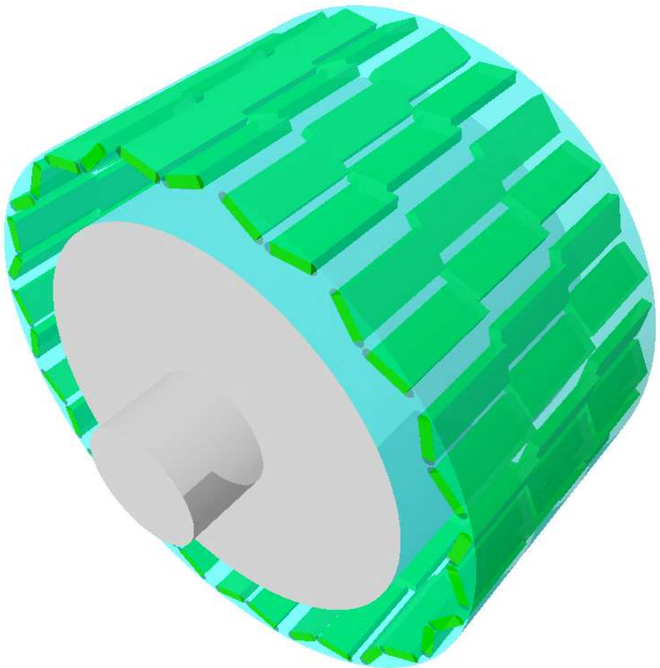
IPM traction motor example
Validation with Motor-CAD

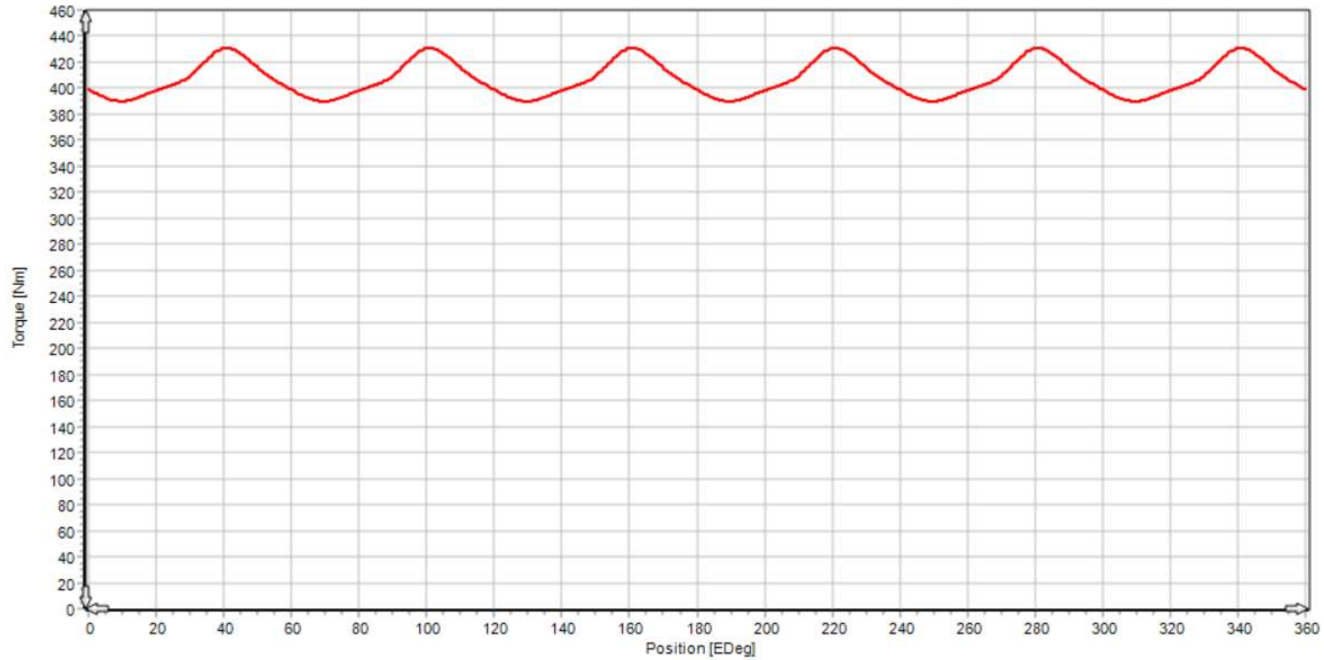
- Efficiency maps in motoring and generating modes with WLTP-3 drive cycle operating points.
- Peak efficiency extended over a large speed range between 1krpm to 6krpm.



IPM traction motor example
Validation with Motor-CAD

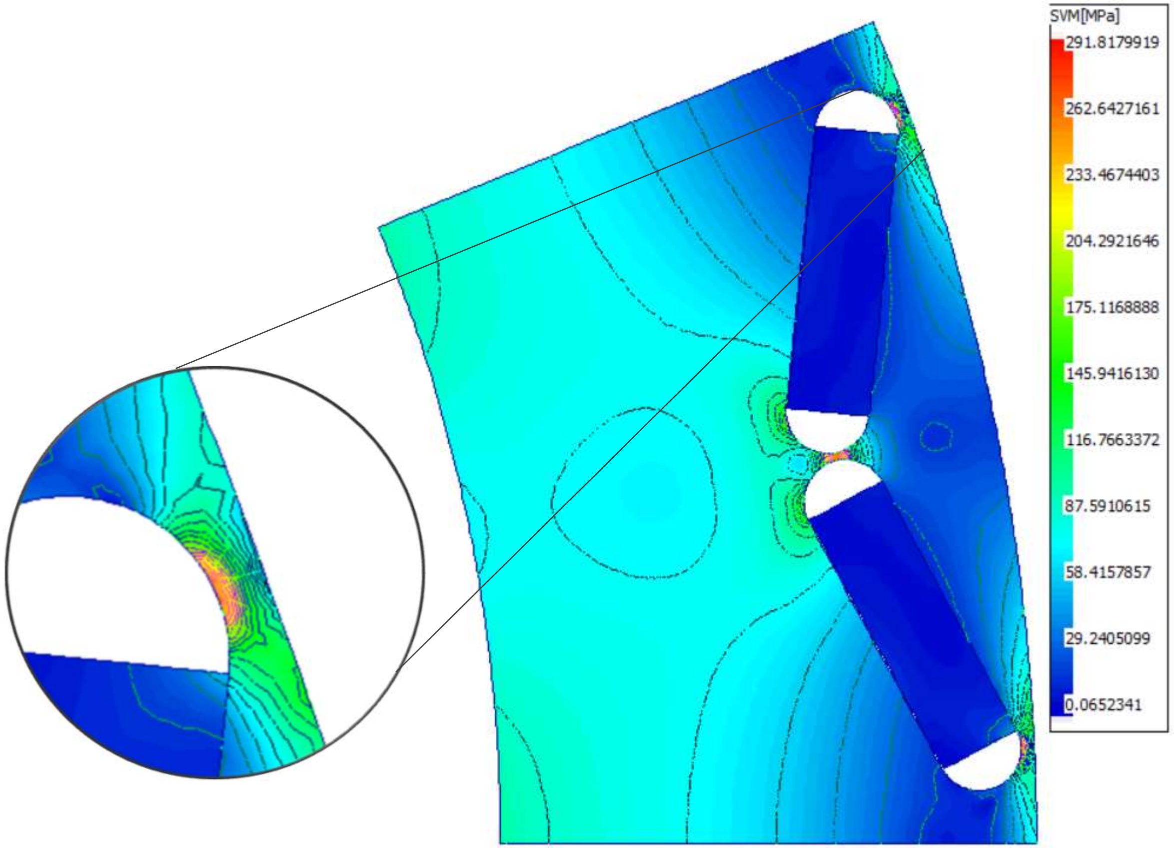
- Torque ripples at 500rpm are below 10% (9.55%).
- The rotor is skewed by 5 mech. degrees with 3 slices.





IPM traction motor example
Validation with Motor-CAD

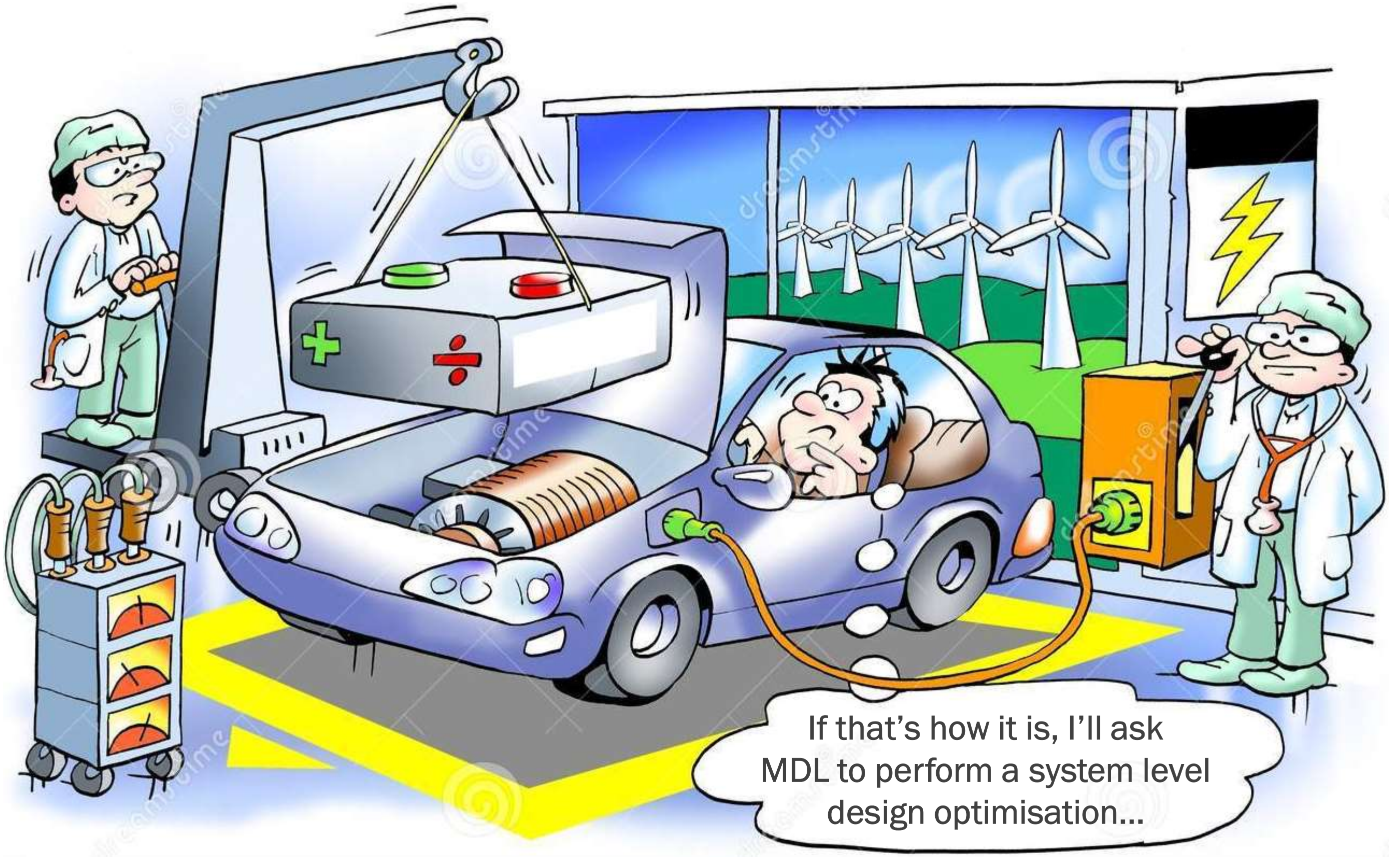
- Rotor mechanical stress analysis is performed at 20% overspeed, that is 8400rpm.
- Maximum Von-Mises stress value is within the rotor mechanical limit with sufficient margin.



Summary

- Design optimisation of e-motors:
  - Complex problem, multidisciplinary and often non-linear.
  - Involves multi-objectives, multi-constraint scenarios.
  - Design trade-offs necessary due to conflicting performance.
- Motor-CAD & optiSLang combination:
  - Unprecedented optimization strategy in both academic literature and industry.
  - Doesn’t require massive HPC capabilities to be used.
  - Parallelization possible (see next slide about black box licenses!).
  - Enables system level trade-offs (e.g. trade-off between cost and drive cycle efficiency).
  - Allow to quickly experiment changes on specifications with respect to the design space.

Thank you for your attention!



Motor Design Software by Motor Design Engineers