Feb. 2023

IQPC 2023 – Advanced EM

Optimization of electric powertrains

BorgWarner

Dr. Gabriel Domingues

Agenda:

- About BorgWarner
- Problem introduction
- Powertrain optimization approach
- Component modelling
  - Electrical Machine
  - Transmission
  - Inverter
- Study Case
- Conclusions

BorgWarner In Numbers

~49k Employees

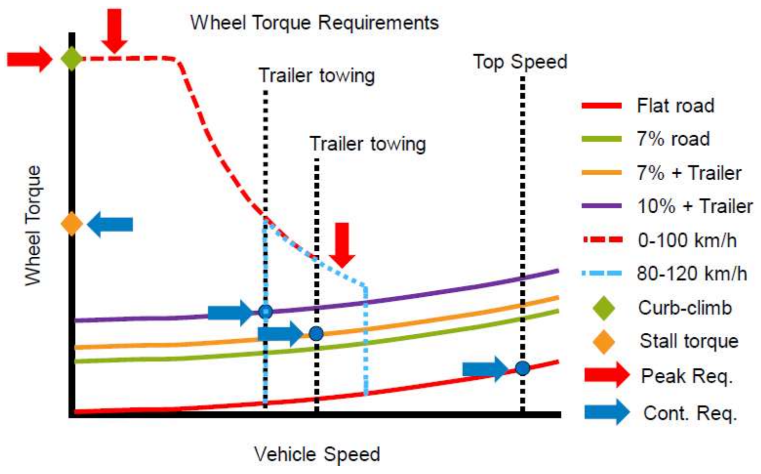
93 Locations

22 Countries

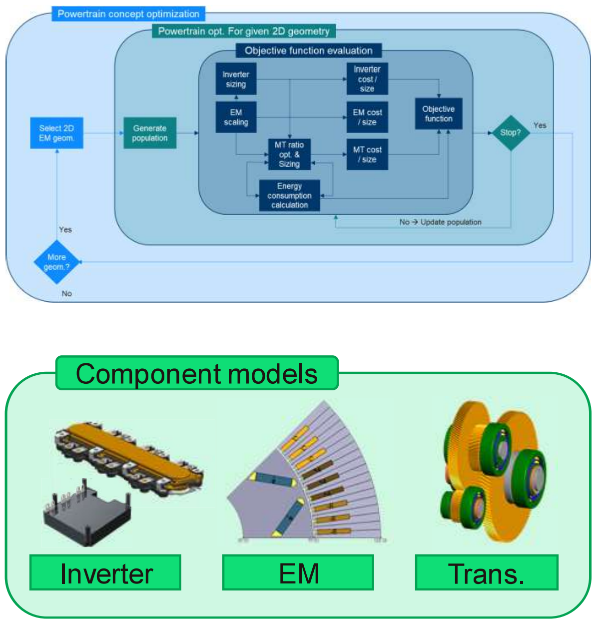
$14.8bn in 2021 Sales

Main objective: translate wheel requirements into preliminary powertrain designs

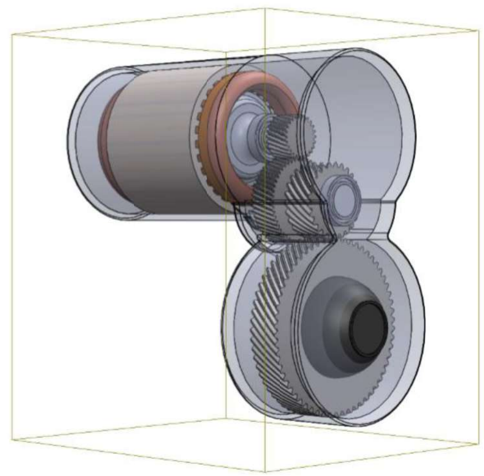
Vehicle level requirements



System optimization



Preliminary design



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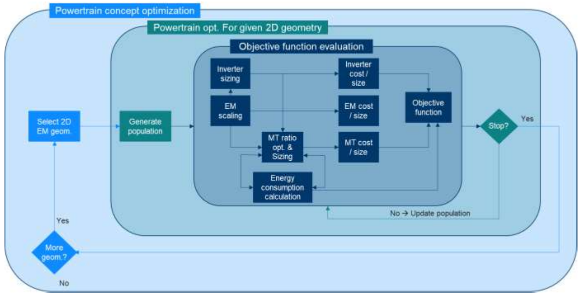
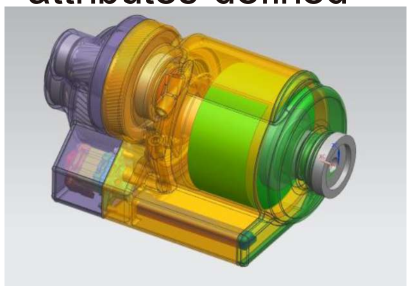
Electric powertrain development workflow

Concept optimization

Initial specifications and requirements

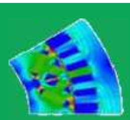
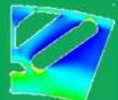
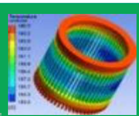
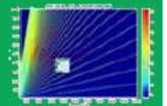


Preliminary design – key attributes defined



Detailed analysis and component optimization and refinement

EM Multi-objective GA optimization

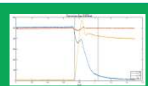





Magnetic, Weight, Thermal, Size, NVH, BOM, Structural, Inertia

PEC Design and Opt.

<u>**Circuit simulations:**</u>
Currents - Voltages - Losses

<u>**Thermal simulations:**</u>
Temperatures – Stresses – Expected lifetime



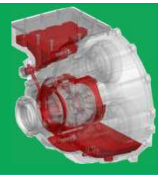
<u>**Component characterization :**</u>
Currents - Voltages - Losses

Trans. Design and Opt.

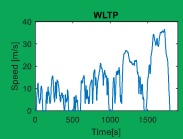
<u>**FEA Structural simulations:**</u>
Stresses – expected life

<u>**Fluid Dynamic simulations:**</u>
Lubrication and cooling

<u>**NVH simulations**</u>



System and Vehicle Simulations



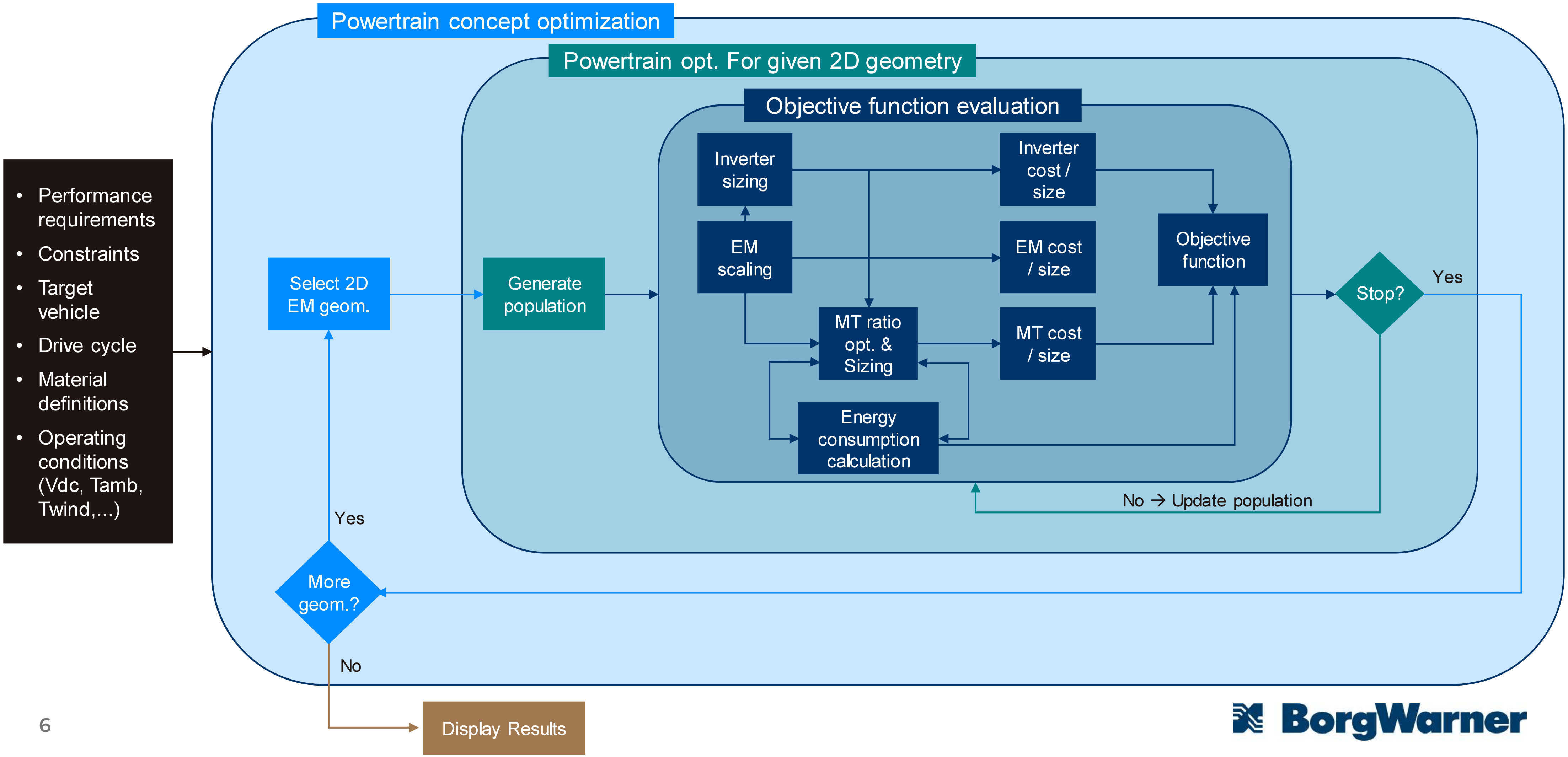
- Overall energy consumption
- Loss separation
- Vehicle performance
- System NVH
- System Thermal Management

Validation and verification

Prototype bench testing – model calibration

Vehicle level testing – control calibration

Powertrain optimization approach



Definition of system requirements

Inputs:

- Target vehicle properties
- Drive cycle to be used for system optimization
- Performance requirements both peak and continuous

Outputs:

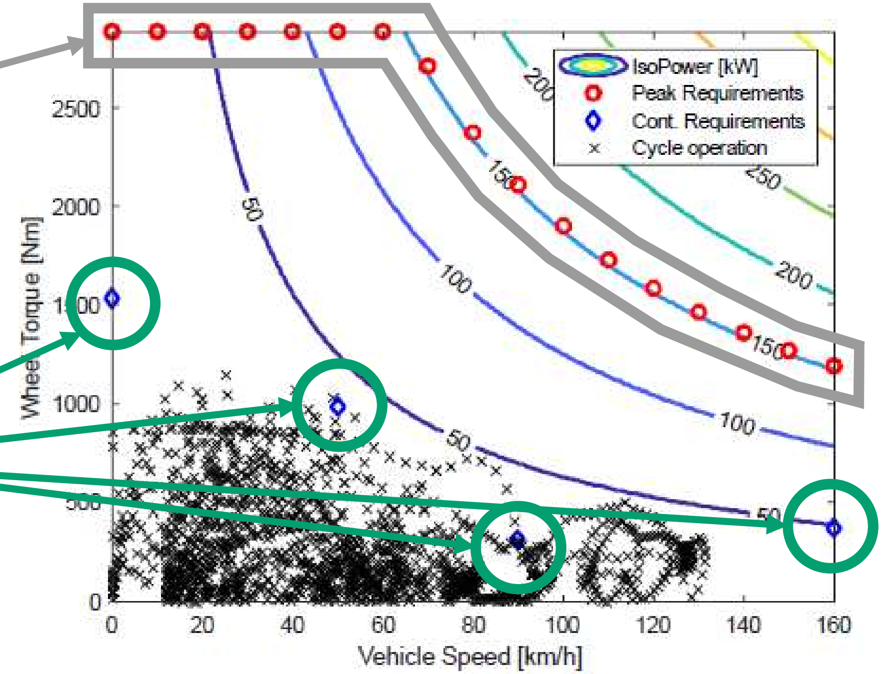
- Peak and continuous wheel torque envelopes

Peak acceleration requirements

Speed initial	Speed final	Target Time
0	100	8
80	120	6

Continuous driving requirements

Speed	Slope
90	1
50	5
0	15
160	2



Additional points can be added manually if needed

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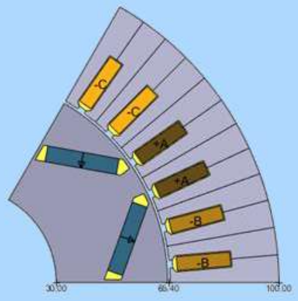
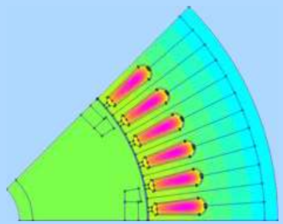
EM modelling & Scaling

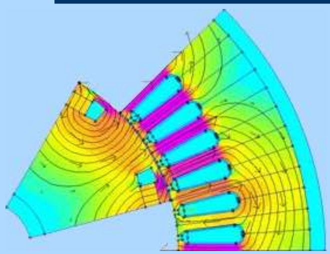
Electrical Machine Database generation



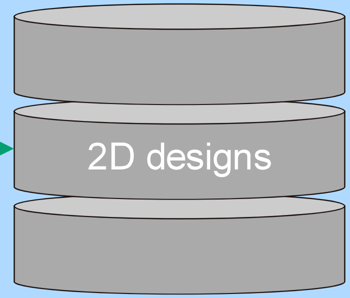
Fully parametrized EM geometry – but only selected parameters are varied

EM Thermal → **EM Electromag** → **Post processing**





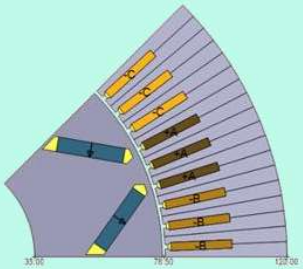
Open-source FE software – interfaced with Matlab



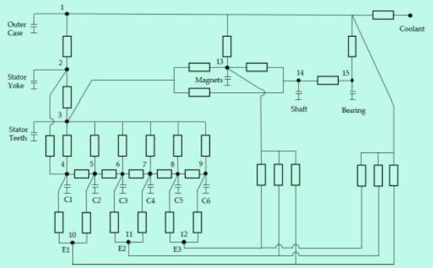
Electrical Machine Scaling

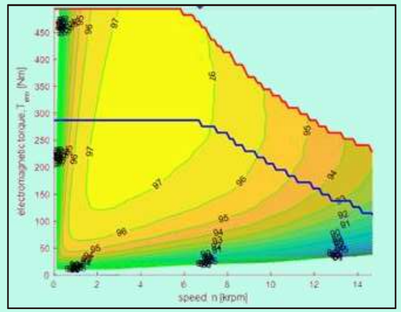
- Phase current
- Length
- Number of turns
- Vdc

2D geom. from database



Auto-generated thermal network





For details on EM Scaling:Domingues-Olavarria, Gabriel, Francisco J. Marquez-Fernandez, Pontus Fyhr, Avo Reinap, Mats Andersson, and Mats Alaküla. "Optimization of electric powertrains based on scalable cost and performance models." IEEE Transactions on Industry Applications 55, no. 1 (2018)

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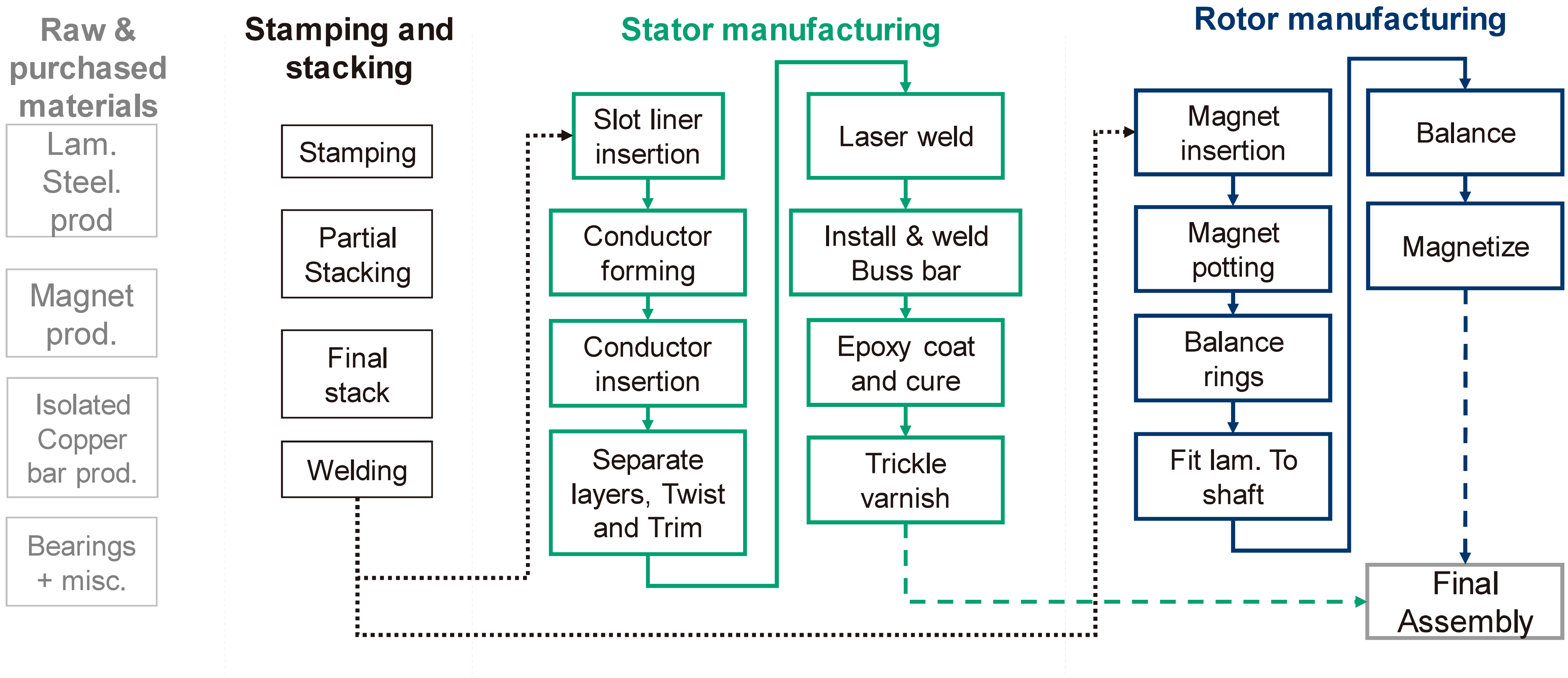
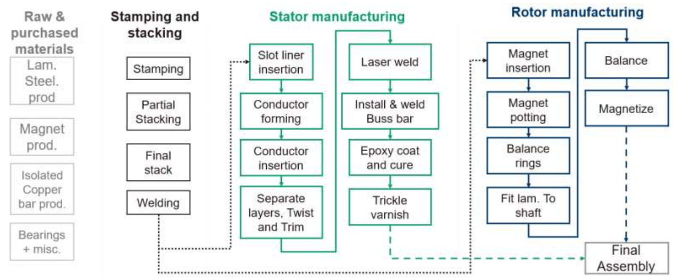
EM Engineering cost model



EM Engineering cost model

	Unit	Value	Symbol
Cycle time per operation	[s]	0	To
Material Yield	[-]	0	qm
Additional material cost	[€]	0	Δk(n+1)
Wage cost	[€/s]	0	Kd
Quality factor	[-]	0	qQ
Stand still factor	[-]	0	qS
CapEx	[€]	0	Ka
Machine Cost running	[€/s]	0	Kcp
Machine Cost standstill	[€/s]	0	Kcs



$$k(\gamma_w, n) = \frac{K_A}{n} + \sum_{u=0}^{v} k(\gamma_{w-1,u}, n)\left[\frac{1}{1-q_Q}\right] + K_{CP}\left[\frac{t_0}{1-q_Q}\right] + K_{CS}\left[\frac{t_0 q_s}{(1-q_Q)(1-q_s)}\right] + K_D\left[\frac{t_0}{(1-q_Q)(1-q_s)}\right] \quad (6.9)$$

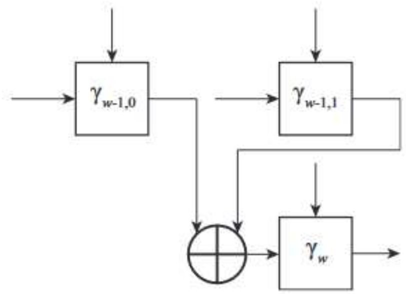


Figure 6.17: Three processes in a system, where there exists a decision between the first two $\gamma_{w-1,0}$ and $\gamma_{w-1,1}$, either of these may be used as materials in γ_w. The symbol $\oplus$ is exclusive or.

Each process is modeled as described in the table and calculates the added value of each step which then becomes an input for the next.

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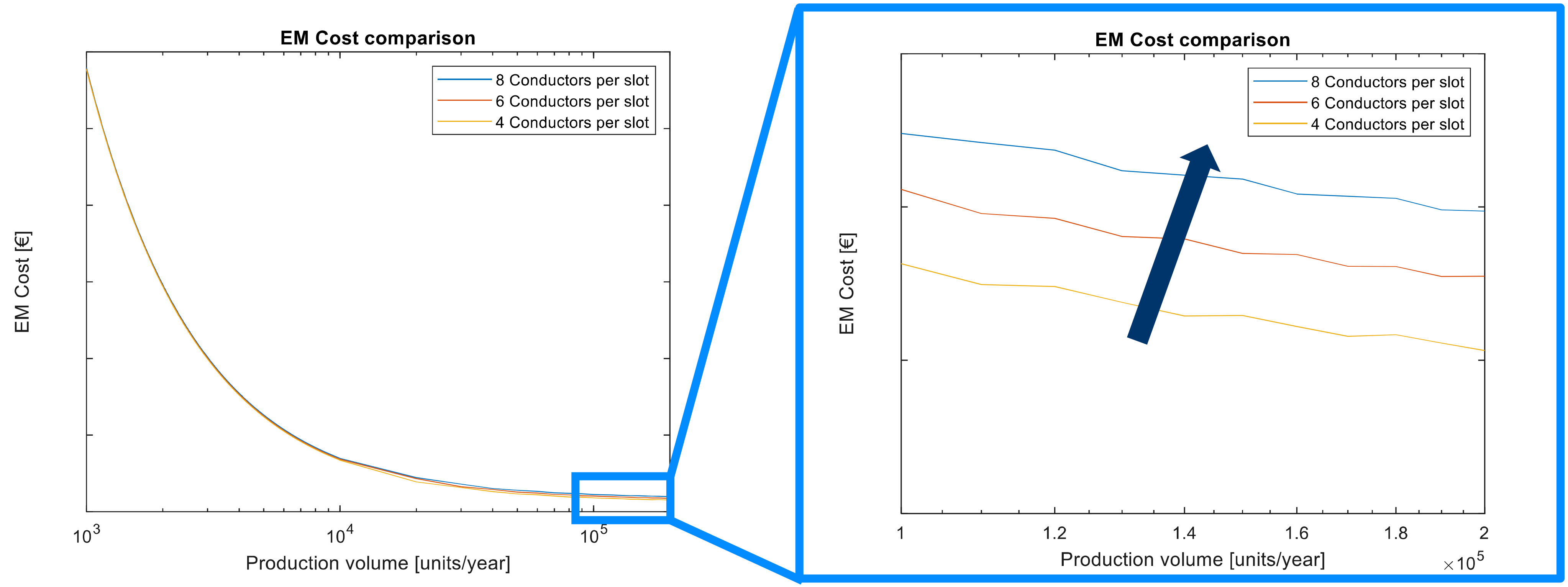
EM Engineering cost model – example



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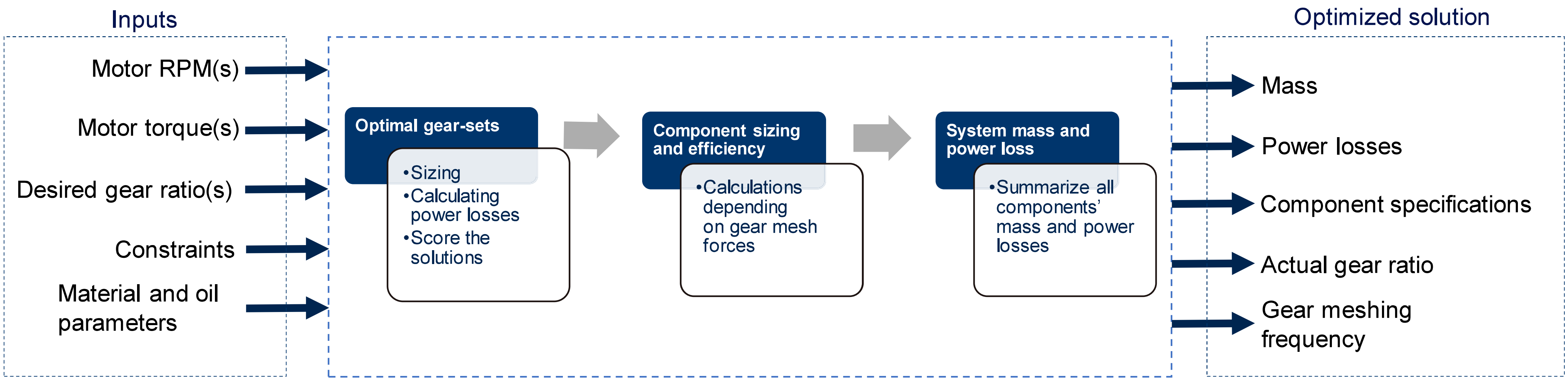
Transmission sizing model: inner most optimization loop



Transmission components are sized following AGMA standards, and the models have been validated against test data and higher fidelity simulations to ensure the validity of the results

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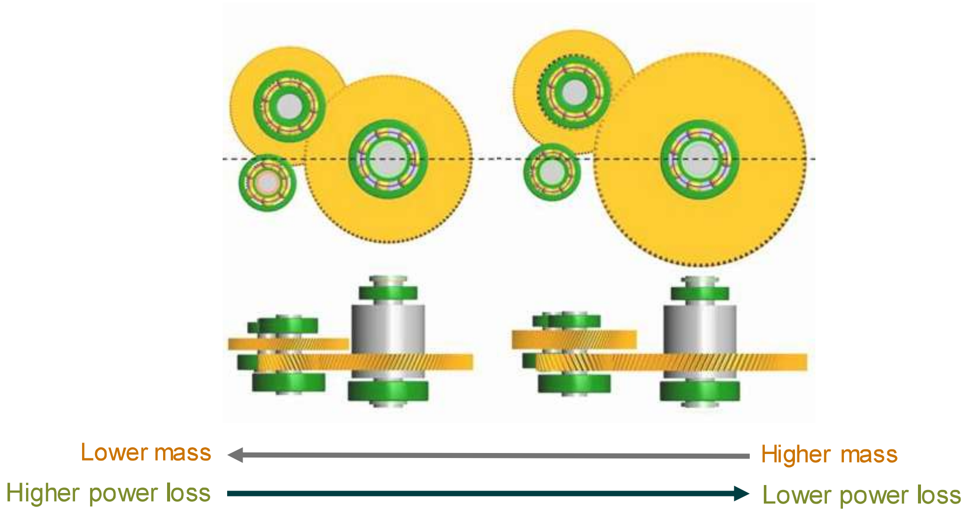
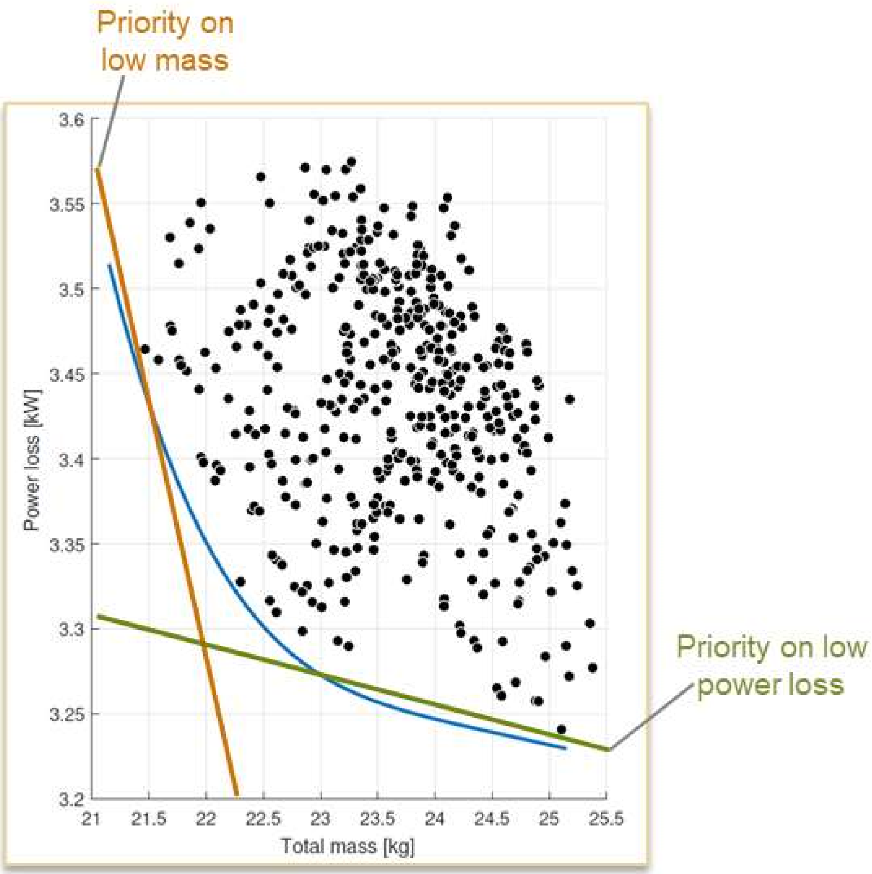
Transmission sizing model: inner most optimization loop

- Determines what is considered “optimal”





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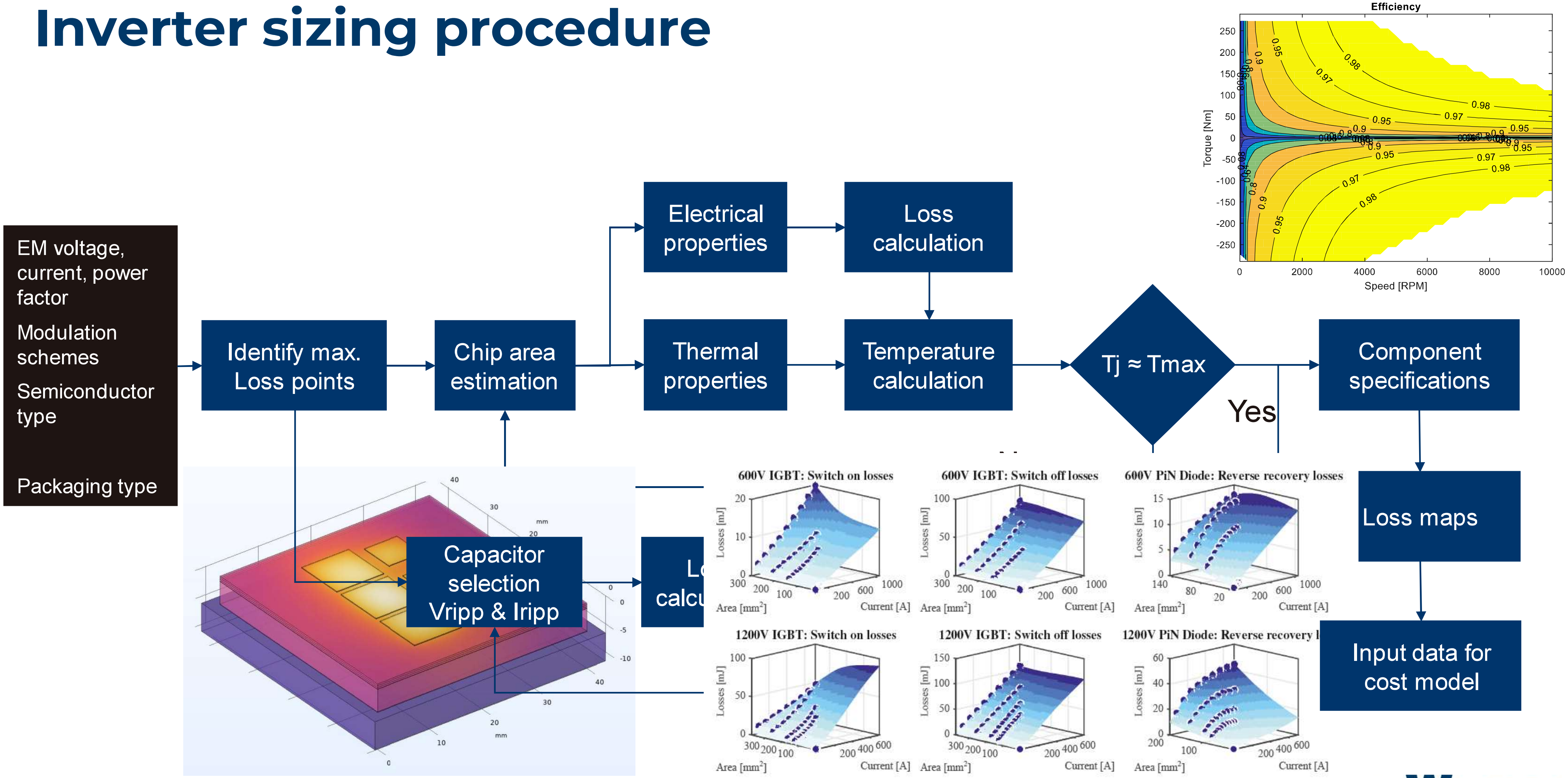
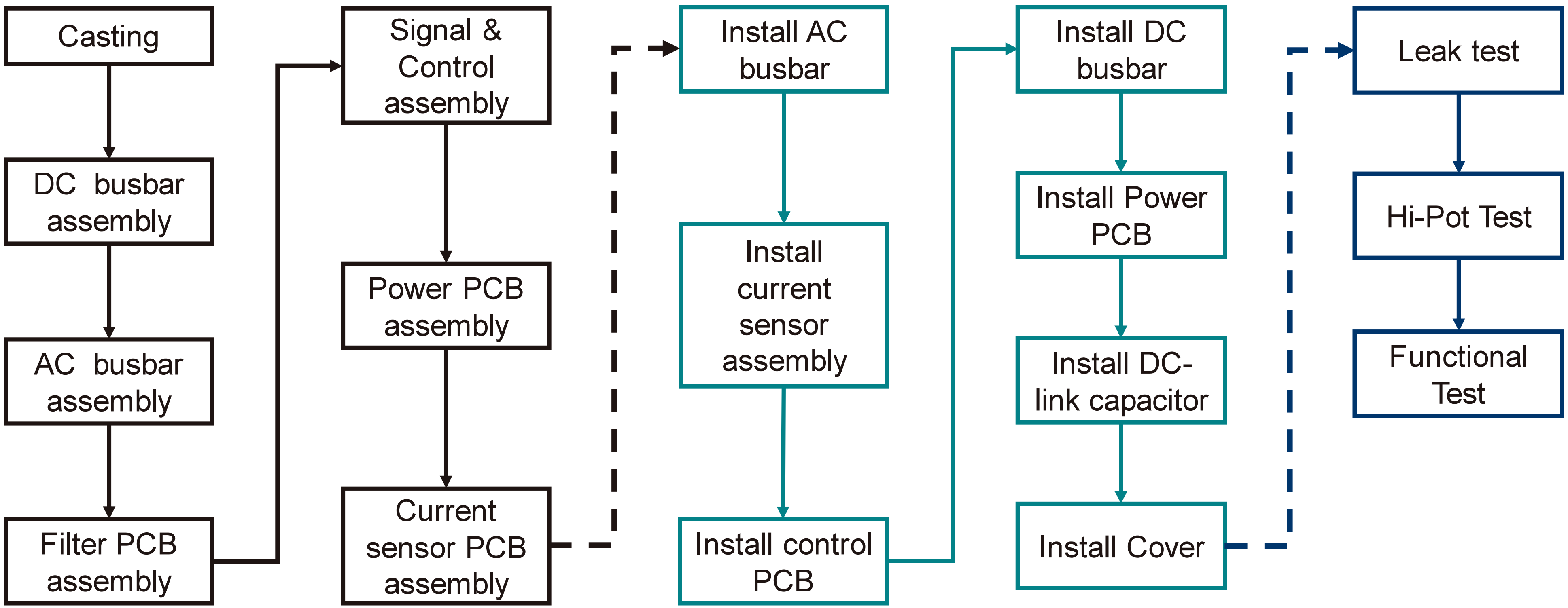
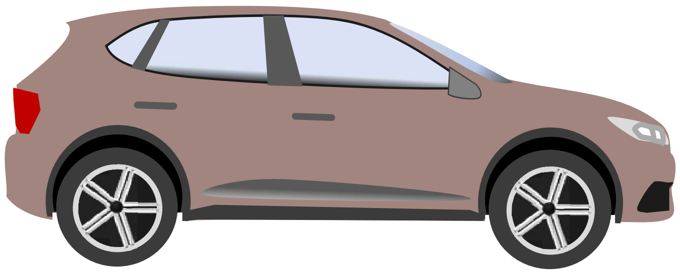
Inverter sizing procedure



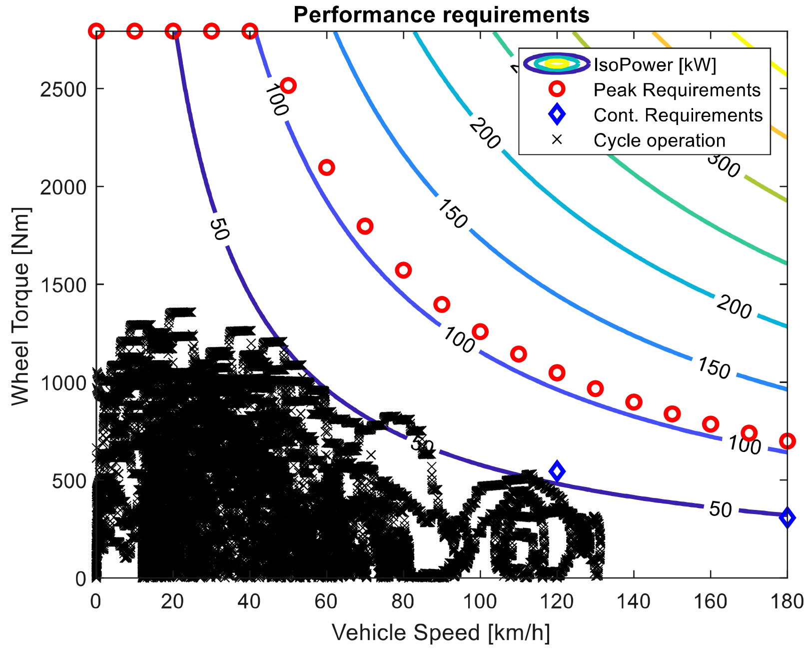
Inverter engineering cost model



Application example:

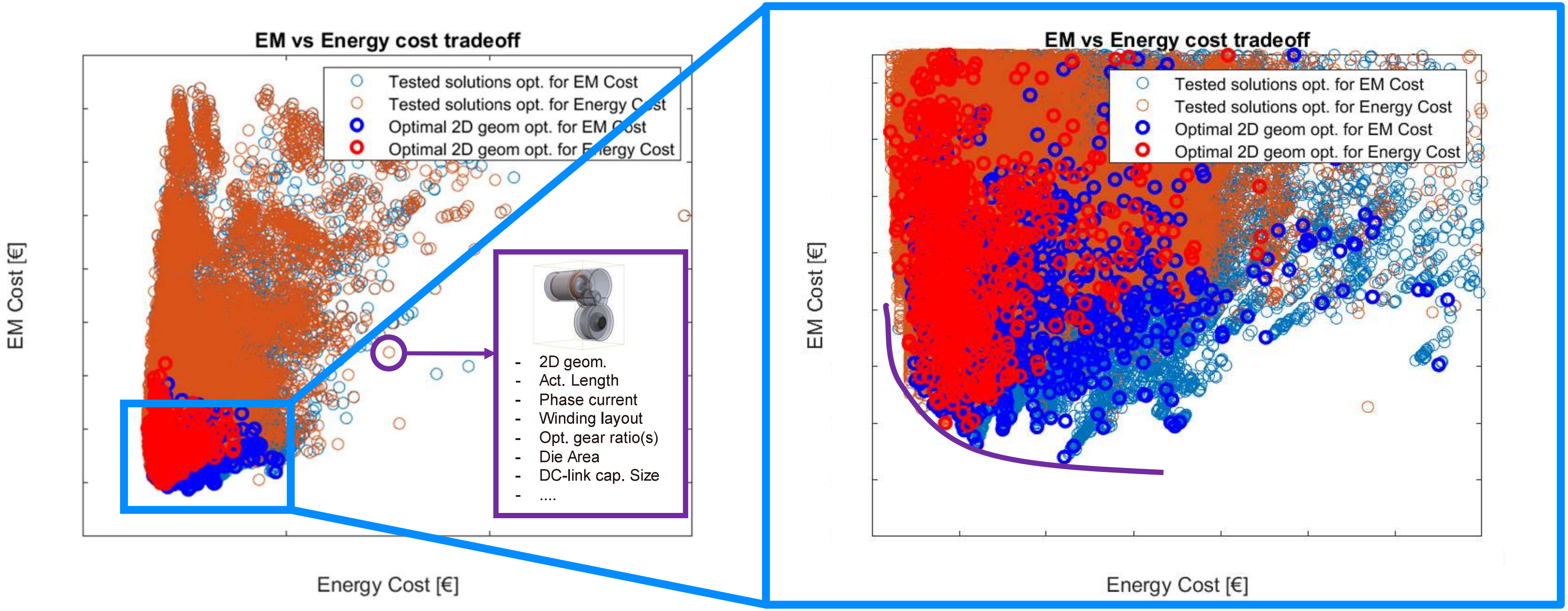


Parameter	Value
Vehicle mass	2000 [kg]
Wheel radius	0.32 [m]
Drag coef.	0.23 [-]
Roll coef.	0.009 [-]
Front. Area	2.22 [m^2]

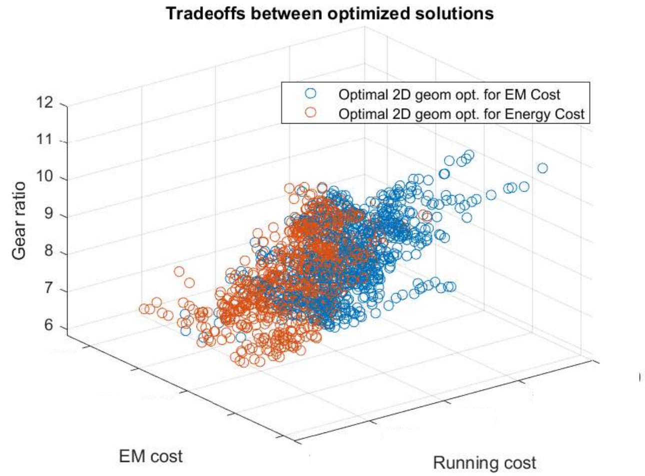


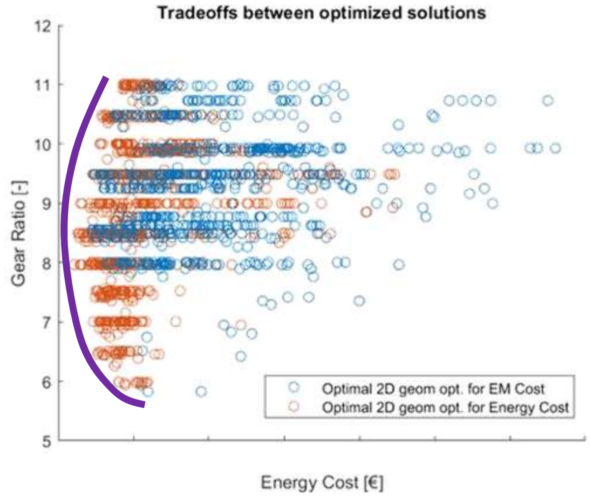
- RWD vehicle
- Initial EM database consisting of ~1000 2D geom.
- Single V-IPMSM, Oil-cooling
- Single speed transmission
- Nominal Vdc – 800V
- Two optimization objectives:
  - EM cost
  - Energy consumption
- Overloading time 60s from 60 deg. C

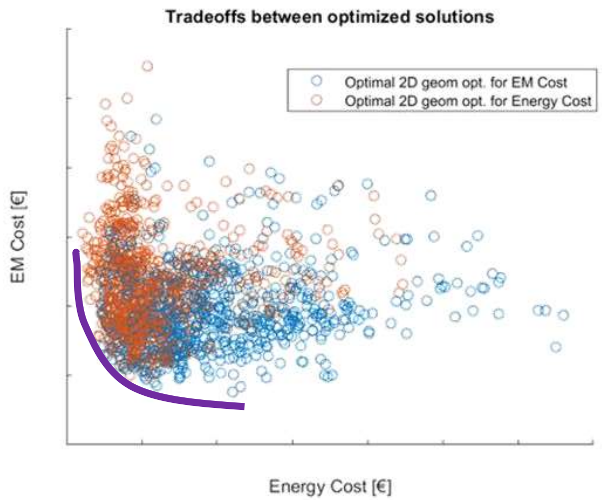
Trade-off between energy consumption and EM cost

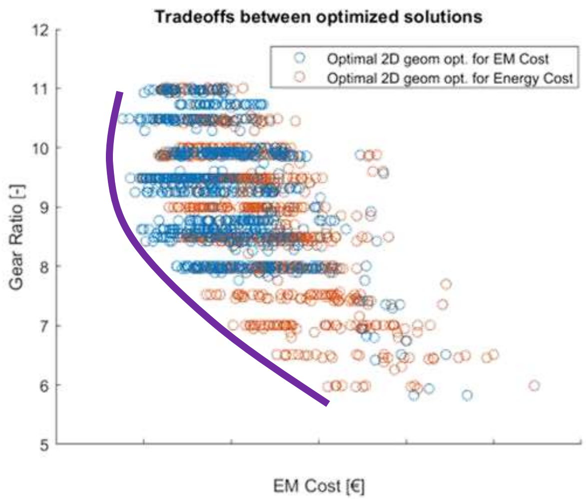


Analysis of optimal results









- Clear trade-off between optimization objectives
- For the included geometries, higher transmission ratios reduce EM cost at a slight detriment of energy cost.
- Lower ratios and larger machines operating at lower speeds improve energy consumption.

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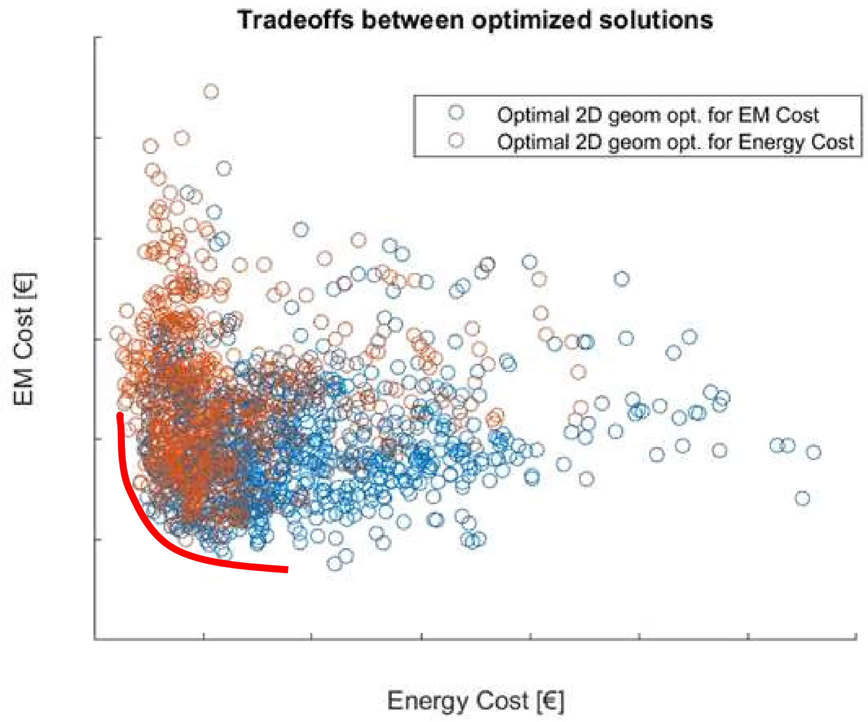
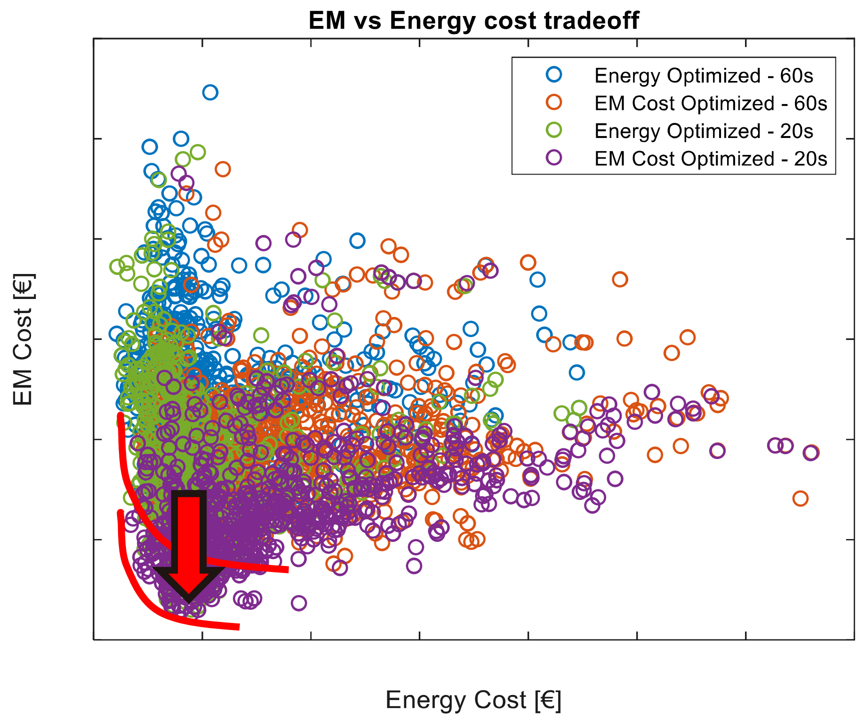
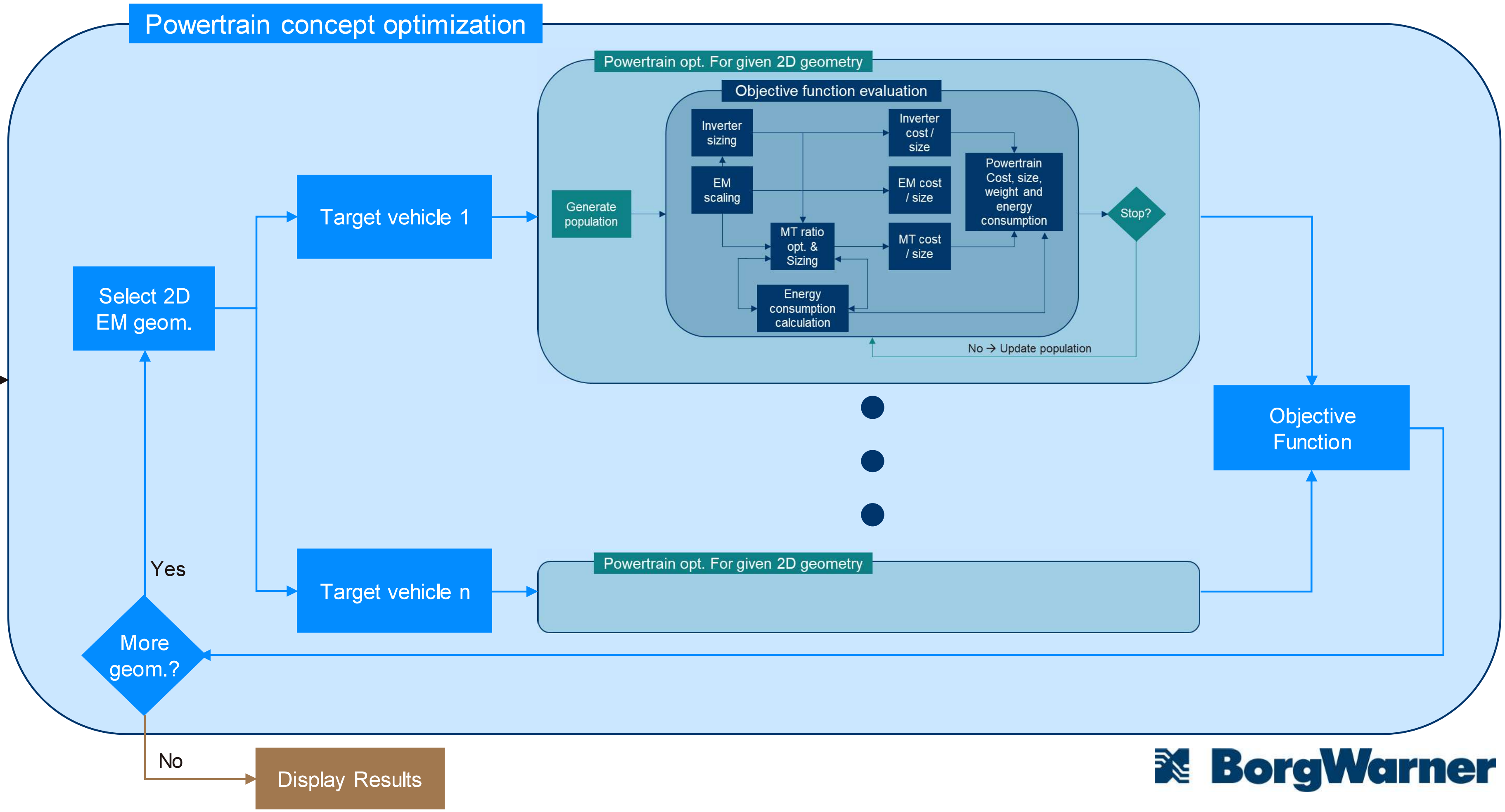
Impact of overloading requirements





Why to stop at the powertrain level? – let's optimize powertrain platforms

- Performance requirements
- Constraints
- Target vehicles
- Drive cycles
- Material definitions
- Operating conditions (Vdc, Tamb, Twind,...)



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Conclusions:

- The Concept development phase for electric powertrains can be significantly shortened and the solution space explored in a more efficient way.
  - Approach the problem from a system perspective from the beginning
  - Develop models that provide a good balance between accuracy and execution time
  - Use a mix of expert knowledge and sensitivity analysis to determine which parameters and simplifications can be made
- Detailed cost models are needed to capture tradeoffs between components accurately.
- Tradeoffs between objectives are better understood when analysed from a system perspective.
- Often, suboptimal components lead to optimal systems!

Thank you for your attention!

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