Leading Edge Power Magnetics Design

Multi-physical, Multi-dimensional Optimization with Respect to Electrical, Thermal and Commercial Objectives

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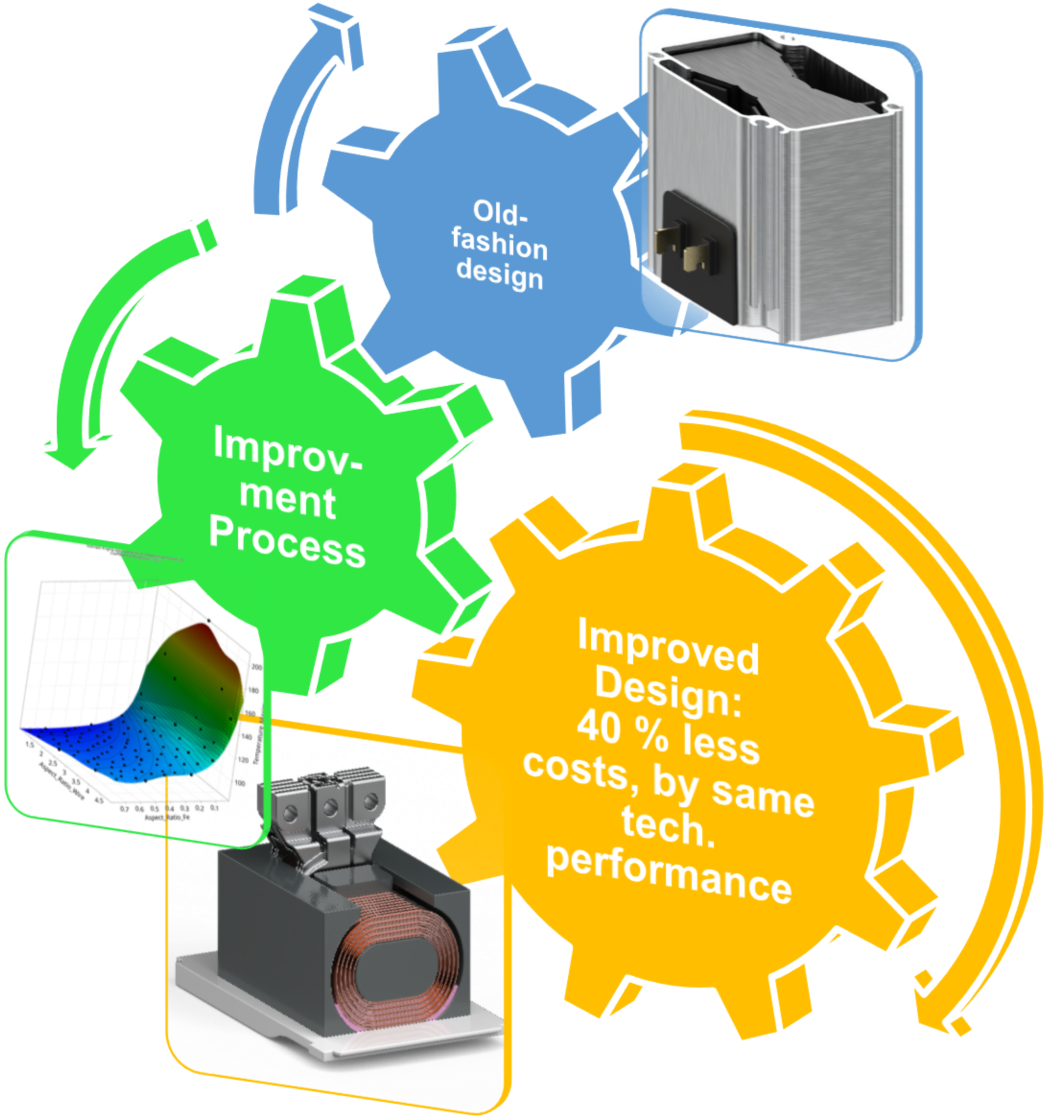
How to optimize a component that exists since the 19th century?



Improvements compared to standard designs

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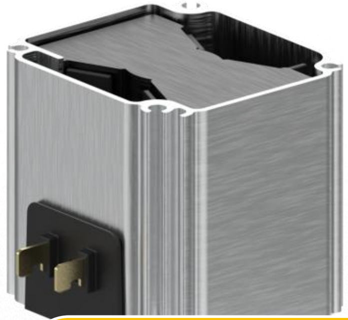
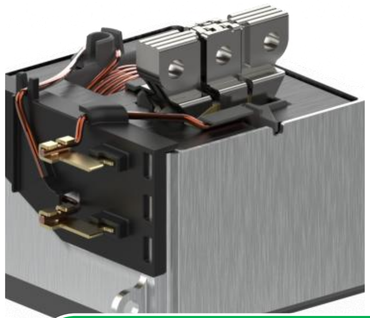
Inductive components (transformers, chokes, filters) with round windings in water-cooled applications are usually embedded and encapsulated in an aluminum housing, as is common in the automotive industry.

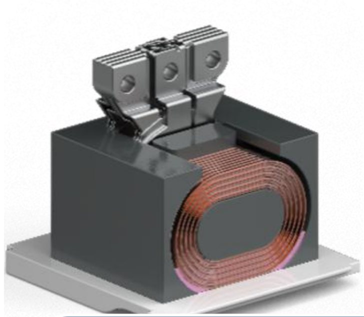
Although this ensures good heat dissipation of the component, it is cost-intensive and can also be improved in terms of thermal resistance.



Initial situation
- Classic design
- Water-cooled inductor

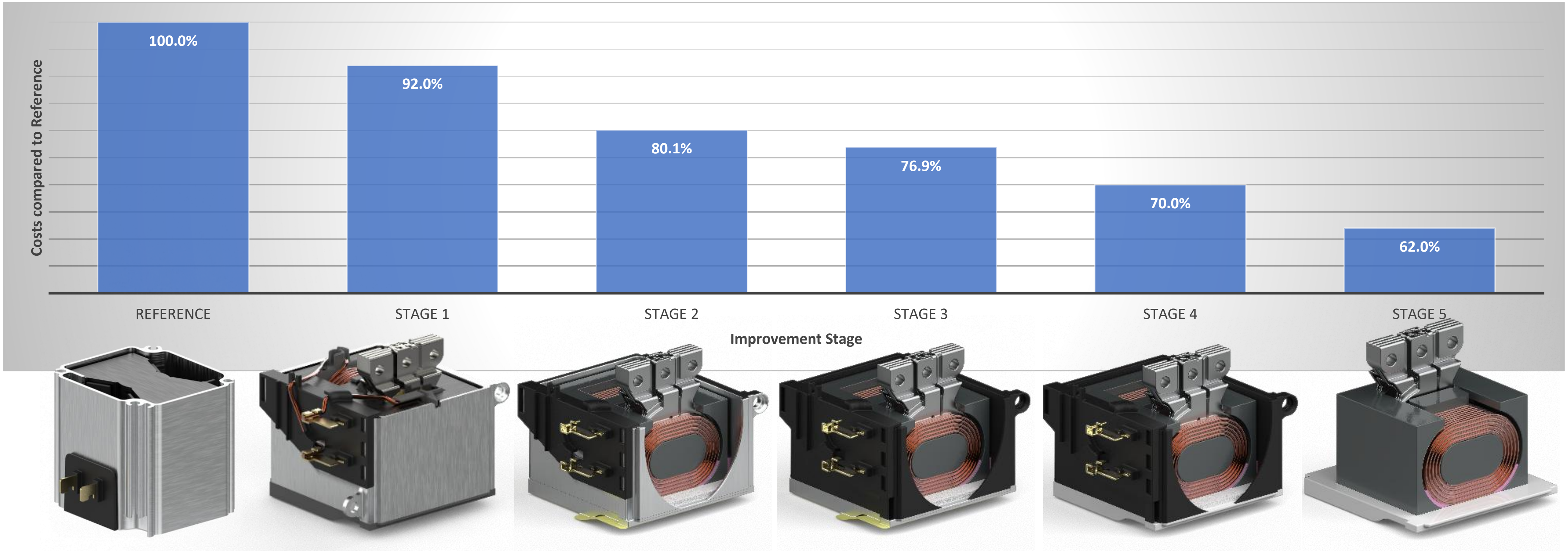


Where do the losses come from?
- Choose orientation of Component



Automated optimization process
- Shape of the core
- Cooling connection
- Insulation
- Potting material, potting quantity
- …

Multi-physical, multi-dimensional optimization with respect to electrical, thermal and commercial objectives



Reference Design	Orientation regarding the losses; Adjusting the required potting quantity	Finding the optimum winding and core geometry	Replacement of the Al housing with a plastic housing with Al cooling plate	Replace Al cooling plate with AL2O3 and omit Kapton insulation	The core can also be used as potting cup to eliminate the housing

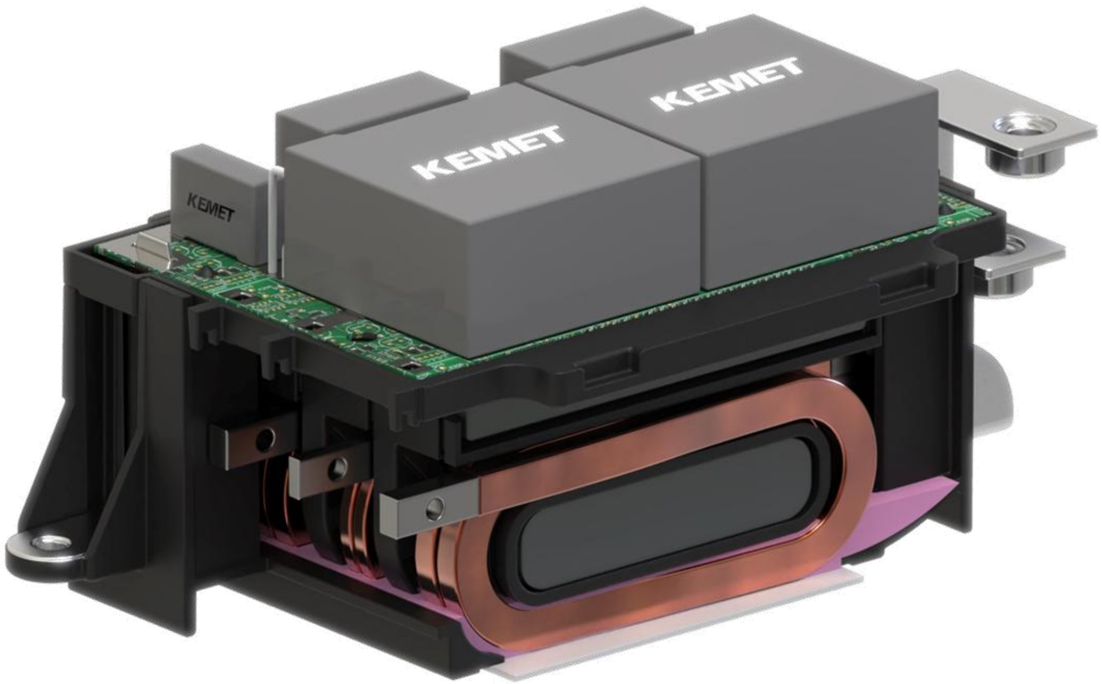
Optimal design of an inductor

Magnetic components are particularly important for power electronic circuits.

For example, the Inductive components account for 20 to 30% of the total costs of switching power supplies.

What leads us to an optimal inductance design:

- Selection of the core material and calculation of the core cross-section
- Dimensioning of the winding:
    - Calculation of the number of turns
    - Selection of the winding type (round wire, flat wire, litz wire or foil)
- Calculation of winding and core losses
- **Finding the optimum geometry considering the cooling method**



Causes for Core-losses

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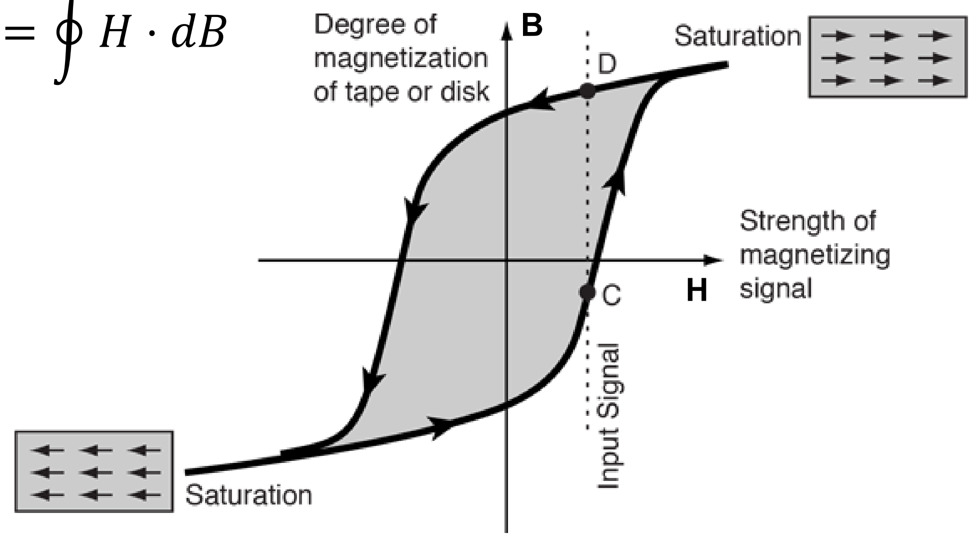
	Iron	Amorphous / nanocrystalline metals	Powder cores	Ferrite cores (MnZn, NiZn)
max. induction	1…2 T	0.5…1.5 T	1 T	0.1…0.3 T
Core loss	High	Very low	Low	Low
Core shape	Conventional M or EI cuts for 50 Hz chokes; ring or cut cores for transformers in the medium frequency range, chokes also at higher frequencies if ripple is low	only as ring or cut cores	Practically rarely used as a transformer; Mostly ring cores; customer-specific shapes possible	Many shapes; as RF chokes and smoothing inductors as well as coupled coils (with air gap) up to the MHz range; Many shapes; also, customer-specific
Max. Temperature	200 °C	100 °C	125…150 °C	125…150°C
Costs	Inexpensive	expensive	Relatively expensive	Relatively inexpensive

Causes for Core-losses

- Magnetic hysteresis
- Eddy currents
- Additional losses at higher frequencies due to phase shift between H and B ($\underline{\mu}$)

$$w_{Fe} = \oint H \cdot dB$$



Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/hyst.html

Steinmetz's equation for sinusoidal flux:

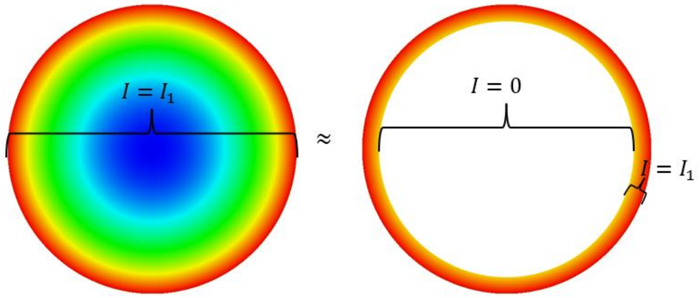
$$P_{Fe} = k_p \cdot f^{\alpha} \cdot B^{\beta} \cdot V$$

Material-dependent parameters

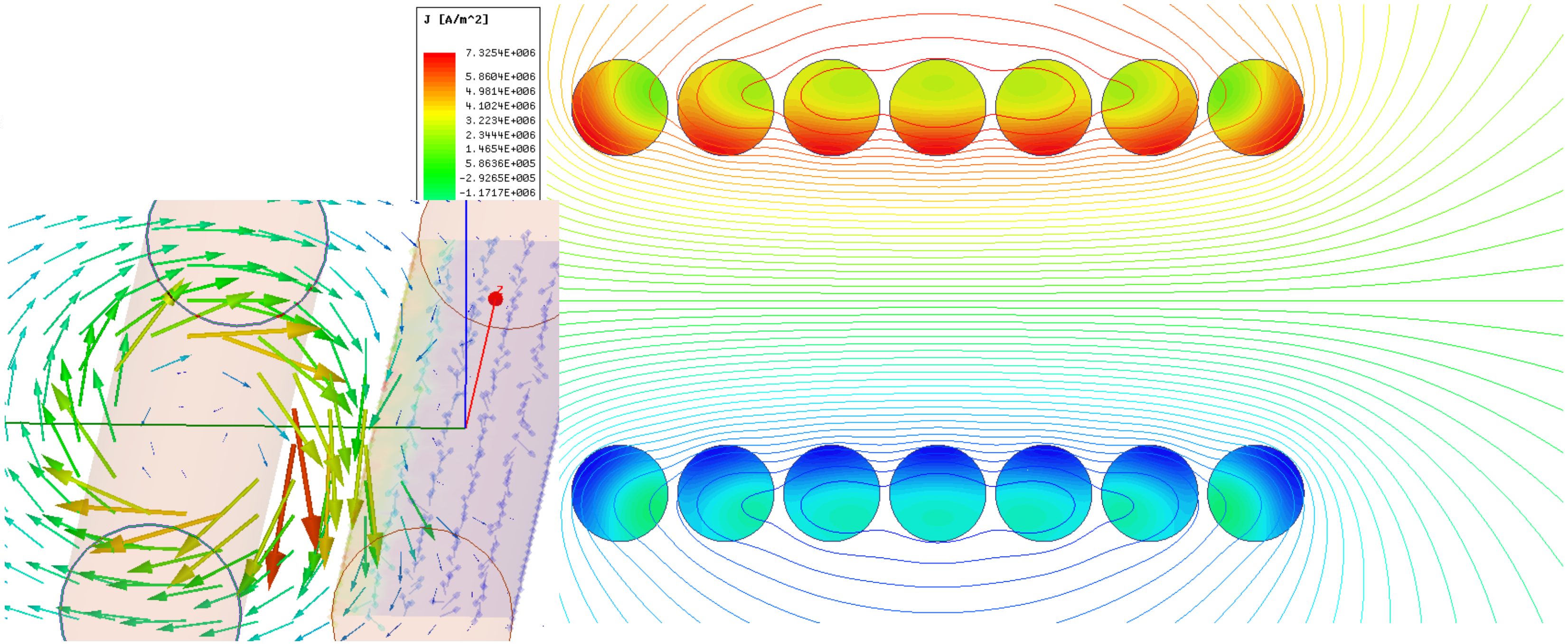
Causes for Winding-losses

- DC-losses
- Eddy current-losses: $$U_e = \oint_C \boldsymbol{E} \cdot d\boldsymbol{r} = -\frac{d\phi}{dt} = -\frac{d}{dt}\int_A \boldsymbol{B} \cdot d\boldsymbol{A}$$

Skin-effect



Proximity-effect



Eddy Current

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Skin-effect

Eddy currents are induced inside the conductor; They surround the field lines in a ring and overlap with the conductor current

Penetration-depth:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Current-density (for round conductors):

$$\boldsymbol{J_r} = \frac{k\boldsymbol{I}}{2\pi R} \cdot \frac{J_0(kr)}{J_1(kr)}$$

Proximity-effect

A conductor is penetrated by the magnetic field of another conductor. Eddy currents are induced to a greater extent, which concentrate the current paths even more than is already the case due to the skin effect. The conductor resistance increases further.

$$F_R = \frac{R_w}{R_{dc}} = X \cdot \frac{\sinh(2X) + \sin(2X)}{\cosh(2X) - \cos(2X)} + \frac{m^2 - 1}{3} \cdot 2X \cdot \frac{\sinh(X) - \sin(X)}{\cosh(X) + \cos(X)}$$

Optimization scenario

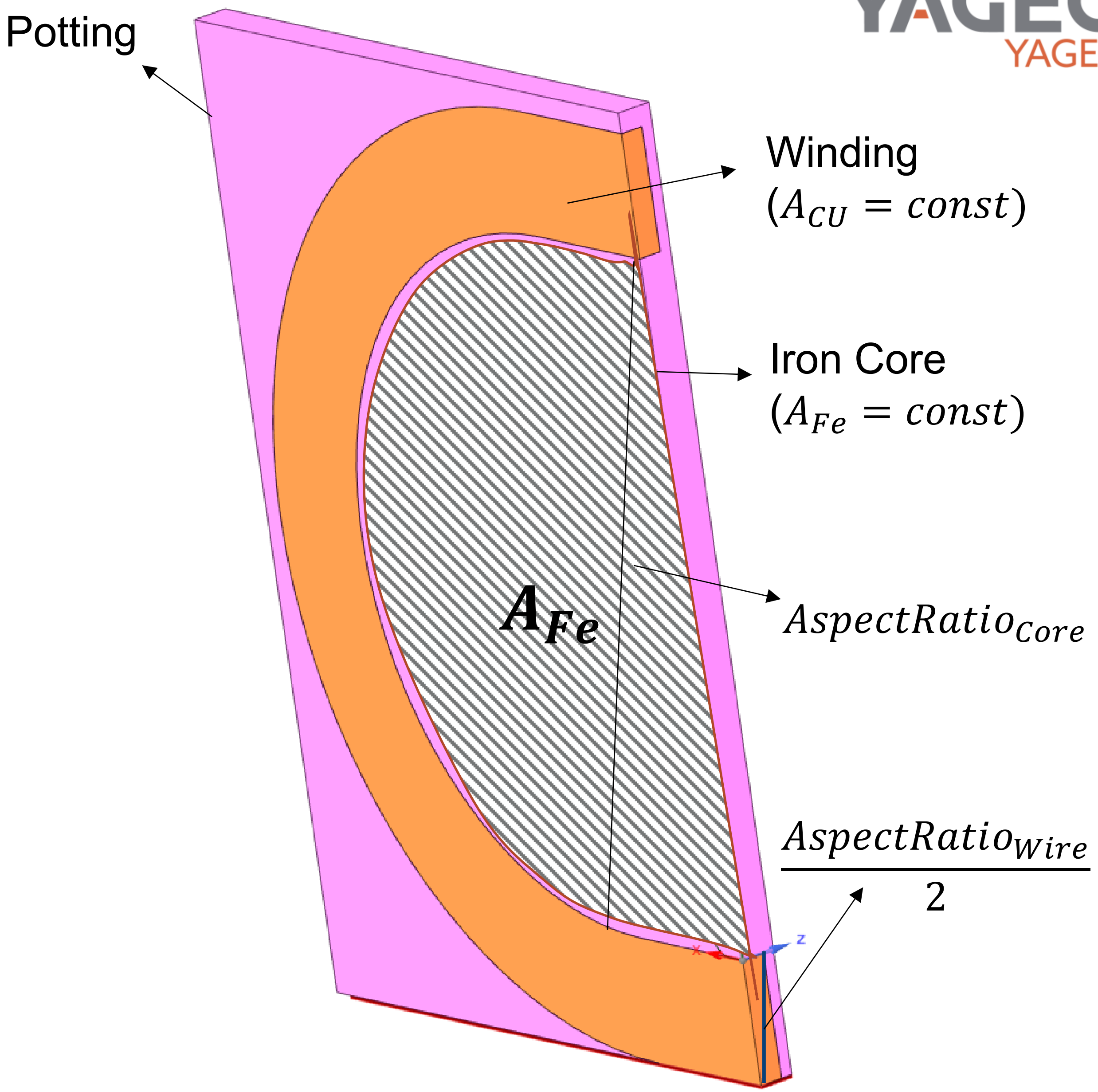
An inductor wound with flat wire is shown here as an example. This example is intended to show how the core and winding geometry can be optimized, both commercially and technically.

In principle, the result applies to all winding types (round wire and stranded wire) with minor adaptations

The idea is not to make a circular winding, but a stadium-shaped one. This means more copper length and therefore higher winding resistance but a better thermal connection for cooling.

The following assumptions are made for simplification purposes:

- The inductance should be constant and thus the iron cross-section (A_{Fe})
- The current density J should be constant



Boundary conditions and excitations

The copper losses change with the copper temperature. Therefore, the final temperature must be calculated in iterations in the FEM simulation.

Heat equation:

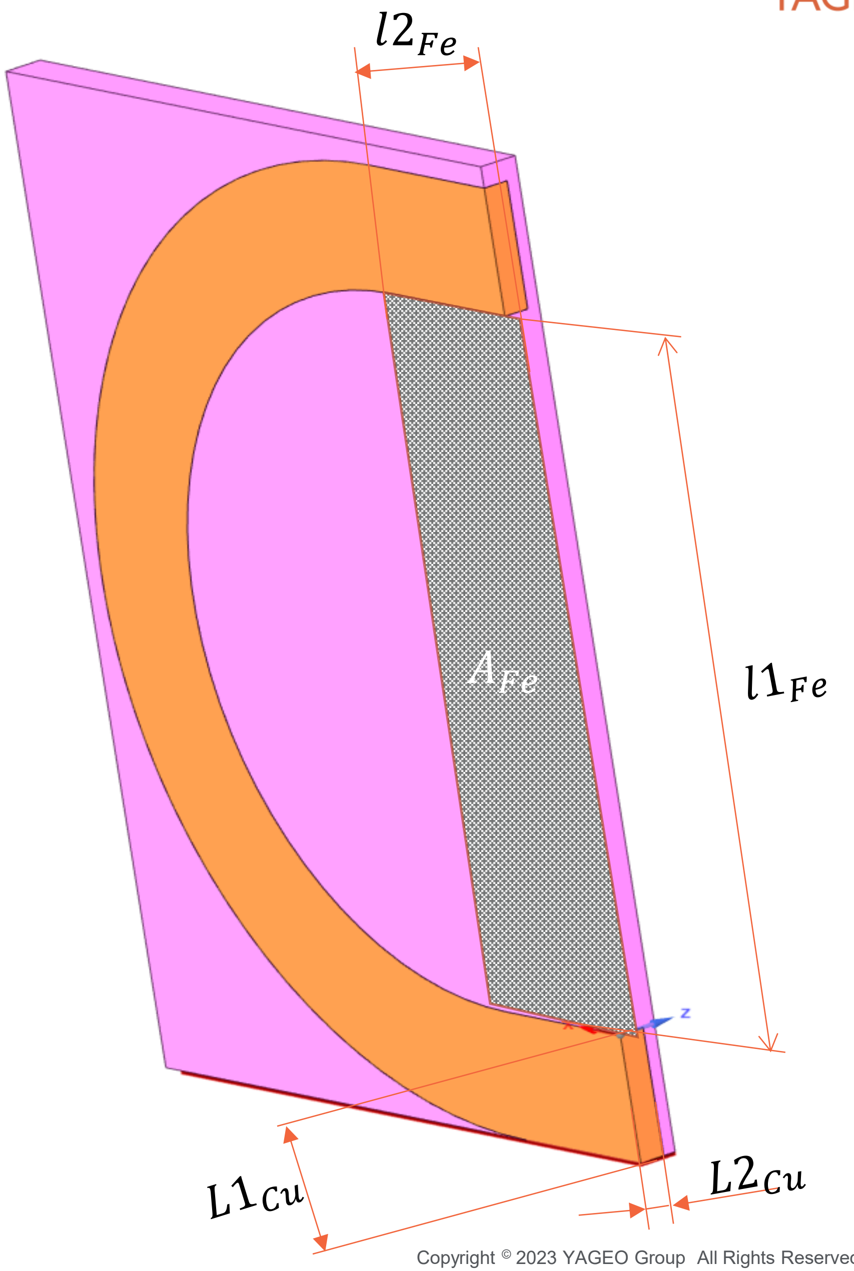
$$\rho c \dot{T} = k \cdot div\ grad\ T + \dot{Q}_v'''$$

$$\underbrace{\rho \cdot c \cdot \frac{\partial T}{\partial t}}_{\text{0 for static}} = k \cdot \frac{\partial^2 T}{\partial x^2} + k \cdot \frac{\partial^2 T}{\partial y^2} + k \cdot \frac{\partial^2 T}{\partial z^2} + \underbrace{I^2 \cdot R(T_0) \cdot e^{\int_{T_0}^{T} k \cdot dT}}_{\dot{Q}_v'''}$$

The problem with the equation is that the solution to the equation (the temperature) occurs as a derivative of it.

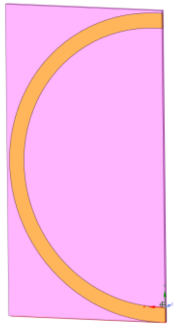
In addition, depending on the material, the thermal conductivity k is also a function of temperature.

→ **We don't want to solve this manually**

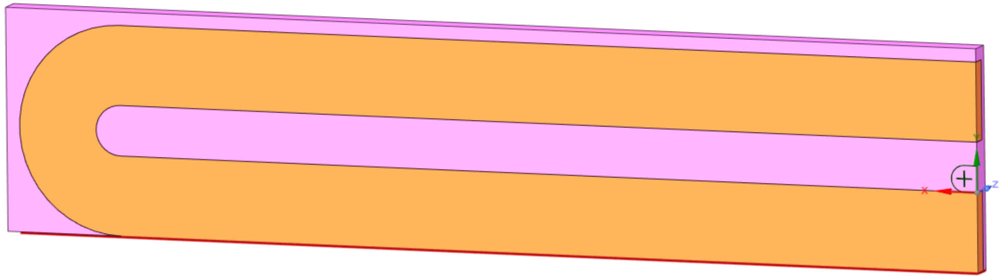


Aspect Ratios

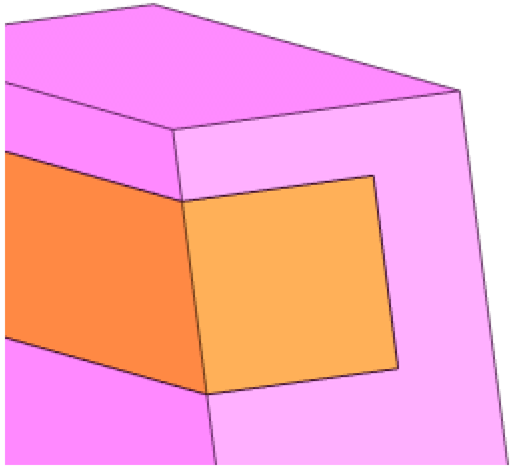
$\lim_{A_{Rc} \to 0}$



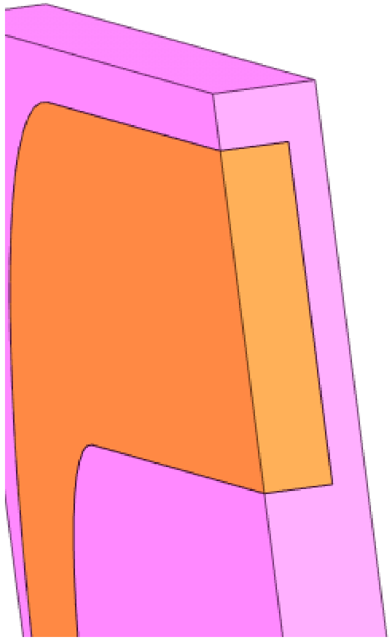
$\lim_{A_{Rc} \to \infty}$



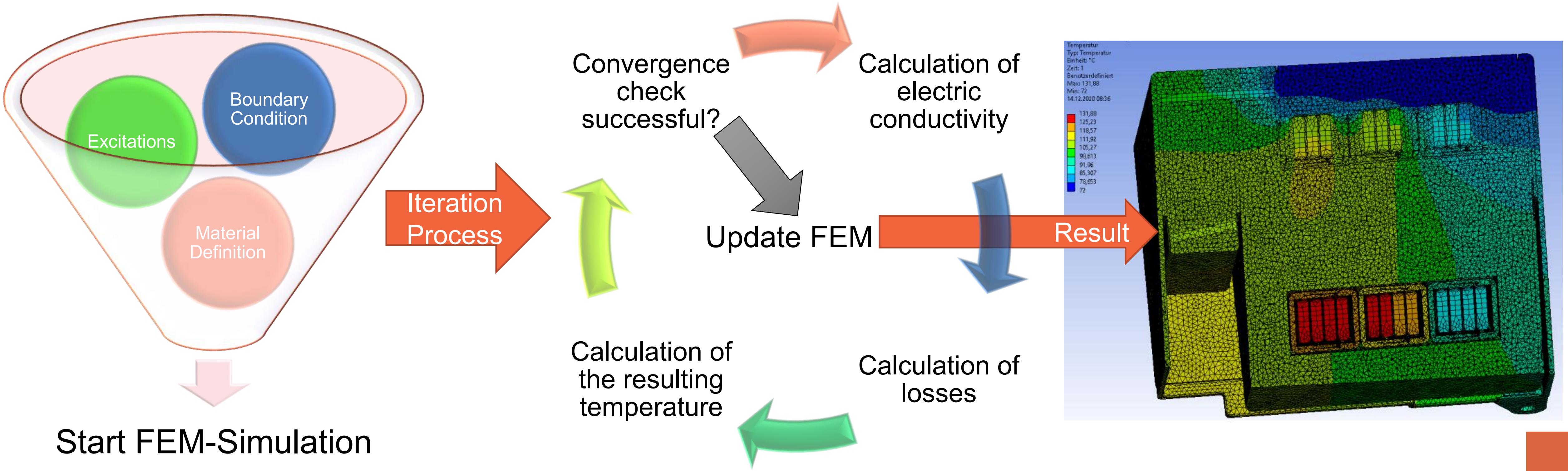
$A_{CU} = 1$



$A_{CU} = 5$



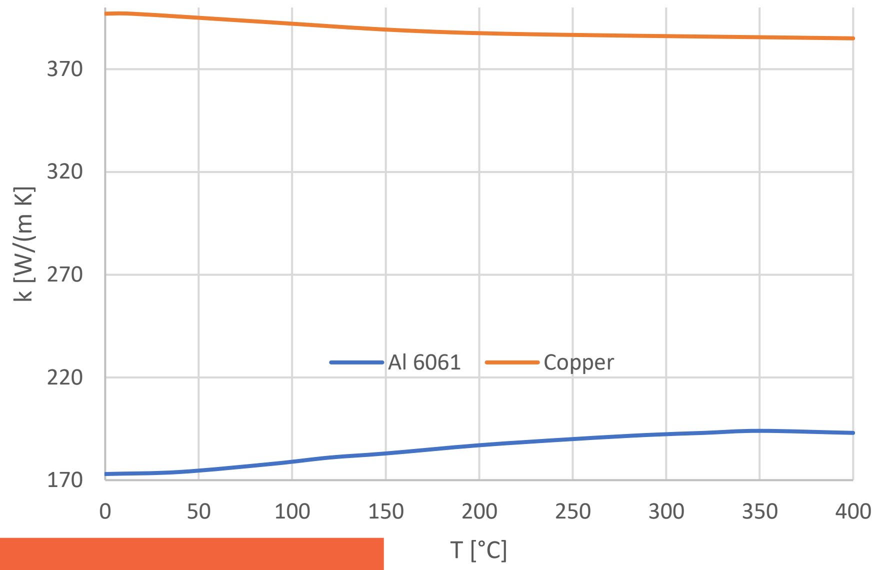
Simulation Process



Materials

Reference Design				
Application	Material	$k\left[\frac{W}{m \cdot K}\right]$	Usage [% of total]	Price/kg [%]
Wire	Copper	380	100	100
Housing	Aluminum	200		
Insulation	PI-Tape	0.3		
Potting	Polyurethane	0.5		

BOM Costs (incl. Capacitors, PCB, …): 100%



Optimized Design					
Application	Material	$k\left[\frac{W}{m \cdot K}\right]$	**Material Costs [% Compared to Reference]**	**Usage [% Compared to Reference]**	Costs [% of total]
Wire	Copper	380	100	50	50
Housing	Polyamide	0.25	30	100	30
Baseplate	Al2O3	24	30	100	30
Potting	Silicone filled	4	400	25	100

BOM Costs (incl. Capacitors, PCB, …): 60 %

Sensitivity Study

To describe the effects of the input variables on the output variables, a sensitivity study was carried out.

The input variables are:

- Aspect ratio of the wire
- Aspect ratio of the core
- Potting material
- Potting height
- Production-related distance between winding and cooling plate

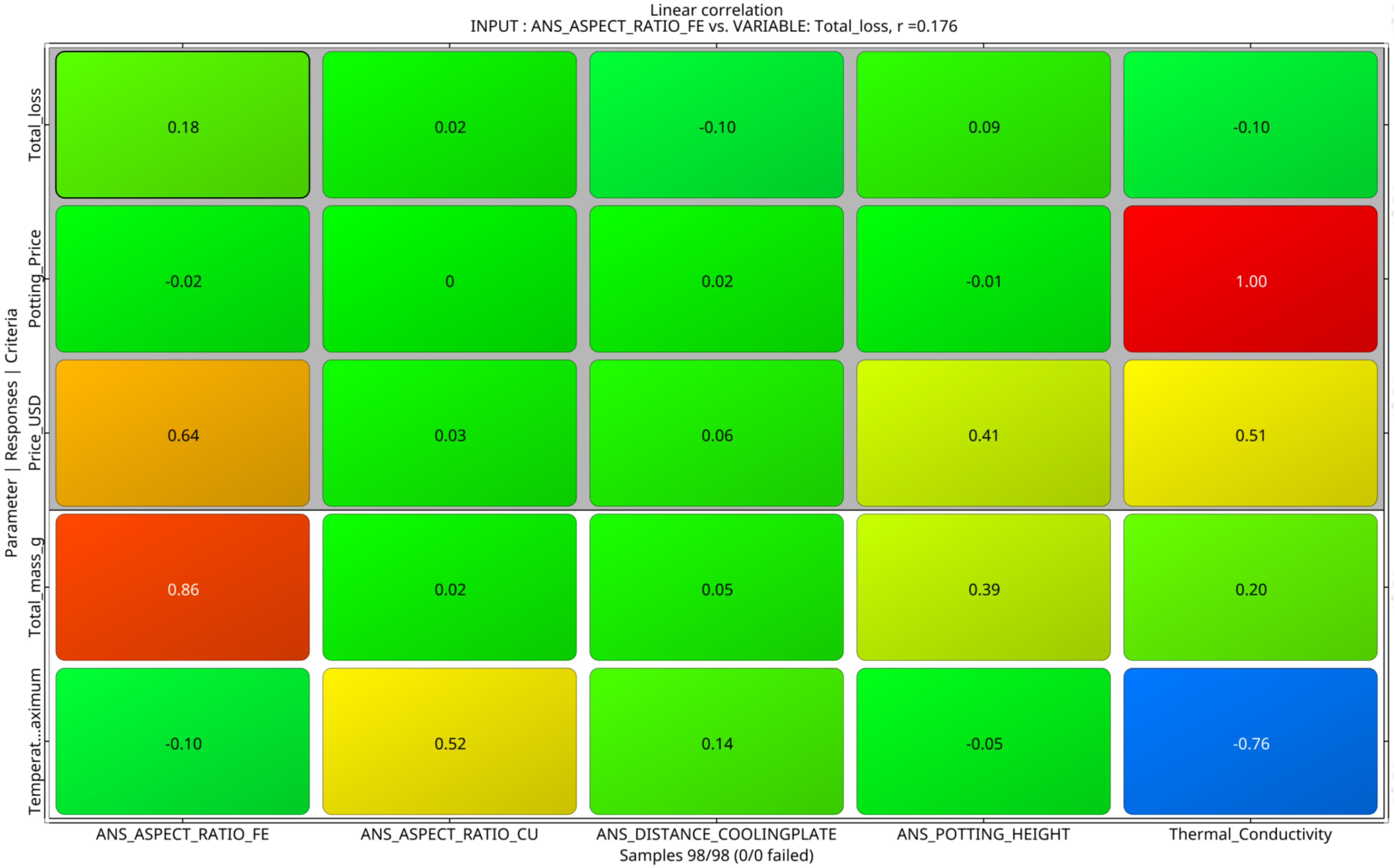
The output variables are:

- Maximum occurring temperature
- Mean value of the temperature
- Total mass
- Total price (consisting of copper, cooling plate and potting compound)
- Total losses (calculated from the voltage drop, considering the change in resistance due to a change in temperature, and constant current)

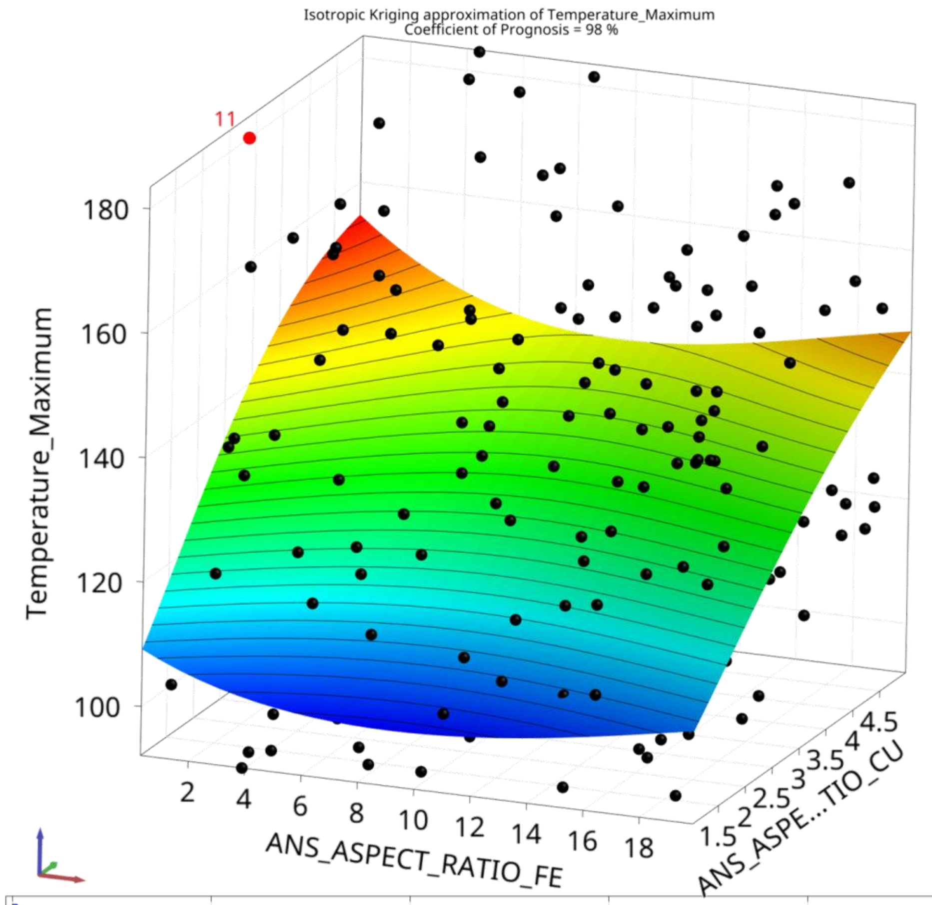
In order to obtain randomly distributed samples in this multidimensional distribution, Latin-hypercube- sampling (LHS) was used as sampling method.

Sensitivity Study - Correlations

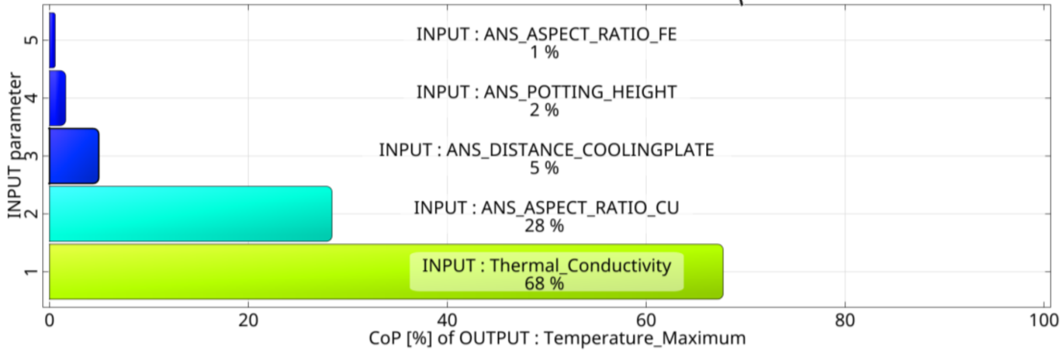
The correlation matrix shows how an input parameter affects an output value.



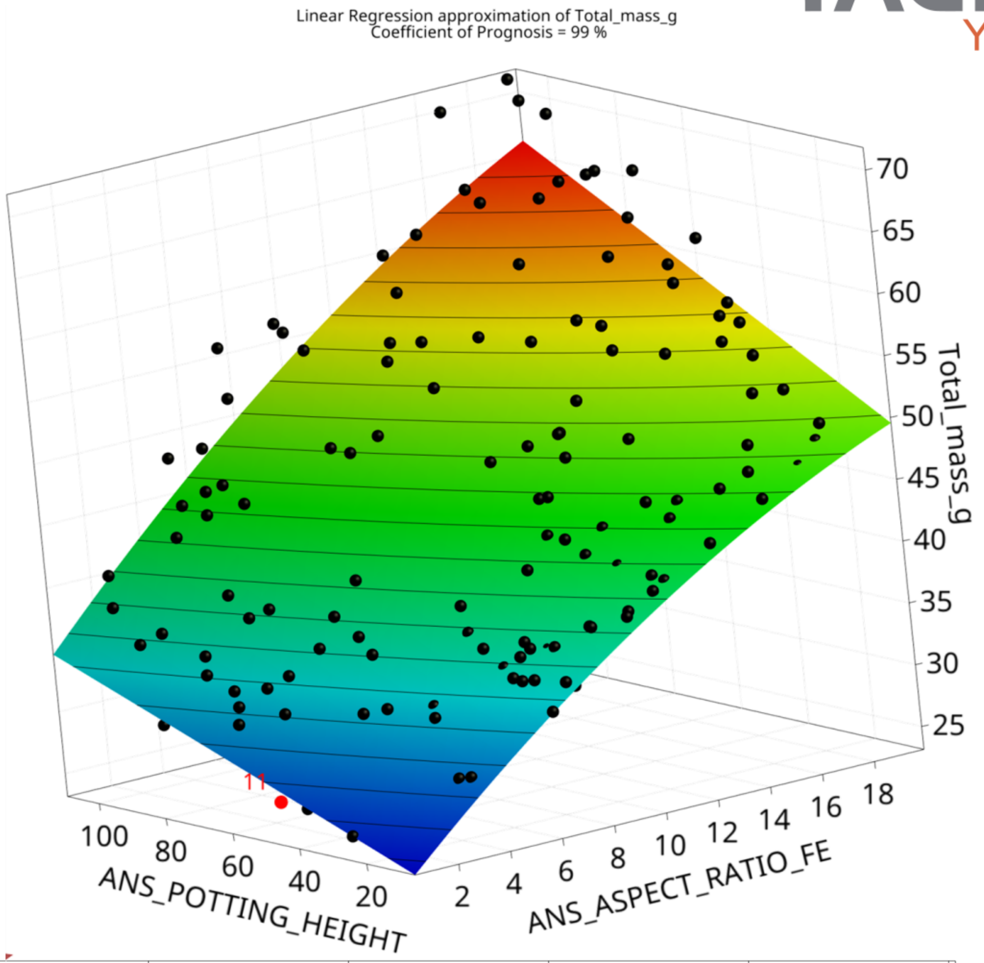
Sensitivity Study

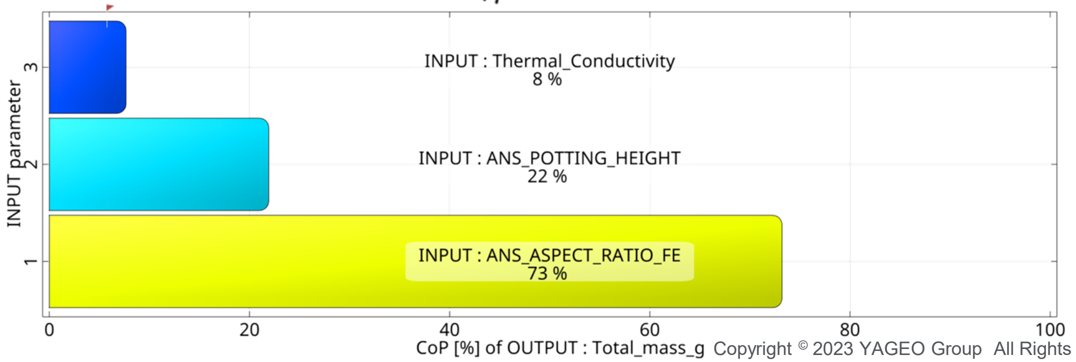


T_{max}(Asprect Ratio Fe, Aspect Ratio Cu)



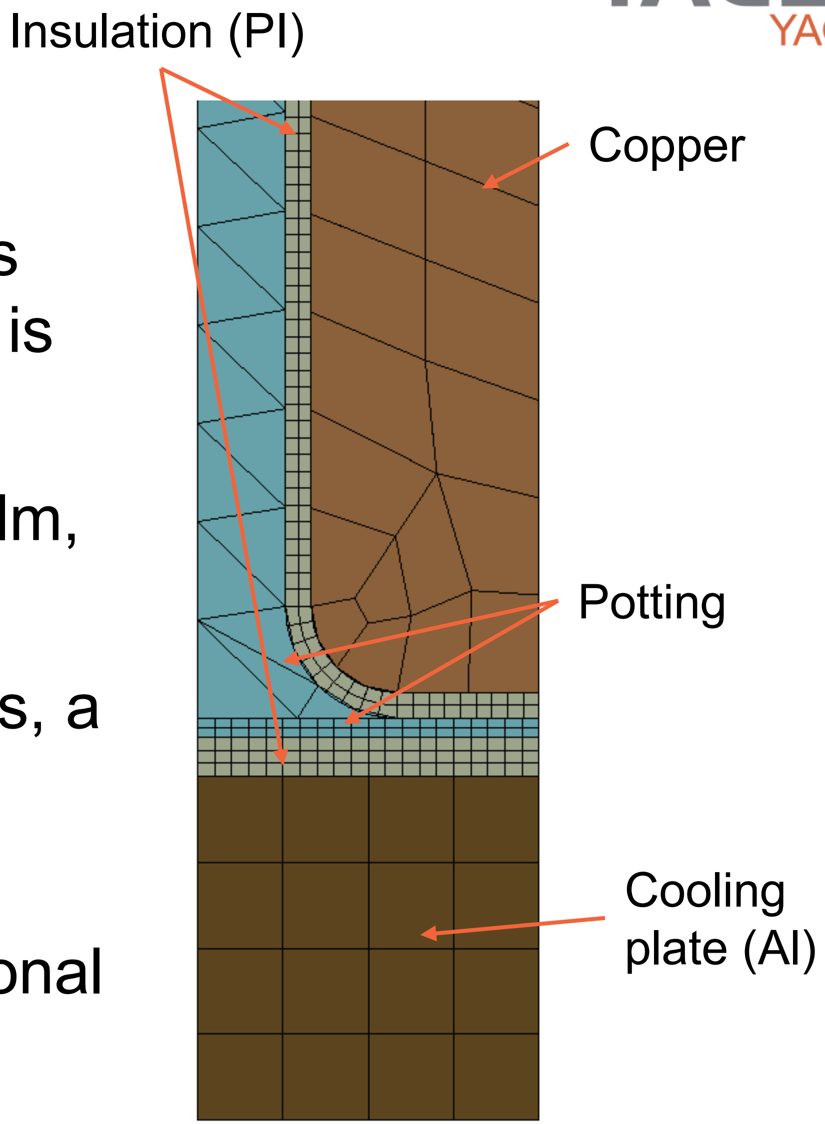
Total Mass (Asprect Ratio Fe, Potting Volum)



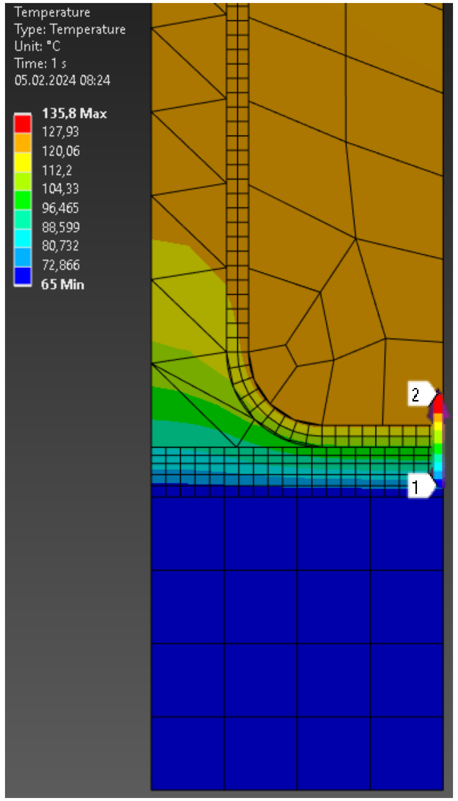


Insulation

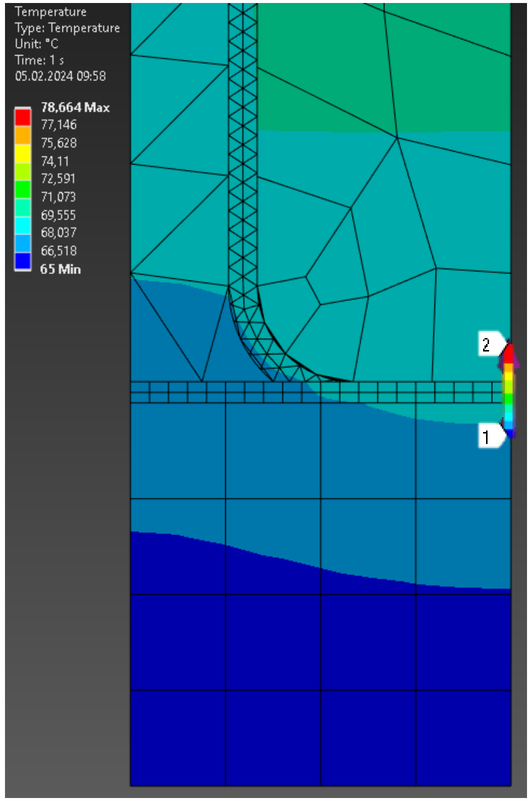
- Depending on the insulation class (functional insulation, basic insulation, etc.), conductive parts must be insulated. In this case, the cold plate if it is made of aluminum.
- Reinforced insulation with 3 layers of polyimide film, each 0.076 mm thick, was assumed here.
- Due to the poor thermal conductivity of polyimides, a large temperature gradient is formed here.
- As a remedy, the cooling plate can be made of electrically insulating aluminum oxide. The additional insulation can then be omitted, but the thermal conductivity is only a tenth of that of aluminum.



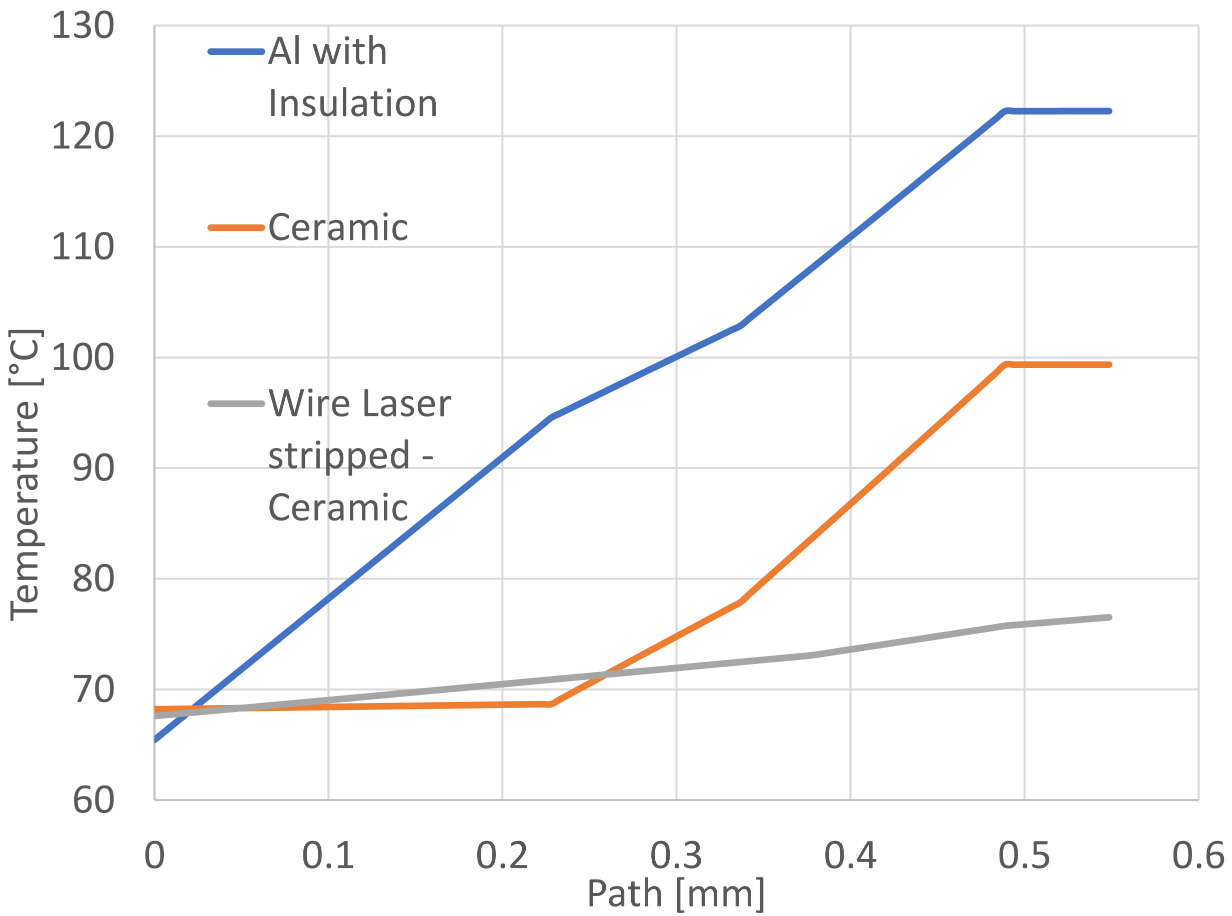
Insulation



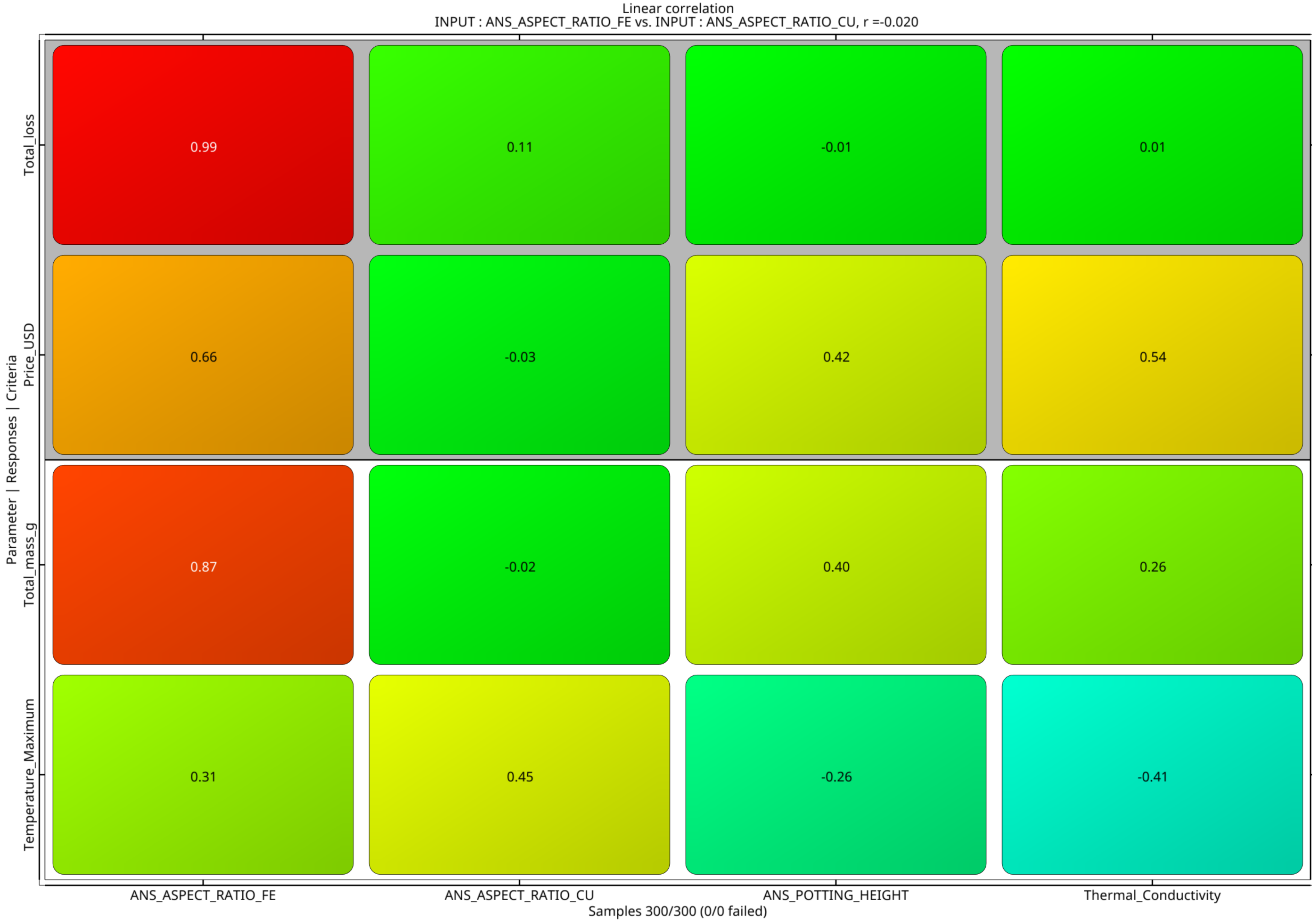
Al with PI-Insulation



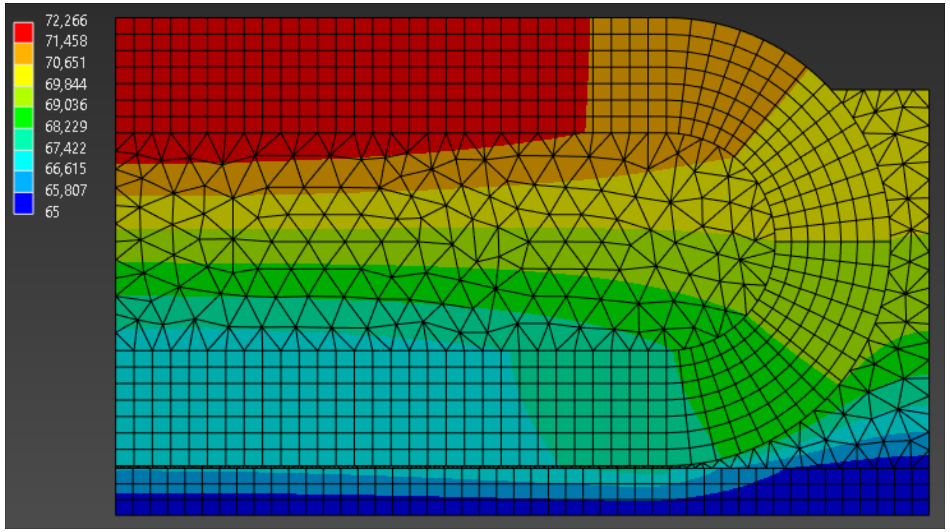
Wire laser stripped-Ceramic

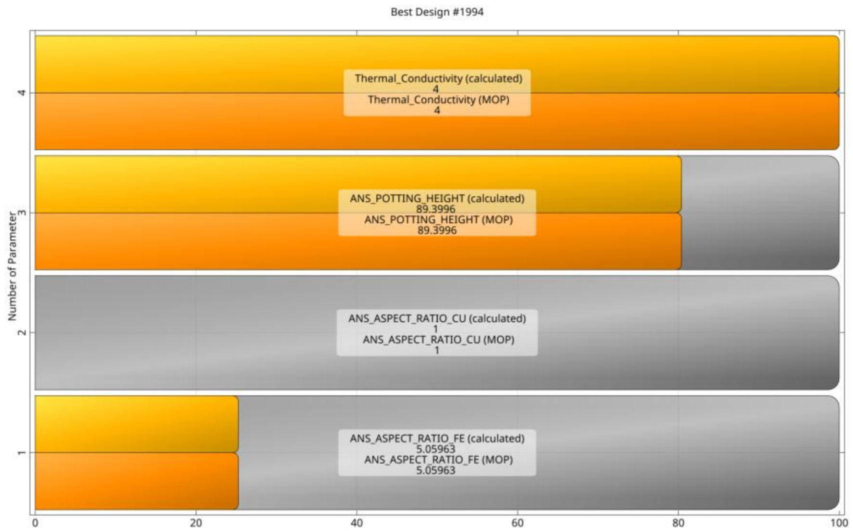


Sensitivity Study – Correlations without Insulation

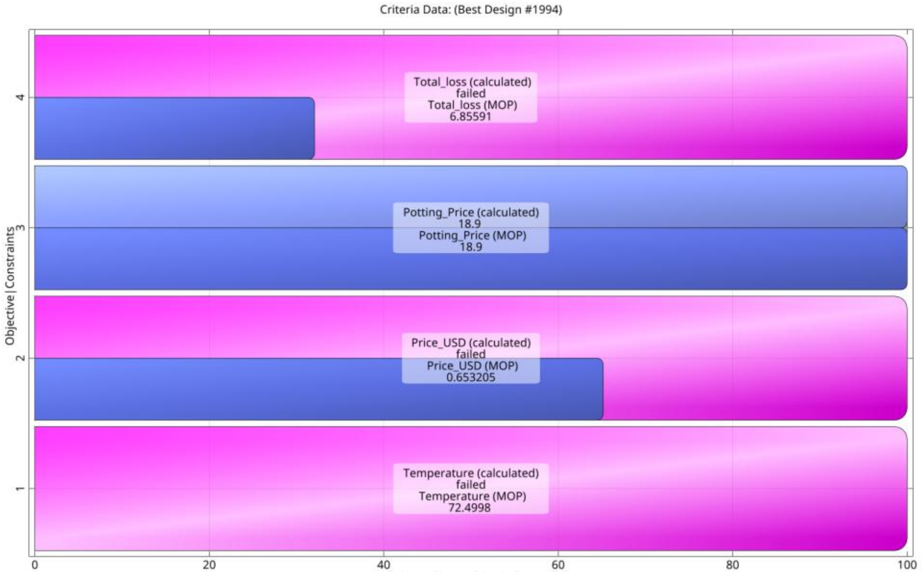


Optimal design regarding Size

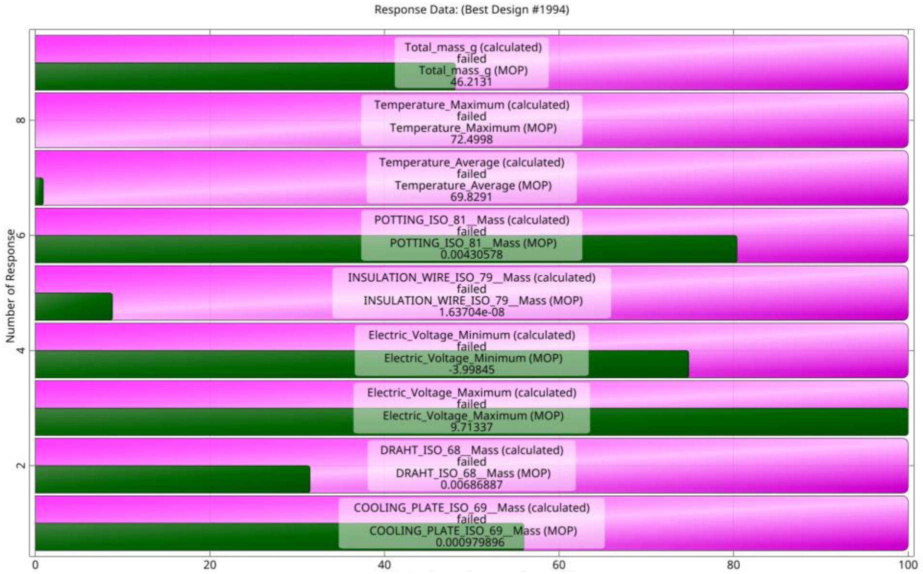




Relative Size



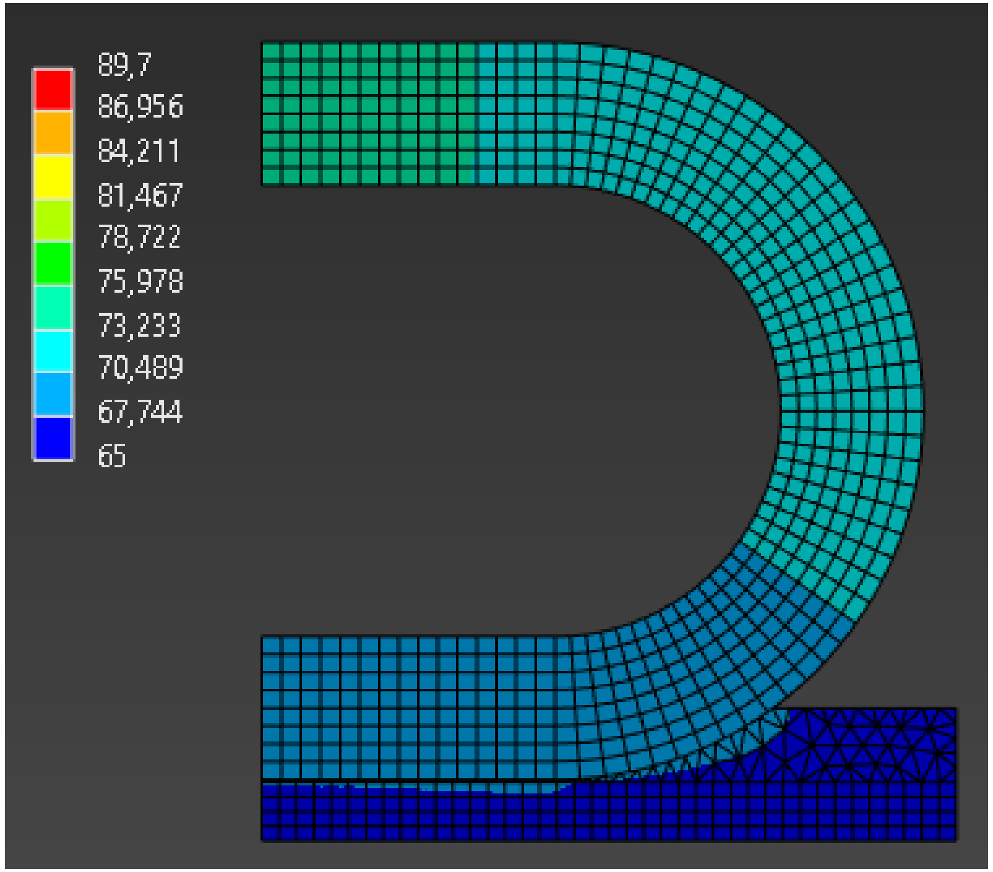
Relative Size

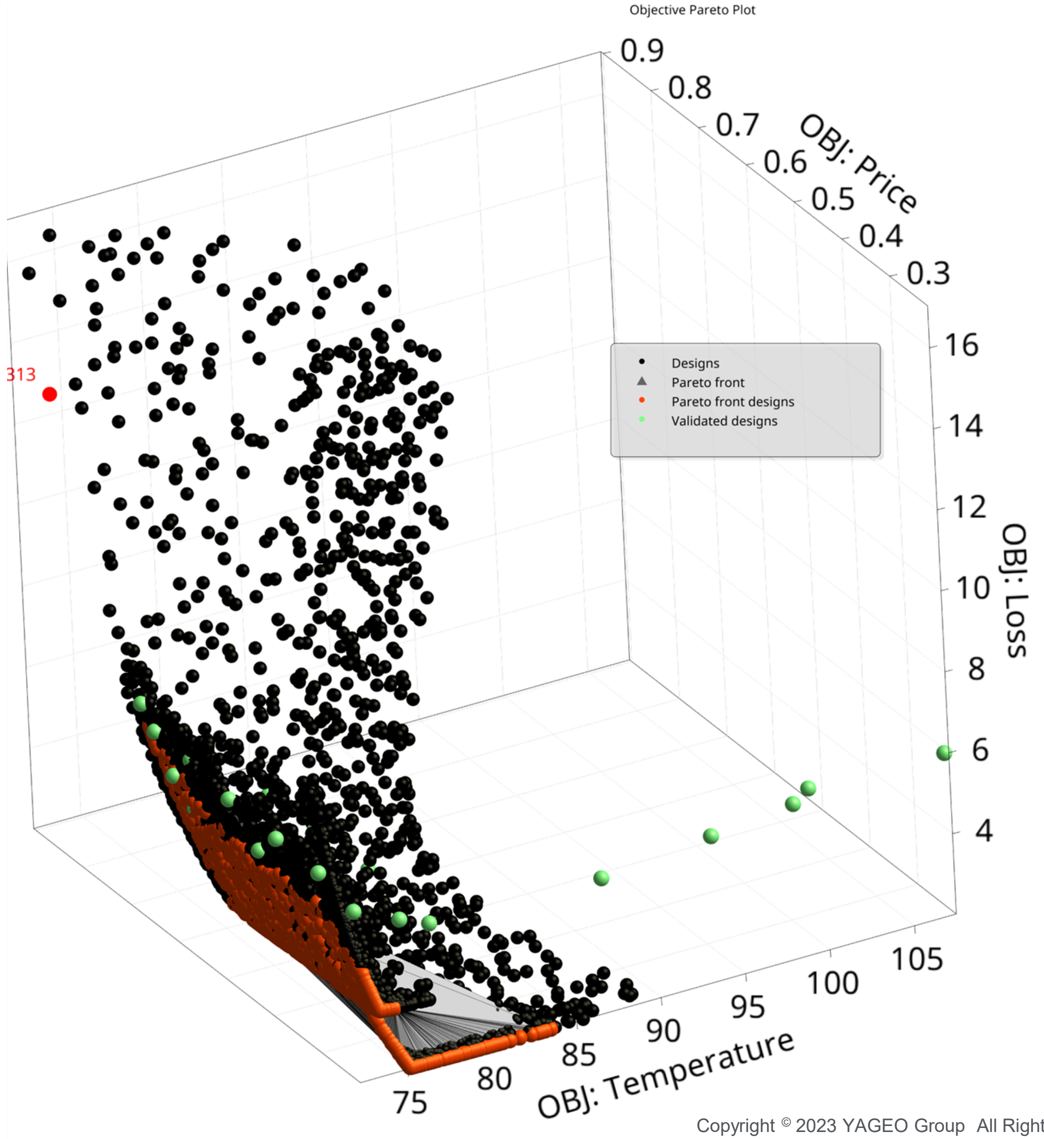


Relative Size

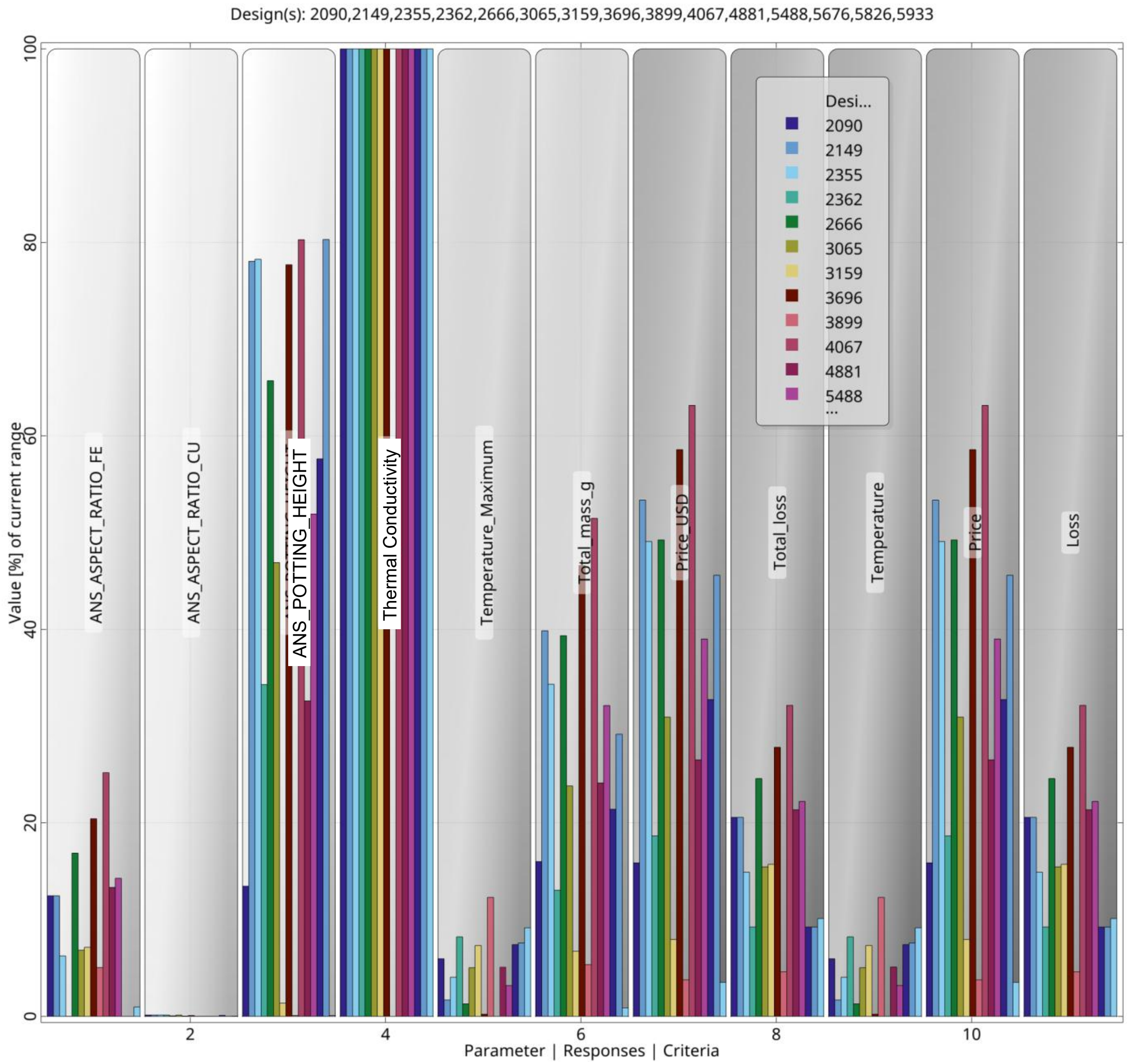
Optimal Design regarding Temperature, Price and Losses

One example design from the Pareto front





Optimal Design regarding Temperature, Price and Losses



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