

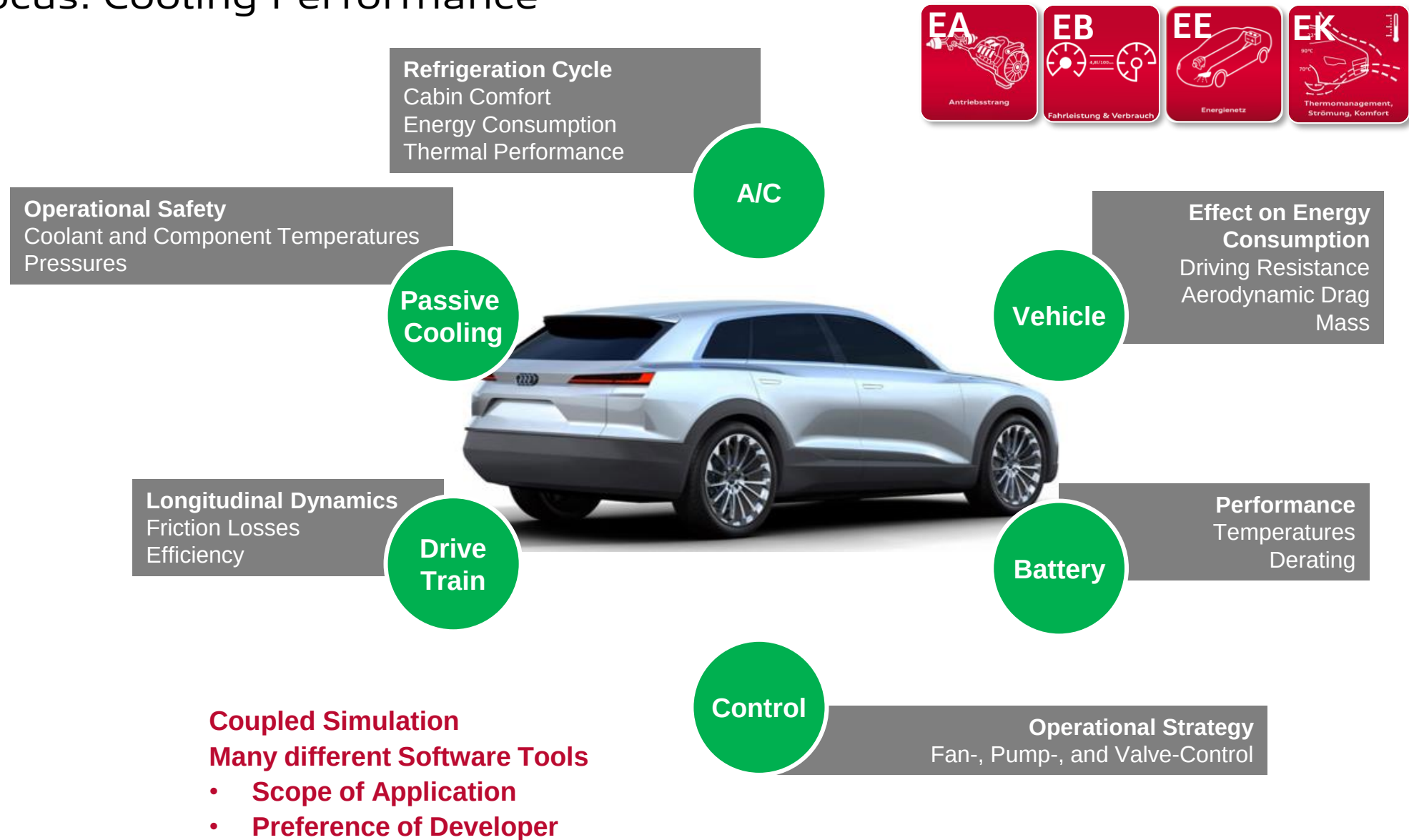
Assessment of Thermal Comfort and Energy Consumption of Car-Cabin Climatization

Evaluation of the KULI-„Extended Passenger Compartment Model“

Ingolstadt, May 2023

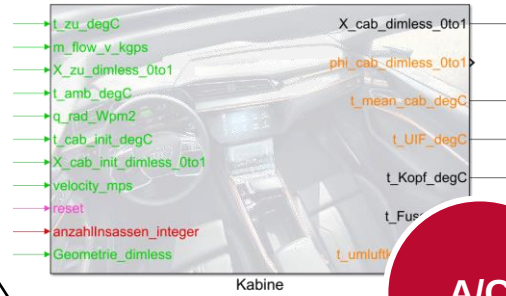
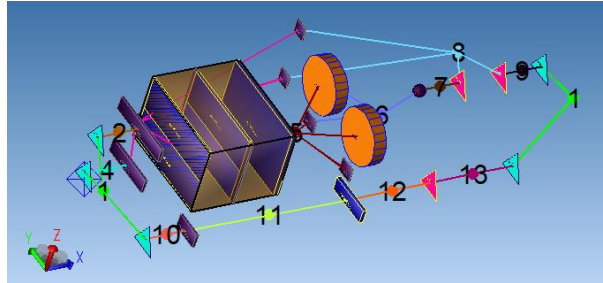
Motivation: Coupled Simulation the Development Process of Eletrical Vehicles

Focus: Cooling Performance



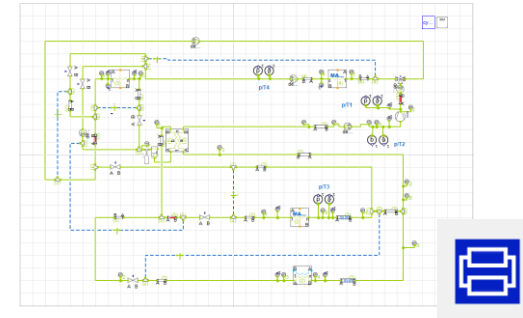
Usage of KULI-Models in the Audi-Co-Simulation-Process

Radiators in the Frontend:
Best User Experiences with KULI
HX-Models and Scaling Algorithms!



MathWorks®
Simulink

Refrigerant Cycle



Passive
Cooling



Vehicle

Drive
Train

Battery

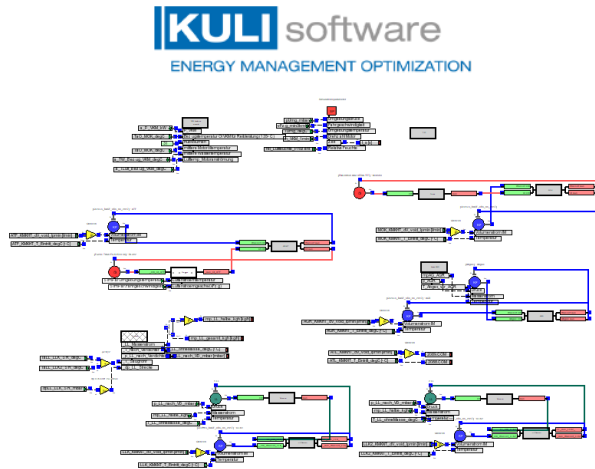
Control

MathWorks®

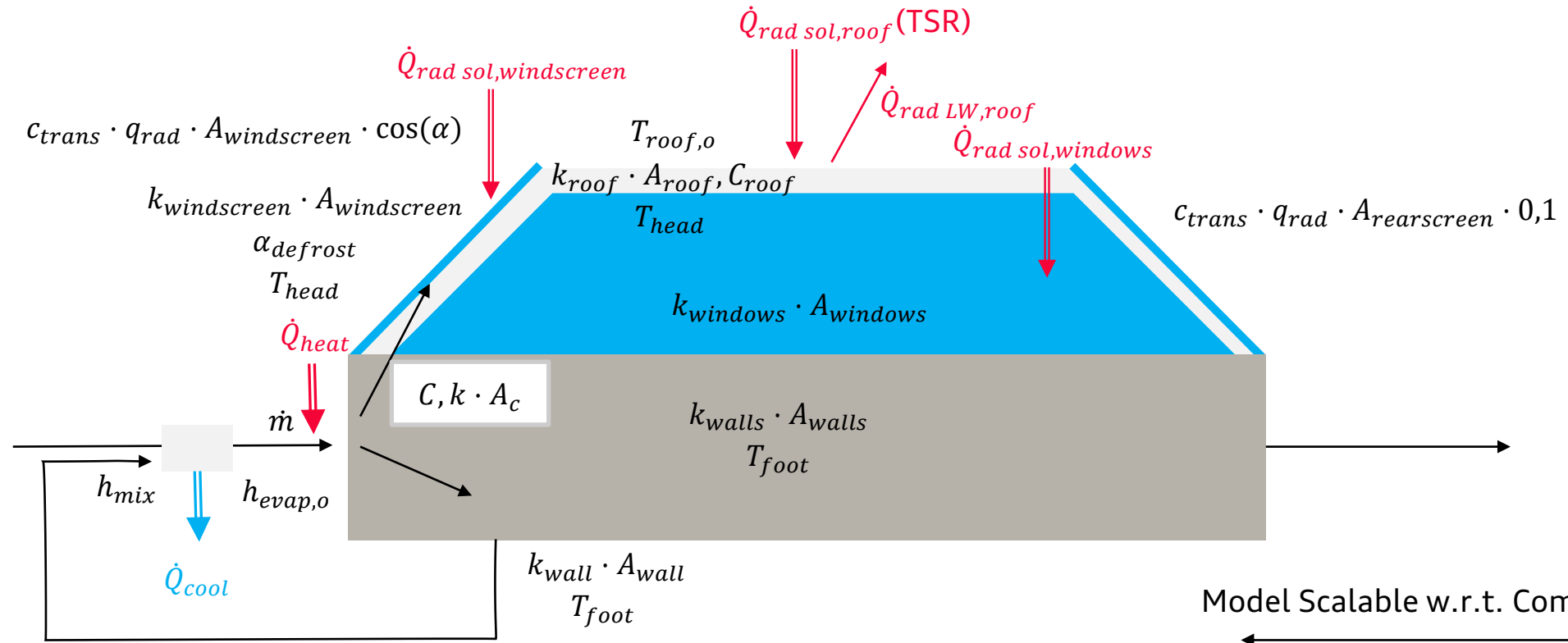
Simulink

Other Contributors

Heat Loads of Combustion Engine



Audi Cabin Modelling Approach -> To be Compared With Kuli-Model!



Temperature Layer Modeling

$$T_{head} = T_{cab} + \Delta T$$

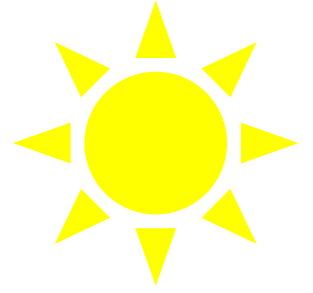
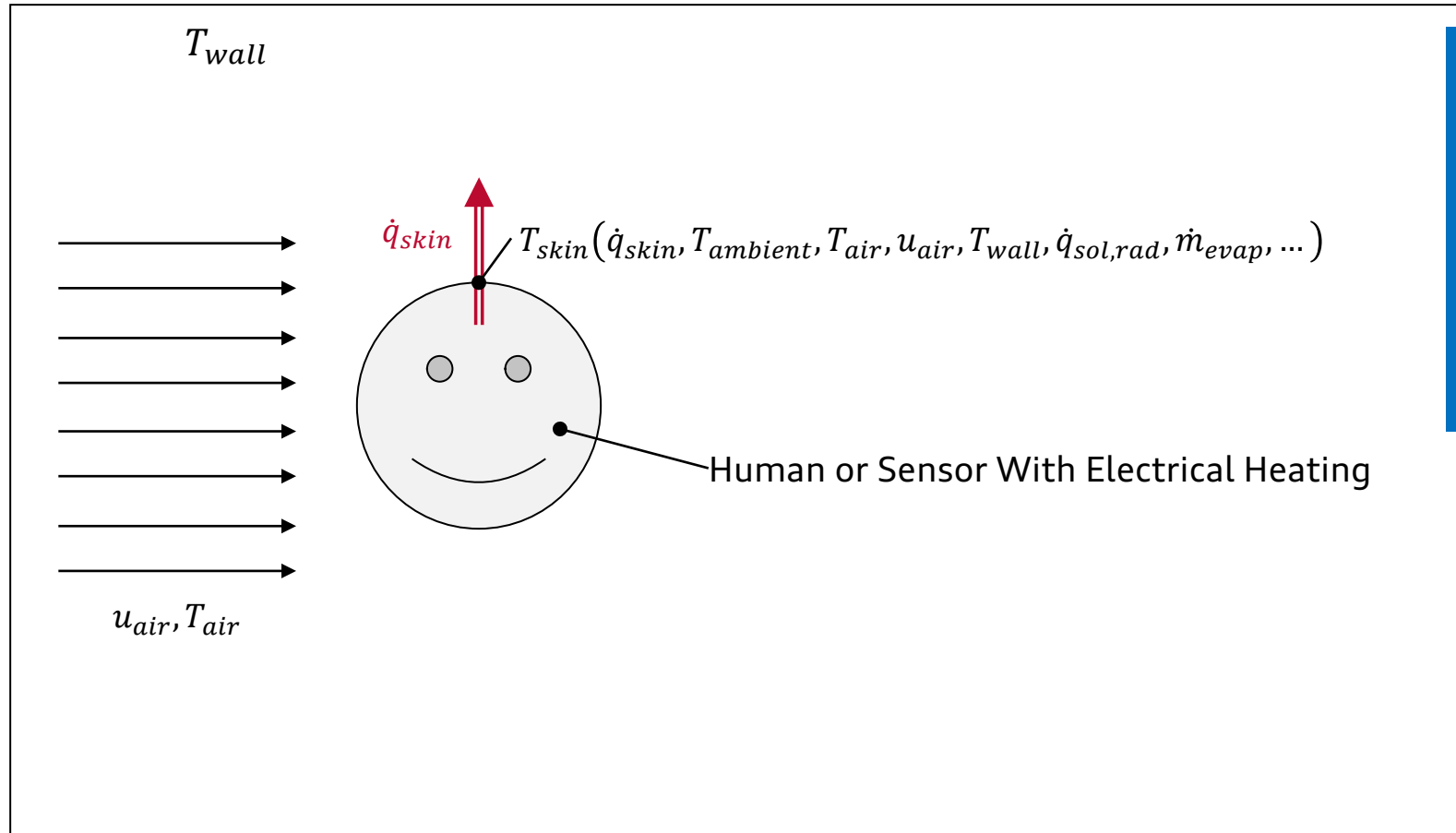
$$T_{head} = T_{cab} - \Delta T$$

$$\Delta T = \Delta T(T_{cab}, T_{ambient}, Vent - Strategie)$$

Klasse(VKM)	$T_U = -20^\circ C$	A0	A	A-SUV	B	B-SUV	C	D-L	C-SUV
Geometriekennzahl	$G = (-)$								
Temp.-Sollwert 15min	$T_{VDA, \tau=15min} = (^\circ C)$								
Temp.-Sollwert 30 min	$T_{VDA, \tau=30min} = (^\circ C)$								
Heizleistung	$\dot{Q} = \dot{Q}(G, \dot{m})$								
Massenstrom	$\dot{m} = (kg/min)$								
Heizleistung nenn	$\dot{Q} = (kW)$								
Heizleistung stat. 23°C	$\dot{Q} = (kW)$								

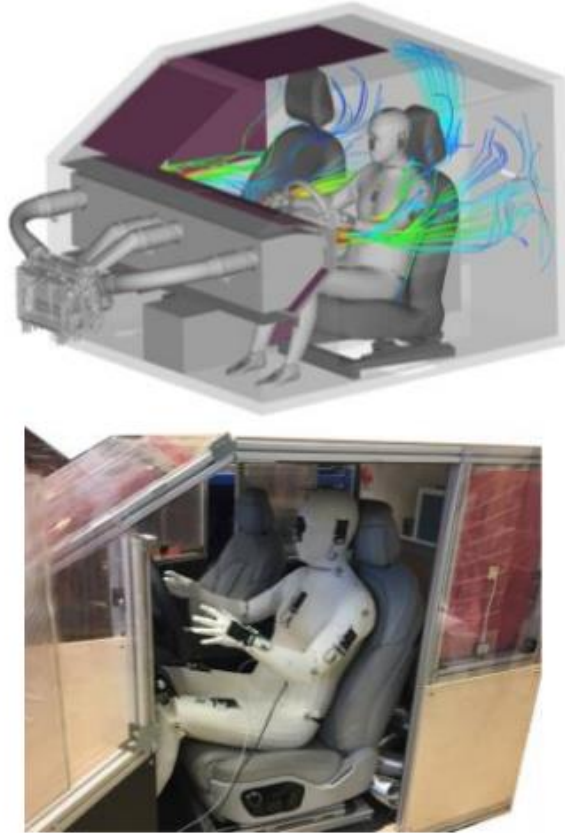
Comfort: More Than Temperature

„Feeling in This Room is Equivalent to Feeling in a Room With XX°C Air- and Walltemperatures Without Draught and Solar Radiation“

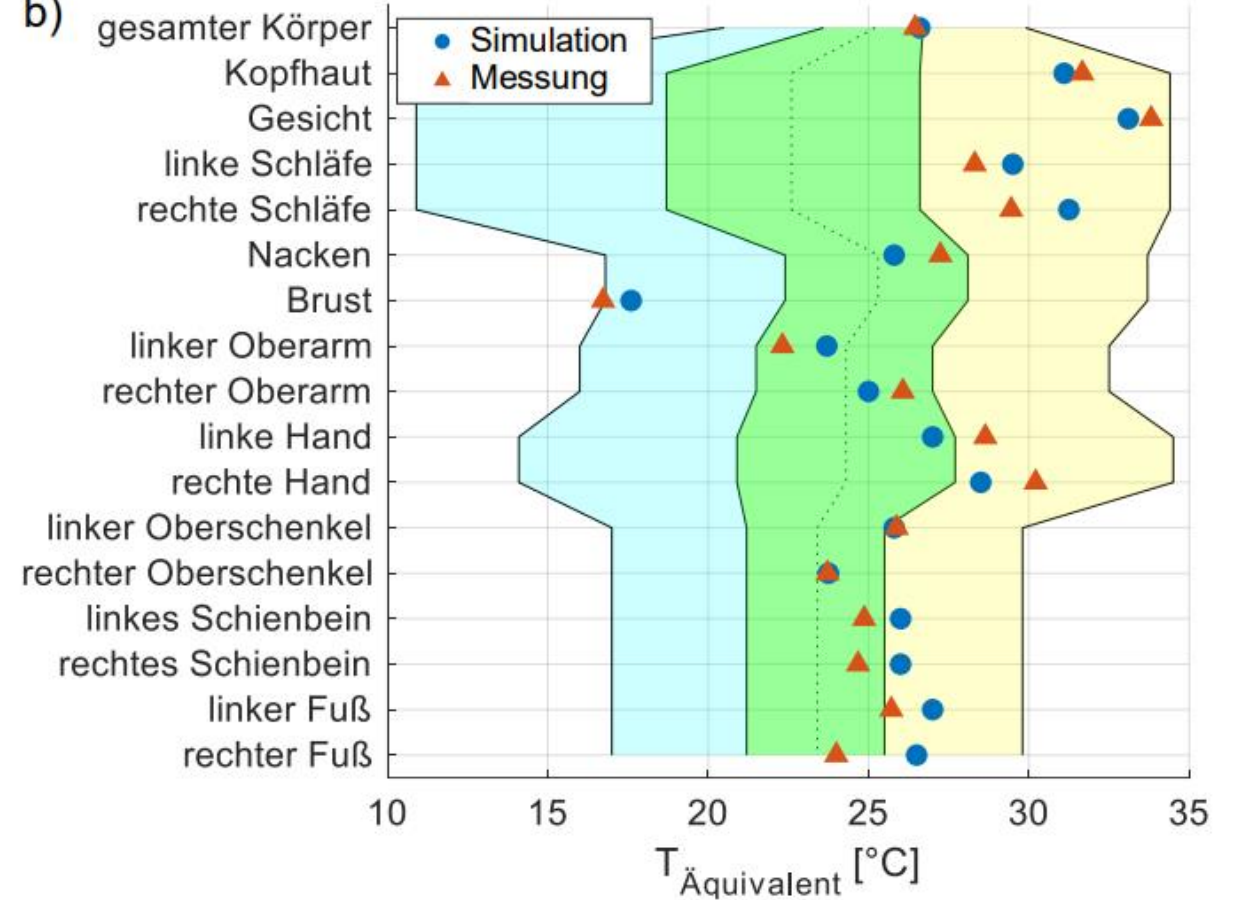


Possible Further Steps -> With AUDI- or KULI-Cabin Model?

a)



b)



a) Numerical and Experimental Setup of 3D-Comfort Simulation

b) Comparison of Equivalent Temperatures Between Measurement and Simulation

=> 1D-Simulation: Simplification of Comfort Model possible?

Critical Evaluation of EN-ISO 14505

Objective Evaluation of Thermal Comfort in Passenger Cars
 Development of Methods for Current and Future Climate Concepts
 Dissertation of Andreas Rolle, 2022
 TUM School of Engineering and Design
 Cooperation Together with Audi

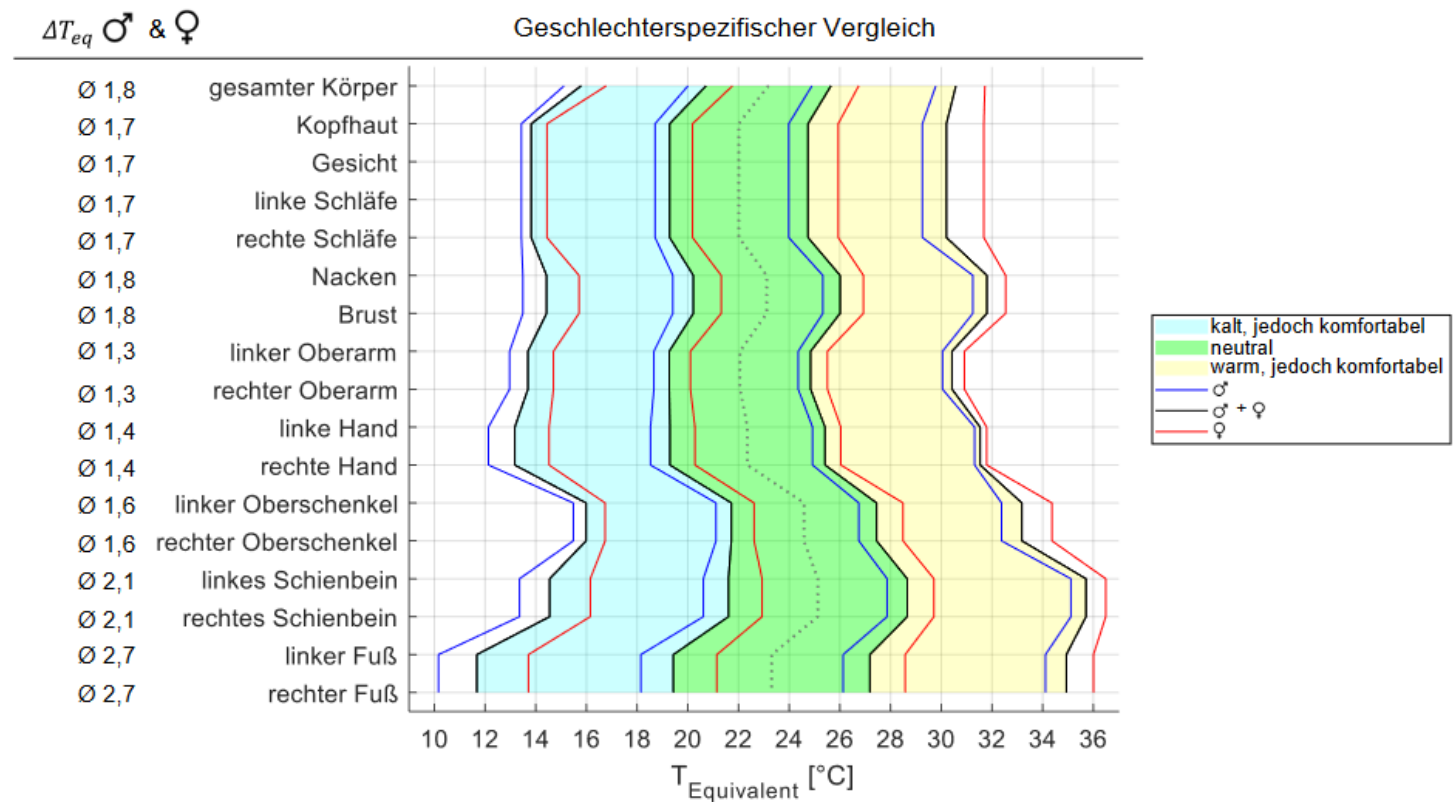
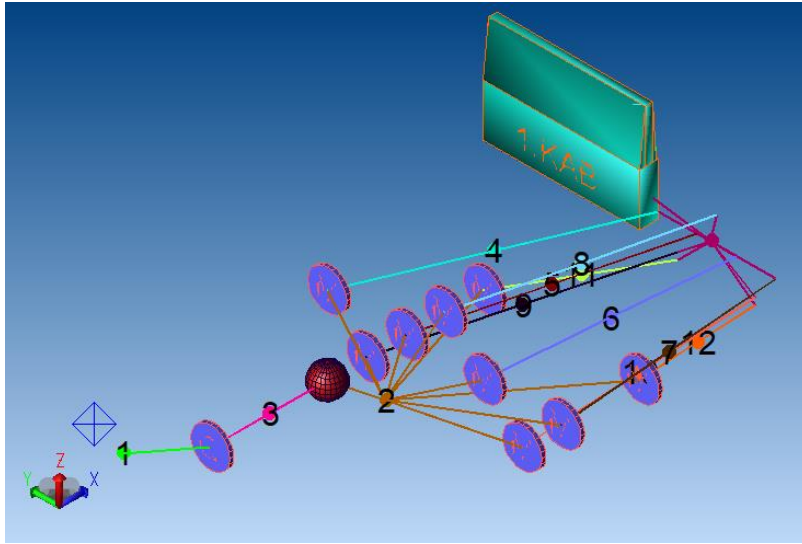


Abbildung 39 Allgemeines Komfortzonenmodell (n = 83) im Vergleich zu den geschlechterspezifischen Grenzen für $clo = 0,72$; ΔT_{eq} entspricht der durchschnittlichen Differenz der T_{eq} zwischen männlich und weiblich

Evaluation of the KULI-„Extended Passenger Compartment Model“

Interfacing via Air-Flow-Network



Parametric Geometry Description and Detailed Layered Wall Models

Fahrgastzelle [B9.kuliVbo]

Datei Extras

Allgemeines Geometrische Daten Wand Eigenschaften Druckverlust

Kennung	Wert
a [m]	1.1
b [m]	0.98
c [m]	0.49
d [m]	0.3
e [m]	0.3
f [m]	0.44
g [m]	0.67
h [m]	0.1
i [m]	0.1
alpha [°]	30
beta [°]	15
gamma [°]	45

Fahrzeugvolumen [m³]

Modelling of Exchange Rates between different Air-Zones via „Cabin-CFD“ files

```
MassFlow2R_Heatup_360kg_h_KULI_WORKSHOP.dat - Editor
Datei Bearbeiten Format Ansicht Hilfe
## Input file for cabin model
## Massflow f in [kg/s]

## Two row cabin model
## Geometric parameters (for KULI cabin model)
## a = 1.1m
## b = 0.98m
## c = 0.49m
## d = 0.3m
## e = 0.3m
## f = 0.44m
## g = 0.67m
## h = 0.1m
## i = 0.1m
## Alpha = 30°
## Beta = 15°
## Gamma = 47°

## m_def_lire=1.5/60*g/(2*g+h); % drittelmassenstrom da über 3 yzonen
## m_def_mi=1.5/60*h/(2*g+h); % drittelmassenstrom da über 3 yzonen
## m_fuss=3.5/60/4;
## m_mi=0;
## m_seite=1/60/2;

## x, y, z: Number of Control - volumes(CV)
4      3      3

## Scaling factor
1

## Massflow f in [kg/s] - X      (yz - face)
0      0      0      0      0      0      0      0
0.0102924229740000      0.000692370370666667      0.0118137789002500      0.00665943032663800      0.0001059059109
-0.00390741569000000      0.000388396553000000      0.0361553774220000      -0.0117863190687100      0.0001271946530
3.31974202200000e-06      -0.000245097709670000      0.00308158955500000      0      3.91637762610000e-05      -0.0023

## Massflow f in [kg/s] - Y      (xz - face)
0      0      0      0.00389738820700000      -8.80390279400000e-05      9.57247938700000e-06      -0.003846072155
0      0      0      0.00447660286200000      0.000189328557999999      -0.00464798994800000      0.0015030746990
0      0      0      -0.000307936315000000      -0.0102854854190000      -0.000198405660000001      0.0142863750550
0      0      0      0      -8.26241383000000e-06      0.00372681833200000      0      3.67298873300000e-05

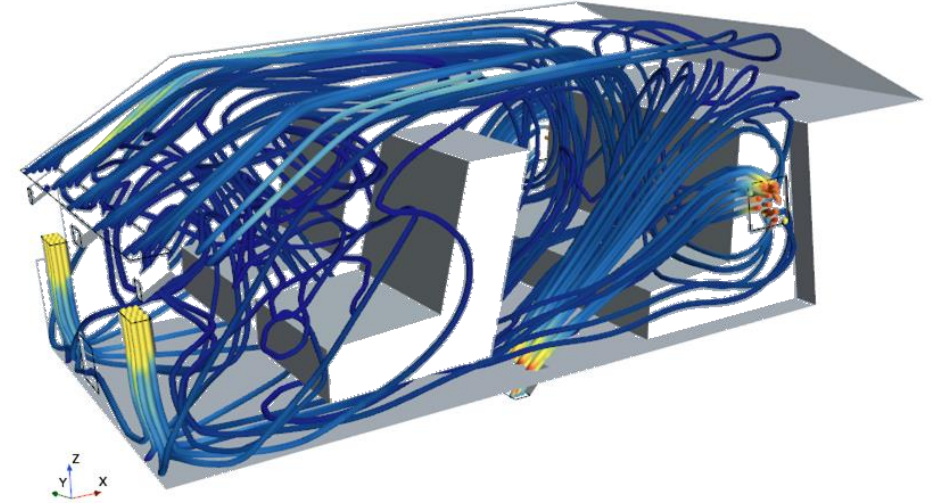
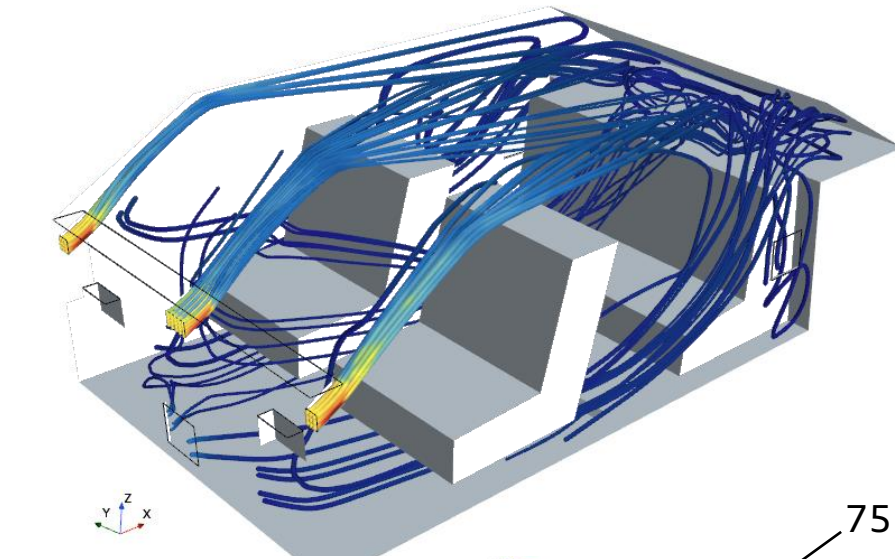
## Massflow f in [kg/s] - Z      (xy - face)
0      -0.000135704069866667      -0.00260118539834444      0      0      6.09361115613000e-05      -0.000292386433
0      0.0179444636600000      0.0238039837400000      0      0      0.0235883869470000      0.0178279724240
0      -0.00291643625000000      -0.0398442214500000      0      0      -0.0319899650379870      -0.039345948883
0      9.12596470600000e-06      -0.000215072927700000      0      0      0      2.41997412400000e-05      0
```

Determination of the Air-Exchange-Rates

Simcenter STAR-CCM+

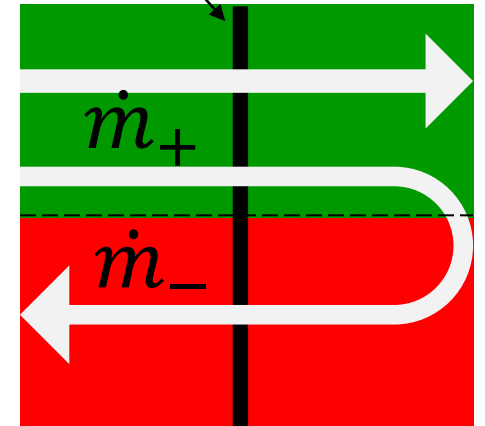
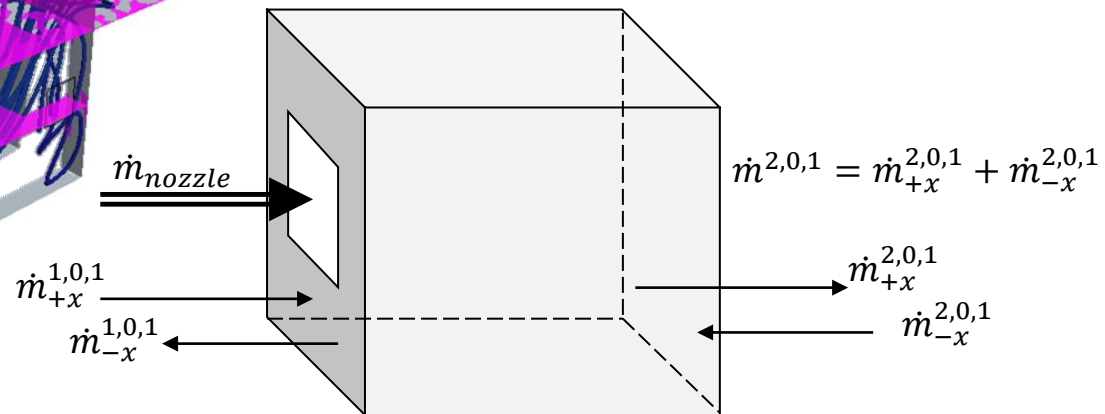
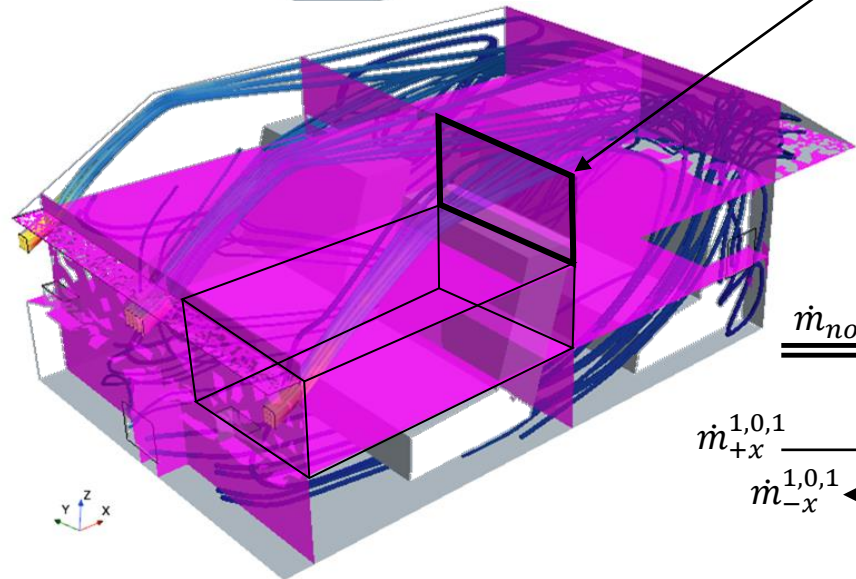
Summer Ventilation Case

Winter Heatup Case



75 Constrained Planes for Convective Exchange Evaluation

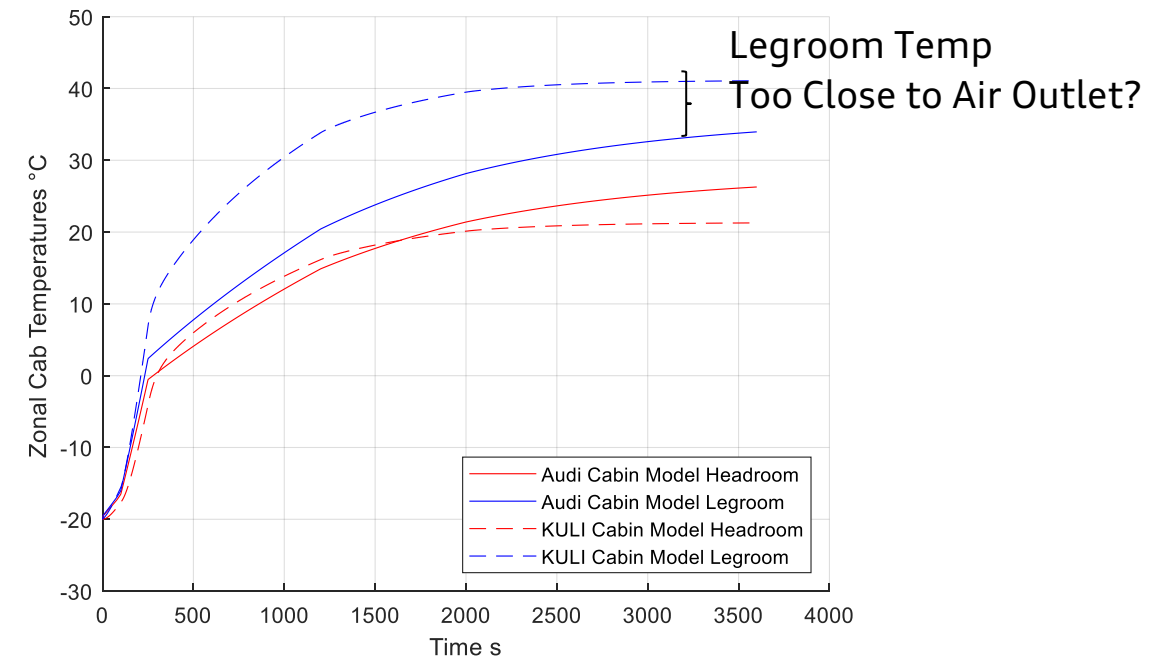
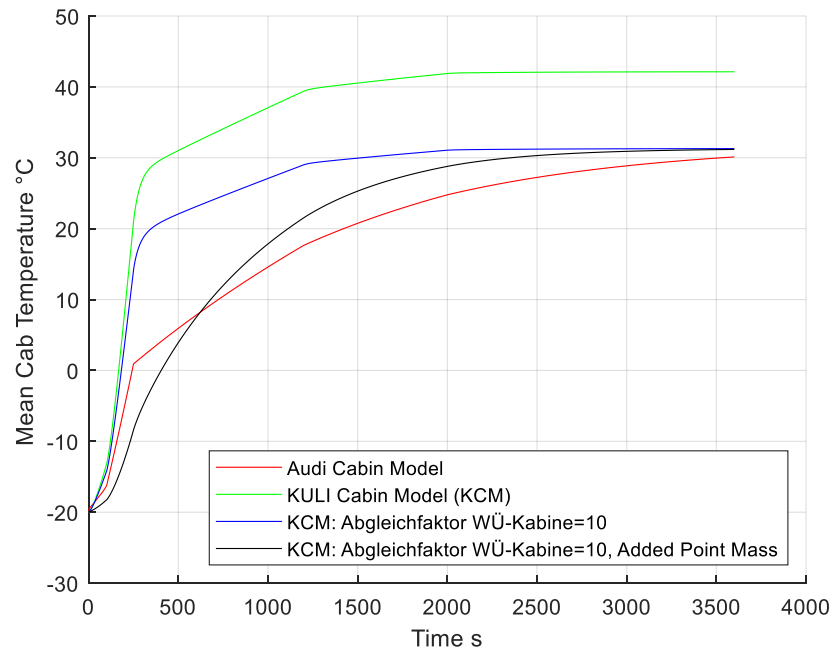
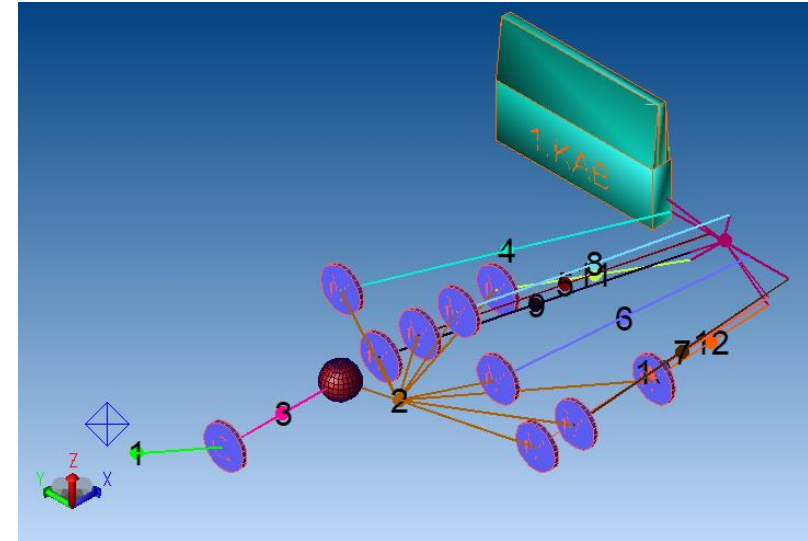
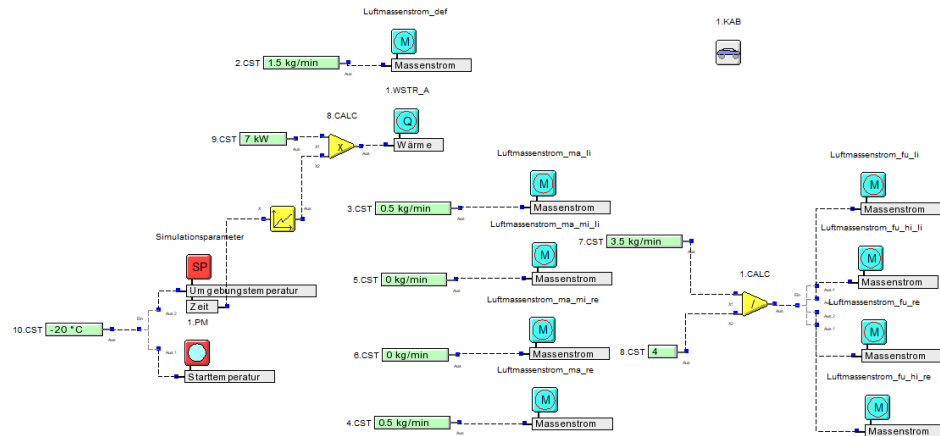
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \begin{cases} > 0, \text{inflow cell} \\ = 0, \text{otherwise} \end{cases}$$



Intermediate Findings

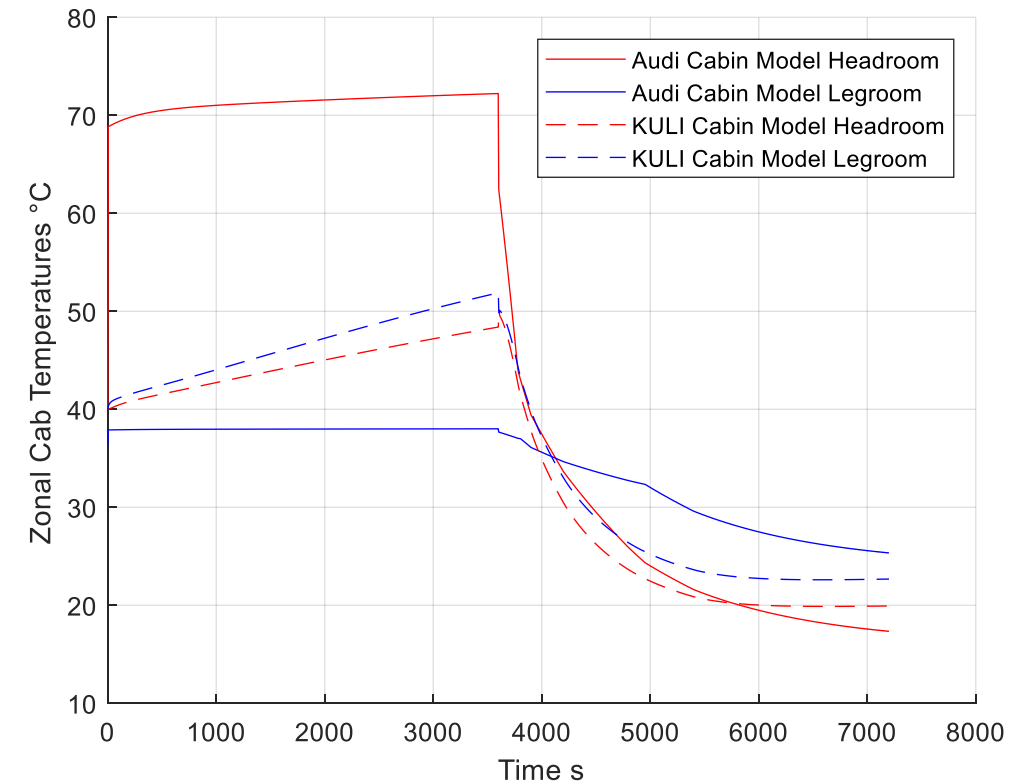
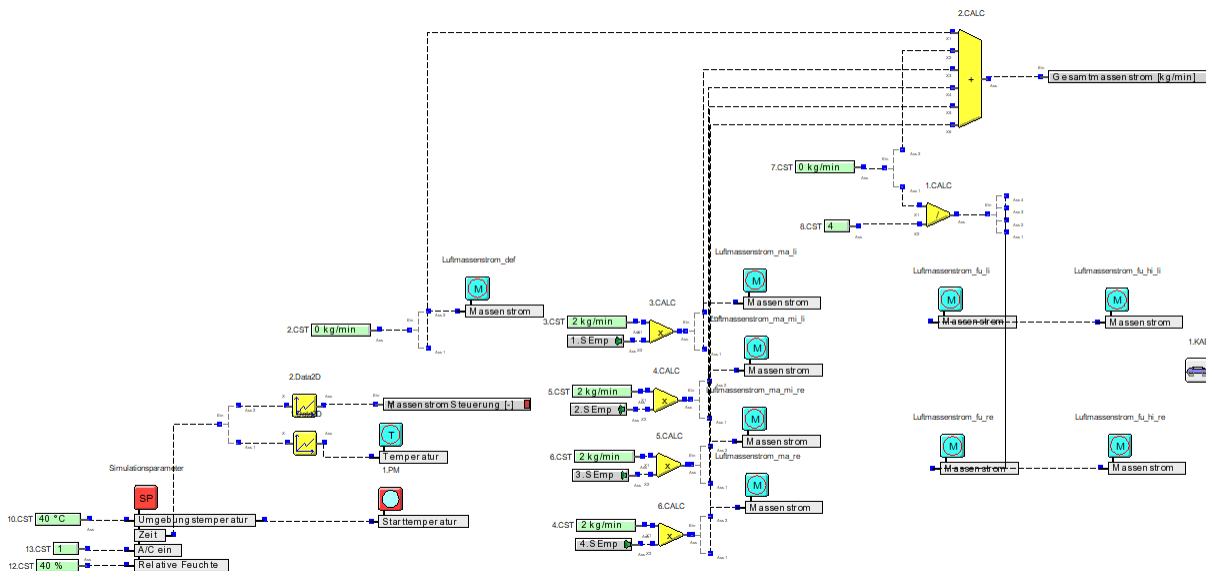
- › 75 Constrained Clipping Planes in CFD-Simulation!
- › Potentially Erroneous, Scripting (e.g. Java-Script in StarCCM+) Inevitable!
- › Convective Exchange Separated Into Linear and „Eddy“ Parts (Positive and Negative Parts of Net-Flows Necessary)!
- › Resulting Fields Have to be Free of Sources and Sinks -> Conservative
- › Exception: Zones Adjacent to Air Nozzles get a Massflow Sourceterm
- › Results From CFD Have to be Arranged in KULI-Required Format -> Also Scripting Inevitable!
- › Manual Might be Improved for Readability and Clarity!

Results Heatup-Case



Results Cooldown-Case

- › Passive Heating due to 1000 W/m^2 Solar Load at 40°C Ambient Temperature During first 3600s
- › Completely Different Behaviour of Headroom and Legroom in Heatup Phase Between Both Models
- › Agreement Between Headroom Temperatures During Cooling Quite Good



Conclusion

- › Results of KULI-Cabin Modell and AUDI-Model do not Completely Agree
- › Identify Reasons for Deviation -> Documentation of Model Physics Available?
- › Develop Simplified Model for Climate Comfort Based on Three-Dimensional-Model