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Digital Twin for simulation of Aircraft Thermal Management System architectures in TheMa4HERA

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Institute of System Dynamics and Control (SR) – Aircraft Energy Systems

Co-funded by
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TheMa4HERA
Grant Agreement No. 101102008

Motivation

Hardware test rig

- Test on a single system / a few systems together
- Real conditions but difficult to test all cases
- Real behaviour

Digital Twin: Virtual test rig

- Possibility to carry out impact assessment at aircraft level
- Tests in multiples conditions and configurations
- Tests of all systems together
- Test possible at an early stage of development
- Results depend on model validity

Complementarity

- Hardware tests validate subsystem models
- Digital Twin evaluates the complete system

➔ Included in the strategy to achieve TRL 5

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DLR ThermoFluid Stream Library

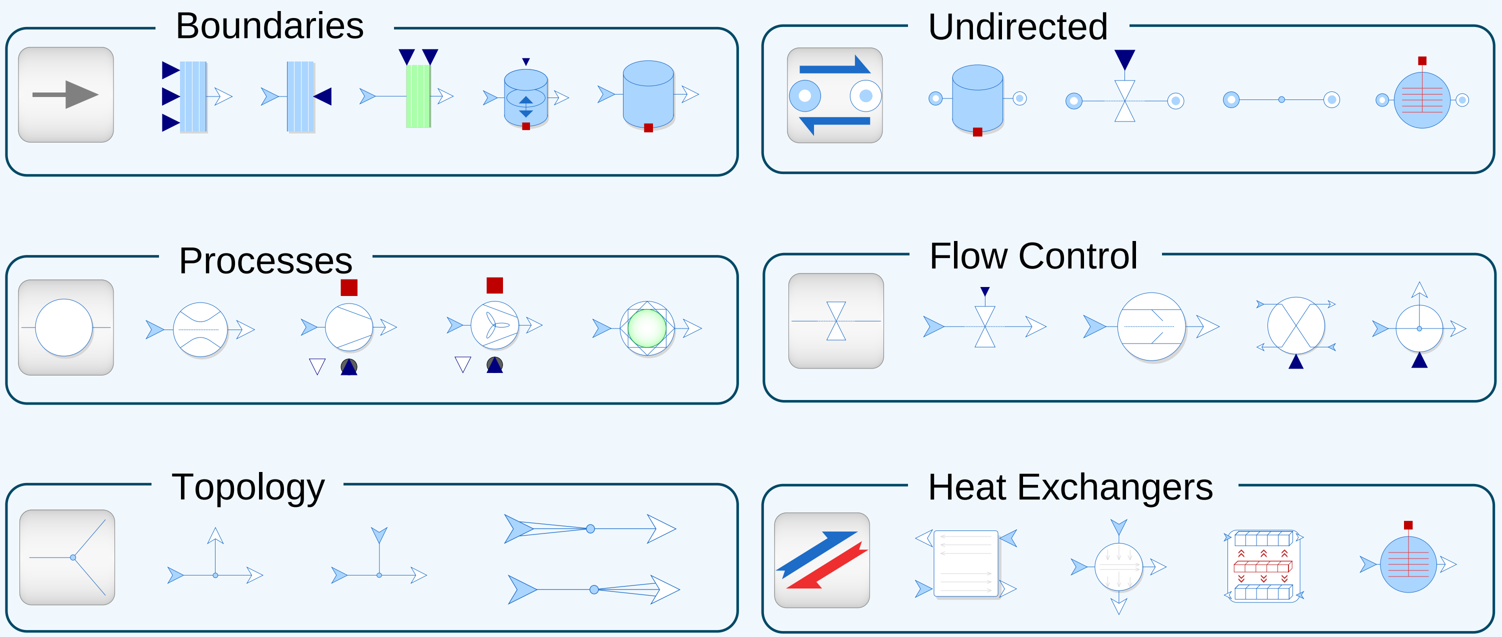
Highlights

Free open-source library
https://github.com/DLR-SR/ThermofluidStream
- Modeling complex thermodynamic systems using gases and/or fluids

Robust
- No larger non-linear equation systems

User friendly
- Simple parameterization, easy to initialize
- Many base components easy to adapt
- Many examples to start with

Tool compatible
- Dymola
- OpenModelica



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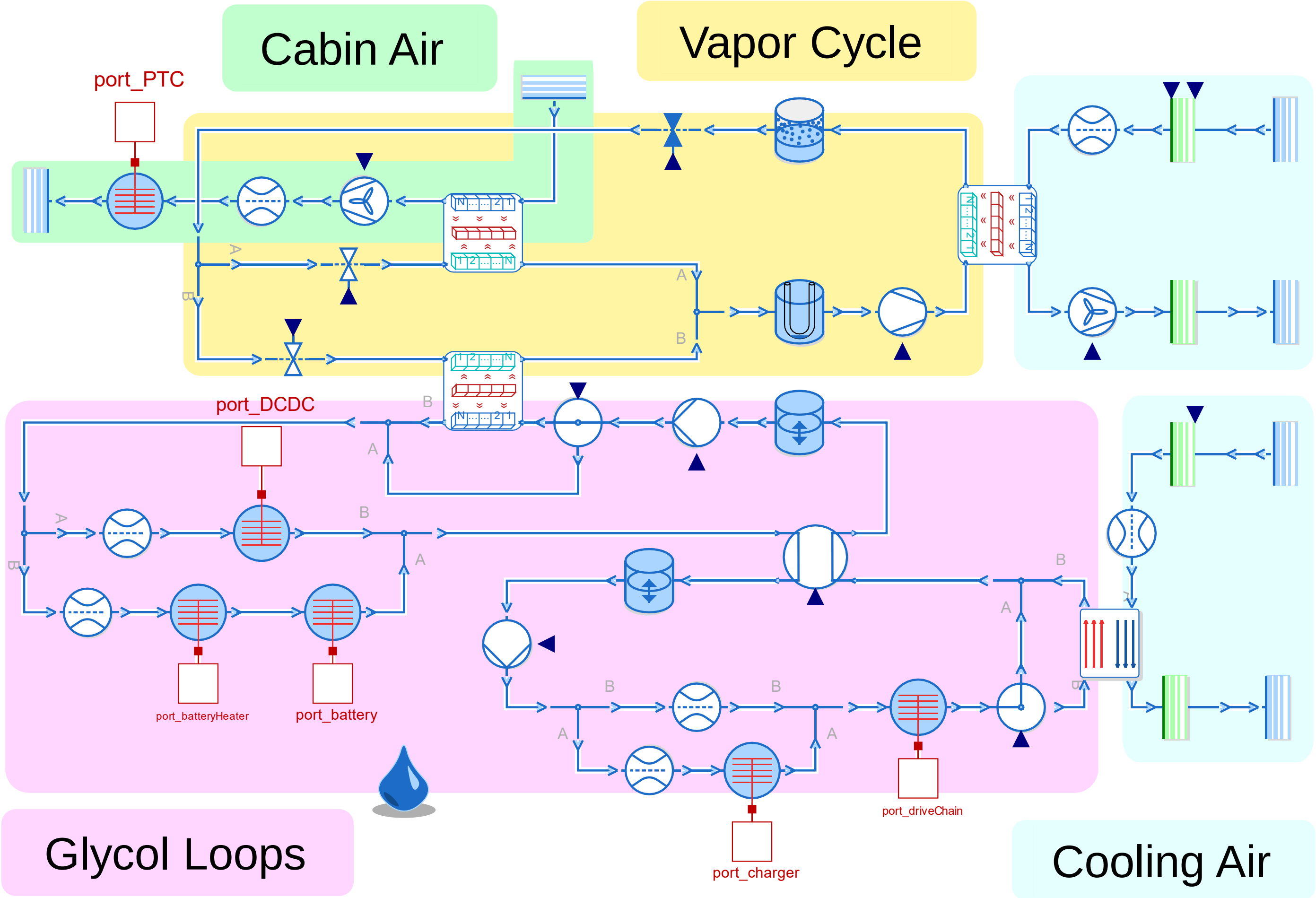
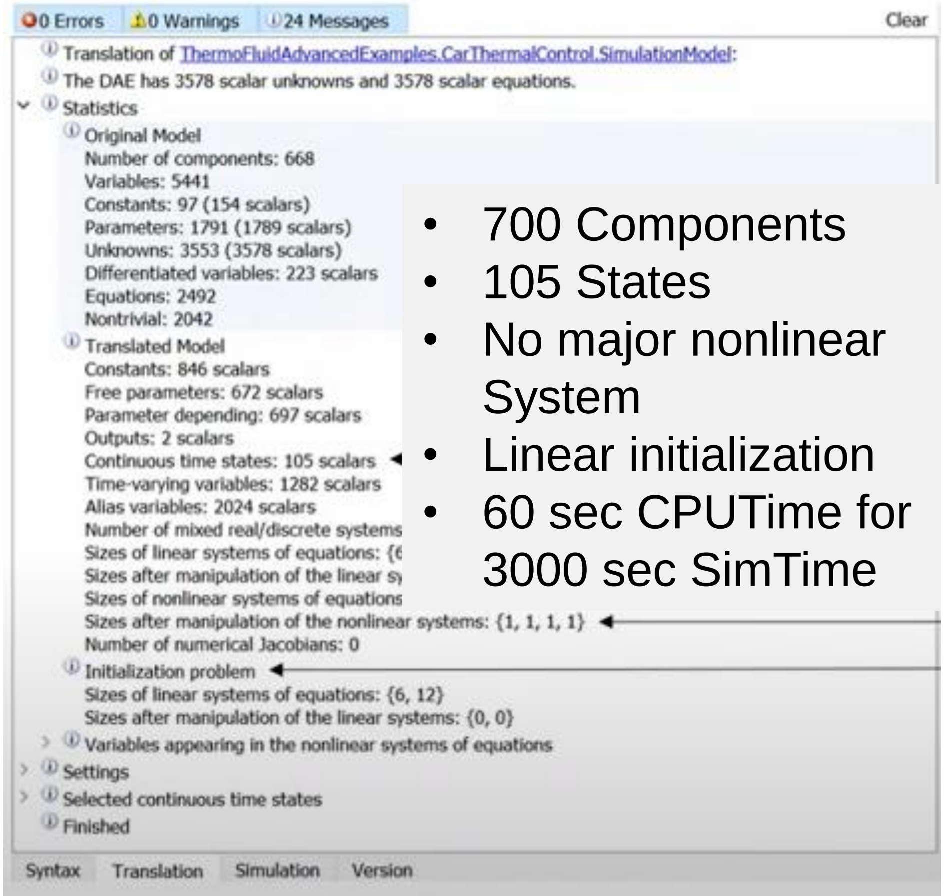
Thermal Management System of an electric car





- 700 Components
- 105 States
- No major nonlinear System
- Linear initialization
- 60 sec CPUTime for 3000 sec SimTime

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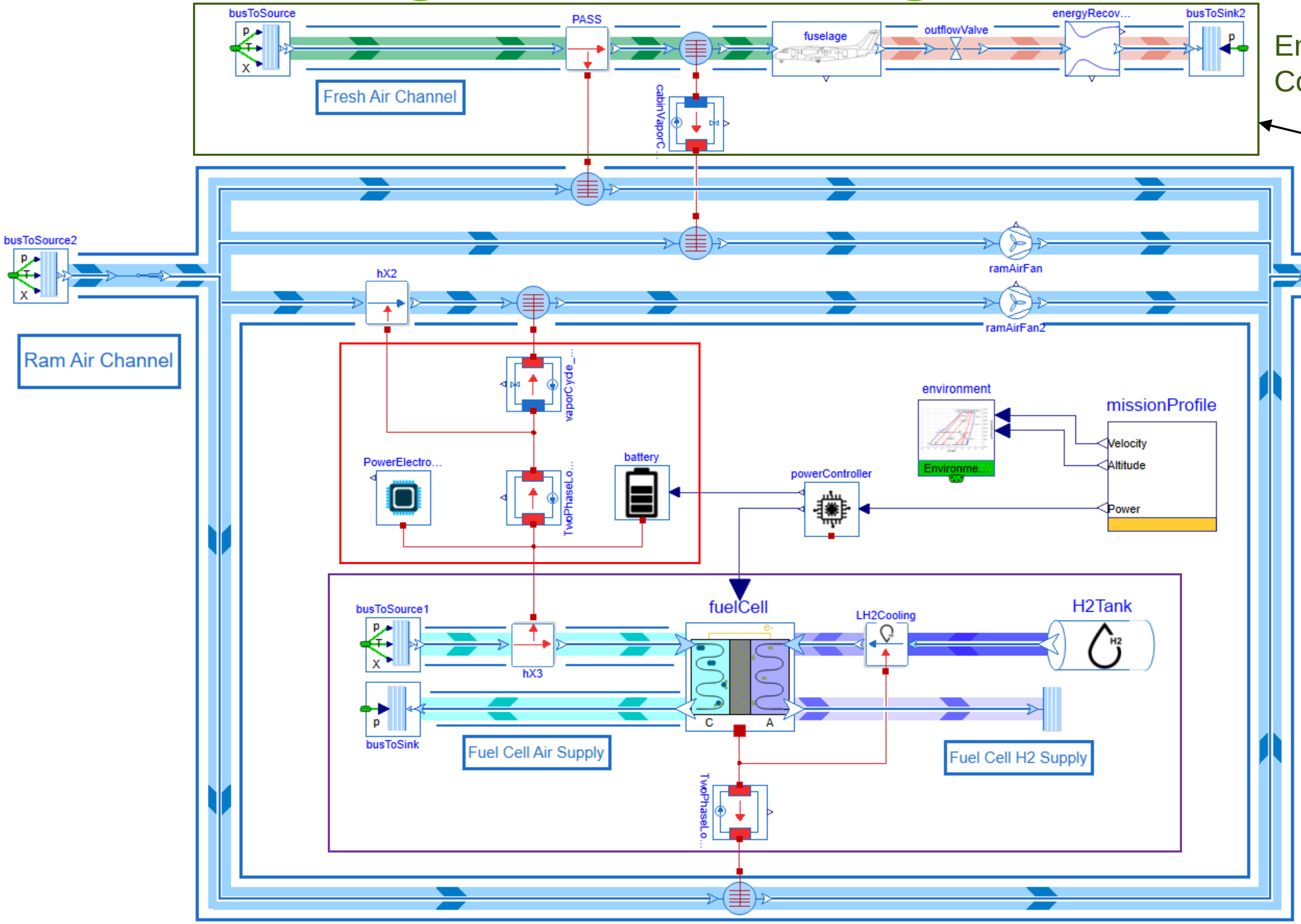
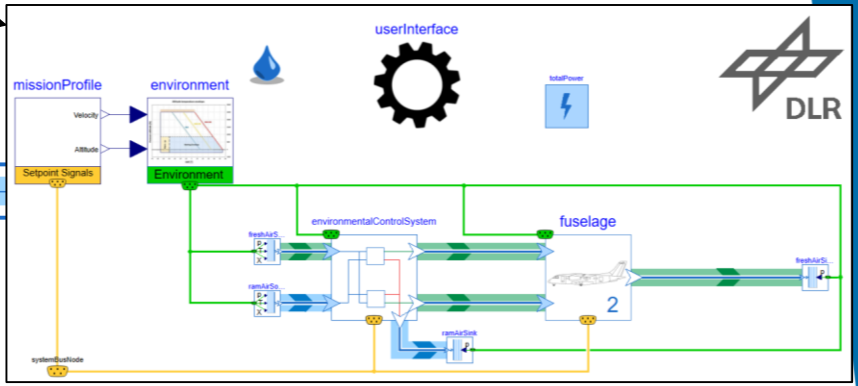
Overall Digital Twin Target



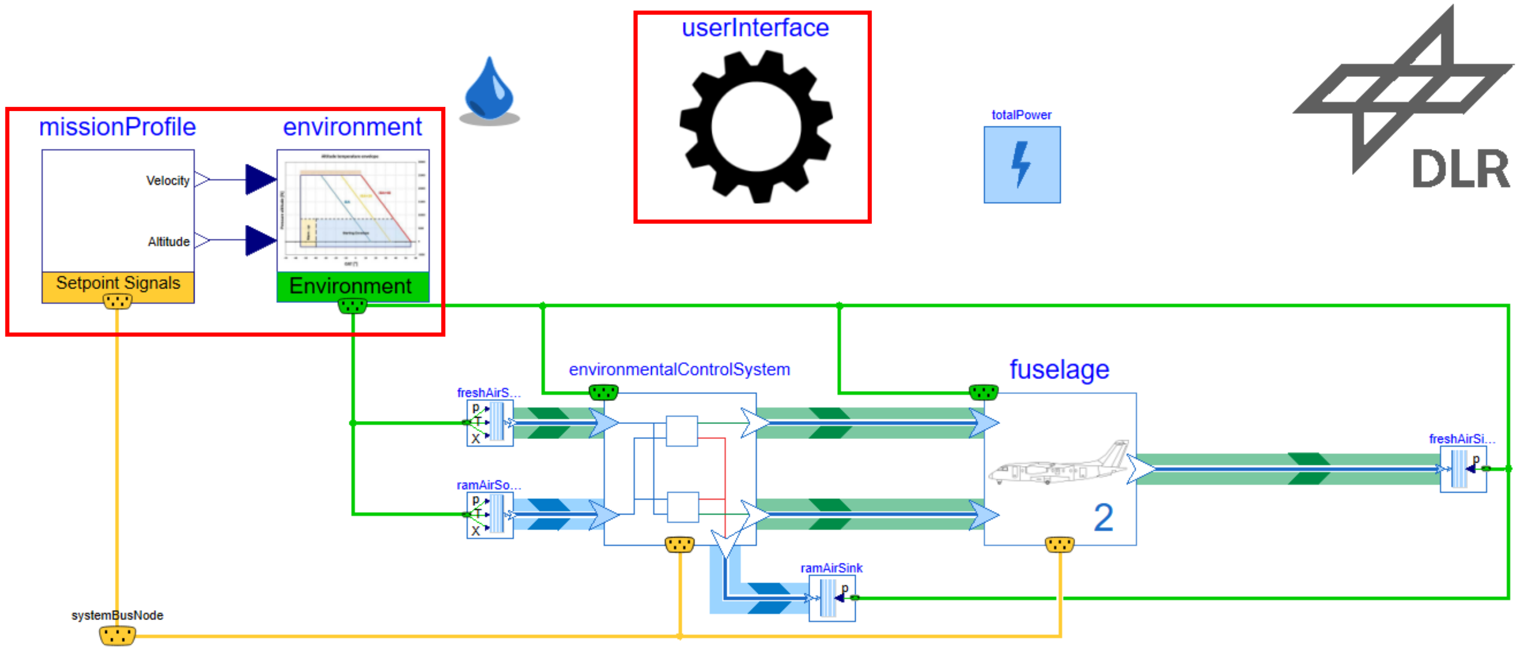
Environmental Control System

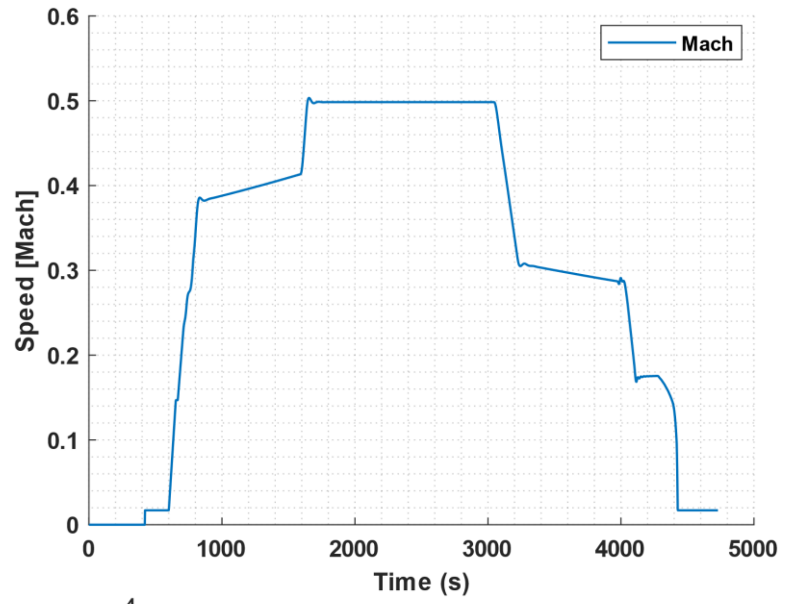


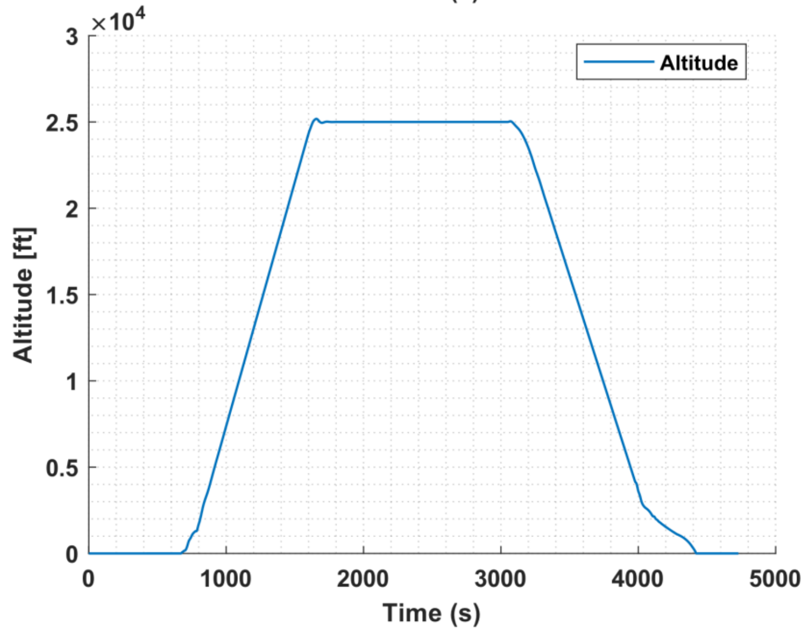
Power Electronics Cooling System

Fuel Cell Cooling System

Digital Twin – Environmental Control System







	Mixer	Cockpit	Cabin	Avionic Bay	Cargo Bay
Temperature in °C	16.6	25	24	36.7	25.4
Humidity in g_H20/kg_t	4.22	4.92	4.46	4.86	4.47
	Enthalphie h in kJ/kg		Pressure in bar		
	27.3		0.97		

KPIs
Power Consumption in W
2.38e+04
Mass of fuel in kg
4.51

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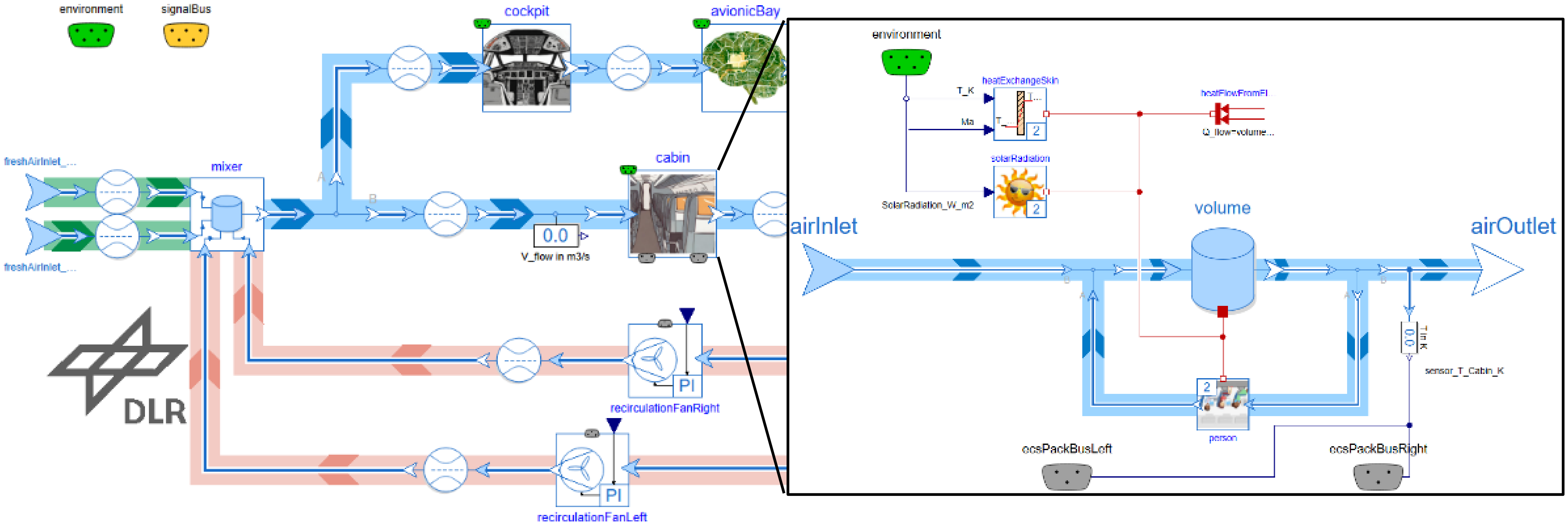
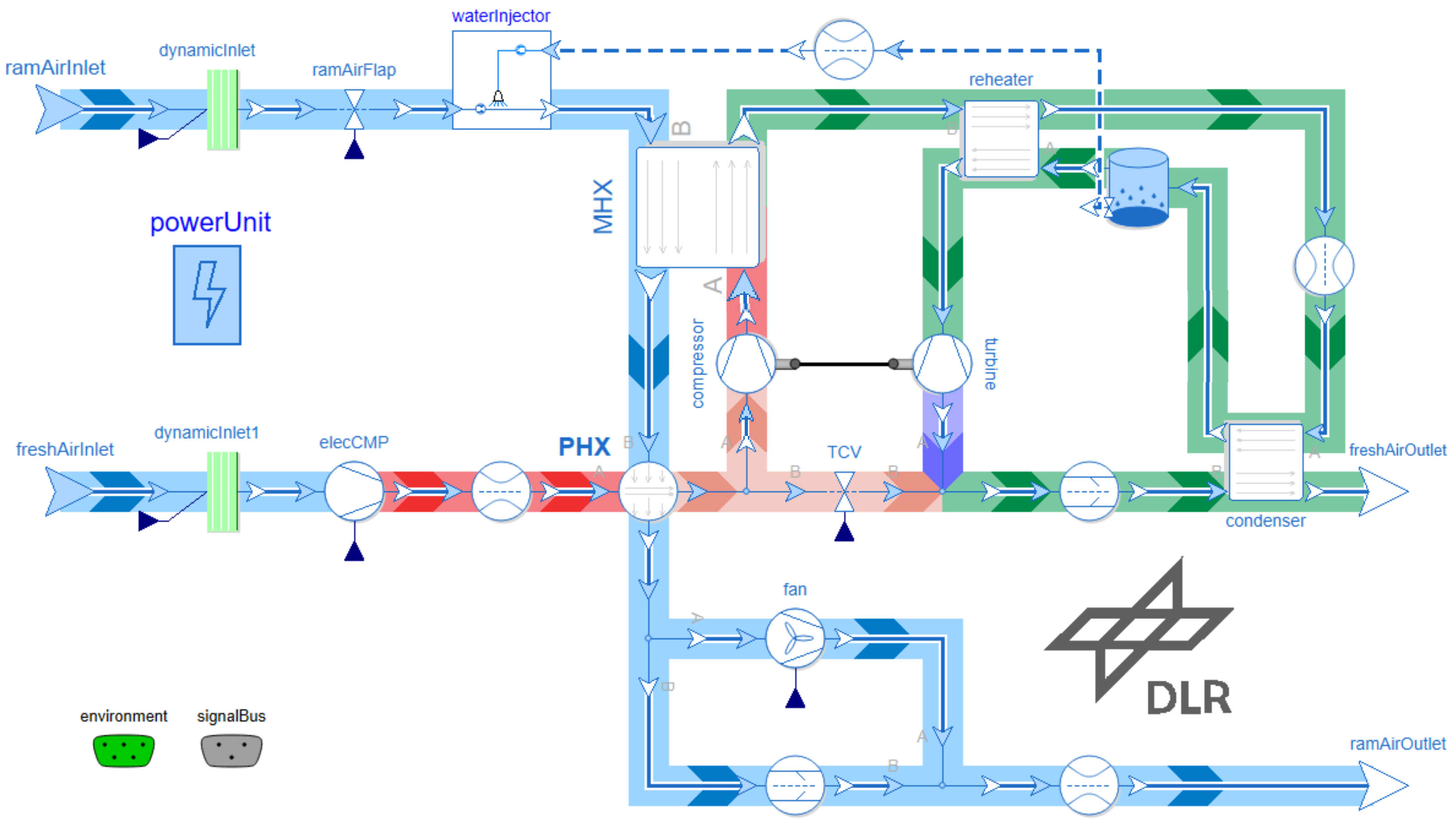
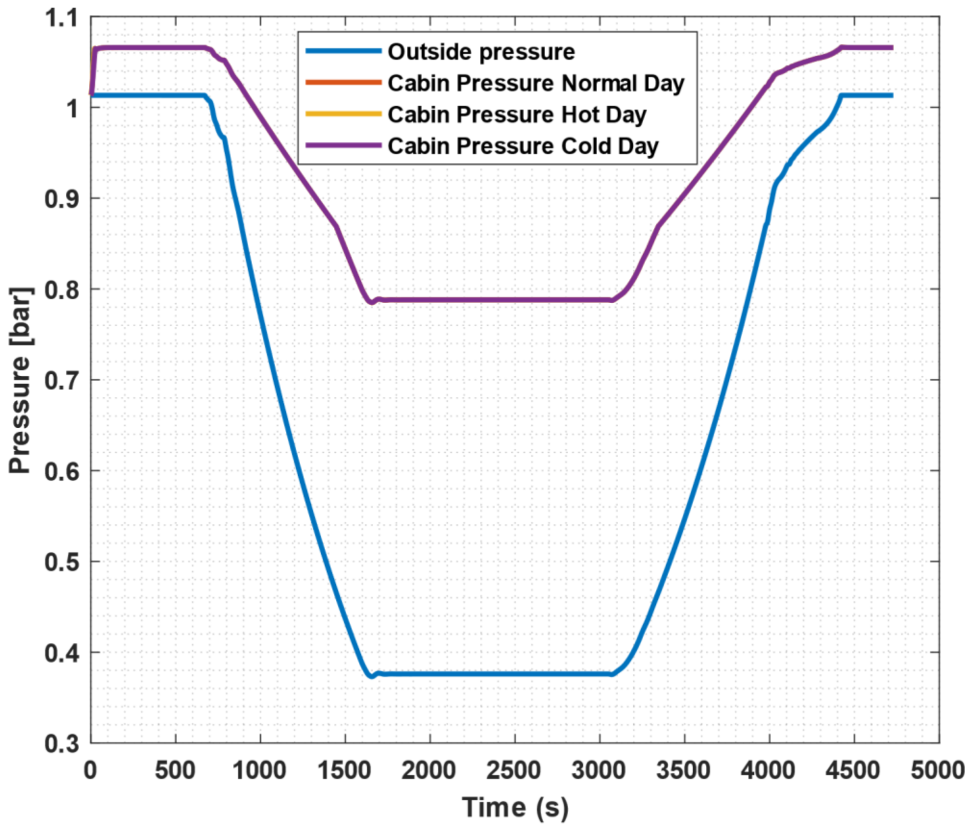
Digital Twin – Fuselage

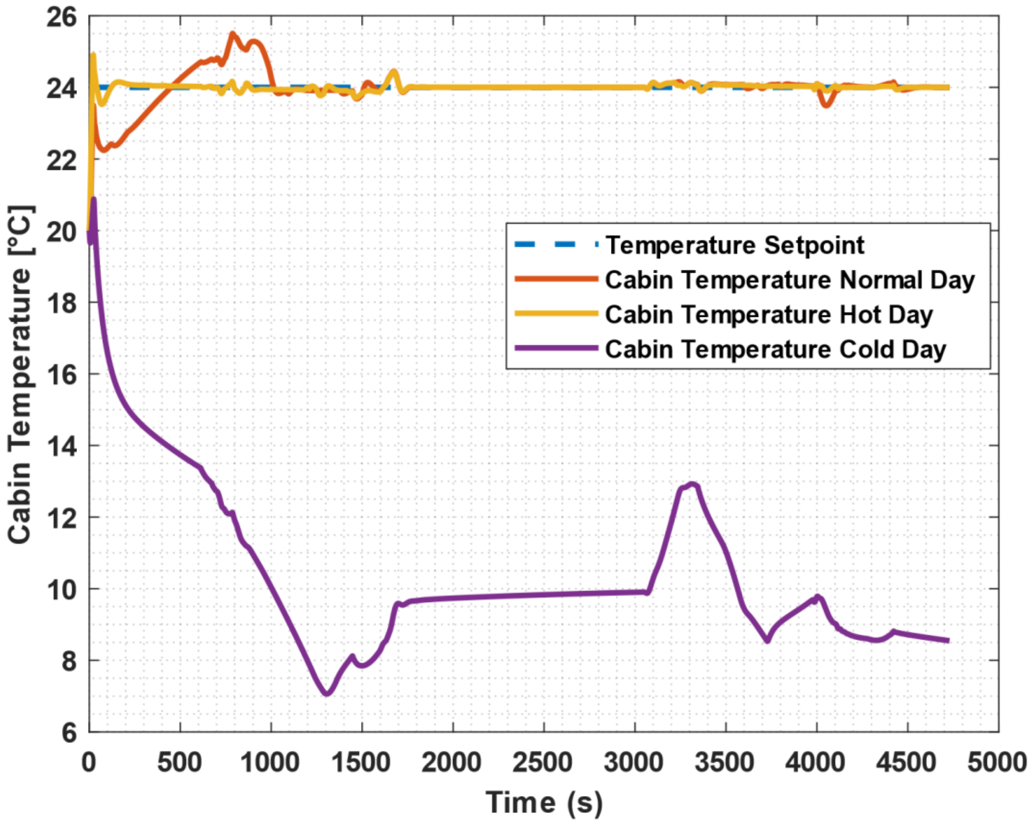


Digital Twin – Environmental Control System



Results





No heating system for cold day

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Integration of external models

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Integration of external models

- Function Mock Up Interface (FMI)
  - Developed in EU project in ~2010 in the Automotive Industry
  - Enables to assemble a virtual product from submodels developed in different software tools
  - For testing the overall system behaviour (e.g. Efficiency and Safety)
  - Possible to share the Functional Mock-Up Unit (FMU) as black box
  - Supported by ~200 Tools

fmi-standard.org

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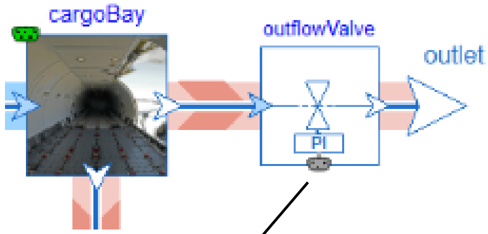
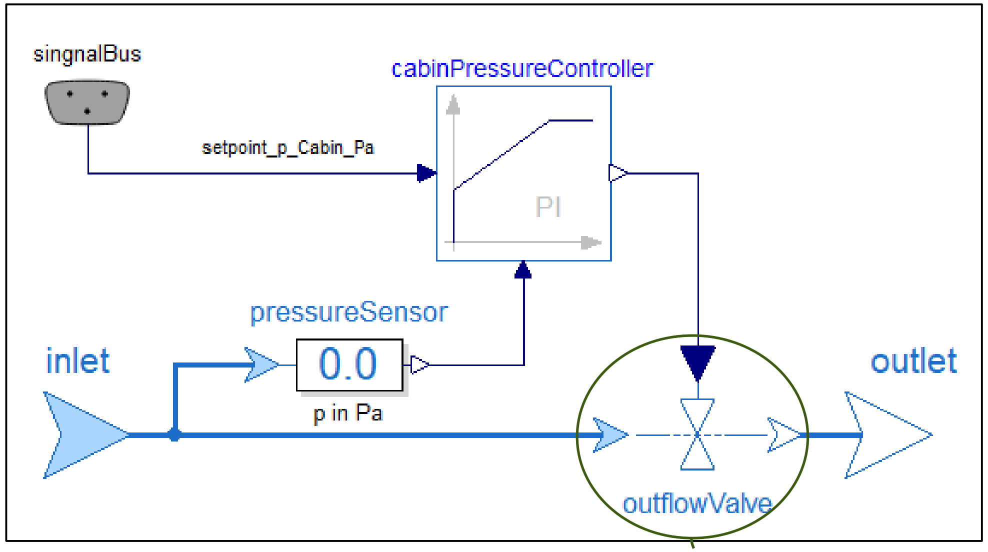
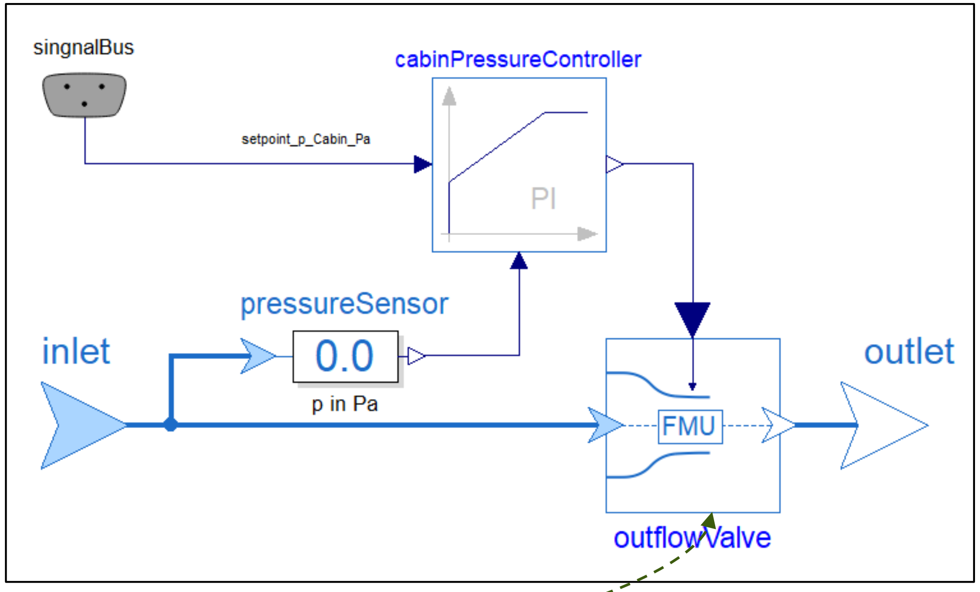
Integration of external models - Outflow Valve



ThermoFluidStream Outflow valve

Integrated FMU Outflow valve





Replaced by

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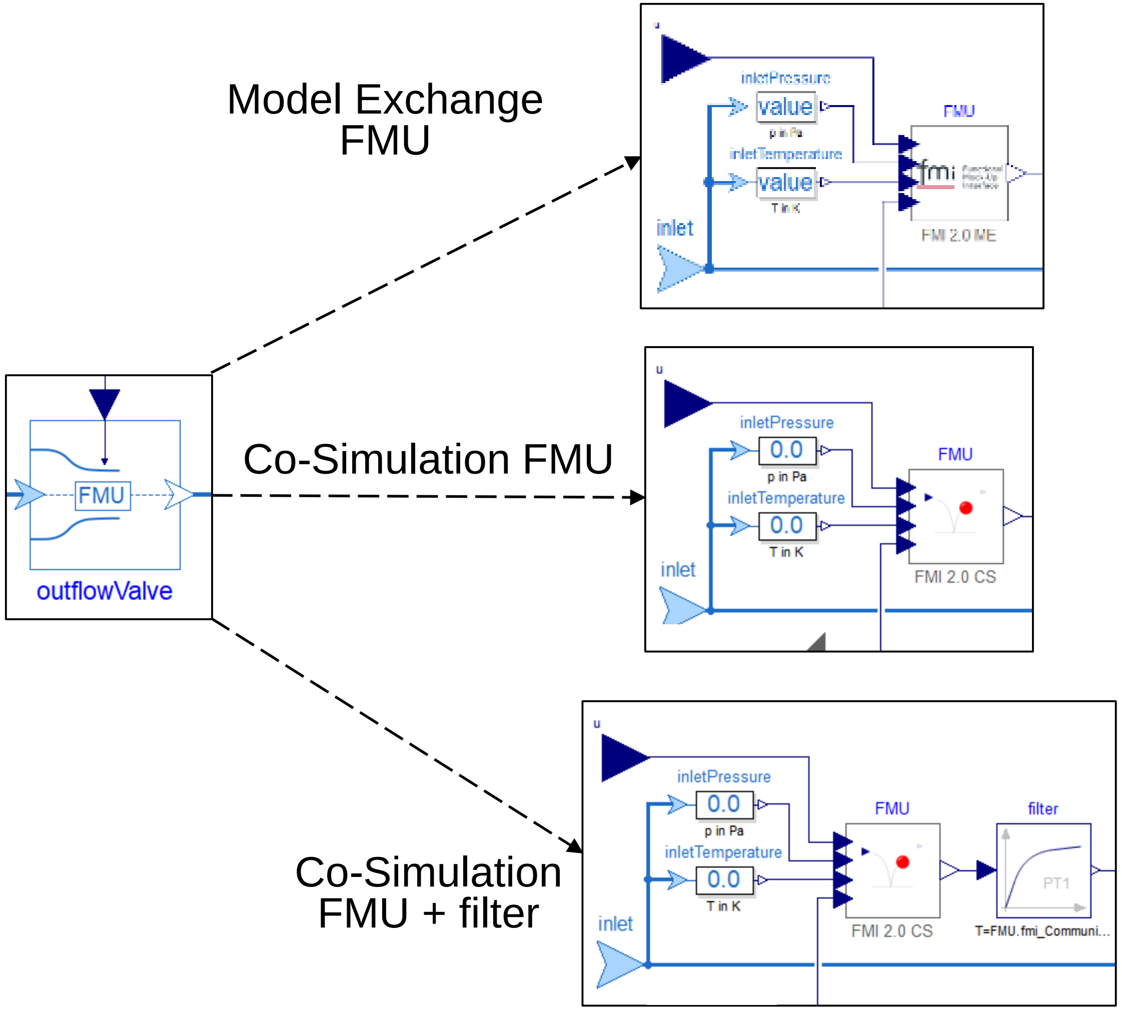
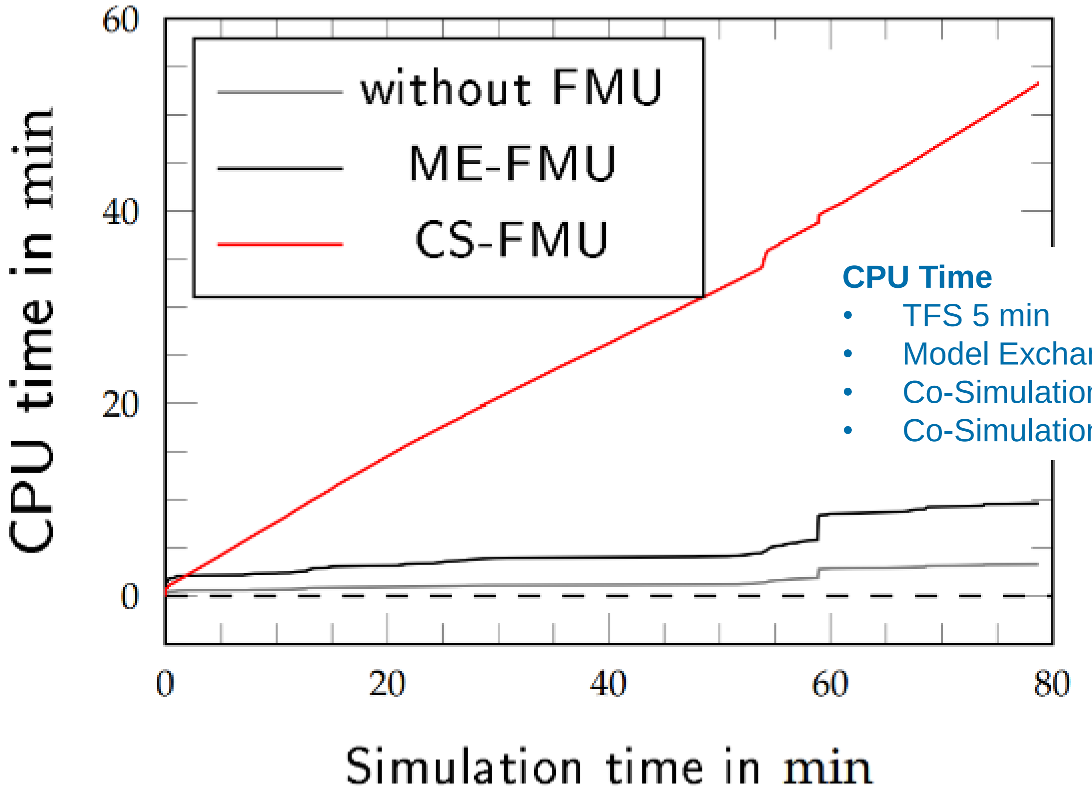
Co-Simulation vs Model Exchange





CPU Time

- TFS 5 min
- Model Exchange 10 min
- Co-Simulation + filter 1 h
- Co-Simulation >> 1 h

- Model Exchange is faster and more accurate

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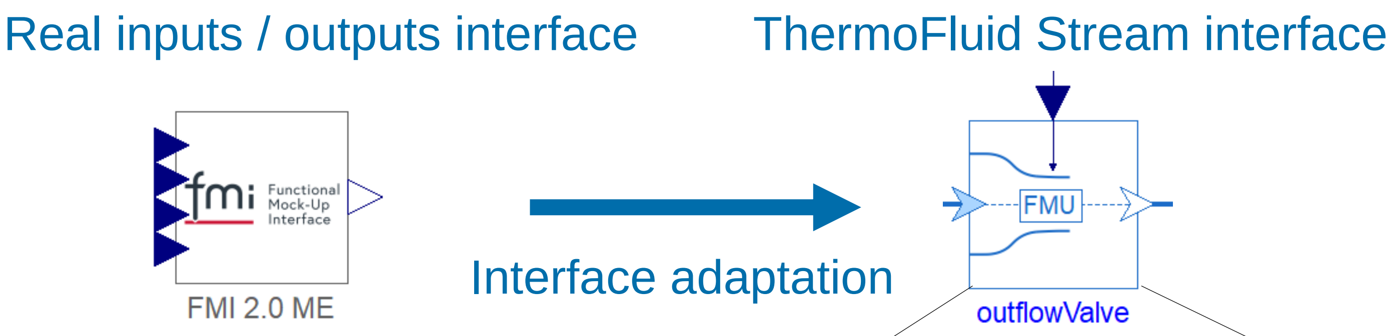
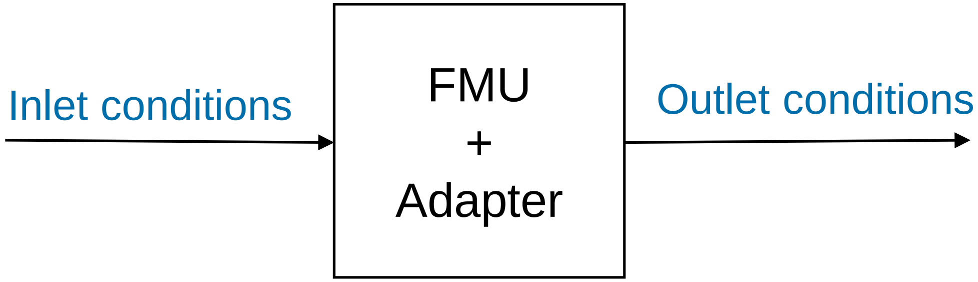
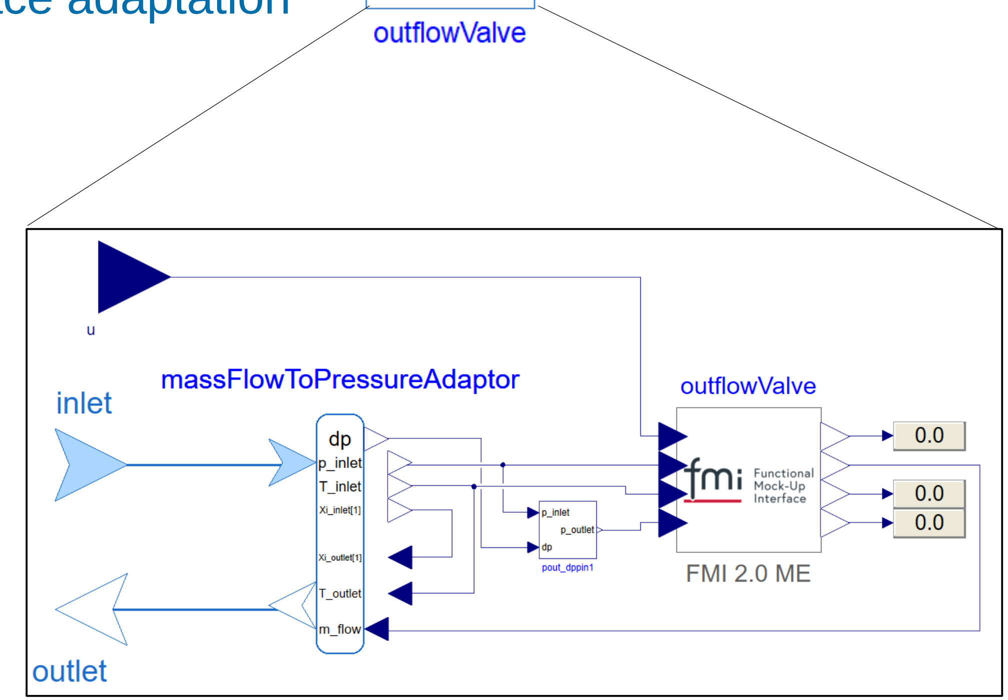
Integration of external models - Outflow Valve

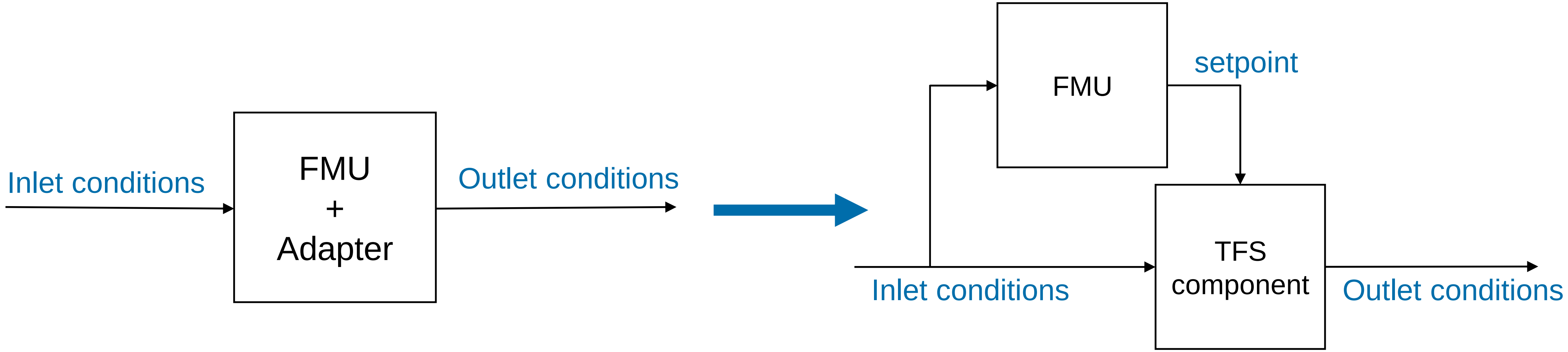




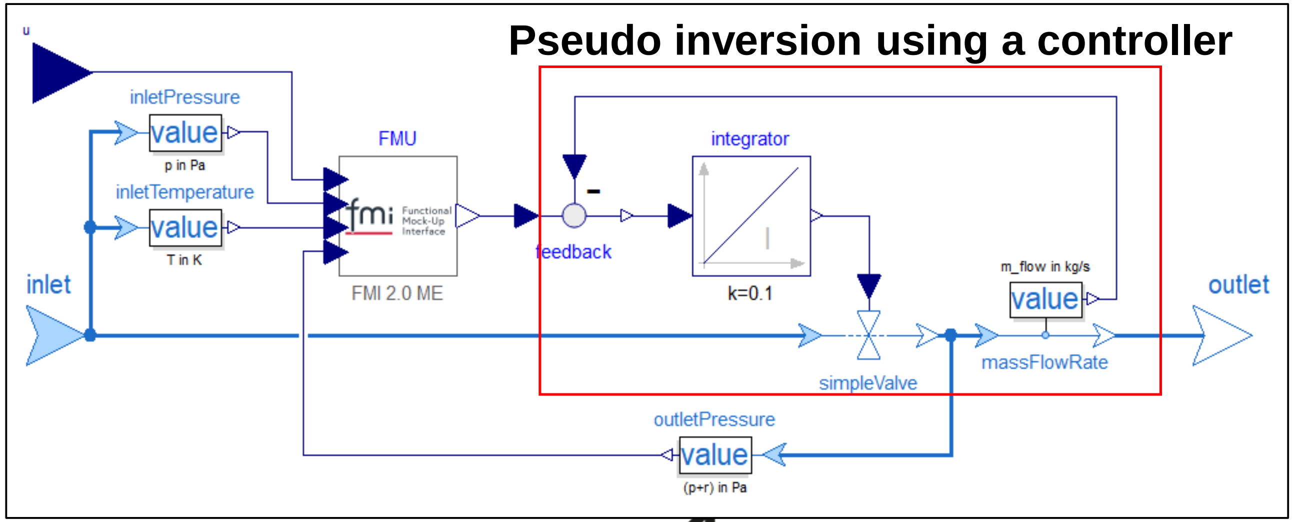


- Common for Modelica Standard Library
- Difficult for Fluid libraries
- Might deteriorate all benefits of the TFS library concerning e.g. robustness, nonlinear equation systems, …

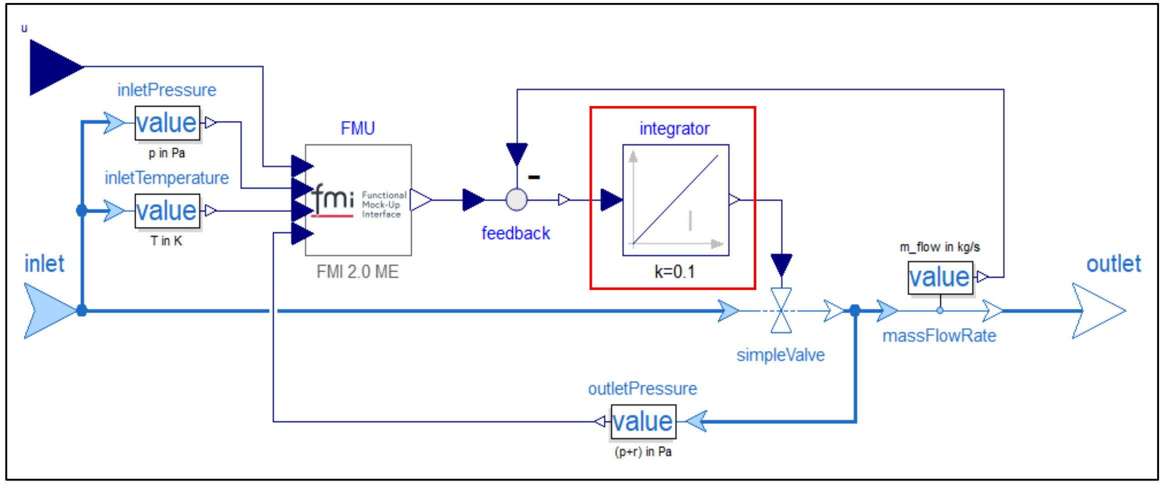
Integration of external models - Outflow Valve

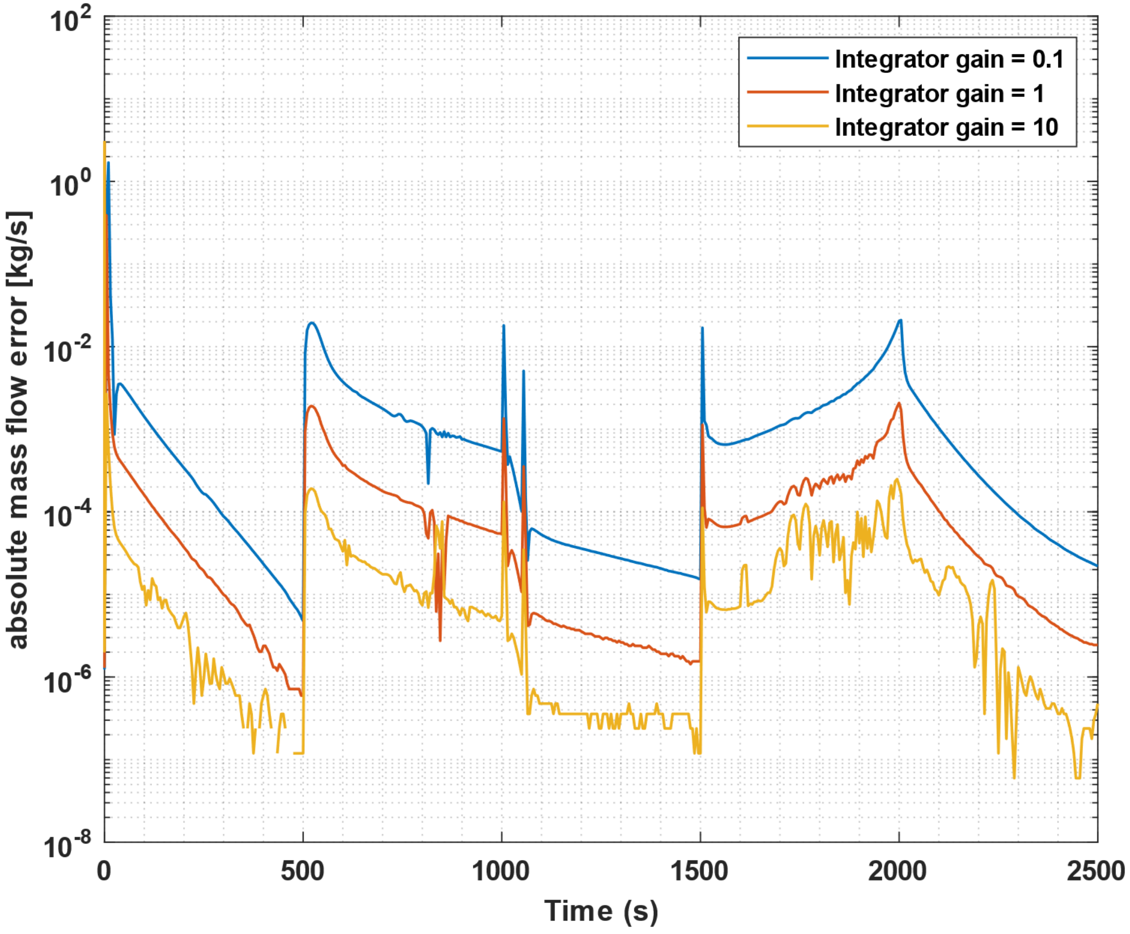


Control a TFS component to mimic the behaviour of the FMU model



Integration of external models - Outflow Valve





Control a TFS component to mimic the behaviour of the FMU model

- No additional systems of nonlinear equations
- No steady state error
- Transient error can be reduced with a fast controller to be neglectable (Beware about stability)
- Less initialization problems
- More robust
- Easy to implement

Conclusion and Outlook

- Virtually test the overall system behavior using FMUs from different partners in the project to support verification and validation
- Test the integration of several FMUs together.

➔To enable efficient and safe clean aviation of the future

Acknowledgements

The project is supported by the Clean Aviation Joint Undertaking and its members.

Clean Aviation is the EU's leading research and innovation program for transforming aviation towards a sustainable and climate neutral future. As a European public-private partnership, Clean Aviation pushes aeronautical science beyond the limits of imagination by creating new technologies that will significantly reduce aviation's impact on the planet, enabling future generations to enjoy the social and economic benefits of air travel far into the future.
Visit the website to find out more about Clean Aviation: www.clean-aviation.eu

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Thank you for your attention!

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References

[1] D. Zimmer, M. Meißner, and N. Weber, “The DLR ThermoFluid Stream Library,” Electronics, vol. 11, no. 22, 2022. [Online]. Available: https://www.mdpi.com/2079-9292/11/22/3790

[2] D. Zimmer, “Robust object-oriented formulation of directed thermofluid stream networks,” Mathematical and Computer Modelling of Dynamical Systems, vol. 26, no. 3, pp. 204–233, 2020. [Online]. Available: https://doi.org/10.1080/13873954.2020.1757726

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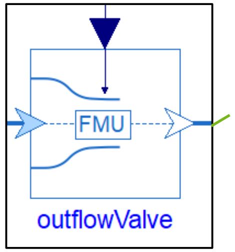
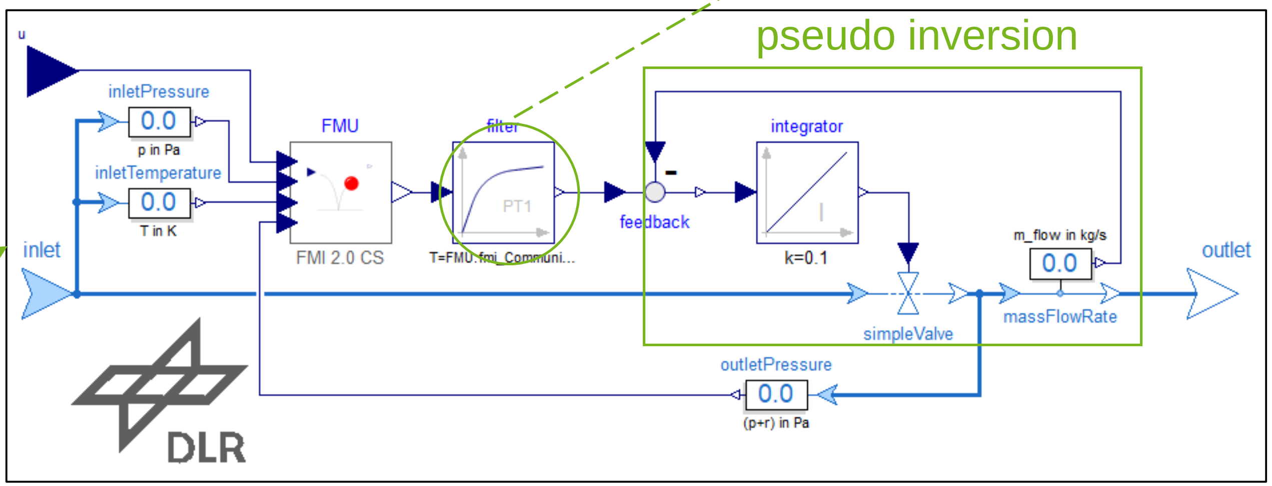
Outflow Valve

- Accelerates simulation

Co-Simulation FMU





Valve equations

$$\frac{\Delta p}{\Delta p_{\mathrm{ref}}} = -\frac{\rho}{\rho_{\mathrm{ref}}}\left(\frac{1}{k_u}\frac{\dot{m}}{\dot{m}_{\mathrm{ref}}}\right)^2$$

$$k_u = k_{\mathrm{min}}^{1-u}$$

Inversion

$$k_u = \sqrt{-\frac{\Delta p}{\Delta p_{\mathrm{ref}}}\frac{\rho_{\mathrm{ref}}}{\rho}\frac{\dot{m}}{\dot{m}_{\mathrm{ref}}}}$$

$$u = 1 - \frac{\ln k_u}{\ln k_{\mathrm{min}}}$$

- Explicit inversion is barely possible

Pseudo inversion

$$\frac{\mathrm{d}u}{\mathrm{d}t} = k(\dot{m} - \dot{m}_{\mathrm{sensor}})$$

- Creates an additional state (stability, stiffness)
- More robust
- Sometimes even faster

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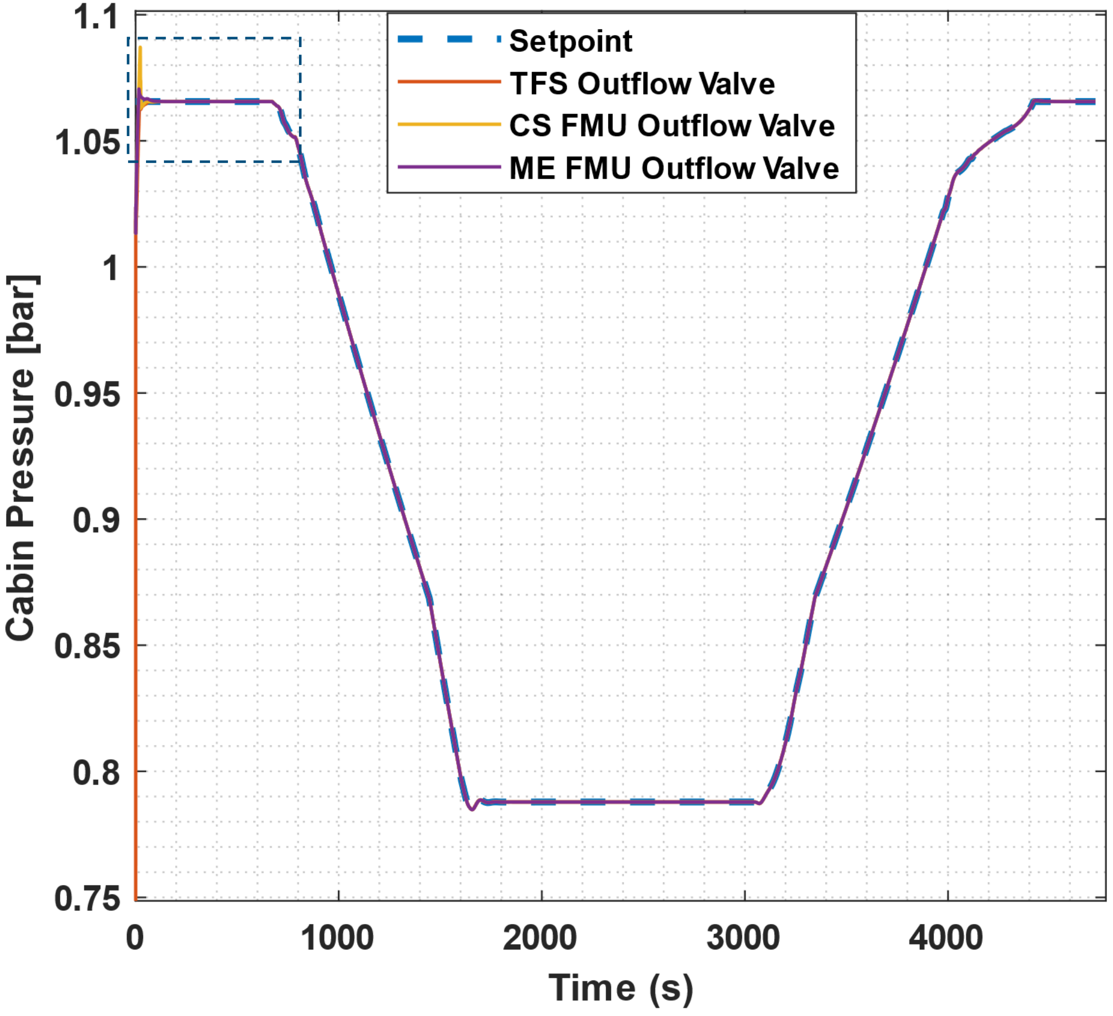
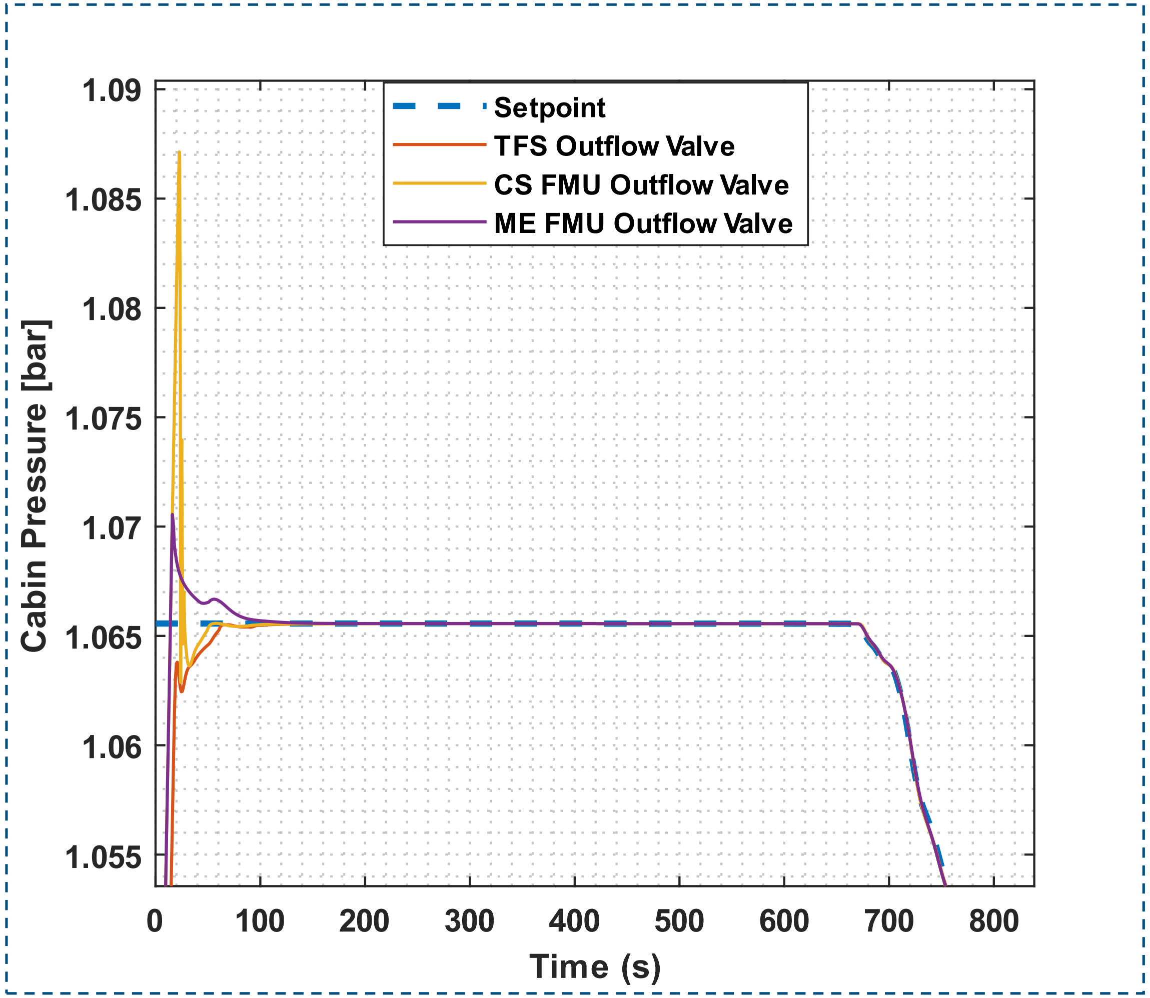
Results

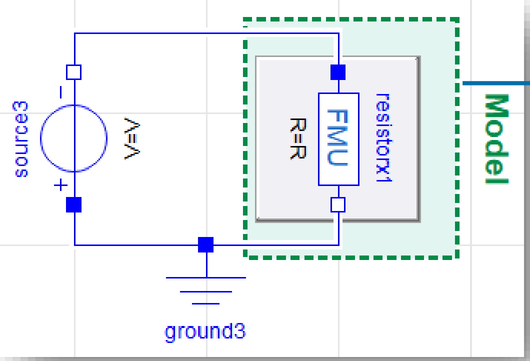


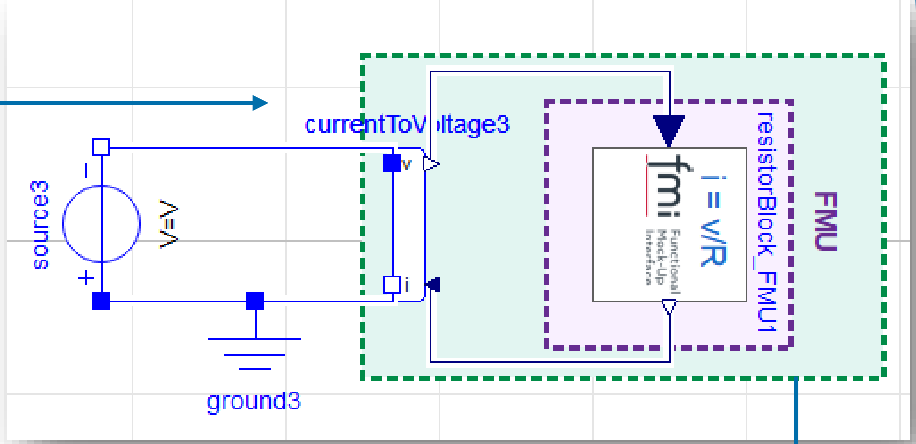
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
Cabin Pressure [bar]
0
1000
2000
3000
4000
Time (s)
Setpoint
TFS Outflow Valve
CS FMU Outflow Valve
ME FMU Outflow Valve

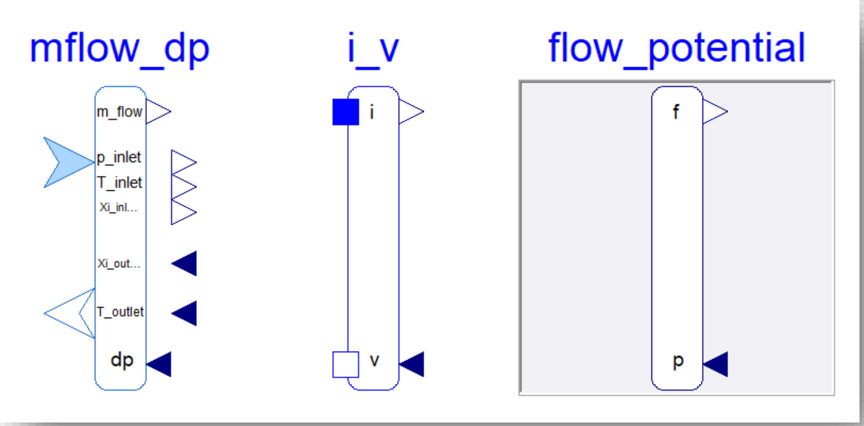


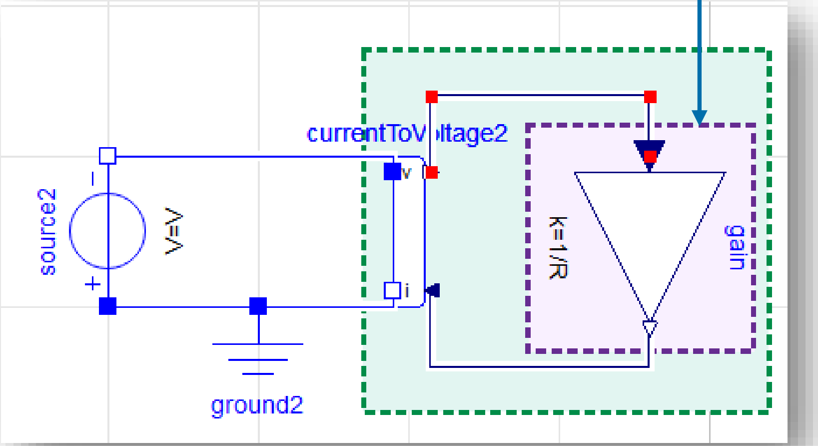
1.09
1.085
1.08
1.075
1.07
1.065
1.06
1.055
Cabin Pressure [bar]
0
100
200
300
400
500
600
700
800
Time (s)
Setpoint
TFS Outflow Valve
CS FMU Outflow Valve
ME FMU Outflow Valve

Adaptors are Well Known For other physical domains









- **Derived from the same base class as adaptors from the Modelica Standard Library**
- **Work in both way, e.g. flow -> pressure or pressure -> flow**

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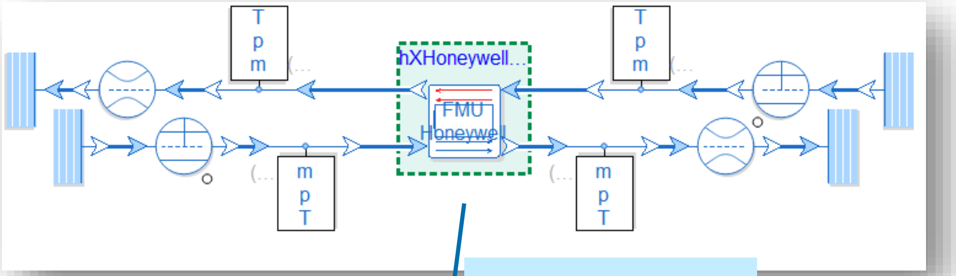
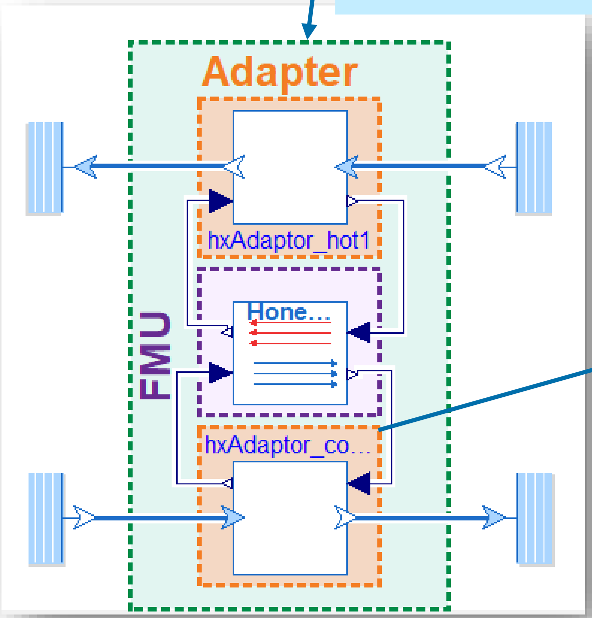
Use of Non-Modelica models: TFS adaptors

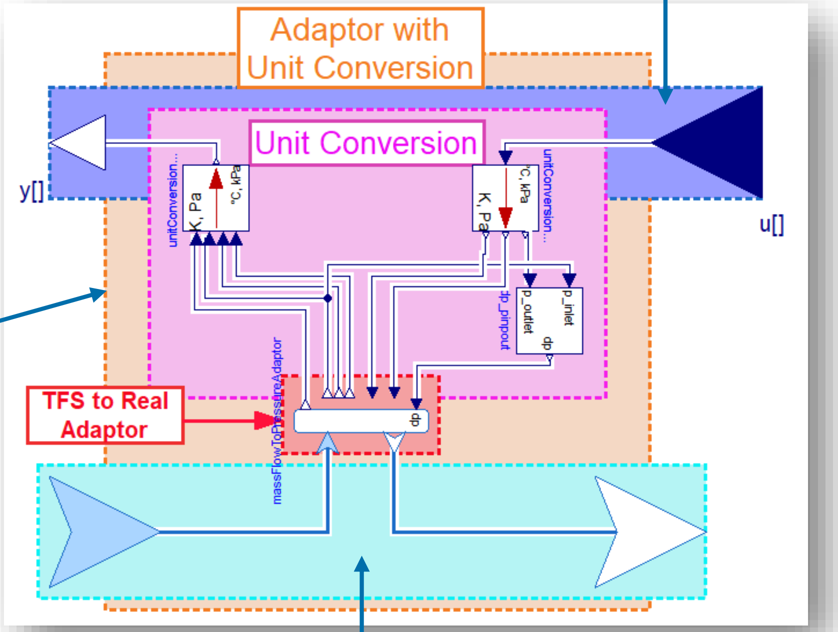


Model with FMU inside



Creation of an adaptor for the TFS library

Real input/output for FMU, Modelica blocks, C functions, etc



ThermoFluidStream