# Methodology applied to couple 1D & 3D models on HPC in context of electric vehicle FIAT 500e thermal management design

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**Summary**

In this article, a smart methodology of coupling simulation between Simcenter Amesim and Simcenter Star-CCM+ is defined. It has been implemented to improve, from a thermal point of view, both 1D *Model in the Loop* simulation and 3D *Computational Fluid Dynamics* simulation; in fact, CFD receives from 1D MIL more accurate boundary conditions, and in turn gives back results to MiL that uses more accurate data to run. Furthermore, CFD simulation has been performed by using High Performance Computing (HPC). In this way *thermal management* development is improved with higher level of fidelity for the electric vehicle.

## 1 Header

In the last decades, the design world has been deeply transformed by computer science. Many industries, including automotive, rely on this technology to develop new products and test processes virtually, thus the need of physical prototypes has been reduced. 1D-3D coupling is already widely used in different domains since the last 2 decades, especially in electronic domain [1], combustion [2] or hydraulic system [3]. Such approach is relevant for component design to enhance local behaviour which cannot be properly modelled in 1D. Almost all simulation tools propose strong coupling, meaning with small communication time. Some new approach has been developed by Siemens Industry Software, by using smart coupling between Simcenter Amesim and Simcenter Star-CCM+ [4]. Nevertheless, only one 1D model and one 3D model have been coupled up to now due to computation power. The novelty of the proposed methodology is to connect several 3D models with single one 1D model used as "variable boundary condition" supplier along some transient scenario by using smarter coupling strategy.

This virtual methodology is implemented in order to improve development of electric vehicles, analyzing all systems and subsystems in different drive cycle scenarios. In this work the focus is on thermal management design, because optimization of energy consumption has become of fundamental importance in electric vehicles, especially to increase autonomy.

As reference case to test the application study, pure electric vehicle FIAT 500e, sold in United States since 2013, has been considered (Fig. 1).
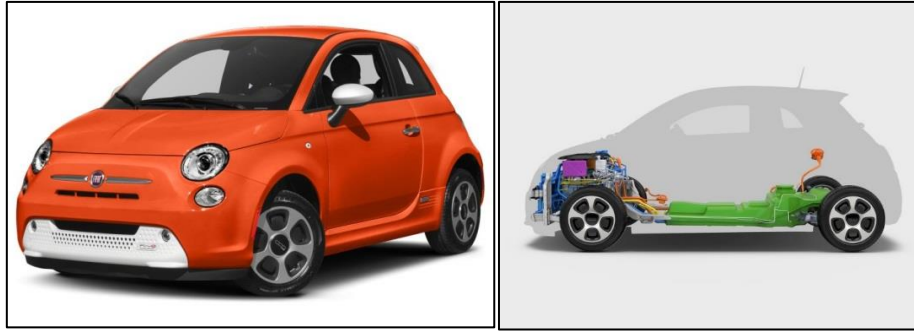
Figure1: FIAT 500e

# 2 Coupling approach

## 2.1 1D vehicle model

1D model is used to simulate components and subsystems of the electric vehicle (battery, inverter, electric motor, cooling system, HVAC and others), replicating how they work and which I/O are required or provided. They are mutually linked to simulate the behaviour of a whole vehicle in real driving conditions, as shown in Fig. 2 for FIAT 500e. Focusing on the thermal management, such numerical simulations can provide information about the temperatures of each component and therefore the influence of the AC system on the vehicle range, through the electric consumption of the compressor. Simcenter Amesim V17 has been used for the 1D modelling.
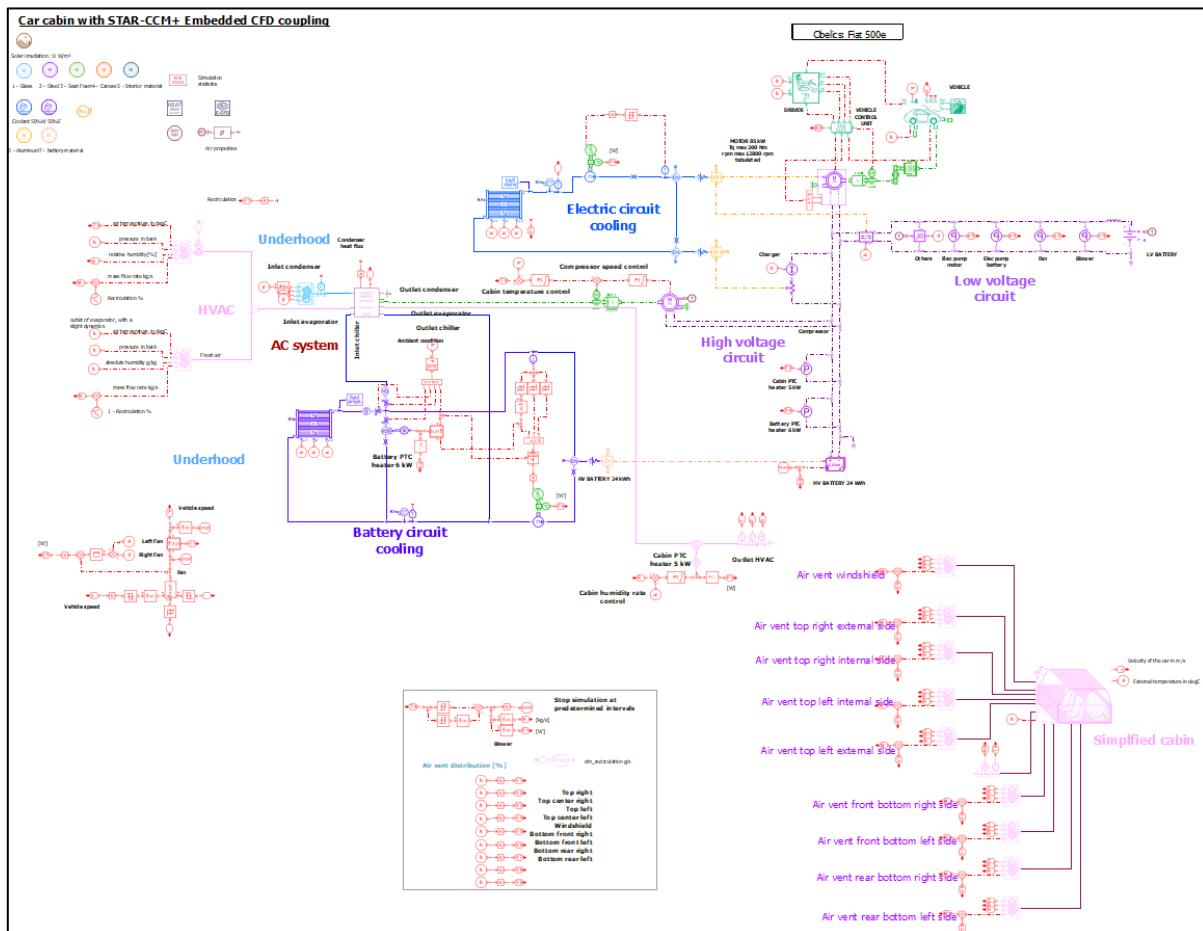


Figure2: Simcenter Amesim 1D for FIAT 500e

### 2.1.1    Electric powertrain

The electric powertrain consists of three main components which are the battery, the inverter and the electric motors as well as different other electric consumers.

In the context of coupling methodology, functional models have been used. So, motor and inverters have been merged by considering global losses, which are transferred to the thermal model. Functional information is given in Table1. Nevertheless, this methodology can be applied with more details on electric components.

Table1: main characteristics of the motor

| Motor characteristics | |
| --- | --- |
| Overall efficiency (-) | 0.92 |
| Maximum torque (Nm) | 200 |
| Maximum power (kW) | 85 |
| Maximum speed (rpm) | 12800 |

Motor model calculates torque (Nm), heat loss (W) and output current (A) based on motor speed (rpm) and input voltage (V). The battery is a Li-Ion Ni-rich NMC-C and the corresponding model has been validated by IFP Energies Nouvelles [5].

Additionally, others electric components have been included, especially ones dealing with thermal management. Indeed blower, fan but also electric pumps must be accounted to have a better estimation of the vehicle range. These components are connected to the main electric circuit through a DC/DC converter from 390 V to 14.5V. Efficiency of the converter is also considered, and electric losses are transferred to the thermal model.

Finally, two Positive Temperature Coefficient (PTC) heaters are used for battery heating in one hand and cabin heating in other hand. All these electric powers consumed by these different components are summarized in the Table2.

Table2: main electric consumption

| Electric circuit consumer (W) | Low voltage | High voltage |
| --- | --- | --- |
| Powertrain pump | 25 | |
| Battery pump | 25 | |
| Fan | 600 | |
| Blower | 300 | |
| Battery PTC heater | | 8000 max |
| Cabin PTC heater | | 5000 max |
| AC compressor | | 7000 max |

### 2.1.2    HVAC & Cabin

The 1D cabin model is used in complementary to the 3D cabin model. Indeed, in this model, thermal walls are considered as well as average air volume temperature. These temperatures are then used in the HVAC control. In the Table3 are listed all heat exchanges between cabin volume split in 10 areas and walls.

Table3: heat exchange in cabin for each area

| Areas | Glass | panel | Roof | Floor | Internal |
| --- | --- | --- | --- | --- | --- |
| Windshield | Windshield | | | | Dashboard |
| Top Front Right | Side glass | | Roof | | Dashboard & Front seat |
| Top Front Left | Side glass | | Roof | | Dashboard & Front seat |
| Top Rear Right | Side glass | | Roof | | Front seat |
| Top Rear Left | Side glass | | Roof | | Front seat |
| Bottom Front Right | | Side panel | | Floor | Front & rear seat |
| Bottom Front Left | | Side panel | | Floor | |

| | | | Front & rear seat |
|---|---|---|---|
| Bottom Rear Right | Side panel | Floor | |
| Bottom Rear Left | Side panel | Floor | Front & rear seat |
| Rearshield | Rearshield | | Front & rear seat Rear shelf |

Radiative heat transfer (W) is considered, especially in glass component where solar heat flux is partially absorbed and transmitted.

Roof and side panel being not only made with one material, several layers of materials and air gap are modelled to calculate conductive heat exchange (W).

The Heat Venting Air Conditioning (HVAC) system is composed of the evaporator, which will be described in the thermal management paragraph and the cabin PTC heater, already described in the previous paragraph.

### 2.1.3    Thermal management

The thermal management model is composed of three main subsystems, which are physically connected with the underhood (from the 3D vehicle model):

- Battery cooling circuit

- Powertrain cooling circuit

- AC system

The battery cooling circuit is composed of 3 different branches, according to the external temperature:

- Chiller branch if external temperature is hot

- Battery PTC heater branch if external temperature is cold

- Battery radiator branch otherwise

The powertrain cooling circuit is composed by powertrain radiator, electric pump and internal flow inside motor and inverter. Pump is working function of the coolant temperature at motor outlet.

The AC system is modelled with functional components:

- Condenser

- Evaporator

- Thermal expansion valve

- Compressor

- Chiller

## 2.2    3D models

Even if 1D model can connect all these subsystems of the vehicle, it cannot reply properly some physical phenomena. This is the case of air flow and all its derivatives, which calculation needs very complex and expensive models. The only way to obtain a high-fidelity simulation is using 3D models, in particular *Computational Fluid Dynamics* (CFD).

For this methodology, air flow is calculated in two different domains, which makes two 3D models, as illustrated in Fig.3:

- Vehicle model: simulation of external flow around vehicle and under the hood

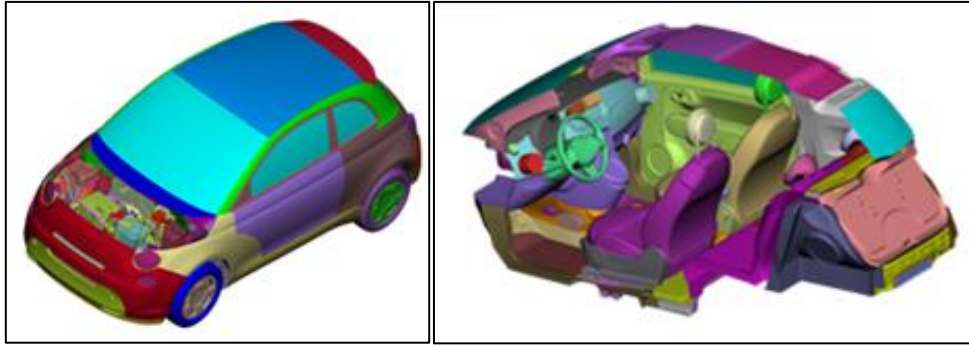- Cabin model: simulation of internal flow for passenger comfort

Figure3: External vehicle and cabin CAD geometries of FIAT 500e

For both simulations, solver used has been Simcenter Star-CCM+ 12.06.011 and same procedure was applied with following steps:

- Watertight geometry definition
- Surface mesh generation
- Volume mesh generation
- Setting CFD model
- Running
- Post-processing

In the next paragraphs both 3D simulations are described in detail.

### 2.2.1    Vehicle model

Vehicle model simulates the air flow around the whole vehicle, while it is moving forward with a certain velocity. The domain is a big box that replicates open air condition as illustrated in Fig.4.

Basic information about model setup are:

- Solver: RANS
- Turbulence model: K-ε
- Trimmed volume mesh
- Number of elements: ~ 15M
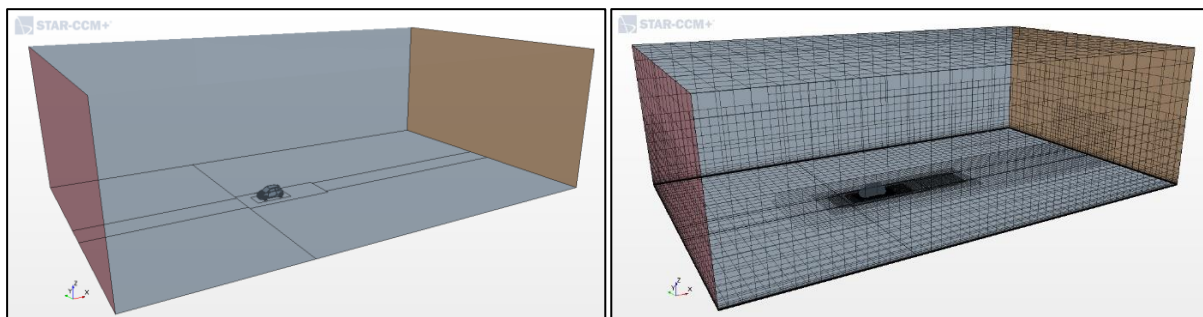


Figure4: External vehicle domain and surface mesh

For thermal management, heat exchangers behaviour becomes fundamental and therefore analysis is highly focused on mass flows, inlet velocities and inlet temperatures on them.

In Fig.5, FIAT 500e heat exchangers configuration is clearly showed:

- Battery radiator (brown colour)

- Condenser (grey colour)

- Powertrain radiator (green colour)

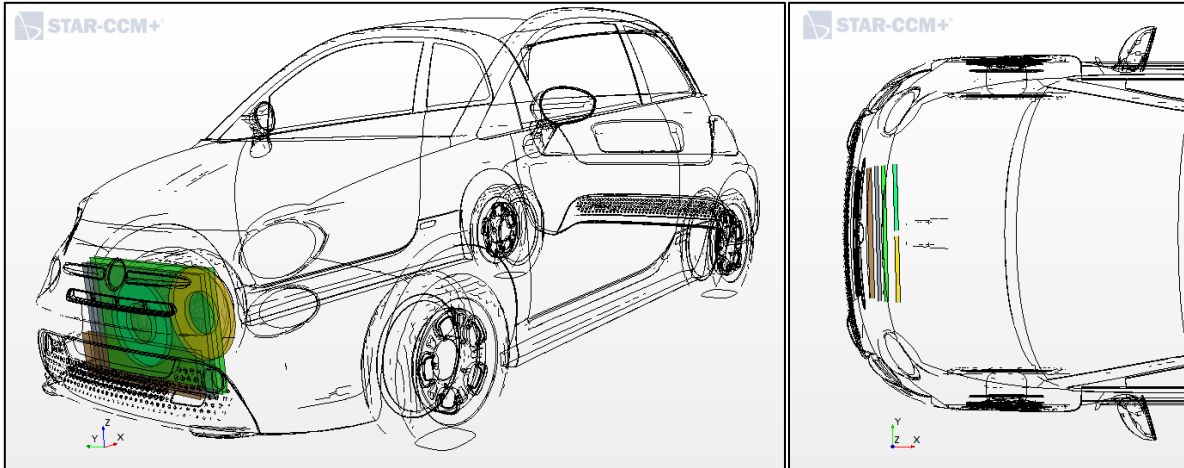- Double fan (green and yellow colours)



Figure5: Heat exchangers and fans.

### 2.2.2 Cabin model

Cabin model (Fig.6) simulates the internal air flow, necessary to heat or cool down cabin for passenger's comfort, studying distribution of velocities inside the vehicle and the convection with internal walls.

Basic information about model setup are:

- Solver: RANS

- Turbulence model: K-ε

- Polyhedral volume mesh

- Number of elements: ~ 1M

- Cool down mode
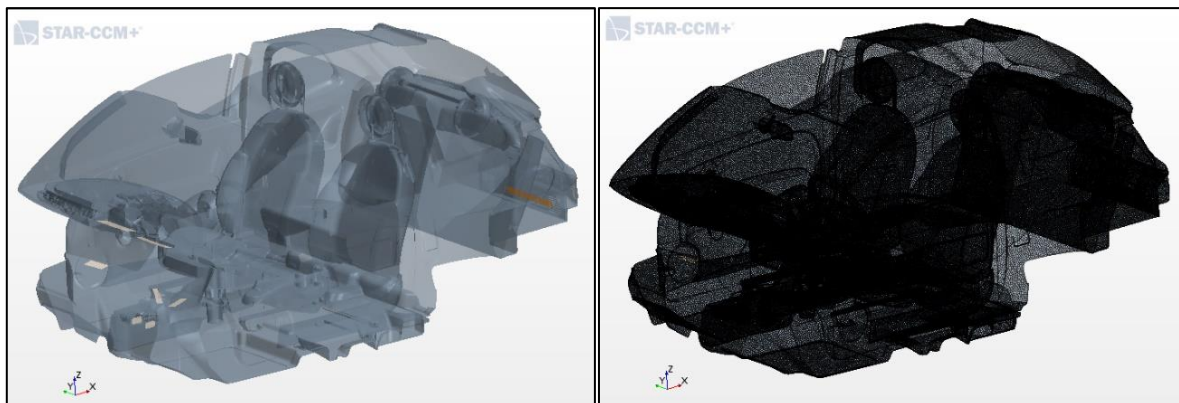


Figure5: Cabin domain and surface mesh

In order to exchange distribution of velocities, the cabin is split into smaller volumes divided by interfaces (orange faces shown in Fig.6). In this way, mass flows between volumes are calculated and provided to Simcenter Amesim.
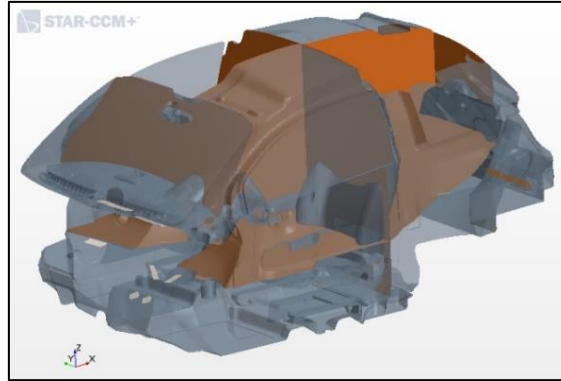
Figure6: Interfaces between cabin sub-regions

## 2.3 HPC

The aim of High Performance Computing (HPC) is to provide the computational power for the simulations needed for virtual design and validation phases. The use of HPC is limited to applications that require high computing performances; focusing the attention to the scope of this work, the main application that will need such amount of resources will be the 3D simulation because it relies on data obtained from Computational Fluid Dynamics analysis. 3D models are launched separately on HPC server by specific scripts basing on call strategies, which are different for both models. But even so, there is still a significant gap between the time needed from 1D and 3D simulation. Anyway, entire simulation with all drive cycle becomes affordable in terms of time: using ~300 CPUs, whole simulation (1D model calling several 3D models) runs in a few hours, depending on driving cycle duration.

## 2.4 Coupling strategy applied on electric vehicle

Coupling strategy applied in this project consists on running 1D model and calling 3D model only when it is necessary. Calling strategy are summarized in the Table4.

Table4: coupling strategies

| 3D model | Vehicle | Cabin |
|---|---|---|
| Vehicle speed | $\Delta V > 5\,m/s$ | |
| Fan | Fan on/off | |
| Blower | | Blower position |

A dedicated component is used in the 1D model to stop the simulation when one of these criteria is achieved. Then when CFD calculation is completed, different boundary conditions to the 3D models are transferred from1D model and vice versa, as illustrated in Fig.7.
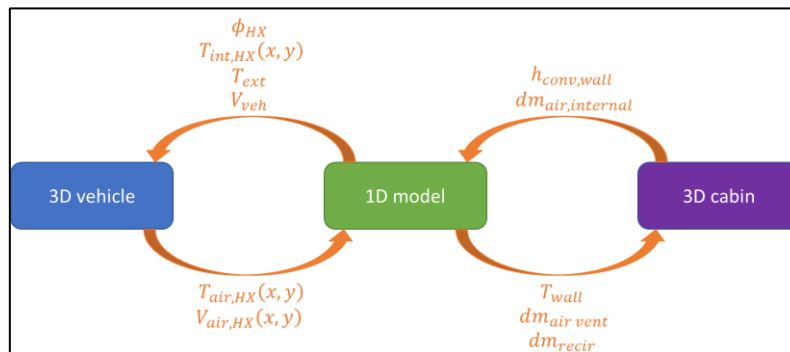


Figure7: Variables exchange between 1D model and 3D models

Heat exchanger heat fluxes, heat exchanger internal temperature, ambient condition and vehicle speed are transferred to 3D vehicle model and wall temperature, HVAC air vent and recirculation mass flows rates distribution are transferred to 3D cabin model. On the other hand, also 3D models transfer some results to

1D model: air velocity and air temperature maps of each heat exchanger from 3D vehicle model, and heat transfer coefficient and mass flows through cabin volumes from 3D vehicle.

# 3 Results

Different driving cycles have been tested to validate the procedure:

- WLTC
- NEDC
- Real driving cycle (Urban, Extra-urban)

Also different ambient temperatures were considered, to verify the influence.

## 3.1 1D model

Methodology has been validated on different conventional driving cycles, like the NED and WLTC. We can observe on both driving cycles, when 3D vehicle model has been called, as shown in Fig.8. Each vehicle speed step of 5 m/s, except at low speed, generates a call. The number of calls can be modified by changing the vehicle speed step: lower is it, higher is the number of calls.

We can observe minimal reference speed is not set at 0 km/h when vehicle is standstill, and therefore 3D model runs with a minimal velocity. 3D simulation with free convection will be investigated later.
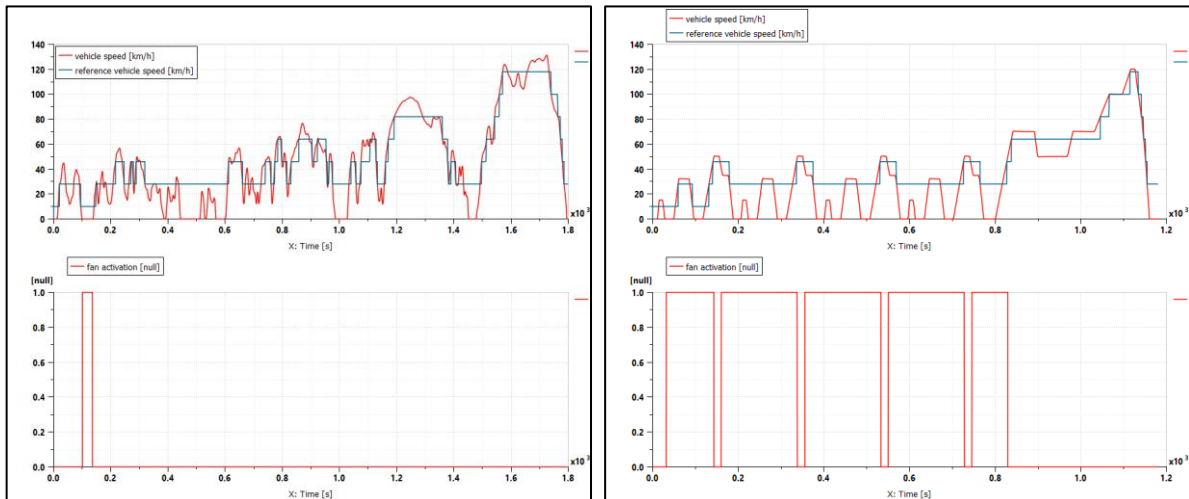


Figure8: Vehicle speed and fan activation during WLTC and NEDC driving cycle

Fan activation also allows a 3D vehicle model call. We can observe on NEDC driving cycle fan is almost activated at low speed, which is not the case with WLTC.

Fan control doesn't correspond to the real control and has only been used for methodology validation. It will be enhanced to optimize the electric consumption in the electric vehicle.

Motor temperature is controlled with dedicated cooling circuit. In this example the pump is not working until coolant temperature achieves 45 degC, as observed in Fig. 9 with the sharp temperature decrease.
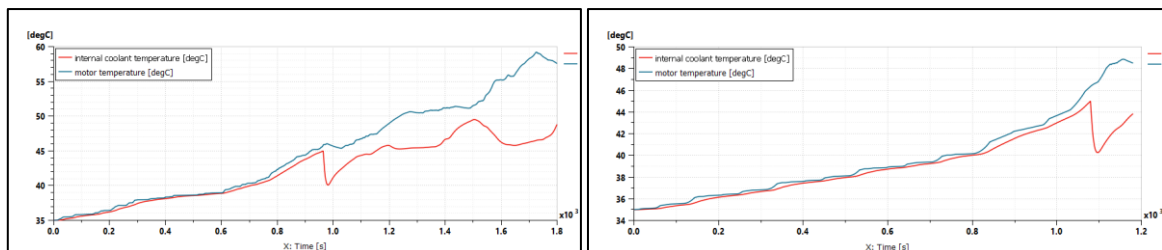


Figure9: Internal coolant and motor temperatures during WLTC and NEDC driving cycle

WLTC driving cycle has also been performed with two different external temperature; 25 & 35 degC to highlight the influence of the blower control on cabin coupling as shown in Fig.10. At 35 degC, only one 3D cabin call is necessary whereas 2 calls are necessary at 25 degC. This number of call will be increased with more complex HVAC control strategy.
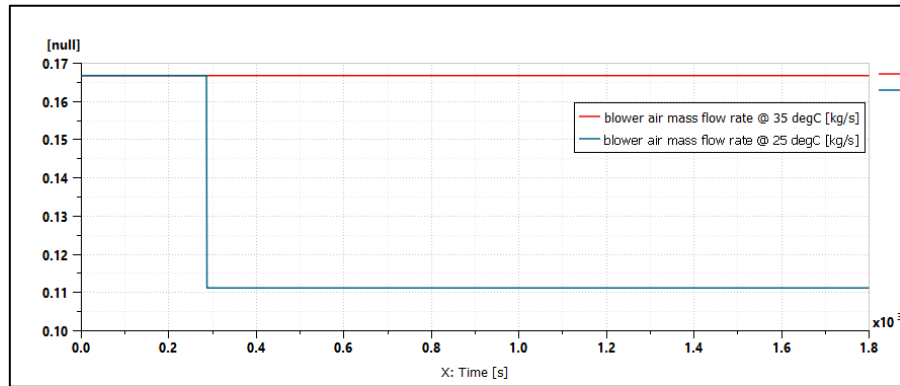


Figure10: Blower air mass flow rate during WLTC driving cycle at 35 & 25 degC

We can observe the influence on the AC system on the vehicle range thanks to the battery state of charge, as shown in Fig.11. In this comparison study, the difference is about 1.5%.
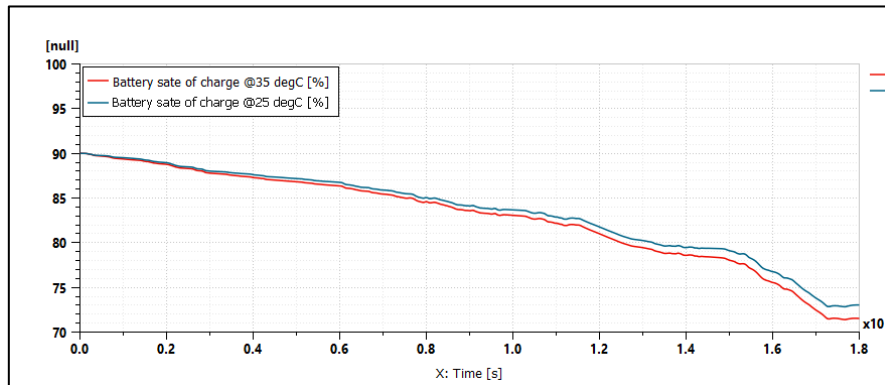


Figure11: Battery state of charge during WLTC driving cycle at 35 & 25 degC

The influence of the decrease of the blower air mass flow rate can be observed on average cabin temperatures, as shown in Fig.11. after 290s.
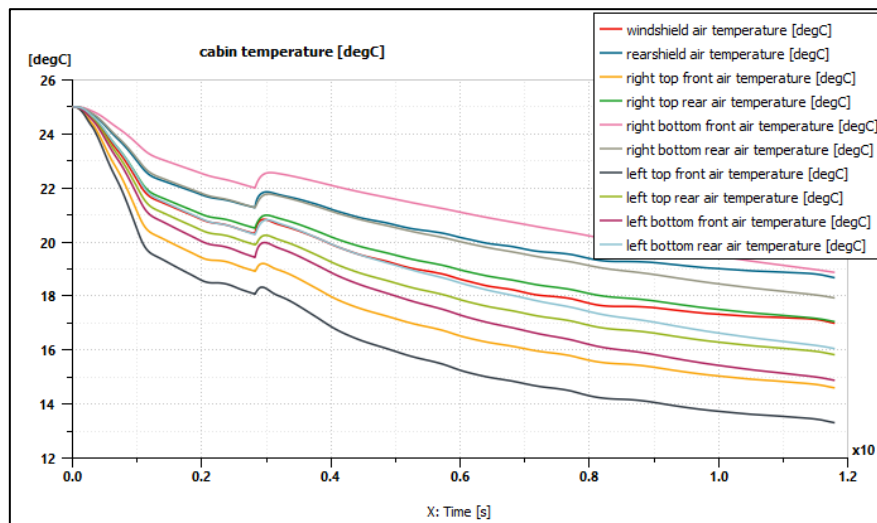


Figure11: average cabin temperatures during NEDC driving cycle 25 degC

This thermal behaviour doesn't correspond to the real behaviour but has been used to validate the coupling methodology and is considered as a reference for thermal management enhancement process.

This methodology can also be applied on real driving condition, as shown in Fig.12, allowing testing specific thermal management control validation.
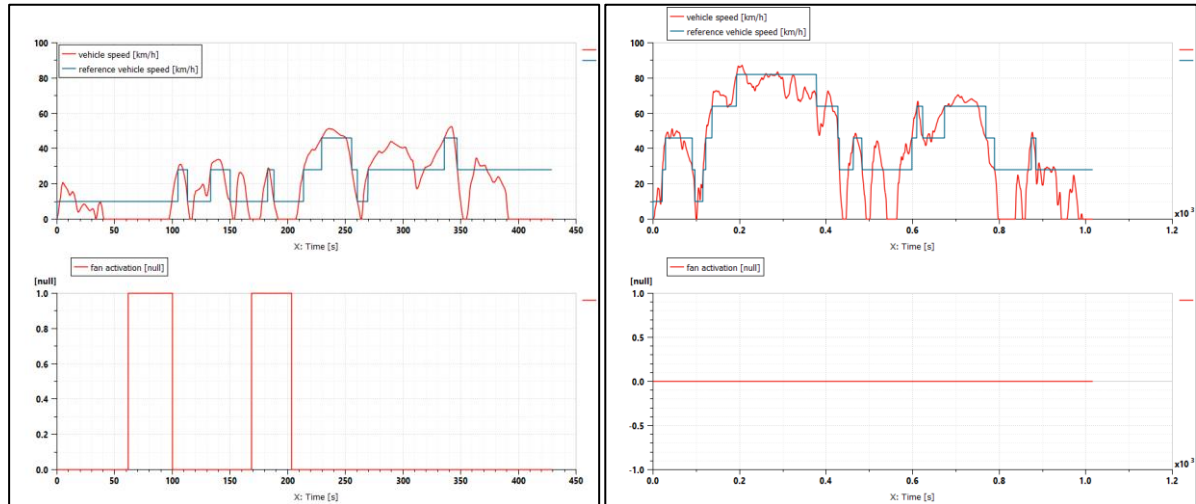


Figure12: Vehicle speed and fan activation during real urban and extra urban driving cycle

## 3.2    3D models

Simulating the flow field around a vehicle, under the hood and inside the cabin, CFD can provide every information that is needed. With this procedure, the great benefit is that boundary conditions are not anymore estimated but they are calculated by 1D Simcenter Amesim model. Therefore, potentially every interested instant or phase in a driving cycle can be studied in detail for each kind of application.

In the next figures, some 3D visualizations are shown. In particular they focus on measures that Simcenter Star-CCM+ calculates in order to use in 1D model, for both vehicle model and cabin model.
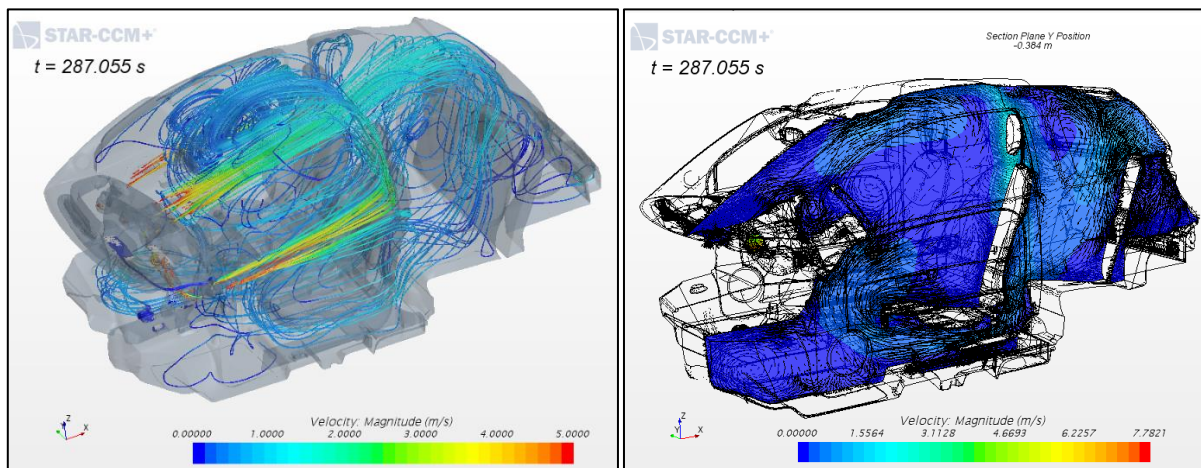


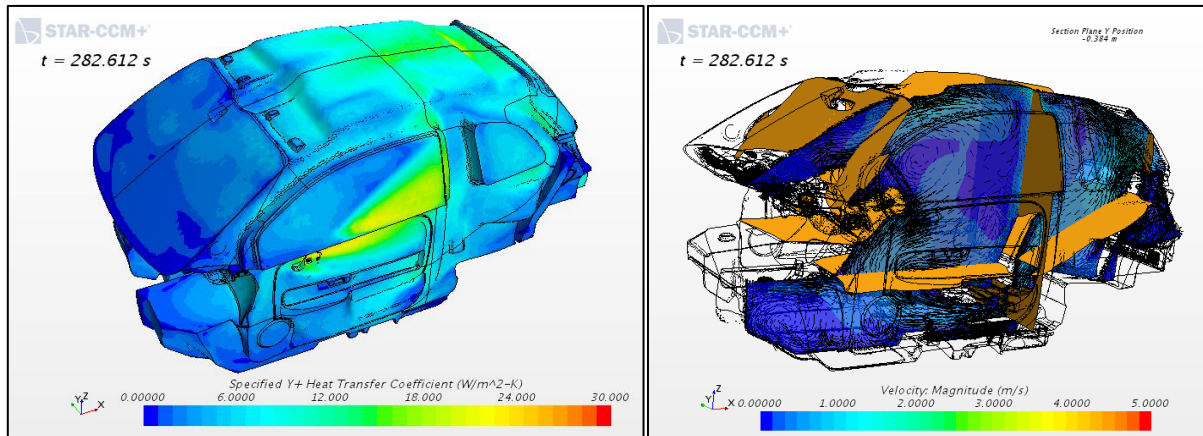Figure13: Velocity streamlines and  plane section with velocity magnitude

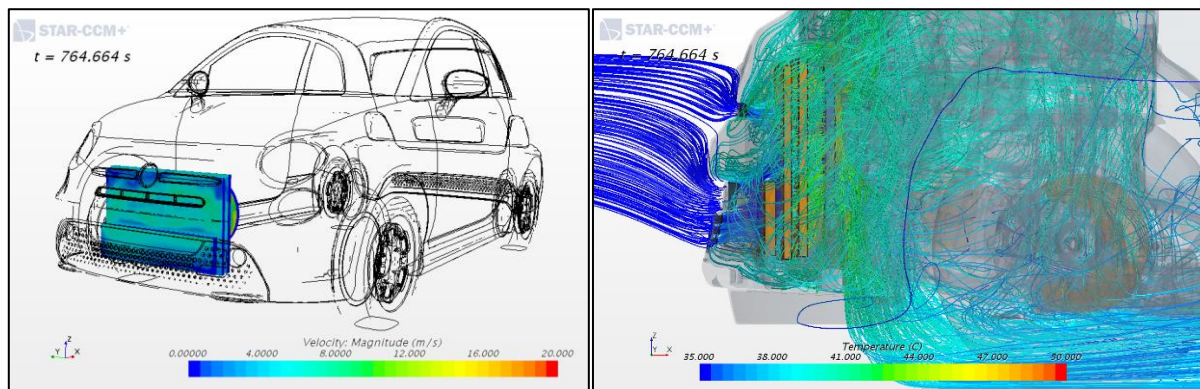Figure14: Heat transfer coefficient and mass flows through interfaces



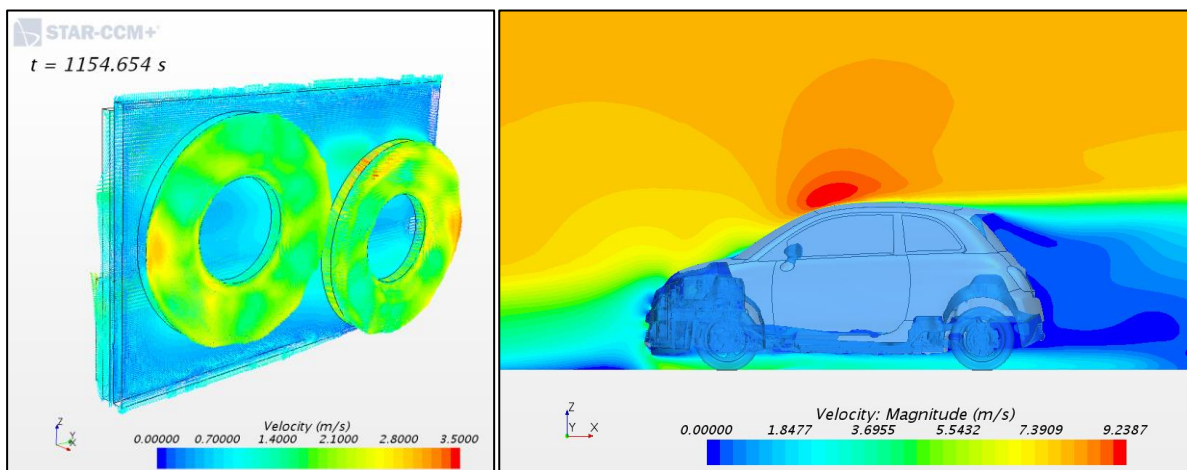Figure15: Heat exchangers velocity maps and temperature streamlines



Figure16: Heat exchangers velocity vector and midplane velocity section

## 4 Conclusion

With such coupling approach, overall simulation, even for long transient scenarios like driving cycle, becomes affordable in terms of time and computational resources thanks to the use of HPC and smart coupling. 3D physical phenomena are still simulated with 3D model, but in a most efficient way with variable boundary conditions from 1D model, allowing a very high fidelity thermal system estimation for the electric vehicle and its components.

Furthermore, this methodology will be used to optimize the thermal management and energy consumption in the electric vehicle, by testing and assessing new different strategies in less than one day each.

## Acknowledgments

## References

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