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Efficient and affordable Zero Emission logistics through
NEXT generation **E**lectric **TRUCK**s

HORIZON Innovation Actions ¦ Project Number: 101056740

D3.2
Improvement potentials of the proposed portfolio of measures for increasing the efficiency of VTMS

Co-funded by the European Union

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ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
BMS	Battery Management System
BTMS	Battery Thermal Management System
DCDC	DC-to-DC
EM	Electrical Motor
EXV	Electrical Expansion Valve
FMU	Functional Mock-up Unit
FRM	Fast Running Model
HVAC	Heating, Ventilation and Air Conditioning
IR	Infrared heating panels
IVI	In-Vehicle Interface
KPI	Key Performance Indicator
OBC	On-Board Charging control unit
PMV	Predicted Mean Vote
PWT	Power Train
TCU	Traction Control Unit
TXV	Thermal Expansion Valve
UC	Use Case
VCU	Vehicle Control Unit
VTMS	Vehicle thermal management system
ZEV	Zero-emission vehicle

EXECUTIVE SUMMARY

NextETRUCK aims to address different optimization challenges regarding tomorrow's urban and suburban logistics for medium-duty vehicles into a systems approach that is reliable, strongly integrated, affordable, and flexible enough to be re-applied to different applications via dedicated tools/methods.

The NextETRUCK project is structured in nine work packages (WPs). The work performed within WP3 of the NextETRUCK project aims to improve the system architecture, design and overall cost optimization. As a part of WP3, the aim of the Task 3.2 is to reduce the required energy and improve the energy efficiency, in order to extend the maximum driving range of the e-truck. To realize these aims, Task 3.3 covers an adapted control strategy to achieve the most efficient system operation without affecting the passenger comfort or the system safety.

The outcomes from both of these WP3 tasks are presented in this deliverable. While fulfilling the aims these two tasks, there were no time delays related to this deliverable.

1 INTRODUCTION

1.1 About NextETRUCK

NextETRUCK is a 3-year Horizon Europe project that develops ZEV concepts tailored for regional medium freight haulage, running from 1 July 2022 until 31 December 2025.

The project aims at playing a pioneering role in the decarbonisation of vehicle fleets, demonstrating next-generation e-mobility concepts. It also contributes to the development of zero-emission vehicles and ecosystems that are holistic, innovative, affordable, competitive, and synergetic.

NextETRUCK is expected to build concepts tailored for regional medium freight haulage with at least a 10% increase in energy efficiency compared to existing highest-end benchmark electric vehicles. In addition, it shall prepare concept and infrastructure demonstrators for fast charging and offer new business models to increase end-user acceptance and foster the market uptake of the project solutions.

The project's consortium consists of 19 partners from 8 countries: The Netherlands, Belgium, Germany, Spain, Greece, Austria, Turkey, United Kingdom[1]. The project's coordinator is TNO (Netherlands Organization for Applied Scientific Research).

NextETRUCK shall conduct demonstrations in Istanbul, Barcelona, and Utrecht.

1.2 Task description

This deliverable reports on the outcomes from two WP3 tasks: Task 3.2 on the development of an innovative thermal system, and Task 3.3 on the thermal system control and management. To reflect this organizational division, these two tasks will be covered in two separate sections: Section 2 for T3.2 and Section 3 for T3.3. Section 4 lists the main outcomes of the presented work. Table 1.1 provides an overview of the participating partners and their main contributions.

Table 1.1: Partner contributions

Who:	Role:
AIT	Task 3.2 lead; simulation models of the HVAC system and the vehicle cabin
AVL-THD	Task 3.3 lead; energy efficient control strategy of the VTMS

[1] The UK participants in this project are co-funded by the UK.

TEC	layout definition of the cooling circuit; definition of interfaces and control strategies for VTMS
CID	adaptive thermal management strategy of the battery pack; battery pack cooling simulations and analysis
OEMs: - FORD - TEVVA - IRIZAR	heating and cooling requirements; implementation of the thermal management

2 DEVELOPMENT AND DESIGN OF AN INNOVATIVE THERMAL SYSTEM AND CABIN CONCEPT FOR THE ELECTRIC TRUCKS

In an effort to reduce the required energy for heating/cooling of the vehicle cabin, which in turn leads to the extension of the maximum driving range, a selection of measures for enhancing the overall thermal management efficiency is elaborated (Task 3.2). Furthermore, the design and optimization of the cooling circuit layout with respect to the provided battery pack characteristics is carried out. The potential analysis in this task is based on virtual vehicle models, while validation of the adopted set of measures belongs to the work to be performed within WP5.

2.1 Innovative cabin thermal concept

For the thermal analysis of an innovative cabin concept, designed for the Use Case (UC) based on Ford vehicle (UC1), the model for the thermal performance of the cabin combined with its Heating, Ventilation and Air Conditioning (HVAC) system has been developed such that it mirrors the structure of the typically deployed systems. As depicted in Figure 2.1, the model of the cabin thermal performance (complemented with the thermal comfort model) replicates the heat transfer involved, determining thus the thermal characteristics of the cabin: ambient temperature and humidity, vehicle speed, solar radiation, inlet air properties, heating panels and insulation. This physical model has been developed in Dymola/Modelica simulation framework, to integrate the characteristic 1D equations in time to obtain the evolution of desired quantities. A closer look at its main features is listed below.

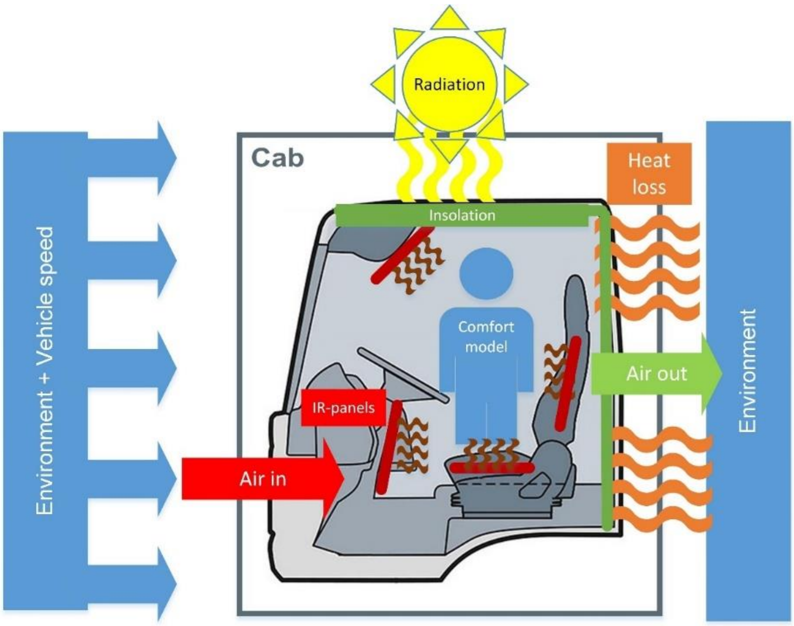

Figure 2.1: Cabin thermal modelling approach.

Energy loss

The cabin thermal model includes different forms of energy losses, including heat dissipation through cabin walls, insulation, radiation, and the loss of energy through output air. This allows to simulate the energy demands required to uphold the desired temperature, with the aim to improve the overall efficiency of the HVAC system.

Linear comfort model

The cabin simulation includes the Linear Comfort Model to calculate the Predicted Mean Vote (PMV) value, which is widely accepted indicator of the indoor thermal comfort. Based on the cabin air temperature and the surface temperature, the linear PMV model efficiently employs a linear comfort map which approximates various parameters to gauge occupants' perceived comfort levels.

IR panels

The main component for the cabin thermal comfort regulation are the infrared (IR) heating panels, as they can act swiftly to attain the desired thermal comfort level. These panels affect the surface temperatures, hence they can ensure optimal indoor thermal comfort at lower cabin air temperatures, which results in a considerable opportunity for energy savings.

HVAC system

The cabin thermal model is coupled with the HVAC simulation to assess the thermal performance, energy efficiency, and occupant comfort of the whole system. As given in Figure 2.2, the entire investigated setup includes the following components: Air-Air Heat Exchanger (facilitate the exchange of heat between the incoming and outgoing air), Recirculation (control air quality by filtering and recirculating the cabin air), Evaporator (cool the air by removing heat and moisture from the cabin), Ventilation (promote the circulation of fresh air within the cabin), Mix Flap (control the mixture of hot and cold air in achieving the desired cabin temperature), Heat Exchanger (transferring thermal energy between different fluids or air streams), IR Panels (provide targeted heating to specific areas of the cabin), Cabin (an over-reaching component) and Controller (manage and regulate the operation of various components).

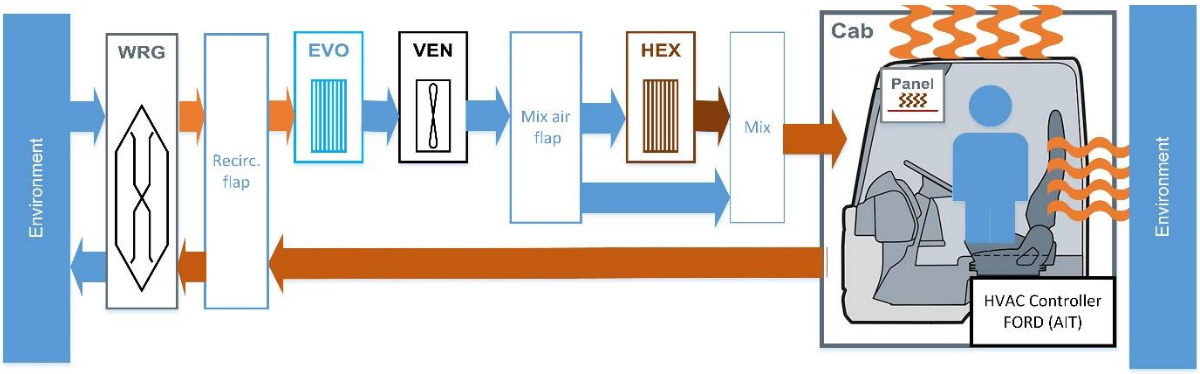

Figure 2.2: The schematic representation of the cabin and HVAC model.

2.1.1 Cabin thermal analysis

The following simplified thermal model relates the dynamic behavior of heating power, heat losses and heat capacity. It includes the transmission losses and exhaust air losses, as well as the convection $Q_{h,convective}$ and radiation $Q_{h,radiation}$ heating:

$$Q_{heat} = Q_{capacity} + Q_{losses}$$
$$Q_{heat} = Q_{h,convective} + Q_{h,radiation}$$
$$Q_{capacity} = m_{cabin} \cdot c_{p,cabin} \cdot \frac{\partial T_{cabin}}{\partial t}$$
$$Q_{losses} = Q_{losses,trans} + Q_{losses,exhaust}$$

The terms constituting the heat generation include the air heating, blower power, and radiation power. The terms constituting the heat loss are the transmission loss, outlet air loss, heat capacity, and latent power required for water condensation at the evaporator:

$$\dot{V}_{air} \cdot c_p \cdot \rho_{air} \cdot (T_2 - T_1) + \mathrm{P}_{\mathrm{fan}} + P_{rad} = \mathrm{G} \cdot (T_i - T_{ambient}) + \frac{T_{out} - T_{ambient}}{T_i - T_{ambient}} \cdot \dot{V}_{air} \cdot c_p \cdot \rho_{air} \cdot (T_i - T_{ambient}) + P_{heatcap} + \mathrm{P}_{\mathrm{dehum}}$$

This thermal model is coupled to the PMV prediction in order to drive the ambient parameters (temperatures) towards the optimum indoor comfort. In the linear PMV model, represented with the diagram given in Figure 2.3, two factors are the most influential: the cabin air temperature and the temperature of the cabin surfaces. The optimum comfort point, as determined by the linear PMV model, is 20°C for both air and surface temperature: this point serves as a reference for maintaining an ideal thermal environment within the cabin. It is important to note, however, the variation in the individual comfort perception when exposed to a range of temperature values: although the linear PMV model provides valuable insights, there are individual preferences to be considered and to flexibly adapt the cabin thermal conditions accordingly.

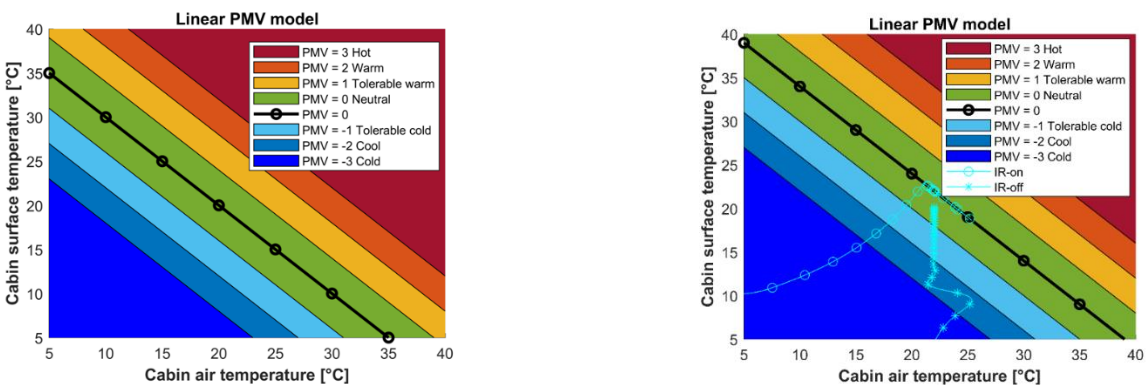

Figure 2.3: The diagram of the linear PMV model (left) and the PMV prediction with and without IR panels (right).

With the IR panels switched on, the surface temperatures within the cabin are immediately affected. In this way the optimum indoor thermal comfort (PMV=0) can be achieved more rapidly, even at non-favourable ambient conditions. This is indicated by the temporal development of the PMV value, as presented in Figure 2.3 by the lines with circles for the IR case, and the lines with stars for the no-IR case. Starting from the cold ambient conditions, the IR case rises quickly to the desired comfort state through the change in the surface temperature. In the no-IR case, however, the surface temperature (and correspondingly PMV) increases gradually over time. This comparison can be quantified from the graphs given in Figure 2.4.

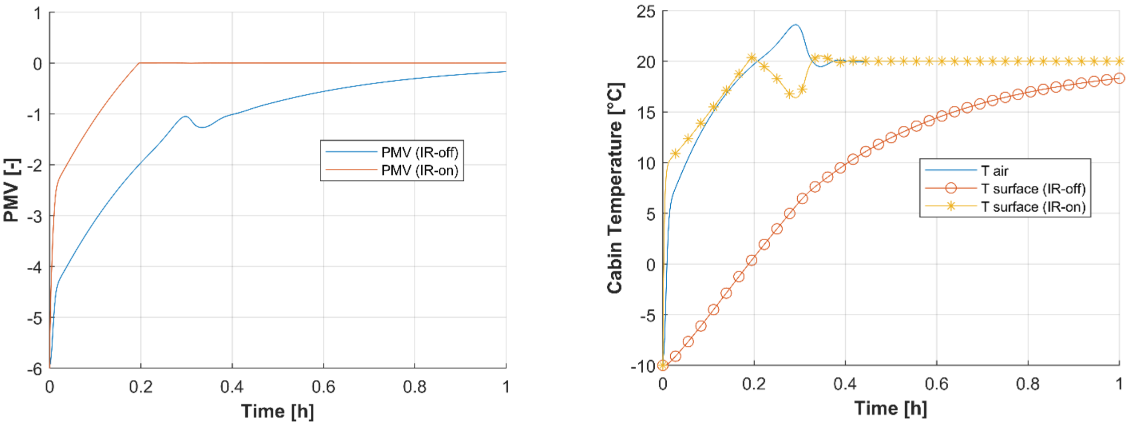

Figure 2.4: The temporal development of PMV (left), and surface and air temperature during heating up phase (right) with and without IR panels.

The analysed energy efficiency measures are focused on the IR panels and air-air heat exchanger, as illustration shown in Figure 2.5. The adopted IR panels are very flexible, and they can cover up to one third of the cabin surface area. Although the surface temperatures of these panels can reach about 50-60°C, there is no risk of burning sensation or discomfort for occupants due to the presence of a protective cover. By integrating air-air heat exchangers in the system, a part of the heat from the outgoing air is used to pre-heat the air coming into the cabin, which resulting in reduced HVAC energy consumption. The estimated energy saving potential is around 20-30% of the cabin energy demand, while the exact figures can be obtained for each individual UC.

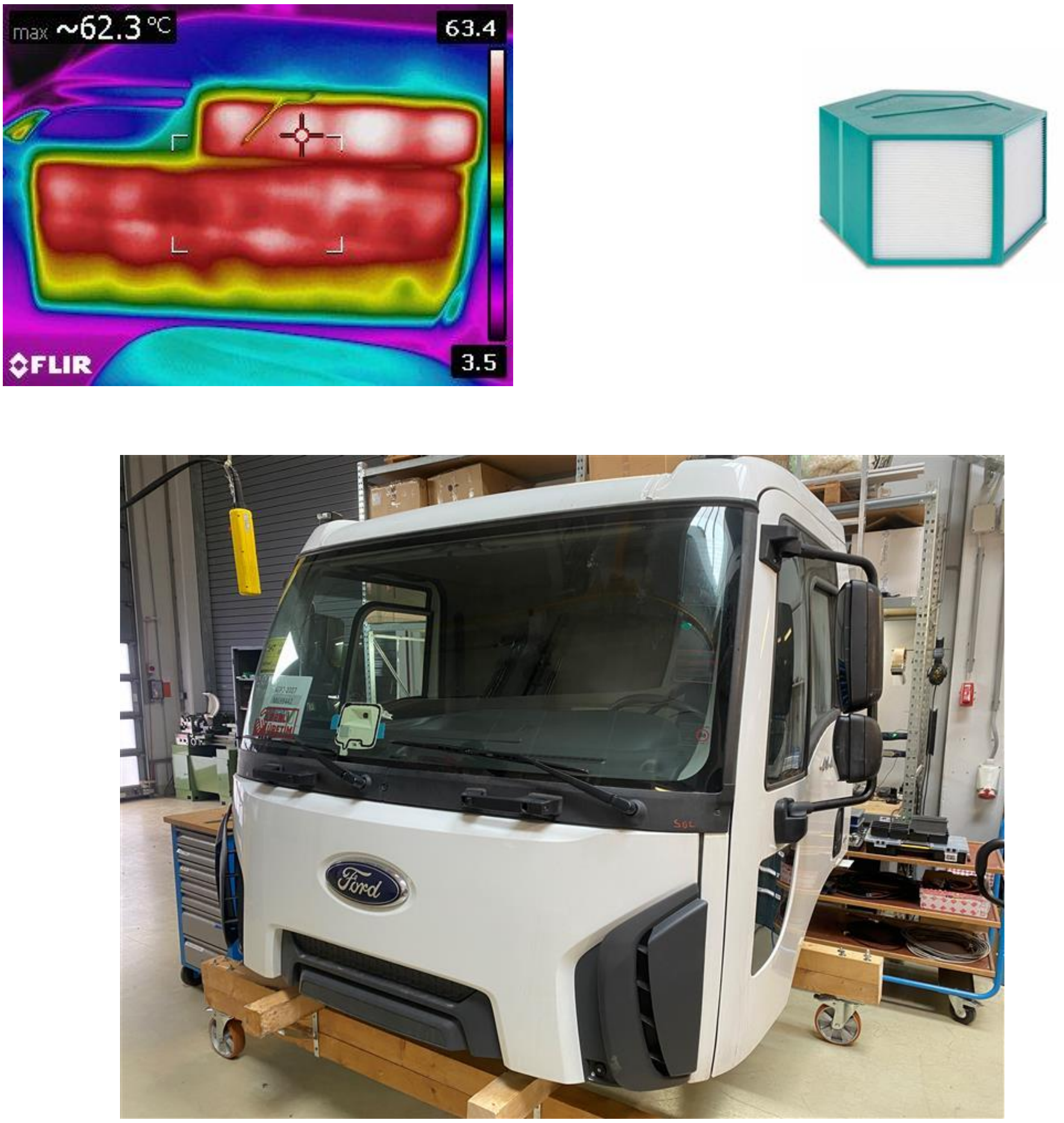

Figure 2.5: The energy efficiency measures for FORD cabin – thermo-camera view of IR panels integrated into the cabin door (top left), the air-air exchanger to be integrated into the air stream (top right), the cabin to be used for the energy efficiency investigation (bottom).

2.1.2 Cabin energy demand

To quantify the energy saving potential, the energy demand for the UC1 with FORD cabin (Figure 2.1.5) has been numerically analysed. For this initial analysis, the cabin geometry and model parameters (cabin heat capacity and thermal resistance) are obtained from the preliminary cabin test or estimated based on the available reference data. The main cabin characteristics are summarized in Table 2.1.

Table 2.1: Estimated FORD cabin parameters

Quantity	Value	Unit
Surface area of cabin	10	m2
Volume of cabin	2	m3
Heat capacity of cabin interior	60000	J/K
Heat capacity of cabin walls	20000	J/K
Heat capacity of air channels	1000	J/K
Heat resistance of cabin walls	1/310	K/W

The simulations for the winter case (ambient temperature -10°C) have been performed for two cabin setups: the standard one representing the original configuration, and the proposed concept with IR panels and air-air heat exchanger. In these initial simulations the intention was not to cover the truck operation in full complexity (e.g. the realistic profiles of driving and environment conditions are not included, but rather assumed constant), therefore the obtained results indicate the potential for saving energy needed for thermal conditioning of the cabin in order to maintain optimum indoor thermal comfort.

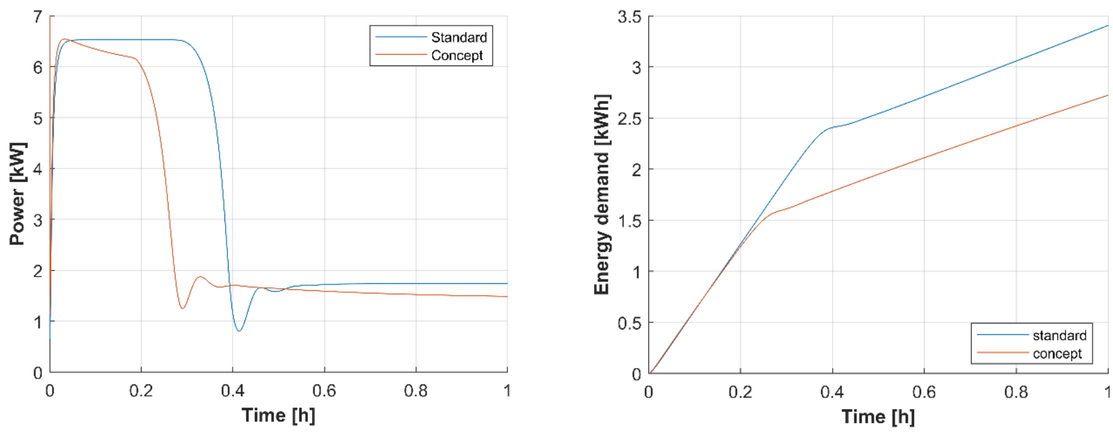

Figure 2.6: The heating power (left) and energy demand (right) in standard and concept cabin at ambient temperature -10°C.

The results shown in Figure 2.6 compare the two cabin setups by looking at the advance in time (until the steady state is reached) of the power used for the cabin thermal conditioning and the corresponding total energy demand. As expected, in the proposed concept the heating power increases strongly in the initial phase, but as the IR panels increase the surface temperature the power needed maintain the target thermal condition reduces significantly. On the other hand, warming up the entire cabin in order to reach the desired indoor comfort (and, in addition, maintain the higher target thermal condition) takes much more power and time. This leads to about 30% higher energy consumed in the original setup, as compared to the proposed concept.

2.2 Thermal management system

In this section the decision for the layout of the thermal management system (TMS) is presented. Different TMS layouts are designed by taking into consideration the thermal conditions of an efficient cabin and the e-drive components. A qualitative approach based on several evaluation criteria and a quantitative approach based on 1D simulations in Cruise M are used for the layout decision.

The Thermal Management System of a truck plays an important role in improving the comfort of the passengers and it is one of the main energy consumers in the vehicle. Therefore, developing a highly efficient TMS is essential for electric vehicles where the range of a truck can be drastically affected when the TMS is inefficient. Numerous configurations of a TMS are applicable to the same truck. However, based on the relevant use cases and the thermal specifications of the truck components certain TMS layouts are beneficial over others with regard to efficiency. The work presented in this section shows the procedure to select a suitable TMS layout for different use cases (heating and cooling) based on quantitative and qualitative evaluation criteria.

2.2.1 Overview of investigated layouts

A number of TMS layouts were designed taking into account the specific boundary conditions given in the project. This includes a good isolation and waste heat recovery for the cabin air by new technologies incorporated by AIT. This results in less power requirements for the cabin heating. Trucks provide more waste heat from the e-drive when compared to conventional passenger vehicle. The excessive waste heat from the e-drive components can be used to reduce the system complexity by avoiding a heat pump function where the heat is extracted from the ambient. In general, heat pumps using ambient as heat source increases the complexity and the costs of the TMS significantly. All the TMS variants investigated for the layout decision are illustrated in Figure 2.7 to Figure 2.12. A short description of the special features is given later in this section.

In order to evaluate the baseline thermal systems from each OEM, the final TMS layout derived from the process described in this report will be compared to the TMS layouts provided by the OEMs. In a first step, the actuator characteristics like pump curves, fan curves, radiator sizes etc. are estimated from experience. The same actuator data will be used for both the TMS layouts from the OEMs and the designed thermal systems. This allows to determine the relative improvement of the designed TMS. The TMS variants investigated in the layout decision use only minimum requirements for the controller logic. The controller logic is later optimized for the final TMS layout. The actuators (pumps and fans) for the final layout will be sized based on the waste heat of the e-components for different load scenarios, maximum temperature of the components, cabin temperature requirements etc. The optimized TMS will be integrated into the digital twin environment provided by AVL.

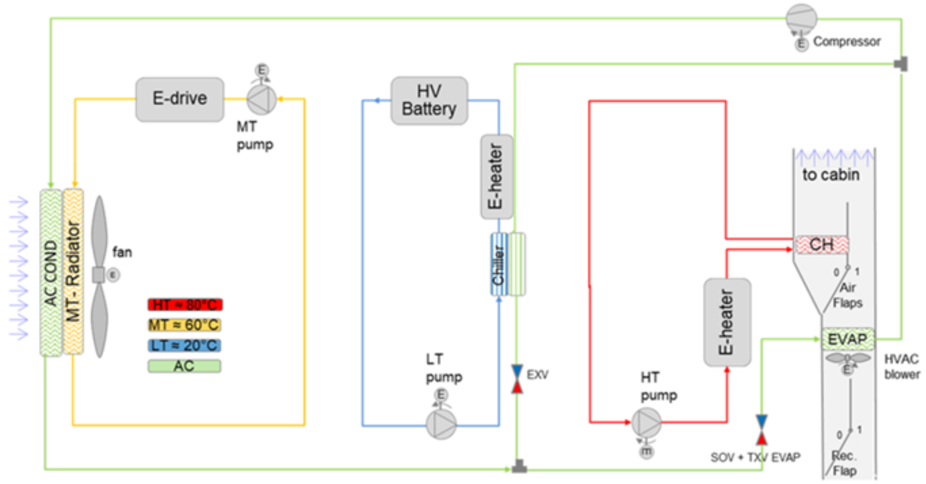

Figure 2.7: The Thermal management system layout variant 1

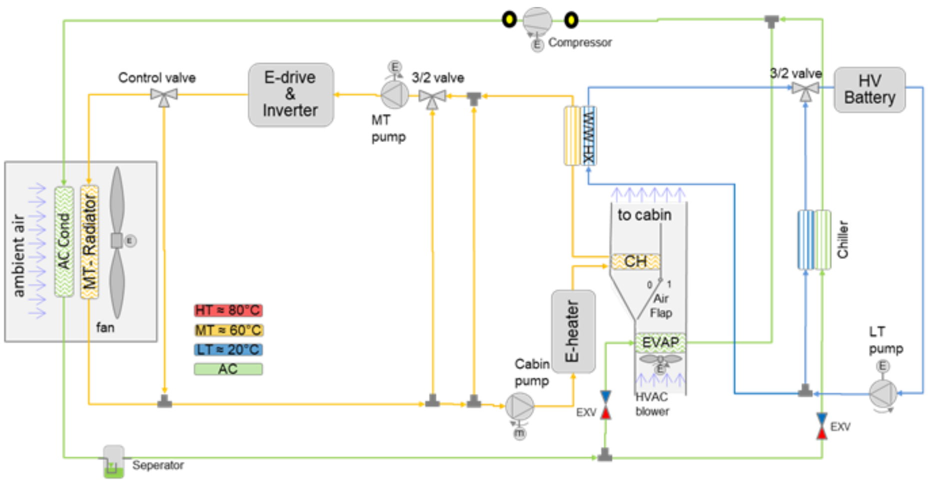

Figure 2.8: The Thermal management system layout variant 2

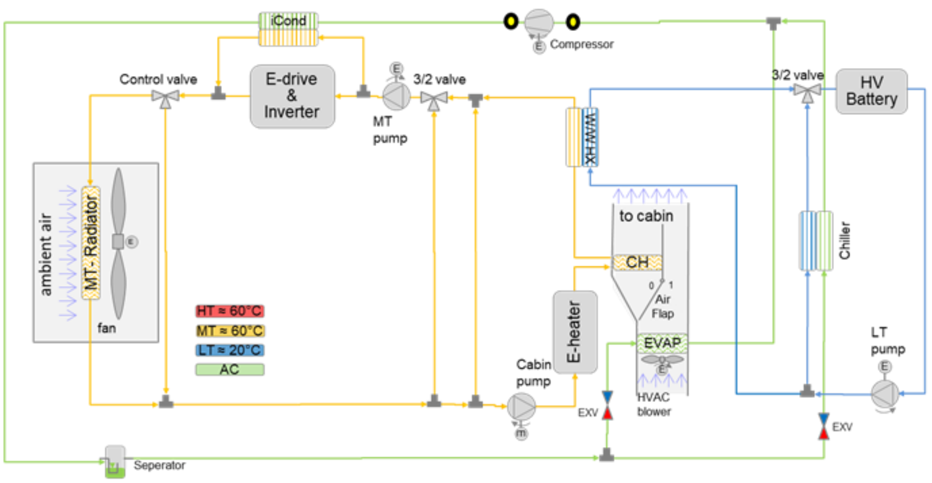

Figure 2.9: The Thermal management system layout variant 3

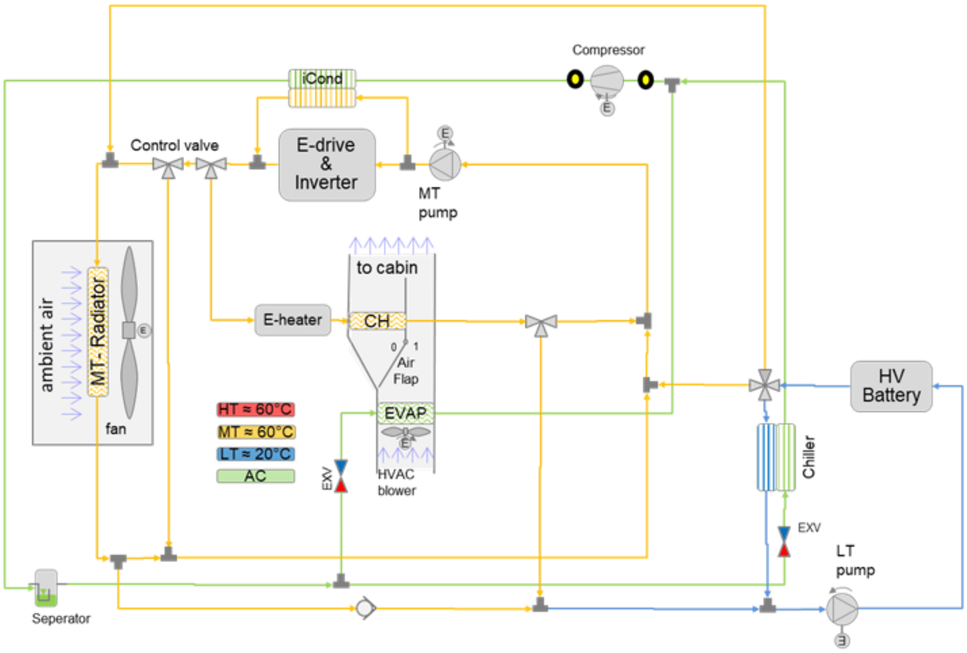

Figure 2.10: The Thermal management system layout variant 4

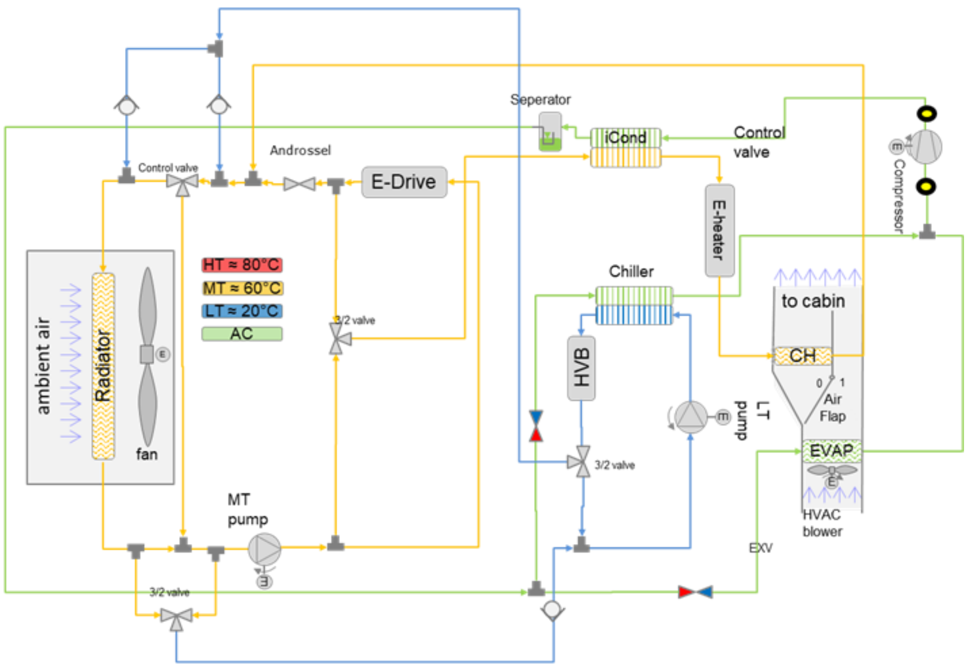

Figure 2.11: The Thermal management system layout variant 5

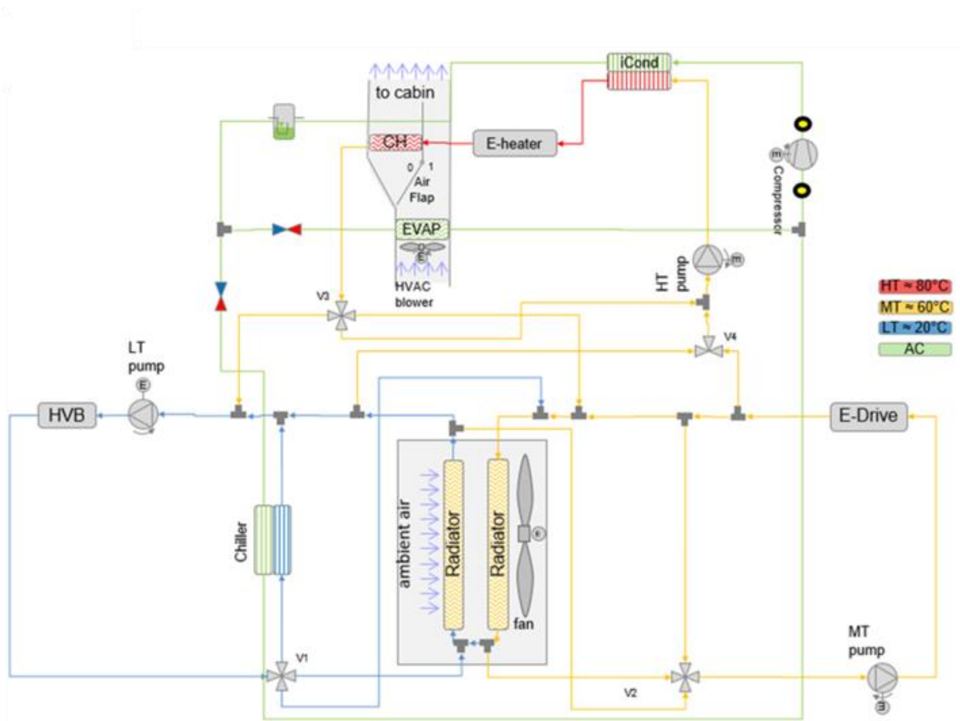

Figure 2.12: The Thermal management system layout variant 6

2.2.2 Qualitative layout decision

In order to reduce the computation effort a pre-selection of layouts is made out of the variants depicted in Figure 1 which will be presented next. Different criteria which cover the number of components, the losses within the fluid and air path, the control strategy and the conditioning of the cabin and the battery are considered. The different criteria are listed in Table 2.2. The layout variants are assessed using five ratings ascending from "--" to "++".

Table 2.2: Qualitative criteria for TMS layout decision.

Criteria	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Number of pumps	-	-	-	+	+	-
Number of valves	++	+	+	+	o	-
Number of heat exchangers	o	-	-	o	o	-
Number of e-heater	--	o	o	o	o	o
Pressure loss air path	-	-	+	+	+	o
Pressure loss fluid path	++	+	o	o	-	-
Length/weight piping	+	o	o	o	-	o
Complexity of the control in relation to actuators	++	o	o	o	o	-
Complexity of the control in relation to required operating modes (structure and application effort)	++	o	o	o	-	-
Convenience of cabin conditioning	++	o	o	o	o	+
Optimum component temperatures	o	o	o	o	o	o
Conditioning of cabin	--	-	++	++	++	++
Conditioning of battery	--	-	-	++	++	++

The number of components within the TMS as listed in Table 2.3 are used as additional evaluation criteria for the pre-selection of the variants. The layout variant 4 has more functionalities as the layout variants 2 and 3 and at the same time lower number of components which results in lower overall costs. Therefore, the variant 2 and 3 are excluded from the further evaluation process.

Table 2.3: Number of components for different layouts

Component	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Number of heat exchangers	5	6	6	5	5	6
Number of valves (cooling circuit)	0	2	2	2	3	4
Number of pumps	3	3	3	2	2	3
Number of e-heater	2	1	1	1	1	1

2.2.3 Quantitative layout decision

The TMS layout variants 1, 4, 5 and 6 are built within the AVL 1D-simulation environment Cruise M. All models of the layouts contain the same component characteristics and stagnation pressure in the air path. This allows an easier comparison of the different layouts. Four different use cases are utilized for the quantitative layout decision. Three cases for cooling of the battery and cabin and two cases for heating the battery and cabin. Summarized in Table 2.4 are the boundary conditions for the different use cases. As mentioned before, a simple basic control strategy is selected for the TMS models at this stage which will be later refined and optimized.

Table 2.4: Use cases for quantitative layout decision

Case	$T_{ambient}$ [°C]	$RH_{ambient}$ [-]	$V_{vehicle}$ [m/s]	e-drive source [kW]	HVB source [kW]
Cabin Cooling + Active Battery Cooling - Pulldown	40	0.5	16.67	5	1.5
Cabin Cooling + Passive Battery Cooling	20	0.5	16.67	10	3
Maximum Cooling	40	0.5	16.67	20	10
Cabin Heating + Battery Heating v1 (e-drive = 1kW)	-10	0.5	16.67	1	1.5
Cabin Heating + Battery Heating v2 (e-drive = 10kW)	-10	0.5	16.67	10	1.5

Different evaluation criteria are selected for the cooling and heating cases. For the cooling cases the energy consumption at steady state conditions represents the main evaluation criteria. The heating cases focus on the temperature curve of the cabin and the battery to evaluate the different layouts regarding their efficiencies.

2.2.4 Proposed TMS layouts

The main characteristics of the TMS layouts shown in Figure 2.7 to Figure 2.12 are briefly described next. The variants 2 and 3 are excluded from the quantitative evaluation process and thus not further described. The variant 1 is the simplest in its complexity out of all investigated variants. It has 3 separated circuits and thus the following advantages. The small number of actuators allow a simple control strategy. The small number of valves leads to low costs. The system can be realized in a compact form with low thermal inertia. The disadvantages are that the battery cannot be cooled passively, the waste heat of the e-drive cannot be used to heat the cabin or the battery. Furthermore, a high fan power is required due to the parallel arrangement of the AC Condenser and the MT-Radiator.

The variant 4 has two separated cooling circuits with a water condenser. For this variant the waste heat of the e-drive can be used to heat the cabin and battery, it allows a limited heat pump functionality and passive battery cooling. However, variant 4 is quite complex and imposes a relatively high thermal inertia due to the direct engaged e-drive. Variant 5 has similar functionalities as variant 4. Different characteristics between variant 4 and 5 can be achieved through different control strategies. However, the presented simulations in this report do not allow a real assessment of the difference between variant 4 and 5. Variant 6 has also two separated cooling circuits with a water condenser. Additionally, to the advantages mentioned for variant 4 and 5, the variant 6 allows a high efficiency in passive battery cooling over a large range of temperature as two radiators are used. The two radiators are beneficial when it comes to ultra-fast charging etc. The disadvantages of variant 6 include the high complexity, the high number of components, which is one additional radiator and one additional pump when compared to variant 4, and a larger pressure drop on the air side.

2.2.4.1 Cooling Cases

The first cooling case represents an AC high load situation. Figure 2.13 shows the energy consumption of the individual actuators within the TMS circuit for the latter use case. Even though the overall energy consumption is at the same level for variant 1, 5 and 6, there is some benefit visible for variant 6. The energy consumption can be reduced by approx. 2,5% when compared to variant 1. This reduction in energy demand is ascribable to the reduced energy consumption of the compressor. The second radiator ensures that temperature level before the indirect condenser (iCond) is lower than in other variants.

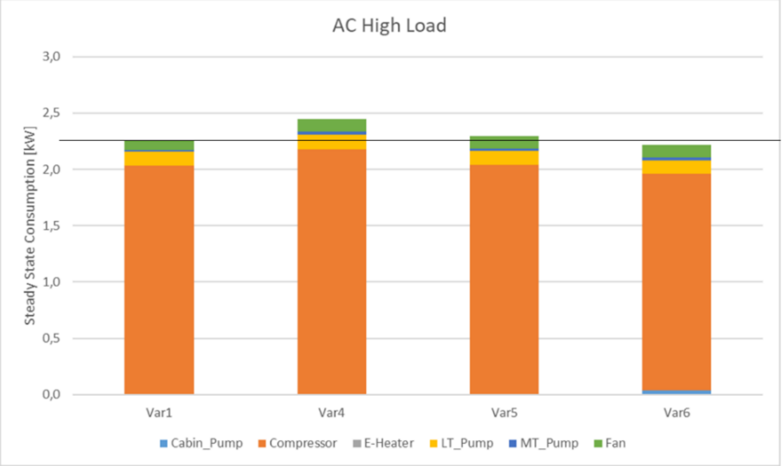

Figure 2.13: The Steady state energy consumption of all TMS actuators for active battery cooling

The second cooling case from Table 2.4 represents a case with passive battery cooling. The energy consumptions at the steady state condition are depicted in Figure 2.14. As the layout of variant 1 does not allow passive cooling, active cooling is used for the purpose of comparability. Thus, variant 1 is inefficient when compared to the other three variants. Again, variant 6 has the best overall efficiency. The variants 4 and 5 are almost the same with regards to energy consumption due to similar volume flow path used for this cooling case.

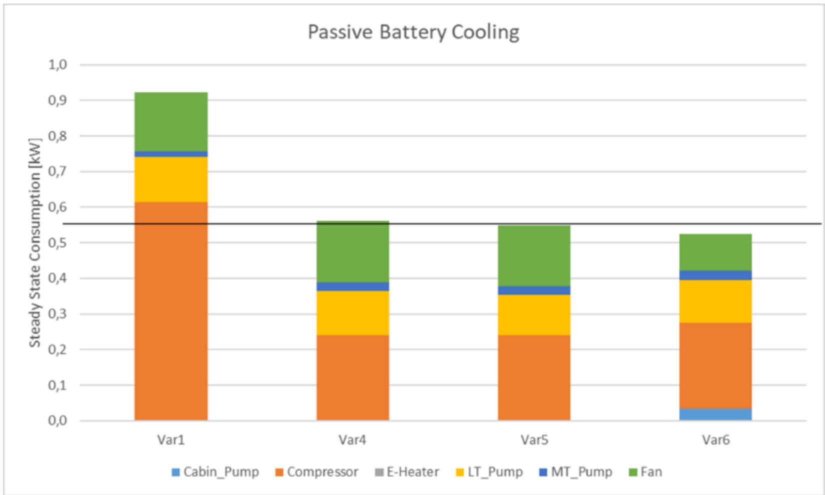

Figure 2.14: The Steady state energy consumption of all TMS actuators for passive battery cooling

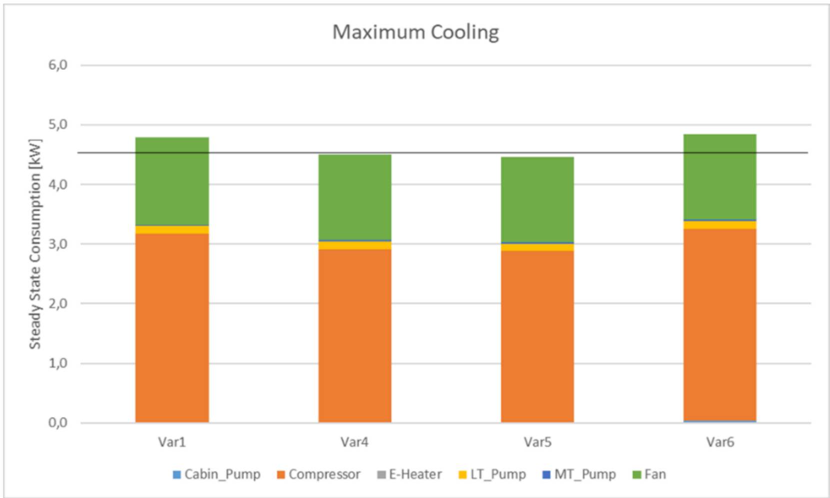

Figure 2.15: The Steady state energy consumption of all TMS actuators for maximum cooling use case

The third cooling case for the evaluation of the maximum cooling performance is analysed below. The power consumption in bar chart in Figure 2.15 show that variant 5 has the best overall efficiency for the maximum cooling use case. However, the cooling performance of variant 6 is much better which enables an extended use of passive cooling. This is apparent from the temperature levels depicted in in Figure 2.16. The energy efficiency is of minor importance for this cooling case as the focus lies on maximum performance. The temperatures observed at the inlet of the e-drives and show that for variant 6 the temperature level stagnates at a lower level compared to the other variants. This indicates that variant 6 has the best maximum cooling performance. If the temperature at the e-drive inlet is set to rise for variant 6 to a comparable level with other variants, approx. 51.5°C in this case, the power consumption for variant 6, shown in Figure 2.15 goes down further and will offer more efficient operation. Since, maximum cooling performance is the main evaluation criteria for this analysis, the efficiency plays a minor role and therefore does not carry importance.

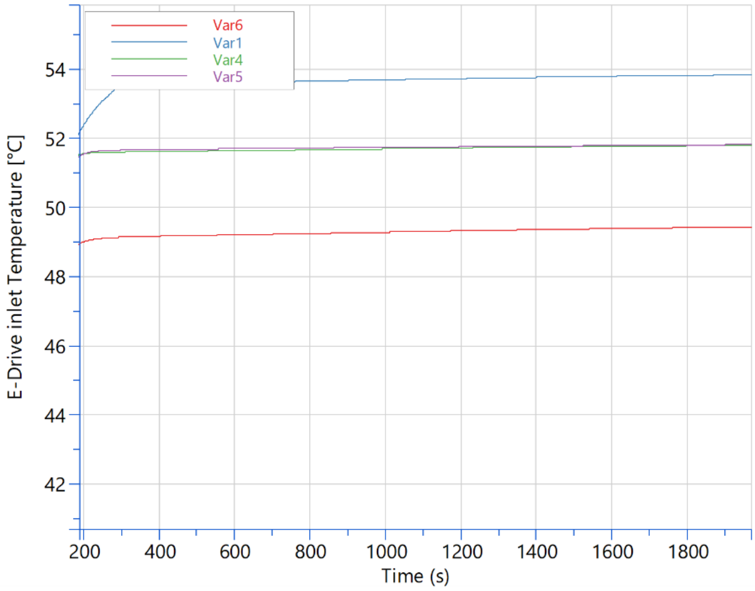

Figure 2.16: The E-drive inlet temperatures for the different layout variants for the maximum cooling use case

2.2.4.2 Heating Cases

Due to the character of the layout for variant 1 no waste heat of the e-drive can be used for cabin heating. Variant 4, 5 and 6 will be able to use up to 8 kW of waste heat depending on the driving situation, the ambient conditions (~8 kW at ambient temperature of -10°C), and the HVAC settings. Additionally, a connection between e-drive and heat exchanger can be established for the variants 4, 5 and 6.

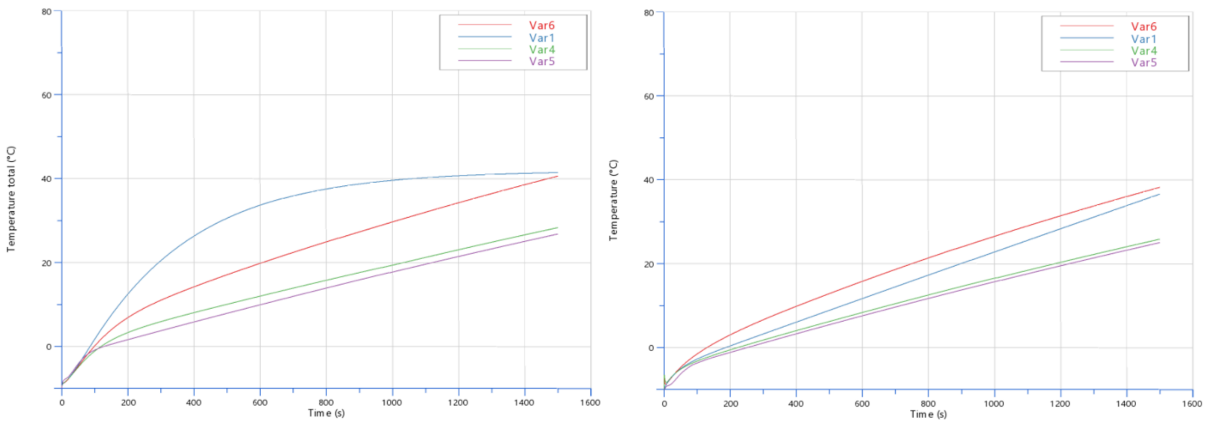

Figure 2.17: The Temperature curves of cabin (left) and battery (right) for different layout variants for heating case with waste heat at e-drive of 1 kW

The first investigated heating case assumes a waste heat of 1kW at the e-motor and 1.5kW at the high voltage battery, see Table 2.4. The respective temperature curves of the cabin and the battery are depicted in Figure 2.17. The results show that variant 6 reaches the target temperature of 22°C earlier when compared to variants 4 and 5. Variant 4 and variant 5 show similar results. The fast increase in the temperature level for variant 1 is attributable to the small thermal inertia as the two e-heater are located directly upstream of the battery and the cabin.

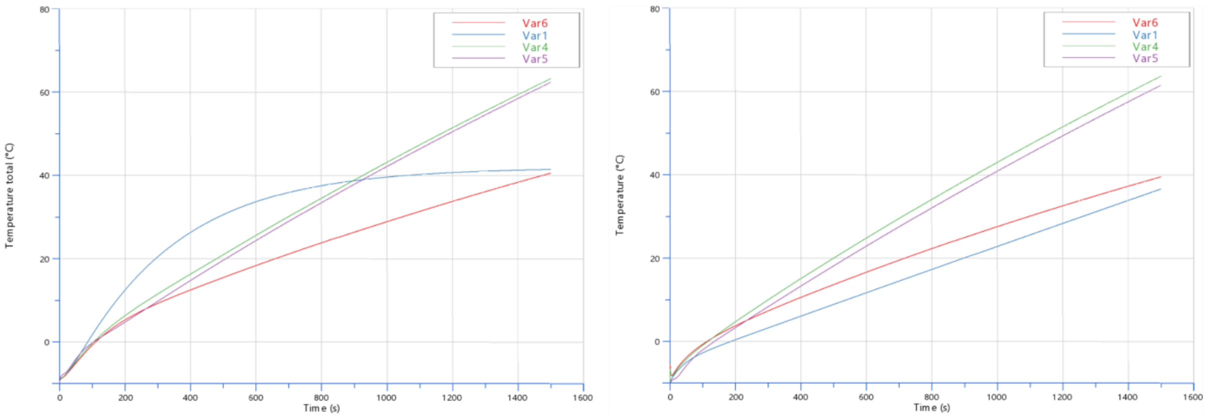

Figure 2.18: The Temperature curves of cabin (left) and battery (right) for different layout variants for heating case with waste heat at e-drive of 10 kW

The temperature curves for the second investigated heating case with a waste heat of 1kW at the e-motor and 1.5kW at the high voltage battery are shown in Figure 2.18. For this case the variants 4 and 5 reach the target temperature level earlier when compared to variant 6. However, this is ascribable to a not yet sophisticated control strategy at this stage of the project. Variant 6 can be improved for high e-drive load case by optimizing the controller.

Finally, Table 2.5 summarizes again the number of actuators with the TMS for the variants 4-6. Even though variant 6 requires a larger number of actuators and thus short-term costs, the presented quantitative evaluation of the different variants allows the conclusion that variant 6 represents a good compromise between performance and costs. The main target for the improvement of the TMS is given by KPI 8 (Vehicle thermal efficiency improvement by 15%), which means that the performance optimization is essential, and the costs are incidental. Furthermore, the improved efficiency reduced the TCO due to less energy costs.

Table 2.5: Number of actuators of different TMS variants

	Variant 4	Variant 5	Variant 6
Valves	2	3	4
Pumps	2	2	3
Heat exchangers	5	5	6
Performance rank	3	2	1

2.3 Battery pack cooling development

The conducted analysis for enhancing the cooling system efficiency and achieving a more thermally competitive battery pack behavior is based on three main points: i) integration characteristics, ii) thermal performance, and iii) hydraulic performance. To do so, 3D simulations have been done.

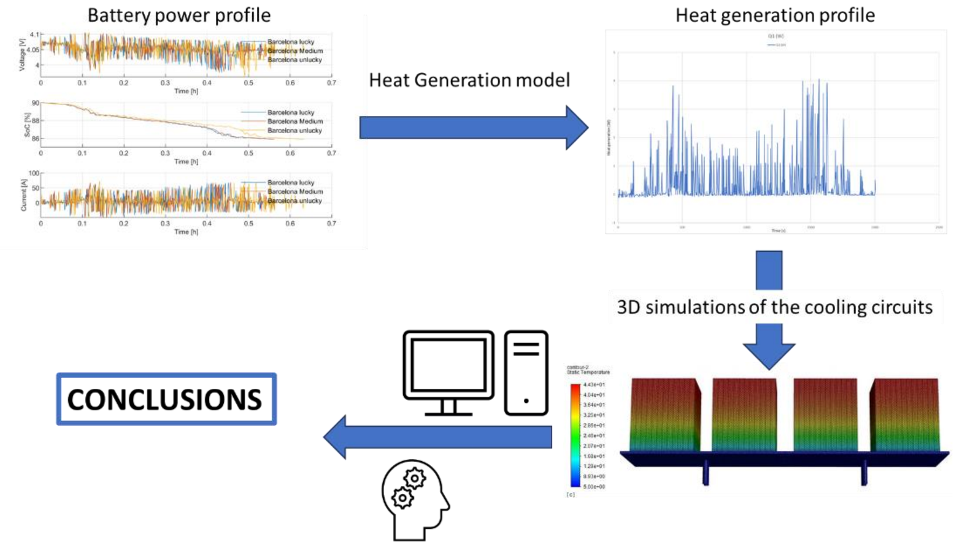

Figure 2.19: The battery pack cooling development workflow.

Using the information from those 3D simulation, the response of IRIZAR's cooling system baseline and the target has been compared (Figure 2.19). The improvements are listed below:

- The cooling plate called baseline was manufactured through the process called vacuum brazing, where the cooling plate is made by welding three aluminum sheets previously overlapped. The middle sheet is the thickest one since the hydraulic circuit is made in it by the machining process. Instead, the top and bottom sheets are the thinnest since they are used to enclosure the fluid channel, but they also need to hold on the internal pressure of the cooling plate. Therefore, the volume and the mass of the cooling plate are quite high and, in addition, the mechanical integration in the vehicle or battery pack is very complicated, which makes the positional and mechanical fit difficult. All this generates a growth in the battery height reducing both the gravimetric density and the volumetric density. For the cooling plate called target, the manufacturing process has been switched to the stamping process, which means the cooling plate is made by welding 2 aluminum sheets instead of three. In this case, the stamped sheet is the thinnest one since the stresses generated by the hydraulic circuit stamping process make the sheet stiffer. Also, for the non-stamped areas, they can be placed near the stiffest parts of the battery pack since the mechanical integration of the stamped cooling plate is much higher. This change in the manufacturing process has allowed to make lighter cooling plates, reducing the weight 60% against the same design; smaller ones, up to 45% smaller; and cooling plates with higher mechanical integration in the battery pack, taking advantage over the channel height inside the battery pack geometry and saving up to 62.5% of the cooling plate height.

- Regarding the thermal performance of both cooling plates, the base cooling plate has considerably higher mass as mentioned before, which improves the thermal performance against the target cooling plate. Additionally, due to the low mechanical integration in the pack and having the circuit in the middle plate, there is complete freedom for the hydraulic channel design making easier a higher performance in the three main thermal parameters: i) maximum temperatures (T_{max}), ii) module thermal homogeneity (ΔT_m), and iii) global thermal homogeneity (ΔT_t). However, a good parallelization strategy for temperature homogenization and an optimized module level circuit design has enabled very similar thermal performances and results, even improving the homogeneity between modules in the target cooling plate against the base one.
- Last but not least, regarding the hydraulic performance of both cooling plates and following the beforementioned point, besides the improvement in the thermal performance, a reduction of 44.3% in the pressure drop has been achieved in the cooling plate due to a lower needed flow for a similar thermal performance, which means an improvement in efficiency. Both the reduction in pressure loss and the reduction in mass flow inlet allow an easier global hydraulic system design at vehicle level since the hydraulic component as pumps, tubes, connectors, collectors… require lower hydraulic requirements.

As an outcome, the mechanical design and the manufacturing process improvement of the target cooling plate over the base cooling plate allow a higher gravimetric density, volumetric density and mechanical vehicle integration.

3 DESIGN OF THE THERMAL SYSTEM CONTROL AND THERMAL MANAGEMENT SYSTEM

Together with the development of a new vehicle thermal management system (VTMS), an adapted control strategy is required to achieve the most efficient system operation without affecting the passenger comfort or the system safety (Task 3.3). The objective is to enable for the given boundary conditions an appropriate thermal conditioning of the system while reducing the energy consumption of the auxiliary consumers.

3.1 Thermal system control

Thermal system control is a critical function in electric vehicles (EVs). It is responsible for maintaining the temperature of the battery, motor, and other components within their optimal operating range. This ensures that the EV can perform at its best and prevents damage to the components.

The tasks of the thermal system control in an EV include:

- Maintaining the battery temperature within its optimal range. This is important because the battery's performance and lifespan can be affected by temperature.
- Cooling the motor. The motor can generate a lot of heat, so it is important to cool it down to prevent overheating.
- Heating the cabin. The cabin can get cold in cold weather, so the thermal system control needs to be able to heat it up.
- Balancing the thermal loads. The thermal system control needs to balance the heat generated by the battery, motor, and other components with the heat that is lost to the environment. This ensures that the EV does not overheat.

Thermal system control is a complex task, but it is essential for the performance and reliability of EVs. The thermal system control in an EV is constantly monitoring the temperature of the battery, motor, and other components and adjusting the flow of coolant or air as needed to keep them within their optimal operating range.

The benefits of having an effective thermal system control in an EV are:

- Improved performance: The battery can operate at its best when it is at a moderate temperature. This means that the EV will have more power and range.
- Increased lifespan: The battery will last longer if it is not exposed to extreme temperatures.
- Improved safety: The thermal system control can prevent the battery from overheating, which could cause a fire.

- Increased comfort: The cabin can be kept at a comfortable temperature, even in cold weather.

As shown in chapter 2, the thermal system for the NextETRUCK vehicle contains various actuators that enable the cooling and heating performance of the system. The following describes how the control of the actuators is divided into subtasks and how the actuators are controlled in these subtasks.

3.1.1 Subtasks of Thermal System Control

For NextETRUCK, the thermal system control tasks are divided into sub-tasks for the partners. AVLD is responsible for the control of the coolant and the AC circuit, AIT covers the control of the HVAC unit and the cabin comfort, CID develops the control strategy for the battery and TEC provides a suitable interface to the MLC.

The main goal in Task 3.3 is to develop a basic control strategy for the developed thermal system. This control strategy is improved and optimized in WP4 with the help of DT technology and MLC. For the basic control strategy, stability is therefore an important issue, as it is mainly used when, for example, the cloud system is not available or when other problems occur.

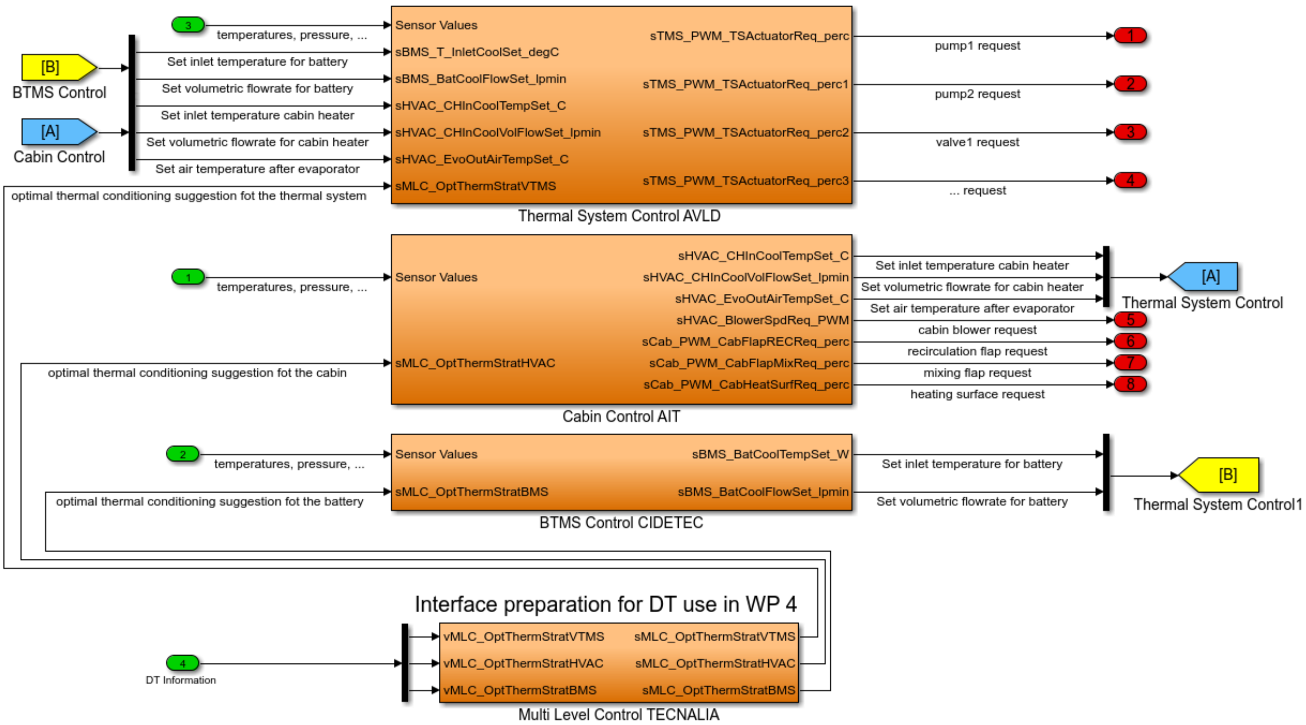

Figure 3.1: Interface between subparts of thermal system controller

The battery and the cabin are important parts of the thermal system, which NextETRUCK has taken a closer look at. Therefore, there are also specific parts in the thermal system control for these parts. Nevertheless, the important interactions with the rest of the thermal system must be taken into account. For this reason, a suitable interface between the parts is necessary. This interface is shown in Figure 3.1.

In coordination with the plant model interface, the controller interface passes on the required setpoints of the battery and the cabin as information to the thermal system control. For the cabin controller, these are the setpoints for the coolant volume flow through the cabin heater, the coolant inlet temperature, and the air temperature after the evaporator. For the battery, the thermal system controller receives the setpoints for the coolant volume flow through the battery and the coolant inlet temperature of the battery. The thermal system controller is then responsible for providing these values by adjusting valves, pumps, and the compressor, for example. The cabin controller also has the task of directly setting the HVAC actuators (blower, recirculation flap, mixing flap, additional heating elements).

The multi-level controller (MLC) provides a proposal for the conditioning of the parts that is optimized from a higher-level perspective. In this way, the consumption of the entire vehicle can be taken into account and reduced.

3.1.2 Coolant Circuit and AC-Circuit Controller

The thermal system control is responsible for controlling all actuators in the thermal system except the HVAC-related actuators. Figure 3.2 illustrates the number of actuators and their positioning in the thermal system. Since the HVAC actuators are not part of this controller, the actuators are mostly located in the refrigerant circuit or in the AC circuit.

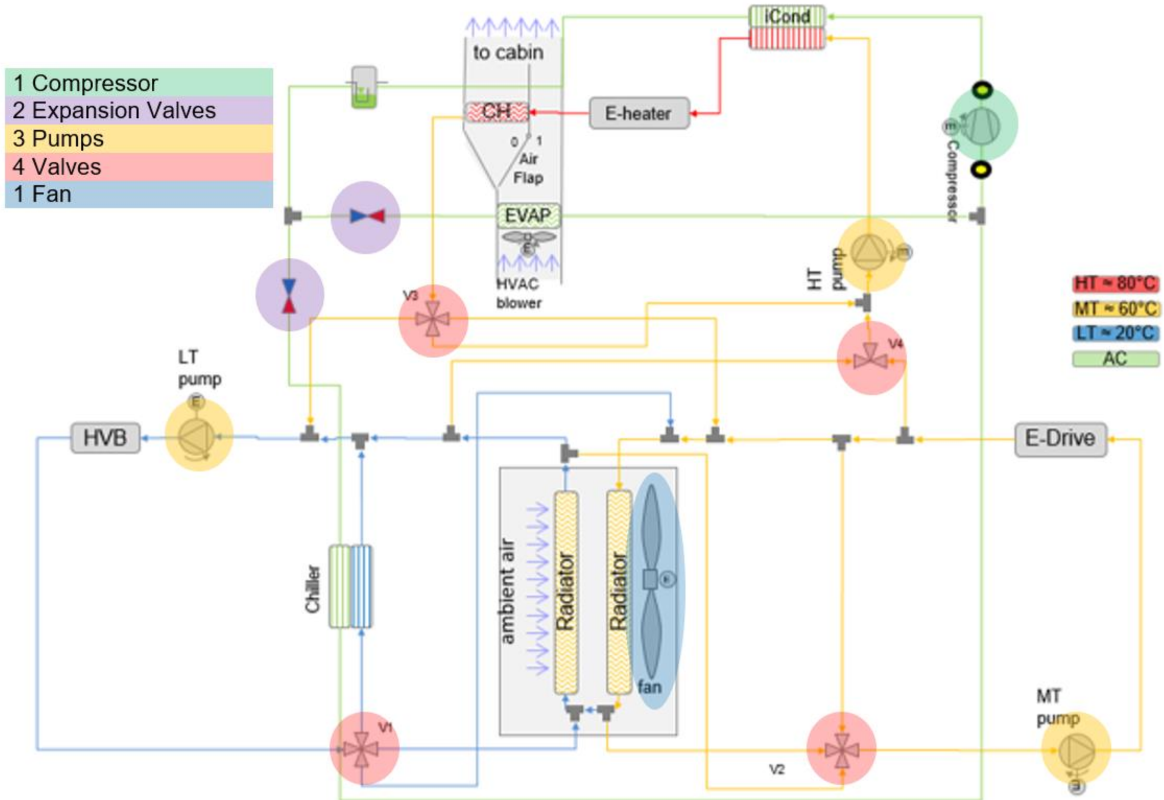

Figure 3.2: Thermal System Layout with highlighted actuators

Figure 3.3 gives an overview of the structure of the TMS controller. The main components are a state detection subsystem, an optimization subsystem, and a control object for each actuator. The state detection subsystem is responsible for determining the current operating state of the vehicle and setting general limits and parameters appropriate for the current state. The optimization subsystem contains an offline optimized request for the fan, MT pump and HT pump. The actuator subsystems contain actuator-specific control algorithms. Figure 3.4 shows the internal structure of an actuator control object. Each controller consists of an optimization part, which can be used to request optimized demand signals from outside the controller. A safety request part ensures an appropriate response to situations where components could be damaged. The fail-safe demand part responds to an external error signal and brings the actuator into the fail-safe state. The minimum activation guarantees a certain activation level of the actuator when required. The dummy subsystem can be filled with additional requirements if necessary.

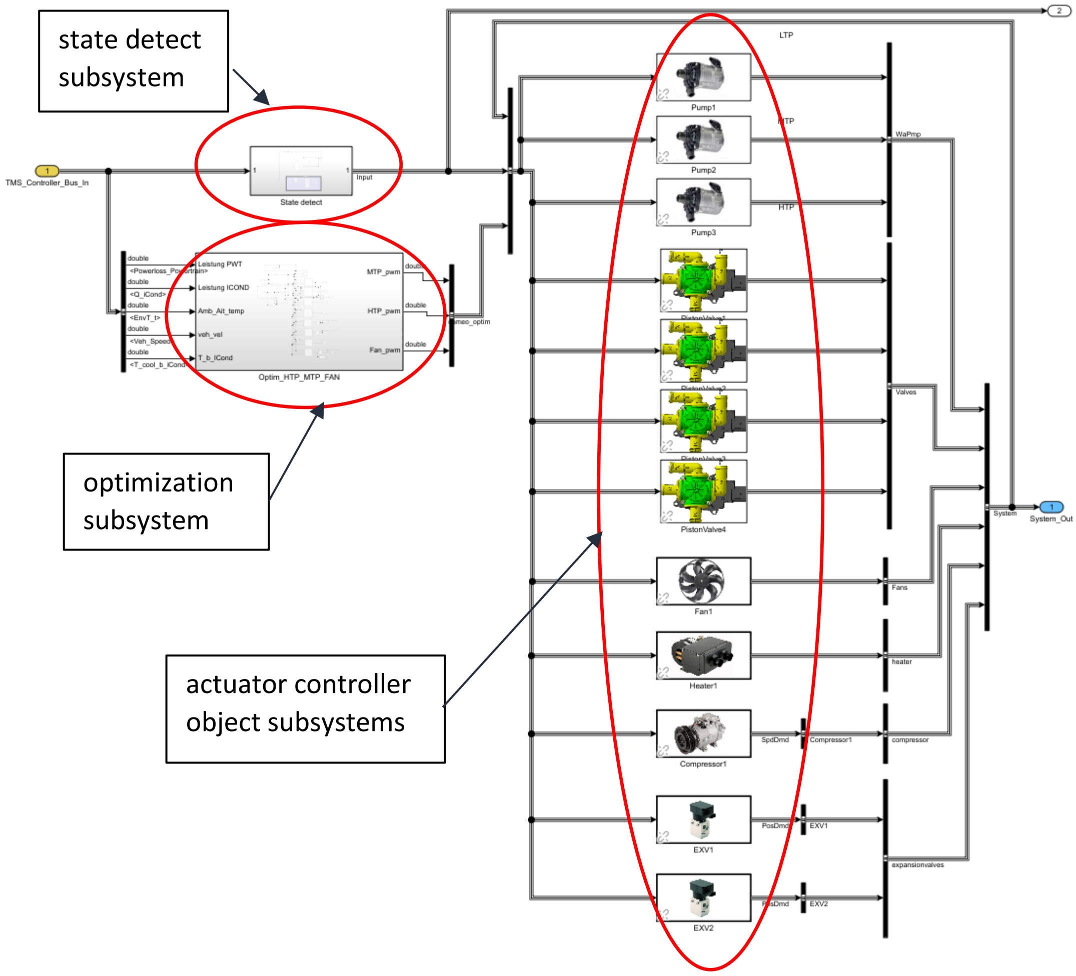

Figure 3.3: Structure of the TMS controller

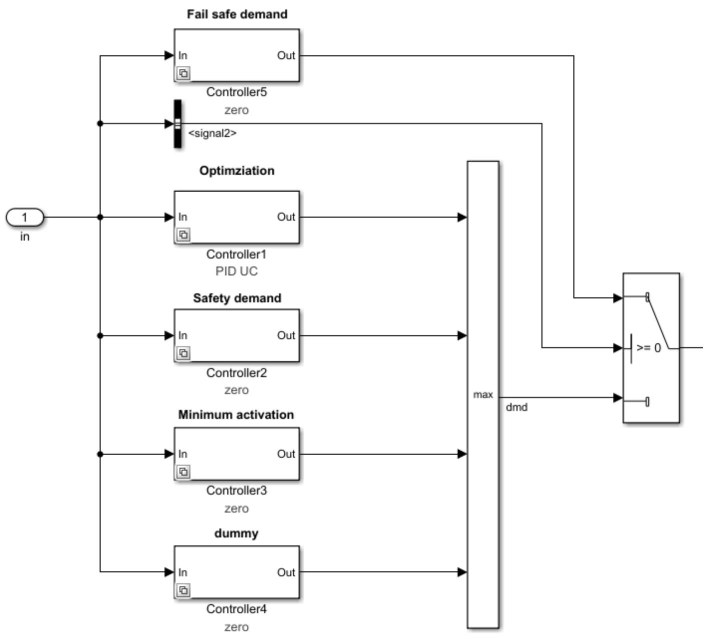

Figure 3.4: Internal structure of an actuator control object

3.1.2.1 States of the TMS system

The state of operation of the thermal management system is determined based on the requirement from the cabin controller and the battery management system. The BMS controller and the cabin controller communicates with the TMS controller the requirement at the battery and cabin respectively. The Figure 3.5 shows the combination of different states of the cabin with the different states of the battery.

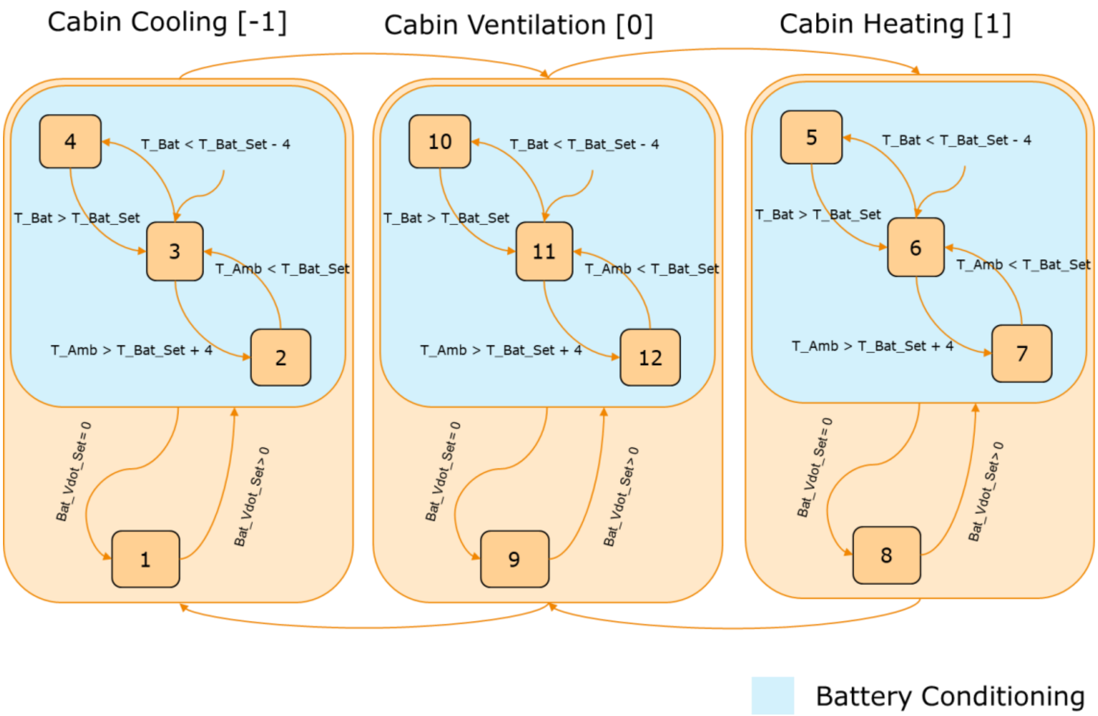

Figure 3.5: State Machine for the TMS controller

The state of the cabin and the conditions to jump between different states are defined by AIT within their cabin controller. A signal which carries the current mode of the cabin is sent by the cabin controller to the TMS controller. The signal contains numbers through which the TMS controller can identify which cabin mode is currently activated. These are as follows:

- Cabin Cooling: -1
- Cabin Ventilation: 0
- Cabin Heating: 1

As it can be seen in the figure, the different states are represented by numbers. This is also how it works inside the controller and the state machine provides these numbers are outputs for further processing in different tables, controllers etc. Table 3.1 shows the different states based on the state number. The signal names in the figure are shortened which is further explained in the Table 3.2.

Table 3.1: State names and the corresponding numbers

State Number	State Name
1	Cabin Cooling
2	Cabin Cooling and Active Battery Cooling
3	Cabin Cooling and Passive Battery Cooling
4	Cabin Cooling and Battery Heating
5	Cabin Heating and Battery Heating
6	Cabin Heating and Passive Battery Cooling
7	Cabin Heating and Active Battery Cooling
8	Cabin Heating
9	Cabin Ventilation
10	Cabin Ventilation and Battery Heating
11	Cabin Ventilation and Passive Battery Cooling
12	Cabin Ventilation and Active Battery Cooling

Table 3.2: Signals used in the State Machine

Signal Name from Figure 3.1.1.1	Signal Name in Model	Description
Bat_Vdot_Set	sBMS_BatCoolFlowSet_lpmin	Set volume flow at battery inlet provided by the BMS Controller
T_Bat_Set	sBMS_BatCoolTempSet_C	Set temperature of coolant at battery inlet from BMS Controller
T_Bat	vCSM_BatInCoolTemp_C	Actual temperature of the coolant at battery inlet
T_Amb	vVV_ExtAirAmbTemp_C	Ambient temperature

The BMS controller provides the TMS controller the required volume flow and the entry temperature of the coolant. Whether the battery needs conditioning or not is determined by monitoring the set volume flow sent by the BMS controller to the TMS controller. If this is greater than zero, then the state is changed to battery conditioning. The blue boxes inside the Figure 3.5 represent the battery conditioning sub state. Inside battery conditioning, it is determined if there is a cooling or a heating requirement in the battery. This is based on the set temperature provided by the BMS controller. The change of state inside battery conditioning substate is based on the set temperature of the coolant provided by the BMS signal (sBMS_BatCoolTempSet_C). The cooling can be categorized into passive and active cooling. In passive cooling, the heat is removed through the radiators, and it is only possible when the ambient temperature is lesser than the set temperature. When the ambient temperature is higher than the set temperature, and there is a cooling requirement, active cooling is activated where the chiller is used to cool down the coolant. When the set temperature is higher than the actual temperature, the heating state is activated. A necessary margin is provided to avoid hysteresis effect. This information is combined along with the state of the cabin to obtain the state of the TMS.

3.1.2.2 Control of Valve3 and Valve4

The position of valves 3 and 4 is determined by the state of the system. Valves 3 and 4 can work together to transfer heat from the E-components to the cabin and to the battery and to ensure the iCond receives the coolant at definite temperature. The performance of the iCond and the AC circuit decreases when the temperature of the coolant at the inlet of the iCond is high.

At low ambient temperatures, when there is a heating requirement at the battery and the cabin, the valve V3 splits the flow of the coolant. One part of the coolant is sent to the low temperature (LT) circuit to heat up the battery and the other part is circulated back to the HT pump. The V4 on the other hand is opened towards the E-Drive. This ensures, a warmer coolant is entering the circuit. The flow of the coolant to low temperature circuit and the flow of the coolant from the medium temperature circuit is also determined by the thermostat valve V1. If V1 is completely open towards chiller, the three circuits are separated. If the V1 has a flow towards the medium temperature circuit, the three circuits are combined. This ensures that all the three circuits reach a common temperature as soon as possible. This operation can be visualized in the Figure 3.6. By moderate temperatures, when there is heating or no cooling requirement at the cabin, the battery can be cooled by using the ambient conditions. During this operation, the valve V3 is opened towards the radiator and the valve V4 is opened towards the E-Drive. This is represented in Figure 3.7.

At warm temperatures, where the battery can still be cooled using the ambient conditions, the thermostat valve V1 switches the flow to the single radiator configuration as shown in Figure 3.8. Even when there is a cooling requirement at the cabin, this will be minimal during these stages and the iCond can be operated for a short time at higher coolant temperatures. Although the AC circuit will not be efficient for a short period of time, the TMS will be altogether efficient since the cooling power for the battery is saved. In cases where maximum cooling (when the ambient temperatures are very high, there is a cooling requirement at the cabin and at the battery) is required, in the high temperature (HT) circuit, valve 3 and valve 4 are switched so that the coolant is drawn off after the radiator and flows back before the other radiator. This will ensure that the iCond receives a colder temperature increasing the performance of the AC circuit. The flow of coolant in the TMS will be as shown in Figure 3.9.

3.1.2.3 Control of Valve 1 and Valve 2

Valve 1 and Valve 2 will be controlled as thermostat valves. That means they will be responsible for maintaining a certain temperature at a certain point in the thermal system. In the case of the V1 this location will be the battery inlet temperature. At low temperatures when the battery has heating requirement, the chiller path is used as bypass to avoid the radiators and in this case, the chiller is not activated (see Figure 3.1.2.3.1). By maintaining the flow in the chiller path, the heat in the low temperature circuit is maintained. If additional heat is required, the valve V1 opens towards the MT circuit which allows the flow of coolant from the HT circuit through the valve V3. Figure 3.1.2.3.2 shows the situation if there is minor cooling required, the valve will use the first and the second radiator to achieve that cooling power. Since in that case there will be also a heat flow from the iCond and the power electronics parts this can’t be maintained for higher ambient temperatures. If the temperature at the Battery inlet rises further the V1 will together with V4 separate the LT Circuit and only the first radiator will be used exclusively for the low temperature circuit as shown in Figure 3.1.2.3.3. For high ambient temperatures it will not be possible to provide enough cooling power to the LT circuit without active cooling. That’s why for even higher battery inlet temperatures V1 will close the radiator path and use the chiller path instead. Figure 3.1.2.3.4 illustrates that situation. With an activated AC-circuit and the expansion valve opened to the chiller, it will be possible to reduce the battery inlet temperature even below the ambient temperature and therefore provide cooling power in high ambient temperature situations. The valve V1 therefore is controlled as thermostat valve where the chiller is not active. When the chiller is active, the temperature at the inlet of the battery is controlled by the AC circuit and in this case, the valve is fully opened along the chiller path.

For the V2 the Task is to maintain the power electronics at the maximum allowed inlet temperature. From the thermal system perspective, it is more efficient to keep the components at a high temperature level because at that higher temperature level it is easier to dissipate the heat. Maybe an overall optimization strategy will decide differently in this case because of the decreasing efficiency of the power electronics, but this topic will be elaborated in WP4. For low temperatures the V2 is open in the bypass path of the radiator and there will be no heat flow from the power electronics to the radiator. Which means that in this situation the complete radiator package is available for passive battery cooling and air conditioning leading to a very good efficiency of the AC-Cycle. If there is also higher cooling performance required for the power electronics V2 will open the path to the second radiator. If this increases the temperature of the battery inlet too much the V1 will react in the previously described way. For high ambient temperatures and high load cases V2 will also open the path of the first radiator.

This leads to maximum cooling performance and a very good utilization of the radiators and the air flow through the radiators. V1 will react by using the chiller path due to that action.

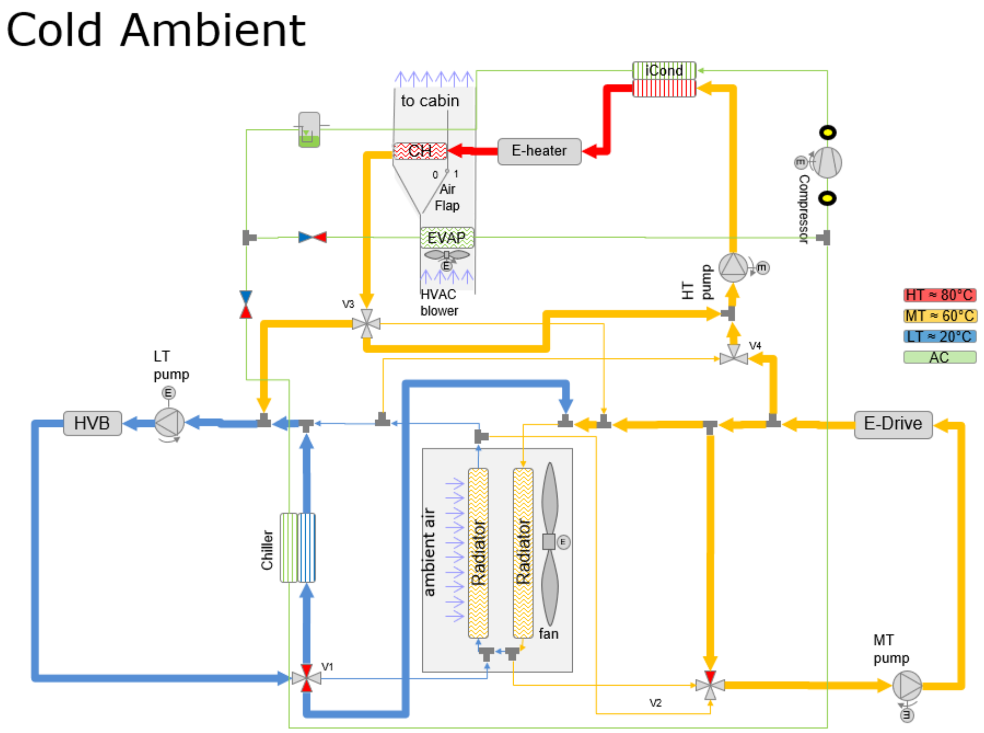

Figure 3.6: Valve 1 and Valve 2 Position – Cabin and Battery Heating

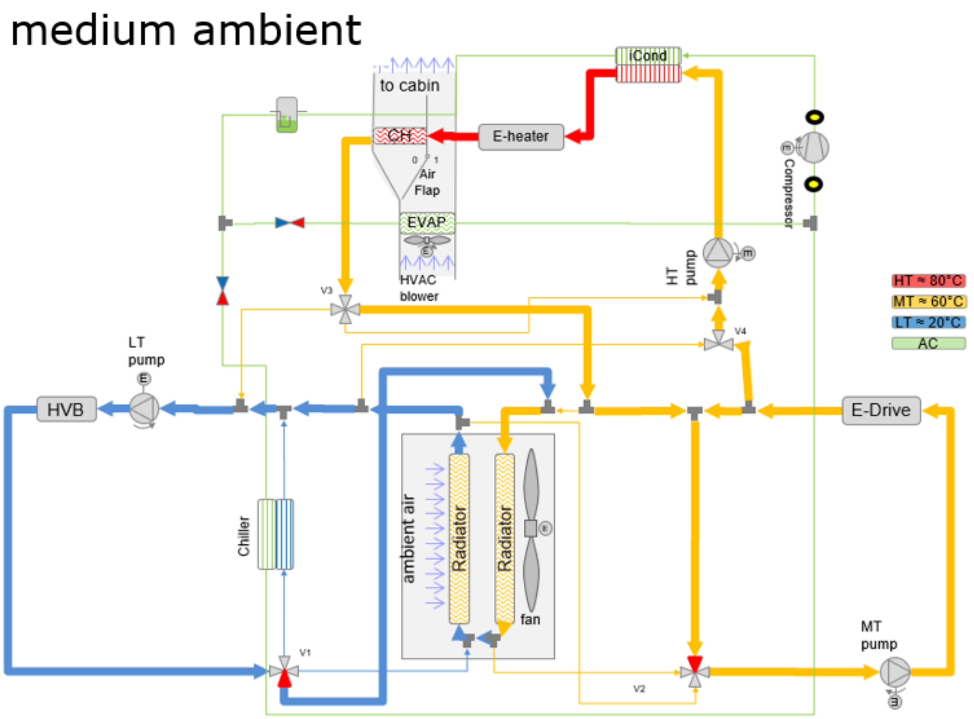

Figure 3.7: Valve 1 and Valve 2 Position for medium ambient temperatures and minor cooling demand of the battery and heating demand for the cabin

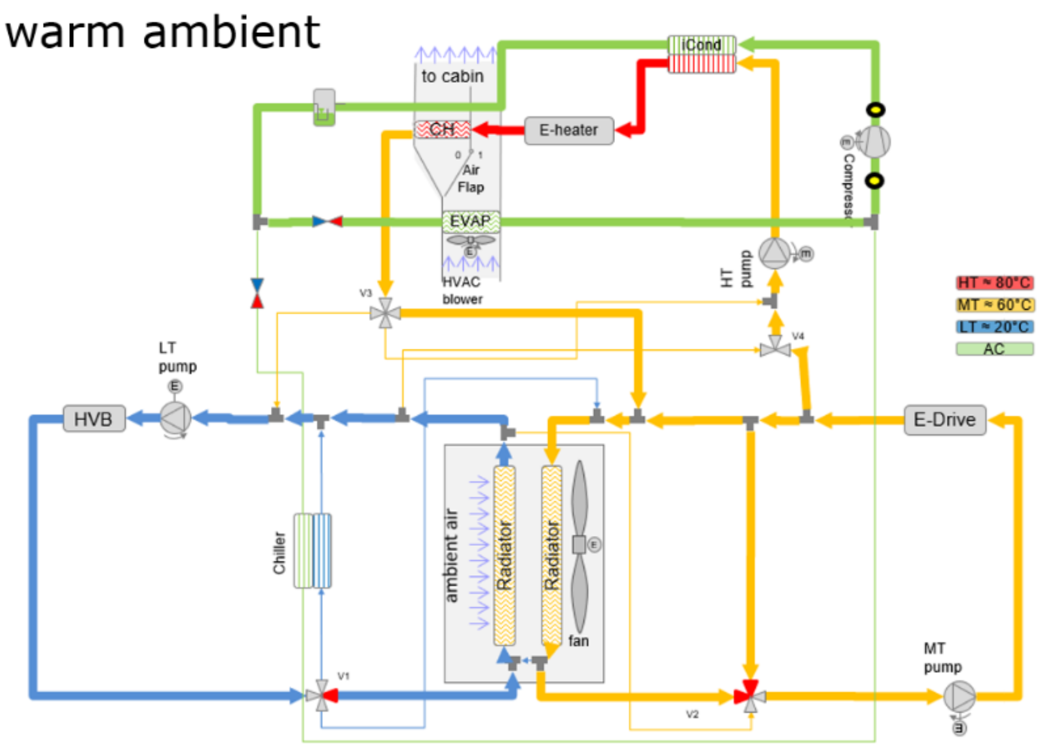

Figure 1.8: Valve 1 and Valve 2 Position for warm ambient temperatures and increased cooling demand of the battery and the E-drive

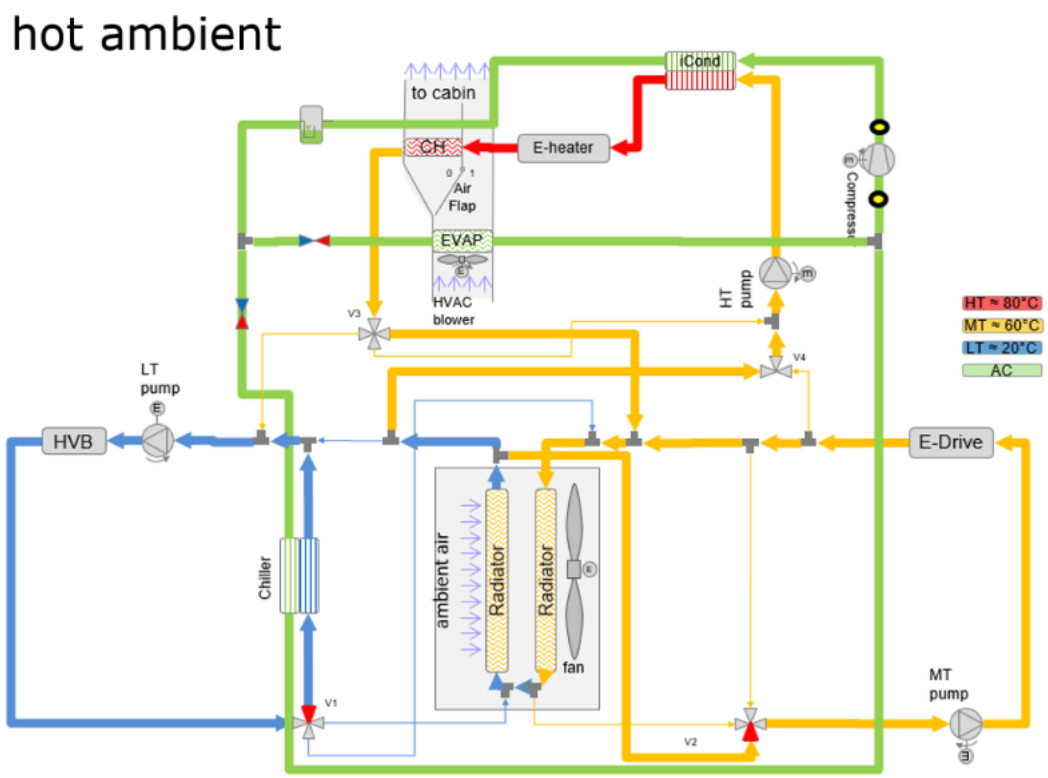

Figure 3.9: Valve 1 and Valve 2 Position for high ambient temperatures and maximum cooling demand of the battery and the E-drive

3.1.2.4 Compressor and Expansion Valve Control

The AC circuit is responsible for cooling the cabin and the battery, as the desired cooling temperature of these components is below the ambient temperature in some situations. PID control is used for the compressor based on reaching target temperatures. A target temperature for the air after the evaporator is supplied by the AIT HVAC controller. Based on this target, the compressor speed can be adjusted, and the thermal expansion valve (TXV) ensures adequate superheat before the compressor. Similarly, the battery inlet temperature can be adjusted. The Cidetec BMS provides a target value for this temperature. This allows the compressor to be set to a suitable speed when only the chiller is activated. The electric expansion valve (EXV) then ensures appropriate superheat before the compressor.

At times when the cabin and battery need to be cooled, the EXV is used to achieve a certain inlet temperature for the battery, with the aim of achieving less superheating before the compressor. The speed of the compressor is controlled based on the air temperature after the evaporator.

3.1.2.5 Control of Pumps and Fan

The LT_Pump is controlled to achieve the target volume flow of the coolant sent to the TMS controller by the BMS controller. The MT_Pump, the HT_Pump and the fan are the remaining actuators in the system. There is a certain degree of freedom with these actuators. In the partial load case, it is possible to lower the system temperature with additional electrical effort. For example, the system temperature can be lowered by switching on the fan. The effect of the lower temperature can have a positive effect on the efficiency of the AC circuit. Therefore, it is not obvious whether the total energy consumption increases or decreases. Rather, it is the case that there is a fan and pump activation level with an optimal efficiency for the overall system. This activation level can be determined in a 1D system simulation. Unfortunately, there are very many possible combinations for the three actuators and the optimal state depends on many boundary conditions such as vehicle speed and ambient temperature. AVLD has therefore developed a method to solve this problem with the help of AVL CAMEO. CAMEO derives a very fast running model (FRM) for some KPIs from a more complex and detailed 1D model.

The FRM model can be used to optimize and determine the most efficient combination of the three actuators for all driving situations. To demonstrate the functionality of the FRM model, an FRM model and basic controller models are prepared for the MT_Pump, HT_Pump and the Fan. In the basic controller, the MT_Pump controller is configured to maintain the temperature difference between the outlet and inlet of the powertrain components at 10°C. The HT_Pump on the other hand is controlled either to maintain the temperature difference between the outlet and the inlet of the iCond at 10°C or to keep the high pressure of the compressor below 12 bar. The fan controls either the maximum allowed pressure at the outlet of the compressor (17 bar in this case) or to maintain the inlet temperature of the MT Radiator at 70°C.

3.1.3 Simulation

Basic Controller vs Optimized Controller

A pulldown simulation is performed with the basic controller and the optimized controller. The simulation conditions are chosen in such a way that there is a cooling demand at the cabin and at the battery. The simulation is performed for constant values, and these are shown in the following table.

Table 3.3: Boundary Conditions for Simulation

Signal Name	Description	Value
vsVEH_T_AirAmb_C	Ambient Temperature	40°C
vsVEH_RH_AirAmb_C	Ambient Relative Humidity	0.4
pTMS_CoolantInitTemp_C	Coolant initial temperature	30°C
sBMS_BatCoolFlowSet_lpmin	Set coolant volume flow at battery	25 l/min
sBMS_BatCoolTempSet_C	Set coolant temperature at battery inlet	20°C
vCAB_EvoOutAirTempSet_C	Set air temperature after evaporator	8°C

The vehicle speed is assumed to be constant at 60 km/h and the total heat loss in the powertrain and the battery is assumed to be 12000 W and 5000 W respectively. The inputs from the BMS controller and the cabin controller are assumed to be as shown above in the Table 3.3. The results can be visualized in the next section (3.1.4 Results).

Basic Controller in Digital Twin

A pull-down simulation is performed to test the functionality of the basic controller with the powertrain components. The simulation is performed for a vehicle of 16 tons, for the Istanbul cycle. The simulation time is fixed for 2.5 hours (9000 seconds). The boundary conditions for the simulation remain the same as shown in the Table 3.1.3.1. The results of the simulation can be visualized in the following section (3.1.4 Results).

3.1.4 Results

Basic vs Optimized Controller

To show the controller functionality a simulation for a pull-down scenario is performed as described in the previous section (3.1.3 Simulations). Figure 3.10 shows a comparison of the compressor and fan speed demand with and without optimization. It can be seen that in the optimized simulation there is more fan activation, especially at the beginning. On the other hand, it is possible to reduce the compressor speed.

Basic simulation Optimized simulation

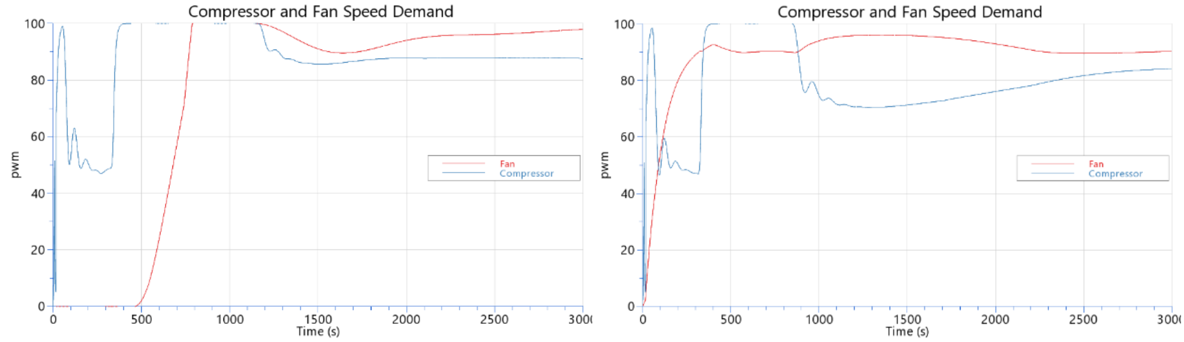

Figure 3.10: Compressor and fan speed comparison

Figure 3.11 illustrates the difference in pump activation. The optimized version opts for a higher activation of the MT pump but a lower activation of the HT pump. The LT pump is not changed by the optimization, as it is controlled by the BTMS system.

Basic simulation Optimized simulation

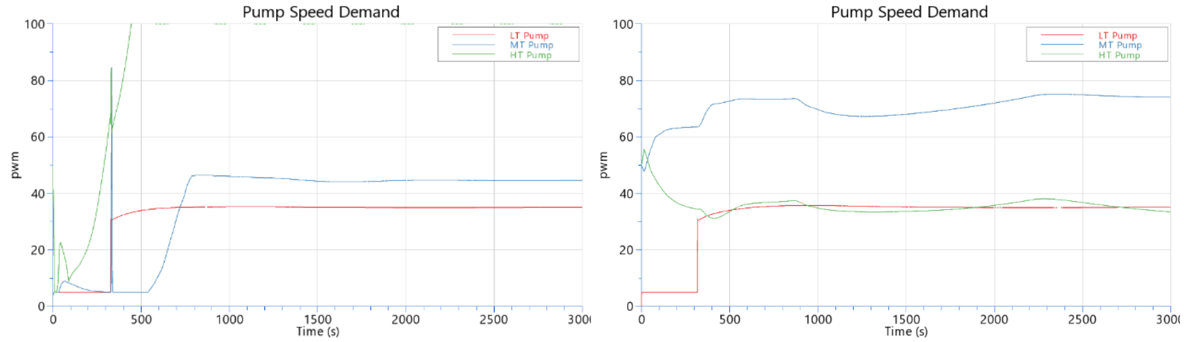

Figure 3.11: Compressor and fan speed comparison

Figure 3.12 compares the iCond coolant temperatures. It can be seen that the iCond inlet temperature, which is also the cooler outlet temperature, does not increase much during optimization. On the other hand, there is a lower iCond inlet temperature at the beginning due to the increased fan activation. This lower inlet temperature improves the efficiency of the AC cycle and reduces the required compressor power.

Basic simulation Optimized simulation

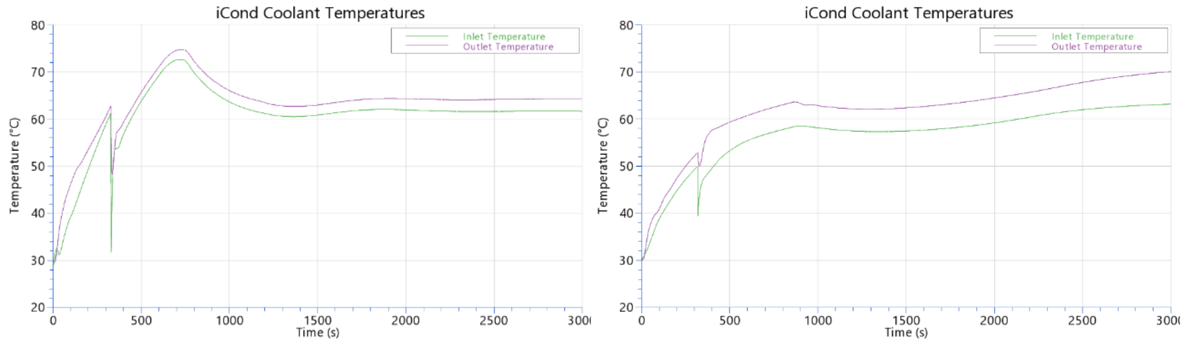

Figure 3.12: Compressor and fan speed comparison

Figure 3.13 shows the total power and energy consumption of the TMS. Due to the more efficient combination of all actuators, the power consumption is lower most of the time than without the optimization. Therefore, the slope of the energy consumption is also lower, and the energy consumption of the optimized control is about 2.4 kWh compared to 2.6 kWh without optimization.

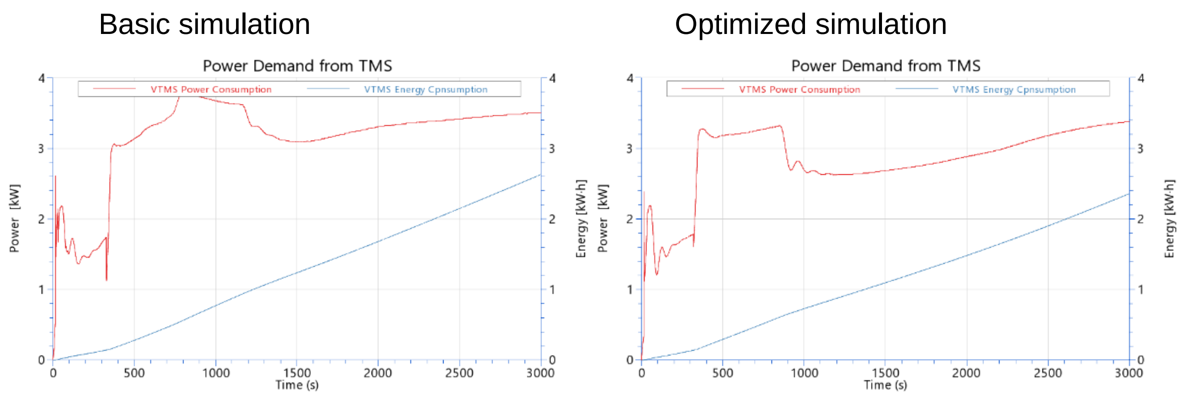

Figure 3.13: Compressor and fan speed comparison

The basic control strategy for the thermal system is without high computational effort and of good stability due to the state definition and map control from the optimization. Furthermore, the optimization improves the efficiency compared to a conventional controller approach. Thus, even without a cloud connection, safe and efficient control of the TMS is guaranteed.

Basic Controller in Digital Twin

The simulation results are analyzed to check if the desired target values are reached, if the components are within the operating temperature range and to check if there are any strong oscillations caused because of the controller. It is normal to have some oscillations in the controller since it is a transient simulation and the sensor values received by the controller also have some fluctuations over a period.

In Figure 3.14, the temperature of the coolant before and after the battery and the powertrain components can be seen. In this figure two target values are to be noted. As listed in the Table 3.3, the target for coolant temperature at the battery inlet is at 20°C and the difference in temperature between the outlet and the inlet of the powertrain components is at 10°C and both are achieved. In the following Figure 3.15, the temperature of the components in the powertrain is plotted over time and these temperatures are very well within their respective operating range.

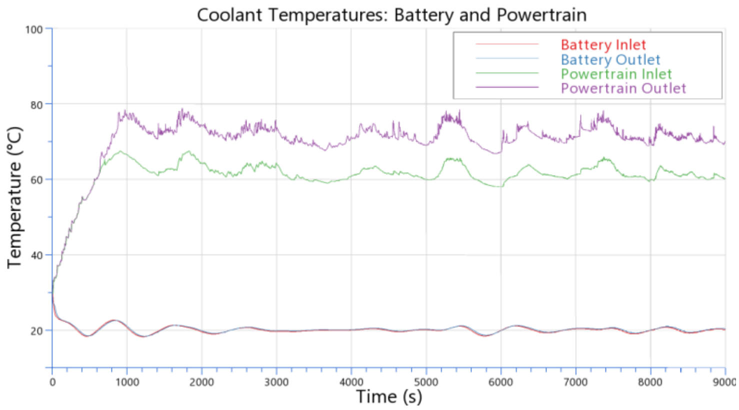

Figure 3.14: Coolant Temperatures

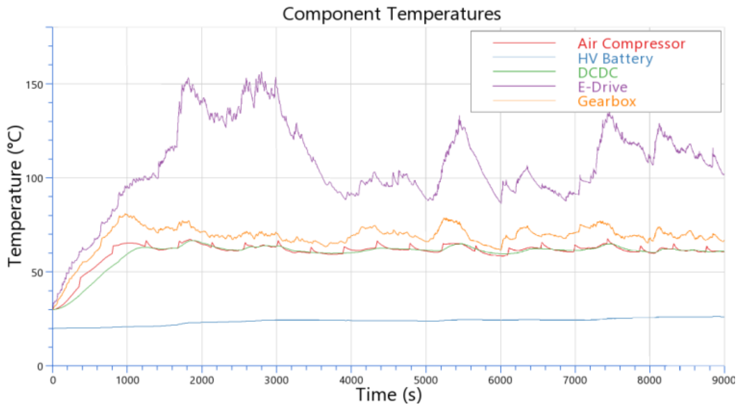

Figure 3.15: Component Temperatures

The Figure 3.16 shows the temperature of the air after the evaporator outlet and the target value. The target value here is provided to the TMS by the cabin controller and it is assumed to be 8°C for this simulation. Some oscillations can be seen in the figure but since they are over a simulation time of 9000 seconds, they are not considered to be so critical.

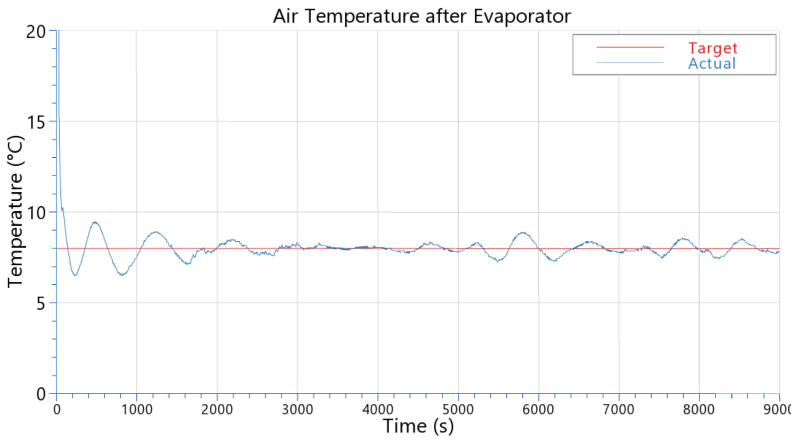

Figure 3.16: Air Temperature after Evaporator

The Figure 3.17 shows the power consumption of the components in the TMS during the simulation. The varying power demand is due to the varying requirements during different stages of the simulation.

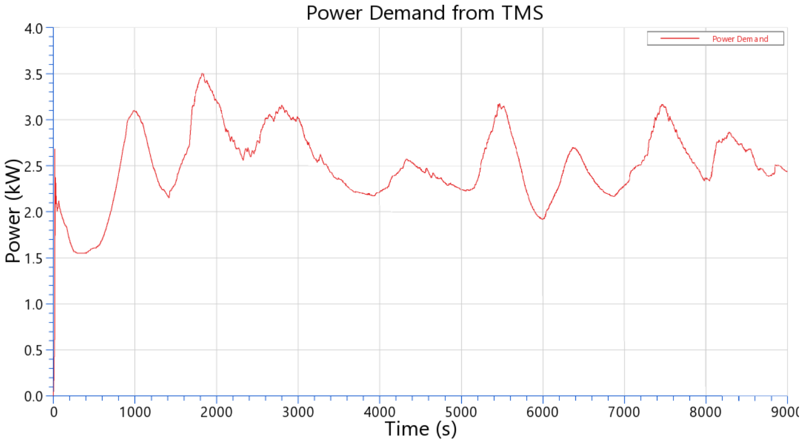

Figure 3.17: Electric power required by Actuators in TMS

3.2 Cabin controller

The cabin controller communicates with the HVAC system and other components of the thermal system and determines set values and control signals for the blower, IR panels, recirculation, mix flap. In addition, it controls the use status of the air-air heat exchanger.

The HVAC system operates in three different statuses: heating, cooling, and ventilation. For security, if any issue arises the controller can send error messages. Heating is activated when both the cabin temperature and ambient temperature are lower than the set temperature:

$$T_{cabin} < T_{set} + 4°C$$
$$T_{ambient} < T_{set}$$

Cooling is activated when both the cabin temperature and ambient temperature are higher than the set temperature:

$$T_{cabin} > T_{set} - 4°C$$
$$T_{ambient} > T_{set}$$

Ventilation is activated when the cabin temperature is lower than the set temperature and the ambient temperature is higher, or vice versa. In this case, only the blower has energy usage:

$$T_{cabin} < T_{set} + 4°C \quad \text{or} \quad T_{cabin} > T_{set} - 4°C$$
$$T_{ambient} > T_{set} \qquad\qquad T_{ambient} < T_{set}$$

When the cabin, ambient, and set temperatures are within a 2°C interval of each other, the cabin is in the ventilation status:

$$T_{set} - 2°C < T_{cabin} < T_{set} + 2°C$$
$$T_{set} - 2°C < T_{ambient} < T_{set} + 2°C$$

IR panels are controlled based on the PMV (Predicted Mean Vote) and operate exclusively in heating mode. As time progresses, the surface temperature of the cabin gradually approaches the cabin air temperature. Consequently, there comes a point where the IR panels are no longer required since the surface temperature aligns with the cabin air temperature.

The cabin model is originally developed in Dymola/Modelica simulation framework, and subsequently exported as Functional Mock-up Unit (FMU), as shown in Figure 3.18. FMUs represent the dynamic models encapsulated in a standardized format, which enable either the exchange or coupling of different models across various simulation tools. By configuring FMU settings strategically, such as adjusting time steps, employing efficient numerical integration methods, and implementing model simplifications, simulation speed can be significantly enhanced without compromising accuracy. Additionally, utilizing parallel or distributed computing resources can further expedite FMU execution.

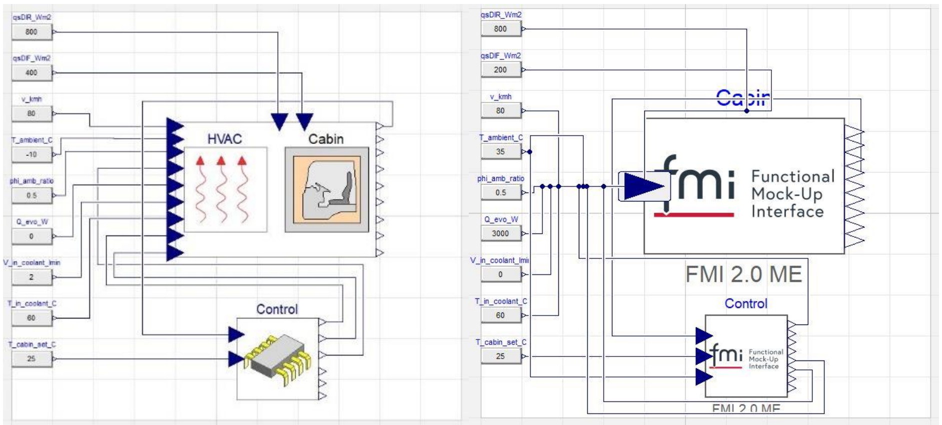

Figure 3.18: The sketch of the cabin and control encapsulated as FMU

To ensure effective communication and interaction between FMUs within a digital twin environment, the interfaces are established to serve as connection points, enabling seamless data exchange between different components. For clarity, they follow consistent naming conventions for variables and signals shared between FMUs. The FMU interface is organized in a structured manner, to further enhance usability by categorizing variables based on their purpose or functionality. The sketch of the cabin controller is shown in Figure 3.19.

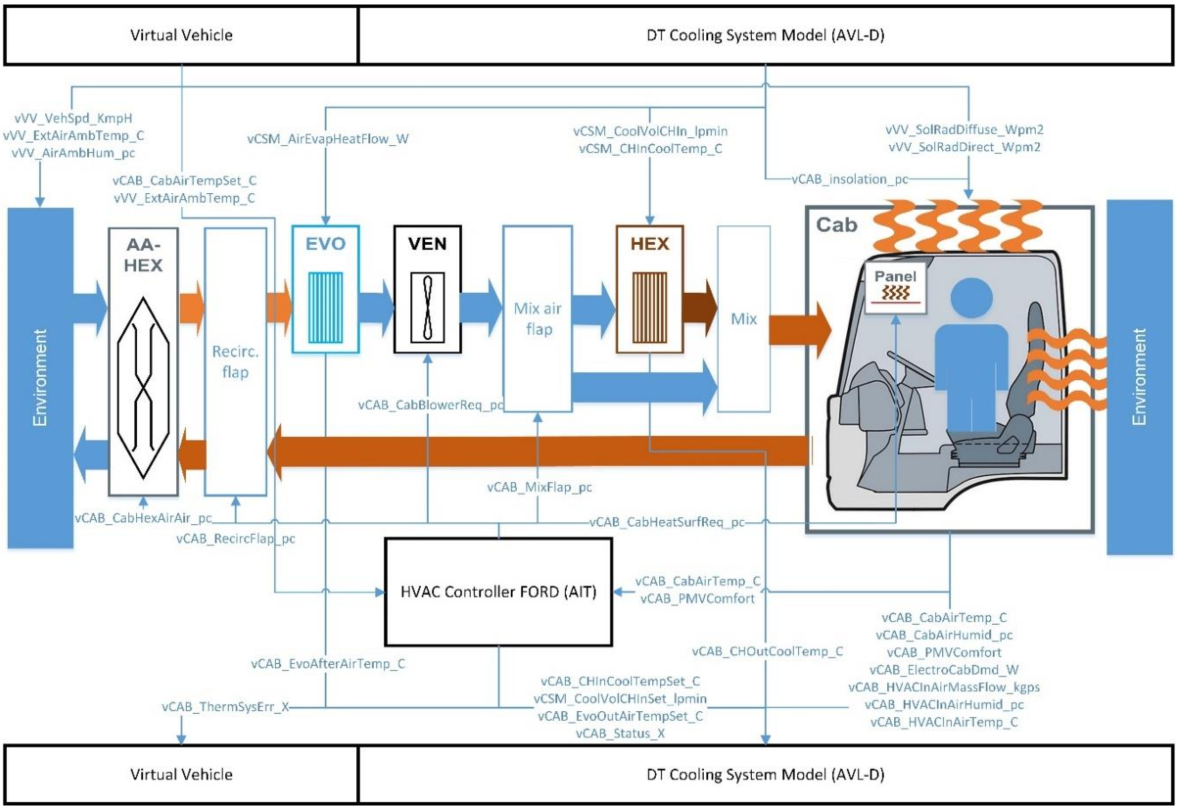

Figure 3.19: The sketch of the cabin controller with interfaces

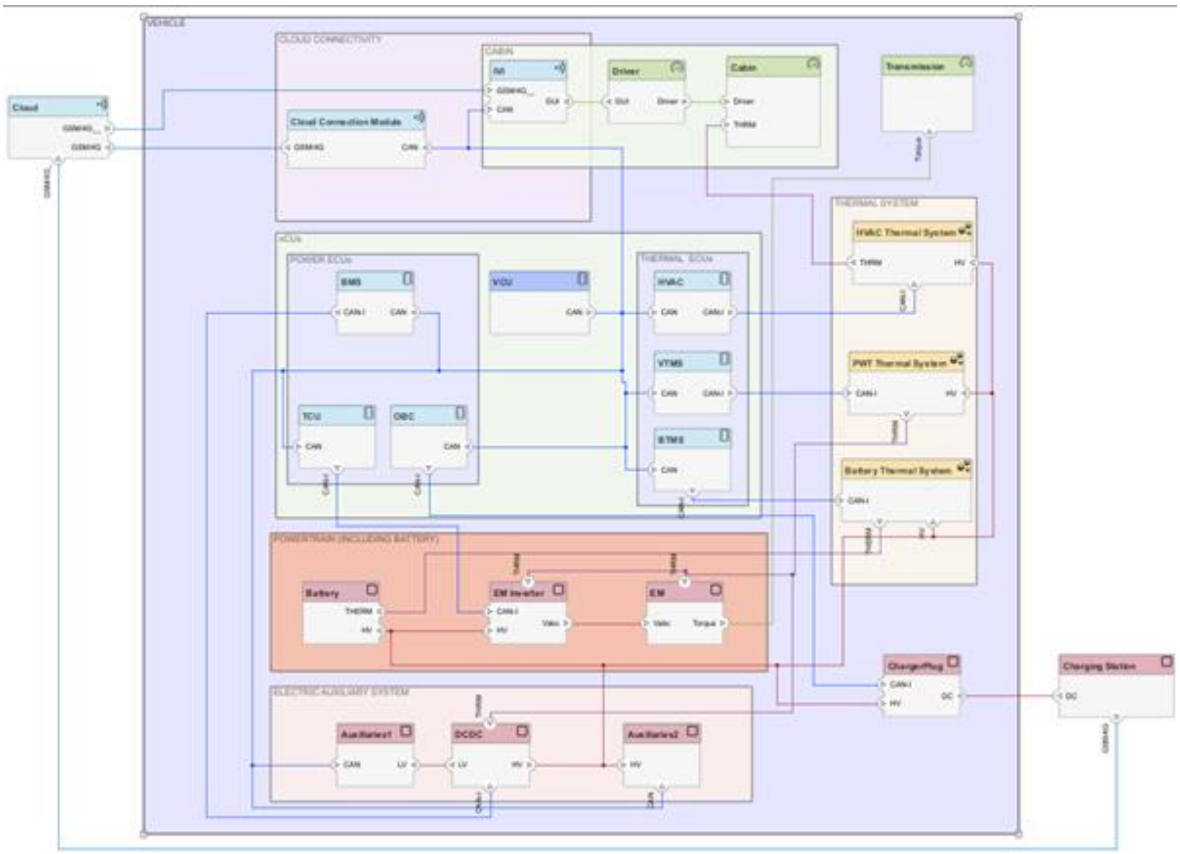
Figure 3.20: General E/E architecture

3.3 E/E architecture

The scheme in Figure 3.20 tries to display a common E/E architecture. This scheme could be adapted to each OEM case according to each OEM provided information and more information about the E/E architecture is given in D3.1

The Figure 3.21 displays this E/E architecture from the point of view of the thermal management. There, the different components and interfaces involved are displayed. The control part is divided in two layers. The VCU is in charge of the higher layer whilst the lower layer is controlled by the following ECUs : BTMS, VTMS and HVAC. Detailed information about the signals exchanged in the CAN bus between the VCU (which is in charge of MLC) and the different ECUs (HVAC, BTMS and VTMS) is in D2.4.

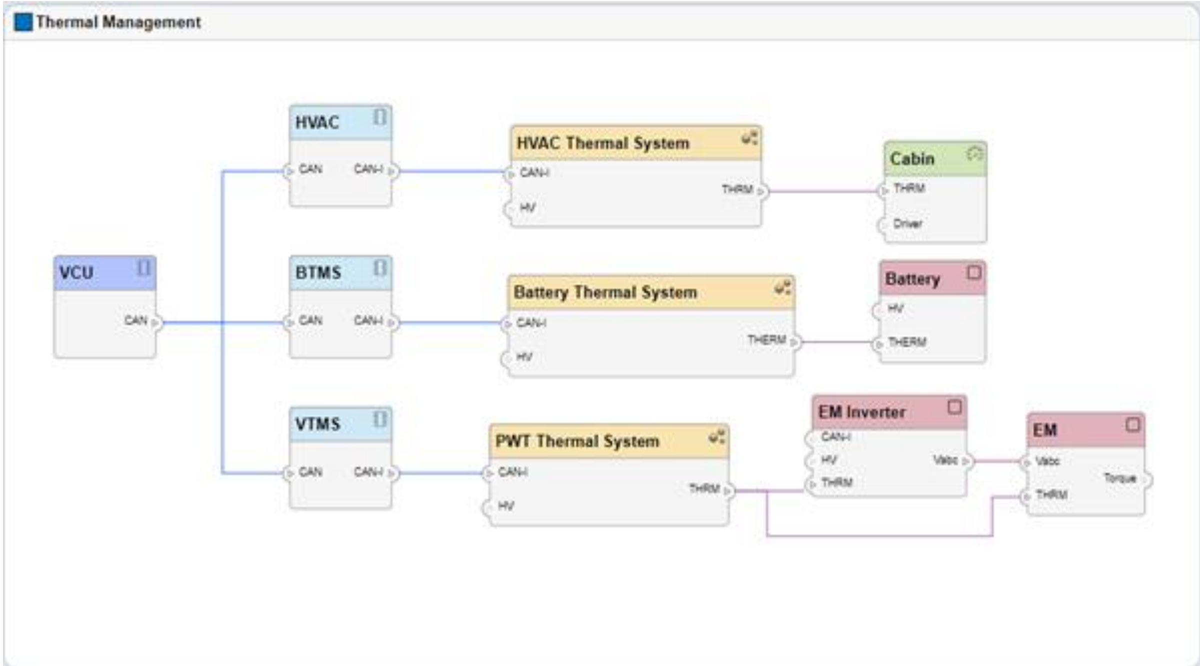

Figure 3.21: Thermal management E/E architecture

MLC will be developed more in deep in WP4.2 but an initial approach has been already discussed and proposed. MLC has to consider the three thermal subsystems to control (cabin, powertrain and battery) but also eco-driving control in order to improve the overall vehicle efficiency.

A specific digital twin (DT) executed in the cloud is required for this optimization strategy. The multi-level control system DT (DT-MLC) will provide the necessary information to the in-vehicle multi-level control (IV-MLC) for overall system optimization (which is executed in the VCU). Then, IV-MLC will only distribute to the different thermal sub-systems (HVAC, VTMS and

BMS) which is the optimal thermal strategy in terms of overall vehicle efficiency. Additionally, the IV-MLC will suggest to the eco-driving module or directly to the TCU (Traction Control Unit) if performance (electrical machine speed, torque or power) should be reduced in terms of overall efficiency.

The DT-MLC will execute a set of simulations in the cloud that will allow to optimize the eco-driving and thermal strategies in terms of vehicle overall efficiency and according to a predefined cost function. The set of simulations will be executed each defined period (e.g., every 10 seconds) and each simulation will require traffic flow and routing information about the oncoming defined kilometres (e.g. 20 km). This information will be available for the DT-MLC thanks to the cloud services depicted in red blocks in the Big Picture from D2.4 (Figure 3.22)

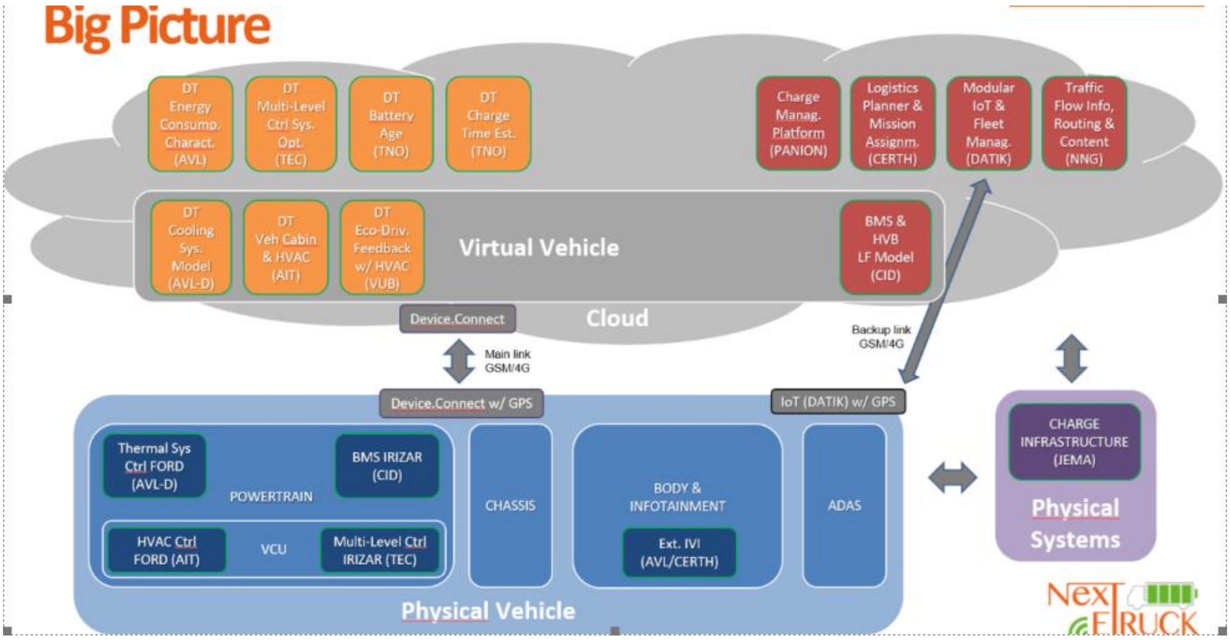

Figure 3.22: The digital twin scheme

The number of simulations in each set and periodicity for each set will depend on the computational capabilities in the computational capacity cloud (which is still under study).

The DT-MLC will require different low-fidelity models (as FMUs) in order to evaluate the vehicle behaviour with the desired accuracy and adequate computational cost. Those models are developed between different partners:

- Battery and BMS (CID)
- VTMS (including BTMS) and its auxiliaries (AVL-D)
- HVAC and cabin model (AIT)
- Eco-driving, driver, electrical machine and inverter (VUB)
- Transmission, vehicle dynamics, VCU, TCU and additional auxiliaries (TEC)

All those models are included in the E/E architecture shown above (those that are in the E/E architecture but not mentioned above are not relevant for the MLC). As a first proposal, the DT-MLC will deliver a speed, torque or power reference ratio to the eco-driving control and a discrete value (e.g. 0 = no conditioning, 1 = low refrigeration, 2 = medium refrigeration and 3= high refrigeration) as a command to the different thermal system controllers (BTMS, VTMS and HVAC). Then, each thermal system will command its actuator and auxiliaries correspondingly to obtain the desired refrigeration level. The commands from the IV-MLC can be used as a suggestion by the different sub-systems. Do not have to be mandatory and those sub-systems can continue to be autonomous (this is how it would be anyway when there is no cloud connection). Nevertheless, OEMs will have the last word on how they want to implement MLC. The optimization algorithm has not been decided yet. A proposal scheme is briefly described in Figure 3.23 below:

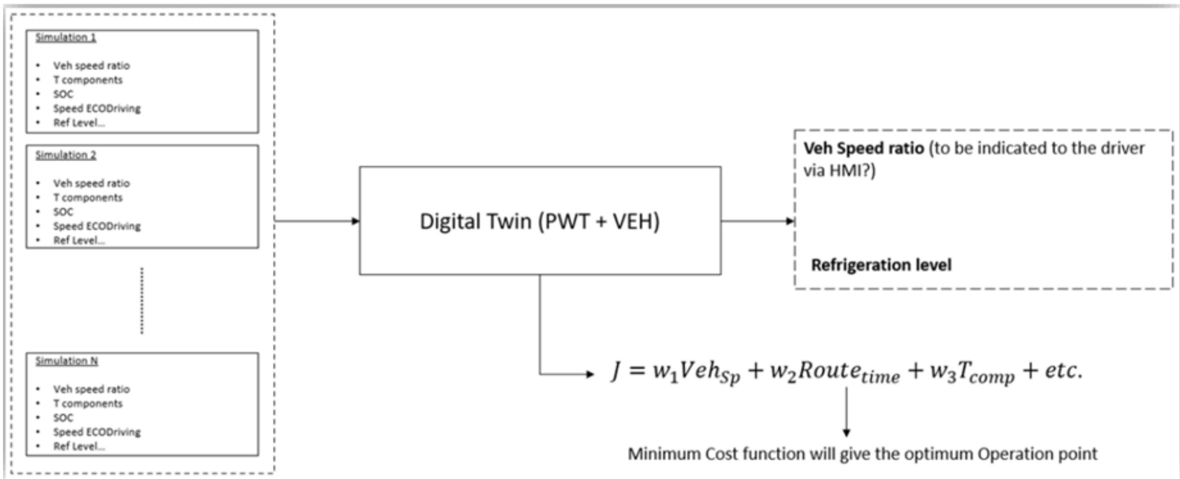

Figure 3.23: Multi-Level Control System Optimization DT strategy

Related to the cost function, this is the key for optimization, and it is still under discussion. An initial proposal could be:

J = w1*(all auxiliaries consumption) + w2*(battery optimal temperature error) + w3*(cabin discomfort);

wX = weighting factor X

Cost function simplicity is interesting according to computational cost. The optimal temperature of the e-components (inverter, EM) could be considered directly in the consumption because it is changing the efficiency and there is no degradation or aging in the e-components in this project (but will be related to the battery). The cabin comfort has to consider aspects like temperature and humidity and is explained in the previous chapter.

3.4 BTMS controller

The BTMS control strategy is integrated on the BMS along with the SOC estimator, SOF estimator and SOH estimator, see Figure 3.24. This controller considers the difference of the battery temperature and the objective temperature to set up the required output of the BTMS: (1) The temperature of the liquid inlet at the gates of the battery system, and (2) the liquid flow on the battery system cooling-circuit.

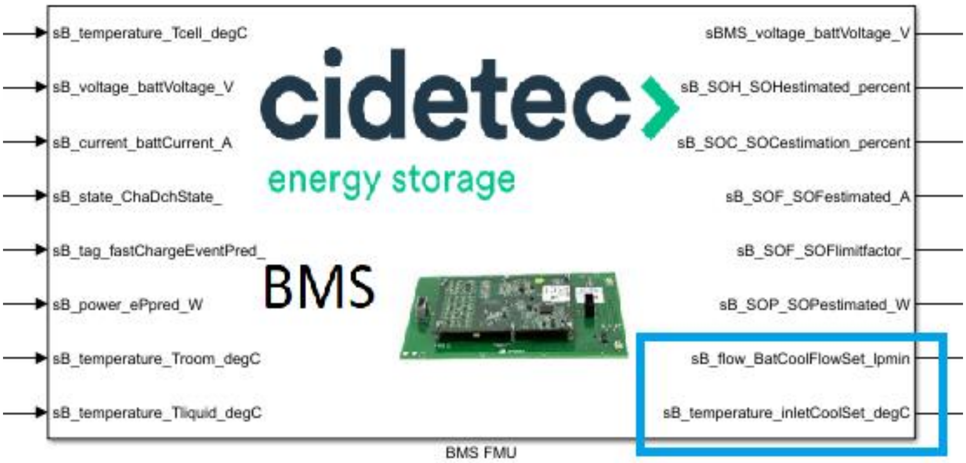

Figure 3.24: low fidelity BMS (BTMS control strategy integrated).

The developed controller (low fidelity) is inspired by the controller designed, tested and validated in i-HeCoBatt project (H2020 Grant Agreement-824300). The developed controller in I-HeCoBatt was done for an EV, while this control will be integrated on an e-truck. Besides, the control smart features are adapted to the use case.

The controller defines the requirements of the BTMS when the battery temperature crosses some temperature thresholds, defining the cooling and heating needs of the battery system, see Figure 3.25. This is the base of the controller. The temperature thresholds of the controller (parametrizable for each use case) define the saturation values of the two PID controllers (each defines one: heating or cooling), generating like this a PID with a death zone (a zone where the control is not applied).

As observed in Figure 3.25, the low-fidelity BTMS controller has some smart features that optimize the performance of the BTMS of the e-truck. In comparison with i-HeCoBatt project's controller, the options for conservative operation when parked and pre-conditioning by demand have been removed since these functionalities are done by the fleet management tool. Nonetheless, the driving preferences of the drivers and the prediction of fast charge events through route monitoring and prediction are considered to optimize the BTMS performance as well as in i-HeCoBatt project.

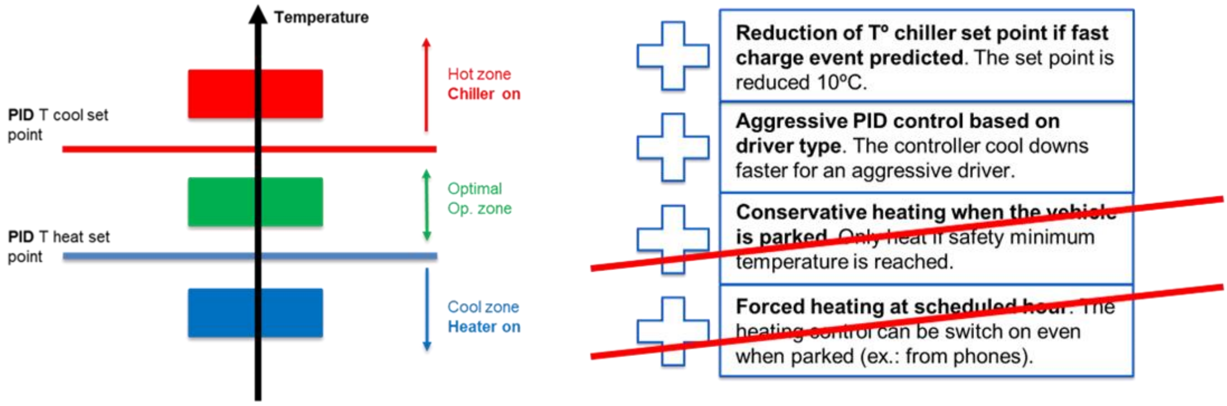

Figure 3.25: BTMS control strategy.

Additionally, the research of a predictive controller has been started. Predictive control strategies are supposed to be done in WP4, but a first state of art research and initial definitions have been already done. The first state-of-art research has pointed us to the selection of a predictive controller based on Model Predictive Control (MPC) algorithms. Thanks to the route prediction, the power/current profile of the battery system for some minutes in the future will be provided to the BMS. In this scenario, the BTMS control strategy on the BMS will define the required heating or cooling power to minimize the temperature effect on the aging and the consumption of the BTMS itself. To do so, the models of the battery system, BMS, ECU of the battery system and the BMTS are required to do linear optimizations on the BTMS performance based on the battery system response all along the predicted time interval. The battery system performance is dependent on the power/current profile (it may be modified by the ECU system due to the BMS response influenced by the battery state), but also to the BTMS response. It is not trivial to develop an accurate MPC algorithm for the whole battery system that can have a result fast enough to be used on a real application. This challenge and further details will be addressed on WP4.

4 CONCLUSION

This deliverable presented the outcomes of two tasks from WP3, dealing with the system architecture and optimization: T3.2 on the thermal system and cabin concept, and T3.3 on the thermal system control and management. The main outcomes from the presented work are summarized below:

- The proposed solutions (thermal management, E/E architecture, cabin) could be adapted for different UCs;
- For the selection of the TMS layout has been based on the configuration simplicity and operating characteristics;
- With the proposed cabin concept, the reduction of 30% in the energy demand for the thermal conditioning of the cabin can be reached;
- The initial DT-MLC optimization strategy proposed, pending OEMs response.

The specifications for the work performed within T3.2 and T3.3 were based on the UC1 with FORD vehicle. However, the concept and design criteria were taken very general, in order to make the extensions to other UCs as simple as possible. In that view, the modifications considered for the energy efficient cabin concept include the IR panels (as they are very flexible, endurable and easy to implement) and heat exchanger (which should be relatively easy to introduce into the existing configuration). The details of the implementation of the cabin energy efficiency measures will be elaborated later in the project (as a part of the WP4, where the work on the actual cabin is planned), where it is envisioned to make use of the original vehicle setup for most of the other auxiliary requirements. The preliminary cabin analysis shows a significant energy saving potential, although it needs to be noted that the cabin energy demand is just a fraction of the overall energy demand. However, this contributes to the synergy effect of reducing the energy demand of other end users, together with the related construction simplifications, which will result in the target energy improvement. In addition to the battery pack cooling development, it directly affects the use range and is aligned with KPI-1 (10% longer range per energy consumption). Furthermore, the battery pack cooling improvements imply considerably less hydraulic needs for similar thermal performance (as compared to the base cooling plate) and hence a lower consumption for the auxiliar/adjacent systems. This is aligned with KPI-2 (achieving at least 95% of the ZEV truck operation range while using heating) and KPI-8 (vehicle thermal efficiency improved by 15%).

The decision for the layout of the thermal management system (TMS) is presented. Different TMS layouts are designed by taking into consideration the thermal conditions of an efficient cabin and the e-drive components. A qualitative approach based on several evaluation criteria and a quantitative approach based on 1D simulations in Cruise M are used for the layout decision. Six different TMS layouts are part of the investigation which reach from a very simple baseline layout with three isolated circuits to complex layouts with high interaction between the circuits. The qualitative comparisons of the TMS circuits includes different cooling and heating use cases. The best performance and efficiency characteristics are reached by a layout variant which is characterized by two separated cooling circuits with a water condenser. The selected layout variant allows a high efficiency in passive battery cooling over a large range of temperature as two radiators are used. Concrete numbers regarding the performance and efficiency improvements and therefore an assessment of KPI 8 (Vehicle thermal efficiency improvement by 15%) requires a comparison of the selected TMS layout to the TMS layouts provided by the OEMS. For the latter mentioned comparison the TMS actuator needs to be sized based on boundary conditions provided by the OEMS. This is part of ongoing work.

The TMS and the TMS Controller models are tested through simulation and further improvement possibilities are discussed. The functioning and stability of the basic controller model when coupled with the other FMUs in the digital twin environment and the ability of the system to reach target temperatures were also discussed under the results section. Developing an optimum operating control strategy involves finding an optimal combination of the actuators' operation without compromising the performance of the system and the initial comparison of the basic and the optimized controller shows promising results. The comparison made between the basic and the optimized controller will further be tested along other FMUs in the digital twin environment to simulate the savings potential for a driving cycle. Testing the optimized control strategy in a transient cycle will provide a better view on the savings potential since it can be evaluated for different load conditions. In the results of the optimized controller in the 3.1.4 Results section, it can be seen that there is a considerable demand requested from the pumps, fan and the compressor and the optimized controller is still able to perform more efficient than the basic controller. Lower load and medium load cases offers more possible combinations of actuator PWMs for the optimized controller to choose from. Therefore, the targeted thermal efficiency improvement of 15% can be achieved for a complete driving cycle.