Functional Model-based Resource Management: An Application to the Electric Vehicle Thermal Control

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Abstract: Environmental and economical constraints lead to designing more and more complex systems. To face these issues, Model Based System Engineering proposes an approach based on an interconnected multi point of view system modeling. Each representation of the system has a different abstraction level that is valuable at different stages of the system design and suits its own objectives respectively: 1) purposes and global constraints definition, 2) architecture choices, components sizing and strategies testing, 3) accurate simulation results on various scenarios. Interconnections between the different levels have two objectives: on one hand be able to define the requirements of a lower level using higher level information and on the other hand send back simulation variable values from a lower level to evaluate the higher level requirements satisfaction. Resource management is carried out through a functional model, which is a macroscopic and low-complexity model of the system providing fast simulation results. In this paper, this multi-level methodology is applied to the thermal system management of an electric vehicle in order to optimize its resource management. The different levels design and the development of their interconnections are detailed.

1 INTRODUCTION

The impact of carbon emissions, resource depletion and over-consumption on global warming and environmental issues is now well established. In order to take into account these constraints in the design stages, engineers develop systems that are more and more complex, leading to some issues:

- A single system handles with several sources and consumers belonging to different energetic fields (mechanical, electrical, thermal, etc.).
- There are multiple objectives (economical, ecological, sizing, etc.).
- The technological structure is complex.

Moreover, the development of these complex systems faces two antagonist issues. On one hand, each component of the system needs to be developed by engineers specialized in the component field. On the other hand, the system needs to be thought and designed as a whole including all the interconnections between components.

The main purpose in the control design is to optimize the global consumption of the system while respecting all the constraints. To achieve this goal, the system needs to be modeled in a way that describes well both sources and consumers as well as their interconnections. These models deal with different physical fields and can become complex and burdensome, making them difficult to handle and modify. A higher level of model abstraction is needed to make it easier to understand and handle.

The modeling methodology introduced in (Fiani et al., 2016) and (Mökükcü et al., 2016) presents how to address the system design from three different points of view (detailed below), each of them having its own abstraction level, and how to easily switch between them. This methodology is based on the systemic approach concept introduced in (Von Bertalanffy, 1968). The system description is inspired by the Bond Graph methodology, which has been shown to be well-suited to systemic modeling and multi-domains simulation in (Brunet et al., 2005) and

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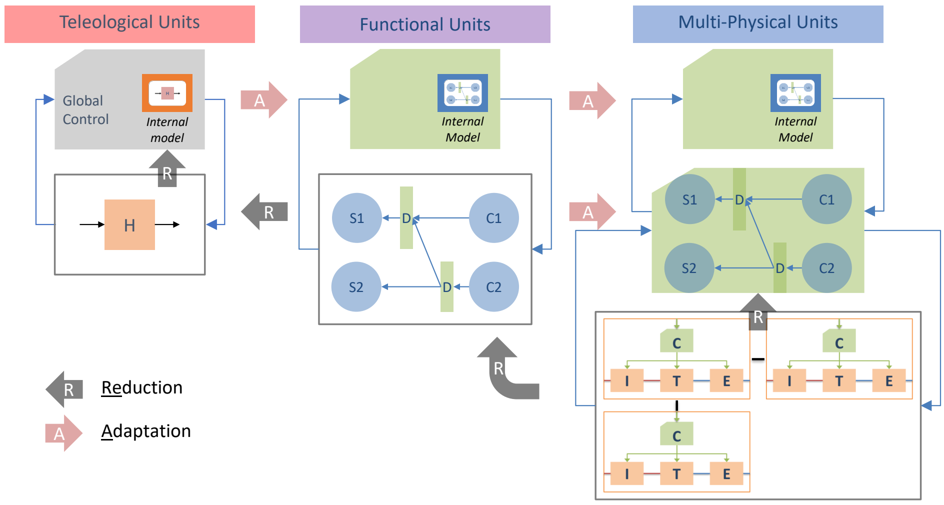


Figure 1: Diagram of electric vehicle cooling and heating circuits (Fiani et al., 2019).

(Borutzky, 2010). The three different modelings are listed below from the highest abstraction level to the lowest and will be detailed in Section 2 :

- A teleological modeling where the global missions and the main properties of the system are defined.
- A functional modeling that is composed of basic modular blocks having a specific function. Blocks are connected to each other with EMI (Energy, Flow, Matter) flow needs and supplies.
- A multi-physical modeling that is composed of all physical components and equipment of the system. At this level, the behaviour of the components and interactions between each other are defined by physical laws.

This methodology is interesting because each abstraction level has its own specificities and is used at different stages in the system design. As illustrated in Figure 1, this methodology is a circular approach in which each higher abstraction level can be seen as a reduction from the lower one. The teleological level does not require neither much time nor any technical knowledge to be developed and gives a first global overview of the system and its main characteristics. Hence, it is often the first one to be elaborated. The functional model is then developed as a refinement of the teleological one, where the different functions of the system and their interactions are defined. By construction, the functional model contains both a control and an operation part that make the model self-sufficient, i.e. it can be run on its own. The major advantage of this modeling is the possibility to quickly simulate the system already in the first design stages; it will be especially useful for architecture choices and components sizing. An adaptation of the teleological level enables the transmission of the global constraints from the highest level of abstraction to the functional one. As the design progresses, a model much closer to experimental observations is needed. The expansion of each function of the system as a set of physical components and the definition of their interactions lead to the development of the multi-physical model. Instead of starting from scratch for the control design of this level, an adaptation of the control part of the functional level can act as the multi-physical model supervisor. Finally, the end-missions of the system can be introduced in the control of this lowest abstraction level by a new adaptation of the teleological level.

The first objective of this work is to connect the functional model to a global supervisor (corresponding to the teleological level) containing macroscopic constraints and criteria that can be transmitted to the functional model through the resolution of an optimization problem that will ensure a better resource management. The second objective is to build the control of the multi-physical model using setpoint values coming from the control part of the functional representation. The coupling between functional and multi-physical models was demonstrated in (Mökükcü et al., 2017) on the power-train of a hybrid electric vehicle and it will be extended here for thermal issues.

In this paper, the methodology is applied to a use-case consisting in the thermal management system of an electric vehicle (EV). In internal combustion engine vehicles, cabin heating is ensured by the thermal energy dissipated by the engine while its cooling is ensured by a refrigerant loop. The development of battery electric vehicles brings some new issues:

- Electric machine does not dissipate enough energy to satisfy the heating needs.
- The battery has sizable heating and cooling needs that must be taken into account.
- Battery temperature has a direct influence on its efficiency, which is a key parameter for the vehicle autonomy.
- The non-negligible impact of battery temperature on its service life was demonstrated in (Gross and Clark, 2011).
- The battery charge dissipates a huge amount of energy that must be evacuated, especially in the case of fast charging.

Due to these new constraints, a multitude of different technical solutions have been developed, leading to as many different architectures, as shown in the large review presented in (Zhang et al., 2018). Hence, thermal management in electric vehicle is becoming an important research topic for car manufacturers.

Section 2 describes three models with different abstraction levels (teleological level, functional level and multi-physical level), the interconnection between these models as well as the advantages and the challenges of the interconnection. In Section 3, the EV thermal management system is detailed and modeled at the three levels of abstraction.The issue of energy management between the consumers is introduced and an optimization problem is formulated at teleological level of abstraction to address this problem. Section 4 provides the simulation results of the functional model, which are confronted to simulations of the multi-physical model for validation. Finally, concluding remarks and perspectives are presented in Section 5.

2 MODELING METHODOLOGY FOR SUPERVISOR ARCHITECTURE DESIGN

This section describes the three abstraction levels of modeling introduced in (Fiani et al., 2016) and (Mökükcü et al., 2016) and shows how they can be interconnected between each other.

2.1 Teleological Modeling

The teleological modeling is the one with the higher level of abstraction and it does not require any technical knowledge to be elaborated. At this level, only the main missions and expectations of the system are represented. Some of the requirements that can be expressed at this level are listed below:

- Financial and realization time constraints.
- Ecological international standards.
- Constraints related to the integration of the system in its environment.
- Global performances of the system (lifetime, autonomy, operation energetic cost, etc.).
- Some comfort criteria like maximal noise or vibration levels.

At teleological level are also defined some arbitration rules that define weighted or heuristic priorities between the different purposes of the system. For an electric vehicle, this arbitration level could be illustrated by different operation modes:

- A sportive mode that focuses on the power-train performances.
- A comfort mode, where comfort parameters are optimized (compressor noise, cabin temperature, speed variations smoothness).
- A normal mode that tries to meet all criteria, as best as possible, without favoring any of them.
- An eco mode, in which priority is given to energy savings.

In the earliest design stages, this level gives a good overview of the main missions and limitations of the system while in the last stages, it can be used to introduce optimization algorithms to minimize a global cost function (financial cost, energy amount, etc.).

2.2 Functional Modeling

The concept of functional modeling has been developed in (Fauvel et al., 2014) and (Mökükcü et al., 2016) and has been illustrated on a hybrid vehicle in (Mökükcü et al., 2017). This representation is based on the use of modular functional blocks assembled together and connected by EMI flow exchanges. Each block is composed of both a control part that determines the flow needs to be transferred to the neighbour blocks, and an operation part that incorporates the flow supplies received by the block into simple models, in order to estimate the different variable values. This architecture of each block enables the functional model to be run on its own. A few functional elements have been introduced in (Mökükcü et al., 2016) and extended to thermal field in (Fiani et al., 2019).

- Source: receives an EMI flow need (power in the case of an energetic system) from another element and delivers a flow supply depending on the need and internal limitations of the source.

- Consumer / Effector: requests an EMI flow to another block that can provide it. The flow is used to achieve the effector's objective thanks to a controller or to satisfy the consumer's flow need.
- Storage: stores EMI according to its maximal capacity. It can behave as a source (deliver EMI flow), consumer (receive EMI flow) or both, depending on the system and the scenario.
- Distributor: functional block that collects flow needs from all the consumers connected to it and distributes the sum of the flow needs to all the sources connected to it. The distributor collects also the flow supplies from the sources and distributes them to the consumers according to their request. The distribution to the sources or to the consumers is made accordingly to their own availability/acceptance. Distributors can have either a heuristic strategy or a more complex optimization algorithm depending on the system.
- Transformer: converts a primary flow in another one (electrical to mechanical power for example). An optional efficiency coefficient and flow limitations are available. The process is reversible, eventually with a different efficiency coefficient. A transformer can convert two or more flows in another one and conversely (chemical reaction for example).
- Actuator: element transforming electrical power into an action. It receives an action request (flow, temperature) and asks for electrical power to achieve the setpoint.
- Exchanger: interface exchanging EMI flow between two circuits. It receives a flow request from both neighbours and sends an action request to two actuators to satisfy the needs. It gets back an action from the actuators and calculates the flow transferred and its limitations to each neighbor, to achieve an equilibrium state. The exchanger block is fully symmetrical, its both neighbours are considered as consumer blocks.

These seven elements presented above constitute the building blocks of the functional modeling. A multitude of models in a large variety of fields can be created by assembling these blocks together. Each block has some editable parameters that can be adjusted to fit the considered system.

Figure 2 shows the functional model of a complex system using the seven elements introduced above. Each geometrical shape corresponds to a specific element related by arrows that indicate only the need direction (the supply is implicitly in the opposite direction). Green, red and blue arrows represent power needs (in their respective energetic fields) while green arrows correspond to flow needs. The system represented is an electric vehicle composed of elements from three different fields:

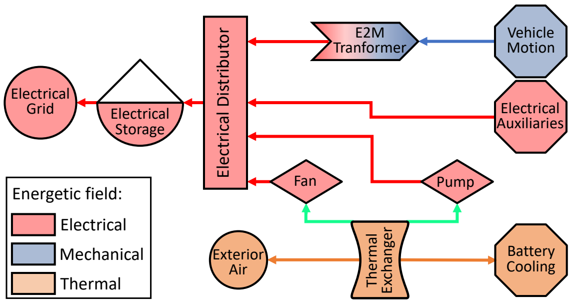


Figure 2: Simplified functional model of an electric vehicle.

- A mechanical part with the vehicle motion effector.
- A thermal part composed by a source, a thermal exchanger and an effector (battery cooling).
- The electrical part, which is the main one, composed by a source, a storage, a distributor that manages the electrical power needs from two actuators, a transformer and a consumer (radio, headlights, etc.).

In the very early stages of the system design, this model can already be run and provides quick simulation results. The architecture can be easily changed and the sizing of the components can be adjusted. Moreover, the energy distribution strategy can be implemented and tested in this functional model, which is time saving.

2.3 Multi-physical Modeling

According to (Fiani et al., 2016), multi-physical modeling is well suited to represent a technological elements architecture. A 0D-1D multi-domains modeling is necessary and sufficient to accurately represent a complex system. Each component of the model is ruled by analytical laws based on the real physical behaviour of the component in its respective field (electrical, mechanical, etc.). Components are connected between each other with physical links containing both a flow and an effort variables. Table 1 lists the different flow and effort variables corresponding to each physical domain.

The main advantage of multi-physical modeling is, as long as the model is well calibrated, to provide very accurate simulation results compared to what can be experimentally observed. However, the price to

Table 1: Multi-physical ports and connectors (Fiani et al., 2016).

Energetic field	Effort	Flow
Mechanical rotation	Torque (N.m)	Speed rot (rad/s)
Mechanical translation	Effort (N)	Speed (m/s)
Hydraulic	Pressure (Pa)	Flow (kg/s)
Thermal	Temperature (K)	Therm flow (J/s)
Thermo-fluid	Pressure (Pa)	Flow (kg/s)
	Temperature (K)	Enthalpie flow (J/s)
Electric	Voltage (V)	Current (A)

pay for this accuracy is the simulation time, which can be very long as soon as the model gets complex. This is the reason why this kind of modeling is very useful for the model validation but it should not be used for designing architecture or control strategies.

2.4 Interconnections between the Three Levels of Modeling

2.4.1 Teleological and Functional Models

The teleological level gives an overview of the system and its global requirements (standards, criteria, constraints, etc.) of the system. The purpose of interconnection is to transmit these global parameters to the functional level. However, the inputs of the functional model are only setpoints, limitations (minimum and maximum values) of variables and activation or not of each element. An interface has to be built to translate the parameters from the teleological level into information understandable by the functional elements. For each global parameter, a list of all the variables estimated by the functional model and required for the determination of the parameter has to be established, as well as the functional elements impacted by this parameter. The second step is to evaluate the global requirements achievement and develop the corresponding equations to relate it to the identified functional elements.

As an example, an electric vehicle is considered to illustrate the interconnection between the teleological and the functional model. One of the requirements of the teleological model is the maximum comfort noise level, which is speed dependent (equal to wind noise at high speeds). In the system, the loudest element is the compressor. A relationship between compressor power and noise level has to be established to determine the maximal power that should be provided to the compressor.

This interconnection is illustrated in Figure 3 with:

- D_{Comp} the compressor availability, i.e. the maximal power the compressor can provide.
- $NoiseLvl$ the maximal noise level requirement.

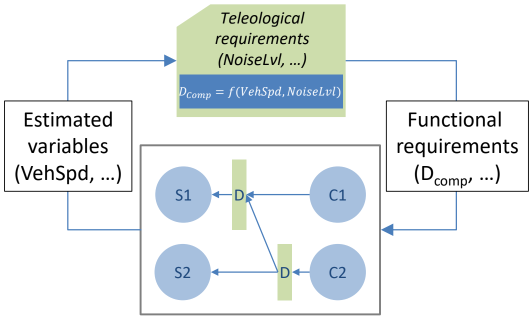


Figure 3: Relationship between teleological requirements and functional model control.

- $VehSpd$ the vehicle speed estimated by the functional model.

2.4.2 Functional and Multi-physical Models

Both functional and multi-physical models are very useful at different stages of the system design. On one hand, the first one is very helpful in the early stages of a system design due to its quick development, its modularity and the fast simulations results it provides. On the other hand, the second one is used in downstream stages to provide a model, although more complex and time-consuming, that is much more accurate than the functional one. The functional model contains both a control and an operation part. The idea of connecting both models is to reuse the control part of the functional model to build the supervisor of the multi-physical level.

However, the flow exchanges are not the same between the two models. While they are energy-based in the functional model, the multi-physical model uses both flow and effort links. Interconnecting both models is not an immediate result and requires a process to translate data from one model to another and inversely. A solution, consisting in building an interface between the two models, was developed in (Mökükcü et al., 2017). It requires, at first, to determine, for each multi-physical block, an equivalent in the functional one (sometimes by combining or splitting elements). The second step consists in building the equations between functional and multi-physical domains for each element. Hence, the interface transforms functional information into physical signals that are used for the control of multi-physical components. Moreover, the variables estimated by the multi-physical model are sent into functional elements and replace their operation part.

3 APPLICATION TO ELECTRIC VEHICLE THERMAL MANAGEMENT

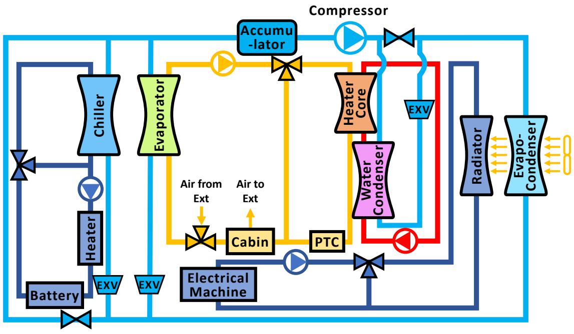
3.1 Motivations

In an electric vehicle, the thermal system is different from the one in a combustion vehicle as explained in Section 1. It is mainly composed by the cabin, the battery and the electric machine (EM). All these components have thermal needs and different structures have been developed by automotive constructors to satisfy them. The main objectives are to ensure convenient temperature both for passengers' comfort and for battery, and to maintain the EM integrity. Prior to trying to optimize the efficiency of the system, the architecture that best meets the specifications has to be elaborated and validated. The functional model is the first one to be designed because it offers a large flexibility, enables easy architecture changes and provides quick simulation results.

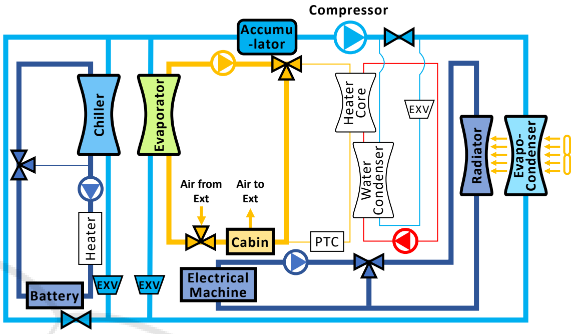
3.2 System Description

The system chosen for this study is a system for which the multi-physical model had already been developed and validated with experimental data. The consumers of this system are the electric machine, the battery and the cabin. The main energy provider is a refrigerant loop functioning as a reversible heat pump supplying cold both to the battery and to the cabin as well as heat to the cabin. The working fluid used in this system in R134a. The switch between cooling mode and heating mode of the heat pump is ensured by a set of regular valves that modify the course of the refrigerant in the pipes, and electronic expansion valves (EXV) that increase or decrease its mass flow. The evapo-condenser, used in both operating modes, acts as an evaporator in heating mode while it acts as a condenser in cooling mode. A diagram of the full thermal system is available in Figure 4a. Figure 4b and Figure 4c show how the system behaves in cooling and heating operating mode respectively.

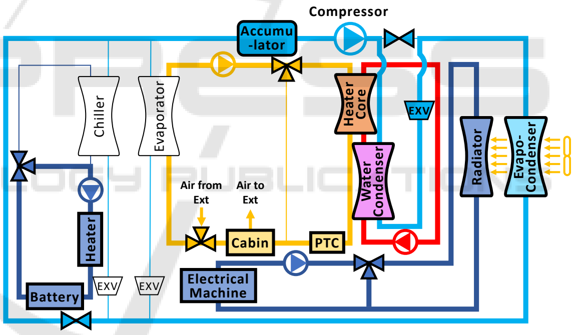
This design is close to the one described in (Zhang et al., 2019) with two main differences. First, an intermediate water loop was added in this design between the refrigerant and the heater core to prevent refrigerant, which is under high pressure, from leaking into the air blown into the cabin. The second difference is that in (Zhang et al., 2019), the design is adapted to electric vehicles in cold regions. Indeed, according to (Ding et al., 2020), the optimum operating temperature range for lithium power batteries is from 10 °C to 35 °C. In cold areas, the battery often needs to be heated up, hence providing the battery's heating needs with the heat pump is an attractive solution, though it makes the design much more complex. In the design shown below, the heat pump only provides heat for the cabin while the battery's heating needs are provided by a heater. There is an additional positive temperature coefficient (PTC) in the cabin air loop to supplement heating supplies to the cabin. The EM cooling is provided by a water loop exchanging directly with external air through the radiator. In each coolant loop, an electrical actuator and eventually a three-way valve control the flows.



(a) Diagram of electric vehicle cooling and heating circuits.



(b) The cabin and battery mixed cooling mode.



(c) The cabin and battery mixed heating mode.

Figure 4.

A functional representation of this diagram is shown in Figure 5. Orange and green links represent

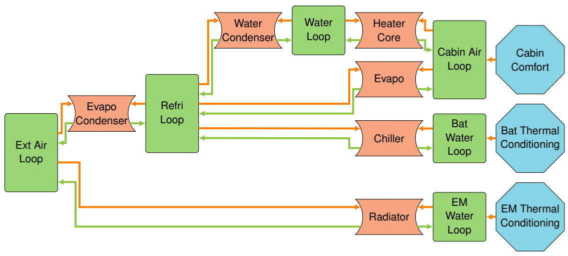


Figure 5: Electric vehicle thermal management diagram.

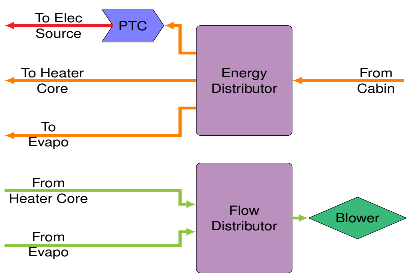


Figure 6: Cabin air loop.

power needs and action needs (mass flow, temperature, etc.) respectively. Blue blocks are effectors receiving a setpoint temperature and sending a thermal power need to achieve it. Red blocks are exchangers that receive thermal power needs from both neighbours and send action needs to actuators to satisfy the power needs. Lastly, green blocks are coolant loops, like the cabin air loop expended in Figure 6. They are composed of a power distributor that splits or gathers the needs it gets, and at least one electrical actuator (compressor, fan, blower, pump, PTC, etc.) that tries to satisfy the action needs it receives. At functional level, the switch between cooling mode and heating mode is handled in the 'Refri Loop' block.

The multi-physical model is represented in Figure 7. The blocks composing the multi-physical model look similar to those of the functional model. However, it is important to keep in mind a major difference between the two models: while functional elements are connected to each other by means of energetic links independent from their field, the connections between physical components are composed of both flow and effort variables that are domain dependent. In order to use the functional model to build the supervisor of the multi-physical one, the interconnection between analog elements in both models has to be ensured by an interface, as described in Section 2.4.2.

3.3 Teleological Modeling for Energy Management

The teleological level enables to introduce global constraints and criteria in the system control, like minimizing the financial or energetic operation cost. In this system, in most cases, electric energetic optimization can be done only with heuristic strategies directly implemented in the functional model (for example, prioritize speeding the blower rather than speeding the compressor). It means the functional model does not really need a manager to minimize the global energetic cost of the system, at least when there is enough energy to satisfy all the needs. However, when energy needs are higher than global availability of the system, some arbitrations have to be made. In this system, when the cabin and the battery both need to be cooled down and the system is saturated (i.e., needs are higher than global availability), the cabin or the battery temperature (or both) have to be degraded in regard to their setpoints. In this case, a method is required to manage how each temperature is degraded.

The first option is to implement directly in the distribution block (of the functional model) priorities between the consumers when needs are higher than availability. This method is quick to set up and priorities are not necessarily exclusive but can be weighted with coefficients. The main inconvenient is that this prioritization is based on energy and not on temperature setpoints achievement. The link between energy provided and temperature is dependent on the scenario, which reduces the modularity of this option.

The second option consists in introducing in the teleological model a new criterion corresponding to the system non-saturation (when needs are lower or equal than global availability). This requirement can be met by degrading the temperature setpoints upstream, resulting in lowering cabin and battery needs. A simplified functional model is needed to estimate the pairs of cabin and battery temperature setpoint values that prevent the system from saturating and lead to the closest temperature achievements to the ideal temperatures (defined by the passengers or the constructor). The connection between the teleological model and the functional requirements is established by solving the following optimization problem:

$$\min_{T_{cab}^{sp}, T_{bat}^{sp}} \delta(T_{cab}^{sp}, T_{bat}^{sp}) \qquad (1)$$

s.t.

$$0 < P_{ratio} = \frac{P_{act}(H)}{P_{act}^{max}} < 1 \qquad (2)$$

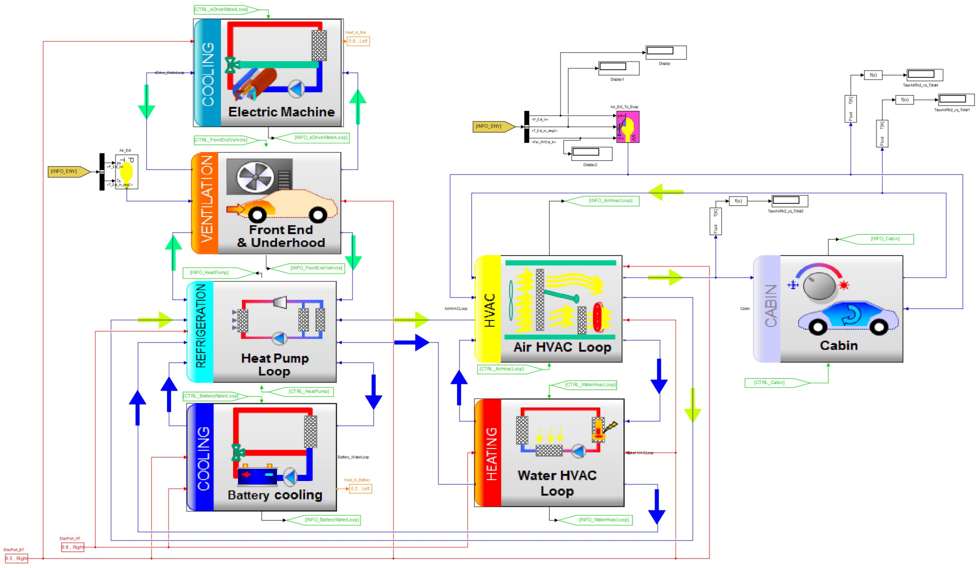


Figure 7: Electric vehicle thermal management multi-physical model.

with $\delta(T_{cab}^{sp}, T_{bat}^{sp}) = (T_{cab}(H) - T_{cab}^{id})^2 + \alpha \cdot (T_{bat}(H) - T_{bat}^{id})^2$ and:

- α a weighting parameter used to prioritize the degradation of one temperature in regard to the other.
- H the time horizon used to simulate the simplified functional model at teleological level.
- T_{cab} and T_{bat} the temperatures of the cabin and the battery respectively, estimated over the time horizon by the reduced functional model.
- T_{cab}^{sp} and T_{bat}^{sp} the temperature setpoints of the cabin and the battery respectively, which are the decision variables.
- T_{cab}^{id} and T_{bat}^{id} the ideal temperature setpoints of the cabin and the battery respectively (values fixed by the user for the cabin and by the constructor for the battery).
- P_{ratio} the load level of the system taking values between 0 and 1; these values correspond to a paused system or a saturated system respectively.
- P_{act} and P_{act}^{max} the power provided by the limiting actuator and the maximum power it can provide respectively.

The cabin and battery optimal temperature setpoint values, solutions of the optimization problem (1) will be noted $T_{cab}^{sp,*}$ and $T_{bat}^{sp,*}$ respectively. The strong non linearity of the problem does not enable the implementation of a classic predictive functional control. The description of the method is detailed below:

1. Develop a simplified functional model that can be run faster than the full functional one. It receives some variables estimated by the full functional model (battery and cabin temperatures, system saturation, etc.).
2. Run this model over a time horizon H for T_{cab}^{sp} in $\{T_{c,1}^{sp}, T_{c,2}^{sp}, ..., T_{c,n_c}^{sp}\}$ and T_{cab}^{sp} in $\{T_{b,1}^{sp}, T_{b,2}^{sp}, ..., T_{b,n_b}^{sp}\}$, n_c and n_b being the number of setpoint values tested for the cabin temperature and the battery temperature respectively.
3. Get two matrices of size n_c x n_b : the first having as elements the criterion values obtained for all the admissible pairs $(T_{c,i}^{sp}, T_{b,j}^{sp})$, with $i = 1 : n_c$ and $j = 1 : n_b$, and the second one being composed of elements of 1 if the constraint (2) is satisfied or 0 in the opposite case.
4. Choose the $(T_{c,i}^{sp}, T_{b,j}^{sp})$ pair that satisfies the constraint (2) and minimizes the criterion, such that $(T_{cab}^{sp,*}, T_{bat}^{sp,*}) = (T_{c,i}^{sp}, T_{b,j}^{sp})$.
5. Send the new setpoints, $T_{cab}^{sp,*}$ and $T_{bat}^{sp,*}$, to the functional model for the next time step T_s. To avoid brutal setpoint changes in entry of the functional model, a first-order filter is applied on the setpoints.

The main advantage of this method, though it is more complex to elaborate, is to be independent from the scenario and based only on the setpoints. Another benefit of this approach is the possibility of including other parameters than temperature setpoints in the criterion as well as other constraints than system saturation.

4 SIMULATION RESULTS

The characteristics of the EV thermal system are summarized in Table 2. A strong assumption is that the electric power is not limited, i.e. the electric battery can provide all the electric needs.

Table 2: Thermal system characteristics.

System characteristics	Value	Unit
Battery mass	500	kg
Battery max thermal exchange	3000	W
Battery charge thermal exchange	5000	W
Compressor max speed	6500	rpm
Compressor displacement	34	cm^3/rev
Parking fan air velocity max	1.5	m/s
130 km/h fan air velocity max	3.9	m/s

Subsection 4.1 and Subsection 4.2 present the simulation results of two use-cases run under the same conditions (same vehicle speed, environment, etc.). The only difference between the two use-cases comes from the cabin and the battery temperature setpoints sent to the model. In the first case, setpoints correspond to ideal constant values while in the second one, the setpoints are determined by the supervisor described in Subsection 3.3. Table 3 lists the conditions used for both use-cases. The chosen scenario consists in a fifty minutes car drive under extreme climatic condition. The scenario also includes a 10 minutes battery charge (time interval [1200, 1800] s), during which the passengers stay in the car.

Table 3: Cool-down scenario parameters.

Time (min)	0-20	20-30	30-50
Vehicle speed (km/h)	70	0	70
Road slope (%)	0		
Exterior temperature (°C)	45		
Battery charge	Off	On	Off
Sun power (W)	1000		
People in the car	Yes		
Ideal max cabin temperature T_{cab}^{id} (°C)	23		
Ideal max battery temperature T_{bat}^{id} (°C)	40		

4.1 Functional Model Simulation

First, the functional model is run under the conditions detailed in Table 3. The cabin and the battery temperature setpoints are constant and equal to T_{cab}^{id} and T_{bat}^{id} respectively throughout the whole simulation. The controller of the distributor in the refrigerant loop uses weighted priorities. It means that both consumers (battery and cabin) are assured to get at least, if needed, a predefined percentage of the total available power. Here the weights are set up to (0.5;0.5), meaning that each consumer can have half of total available power. If one of them needs less, it can be reported on the other one. The initial temperature of the cabin and the battery are 55 °C and 34 °C respectively and the temperature setpoints are set to their ideal max temperature (see Table 3). Simulation results are given in Figure 8.

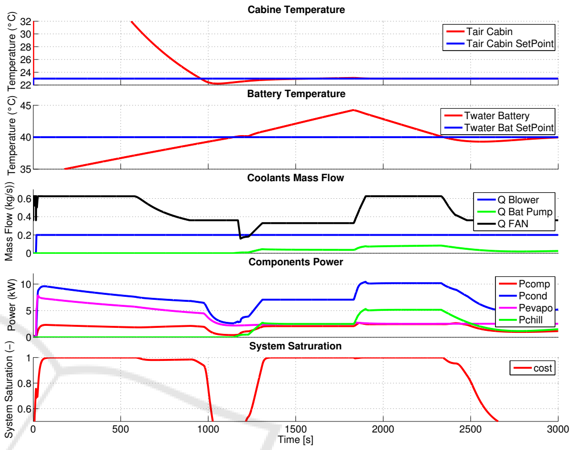


Figure 8: Functional model simulation with constant temperature setpoints.

A first phase can be observed between 0 s and 1000 s: only the cabin is cooled down while the battery has not reached the critical temperature yet. During the second phase, the battery is on charge and needs to evacuate a large thermal power, the system becomes saturated, the setpoints can not be reached anymore. Only the battery temperature is degraded while the cabin temperature remains at the setpoint. It is because the cabin needs less than 50% of the available power and gets it as explained above.

4.2 Functional Model Driven by the Teleological Requirements

The functional model is run once again under the same conditions introduced in Table 3, exept in this use-case the temperature setpoints are determined by the supervisor described in Subsection 3.3 instead of being constant. Parameters of the supervisor are listed in Table 4.

The coefficient α determines the degradation of the battery ideal temperature achievement in regard to the cabin one. In this simulation, α is set to 1, which means that both temperatures should be degraded at the same rate.

The results are presented in Figure 9. As long as

Table 4: Supervisor parameters.

Supervisor characteristics	Value	Unit
Time horizon H	60	s
Time step T_s	10	s
Weighting parameter α	1	-

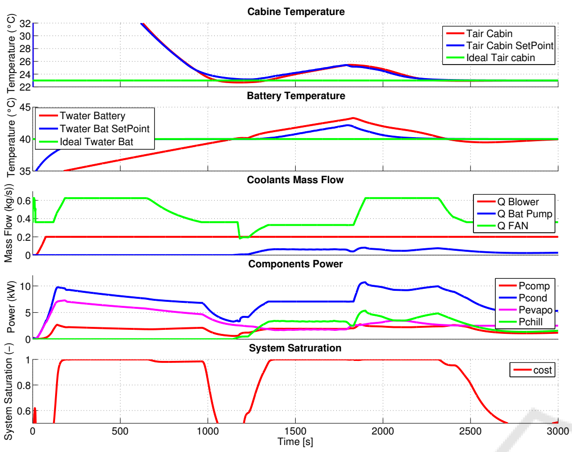


Figure 9: Functional model simulation with global supervisor control.

the system is not saturated, it has the same behaviour than previously without global supervisor. During the saturation phase, between 1200 s and 2400 s, it can be observed that both cabin and battery temperatures are degraded at a similar rate. Taking α greater than 1 would lead to a degradation of the battery temperature faster than the cabin temperature, while taking α smaller than 1 would have the opposite effect. At 1800 s, which is the most critical moment, battery and cabin temperatures are 2.6 °C and 3.2 °C above the setpoint respectively. Moreover, the system saturation is close to 1 when setpoints are degraded. This means that the management of the temperatures degradation rates does not affect the performance of the system, which still uses 100% of its capacities when needed. The control strategy can be tested and modified at this stage to better meet the constructor requirements.

4.3 Validation on the Multi-physical Model

The functional model is then adapted and used as a supervisor for the multi-physical model. The functional model is itself connected to a supervisor computing the setpoints values as described in Subsection 4.2. The simulation is run under the same conditions presented in Table 3 and the results are shown in Figure 10.

The overall behaviour of the system corresponds to the expectations and the temperature setpoints are

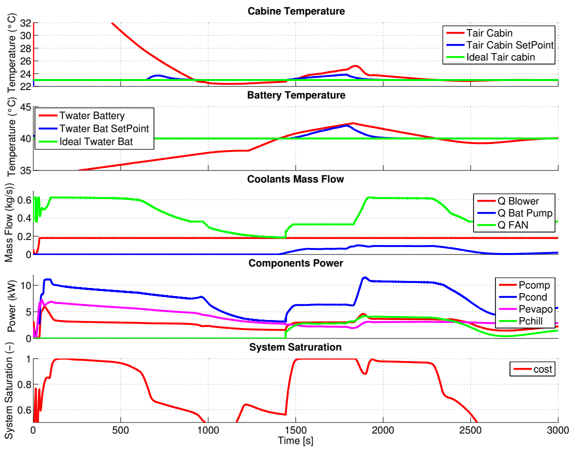


Figure 10: Multi-physical model simulation controlled by adapted functional model, itself monitored by a global supervisor.

achieved when it is possible (i.e. available power is greater than total power needs). Some observations can be made about the simulation:

- The system needs about 1000 s to achieve the cabin temperature setpoint, which corresponds to experimental observations for similar systems.
- The setpoint overshoots are 0.6 °C and 0.7 °C for the cabin and the battery temperature respectively, which is completely reasonable in this kind of thermal system.
- At 1200 s, the battery gets charged, a large amount of thermal energy coming from Joule effect needs to be dissipated, leading to a singular point on the battery temperature curve.
- At 1800 s, the battery is disconnected and the driver starts driving. The mass flow available at the fan is much bigger and the energy availability for the consumers as well. The system saturation gets down to 90 % for about one minute around 1800 s because the refrigerant loop needs to accommodate to the new situation.

5 CONCLUSION

In this work, a methodology for the modeling and design of a complex system and the development of its control has been introduced. This methodology uses three levels of abstraction that are based on purposes definition, energy links and physical laws respectively. The three levels are interconnected and exchange information and control parameters between each other. The teleological level gives a good overview of the system main missions. It introduces global criteria and arbitration rules that can be satisfied by means of heuristic models or by solving optimization problems. The functional level enables to run fast simulations and get approximated results in the early stages of system design, which provides a good way to test and validate control strategies. Also, architecture changes are easy and not much time-consuming at this level. Lastly, a multi-physical model well calibrated can provide results close to experimental data and enables to evaluate a large variety of scenarios with good accuracy. This methodology was applied to a thermal management system use-case and has provided positive results. A non-saturation criterion has been introduced in the teleological level in order to improve the resource management with critical conditions.

A first perspective of this work is to use this three-level abstraction modeling to optimize the global energy consumption of a system. An interesting use-case could be a whole electric vehicle composed by the thermal management and the power-train subsystems.

Another objective is the extension of the functional modeling to systems in which energy and matter flows are coupled. A use-case could be a water recycling system, in which consumers have both matter (water) and energy (heat) needs that must be distributed between matter or energy (or both) sources.

Future work intends to develop and implement optimization algorithms directly in the functional model.

Lastly, the teleological level could integrate some levels of arbitration between several missions of the system, which would have several operating modes optimizing different objectives.

REFERENCES

Borutzky, W. (2010). *Bond Graph Methodology: Development and Analysis of Multidisciplinary Dynamic System Models*. Springer-Verlag London.

Brunet, J., Flambard, L., and Yazman, A. (2005). A hardware in the loop (hil) model development and implementation methodology and support tools for testing and validating car engine electronic control unit. In *International Conference on Simulation Based Engineering and Studies, TCN CAE*, Lecce, Italy.

Ding, P., Wang, Z., Wang, Y., and Li, K. (2020). A distributed multiple-heat source staged heating method in an electric vehicle. *Renewable Energy*, 150:1010–1018.

Fauvel, C., Claveau, F., and Chevrel, P. (2014). Energy management in multi-consumers multi-sources system : a practical framework. In *IFAC World Congress.*, pages 2260–2266, Cape Town, South Africa.

Fiani, P., Boyer, B., Brunet, C., and Bruniquel, G. (2019). Utilisation de la modélisation énergétique fonctionnelle pour la synthèse thermique des véhicules hybrides et électriques. In *SIA Simulation numérique : La simulation numérique au sein de l'innovation automobile.*, Saint-Quentin en Yvelines, France.

Fiani, P., Chavanne, S., Taleb, L. A., and Mökükcü, M. (2016). Modélisation pour la conception et l'évaluation de systèmes complexes. *Revue Ingénieurs de l'automobile*, 841.

Gross, O. and Clark, S. (2011). Optimizing electric vehicle battery life through battery thermal management. *SAE International Journal of Engines*.

Mökükcü, M., Fiani, P., Chavanne, S., Taleb, L. A., Vlad, C., and Godoy, E. (2017). Control architecture modeling using functional energetic method: Demonstration on a hybrid electric vehicle. In *14th International Conference on Informatics in Control, Automation and Robotics (ICINCO)*, Madrid, Spain.

Mökükcü, M., Fiani, P., Chavanne, S., Taleb, L. A., Vlad, C., Godoy, E., and Fauvel, C. (2016). A new concept of functional energetic modelling and simulation. In *The 9th Eurosim Congress on Modelling and Simulation.*, Oulu, Finland.

Von Bertalanffy, L. (1968). *General System Theory.* George Braziller, Inc.

Zhang, K., Li, M., Yang, C., Shao, Z., and Wang, L. (2019). Exergy analysis of electric vehicle heat pump air conditioning system with battery thermal management system. *Journal of Thermal Science*, 29(2):408–422.

Zhang, Z., Wang, J., Feng, X., Chang, L., Chen, Y., and Wang, X. (2018). The solutions to electric vehicle air conditioning systems: A review. *Renewable and Sustainable Energy Reviews*, 91:443–463.