An Optimised Thermal Design and Development Process for Passenger Compartments of Vehicles

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SYNOPSIS

Achieving thermal comfort in a vehicle cabin is still a very challenging task and often inconsistent with the fuel reduction demands of Vehicle Thermal Management. This ultimately means simultaneously modelling the air conditioning system, engine cooling system, HVAC module including control strategies, ventilation ducts, passenger compartment and climate environment and the occupants themselves.

Published work indicates that neither a single 1D tool, a 3D tool nor a co-simulation approach alone will fulfil the financial pressures of today's automotive industry to achieve tough time and quality targets. Virtual Product Development (VPD) has to be optimised individually for each stage of the design process, while all simulation methods and software tools have to work together towards a best-in-class VPD process.

This paper demonstrates a complementary approach for the complete process of development, which at the end can yield large benefit at low cost. The overall concept is illustrated by explicit examples.

1 INTRODUCTION

For a couple of years now, climate considerations have made reduction of fuel consumption and CO_2 emissions a universal requirement and a fixed optimisation target in modern AC system development. The projected use of alternative refrigerants after 2011 as well as new technologies like alternative powertrain types, heat pumps, new compressor drives etc. (which are required from the legal and technical point of view to reach these targets) create additional boundary conditions for current AC system development.

Consequently, an increasing range of different AC system variants are coming rapidly into development and even into series production. Recently, the economic crisis moreover calls for further reduction in the cost and time of developments. Facing such challenges, it is surprising that many AC systems are still built by prototyping and expensive test bench results.

These circumstances now demand an optimised process of air-conditioning development, which considers all aspects and every phase of the development process through the extensive use of virtual product engineering. On one hand, the development tasks and targets are so different in each phase of the process that it is essential to use various tools and simulation methods adapted to that phase. On the other hand, using too many tools is costly and inefficient.

Further, all the tools used must be able to communicate with each other in a lossless, integrated way through the whole process. They should also be flexible enough for individual customising. Therefore a well-balanced approach:

- Starts with a task-optimised selection of the latest simulation software
- Specifies a schedule-optimised sequence of necessary development steps
- Uses as much synergy and automation during model engineering as possible
- Focuses on a good compromise between accuracy and effort.

There are many 1D and 3D tools available on the market today, which on a first sight seem to be very similar. But a closer look will display detailed differences. In this paper, we consider Flowmaster for 1D thermo-fluid simulation and THESEUS-FE plus CFD for 3D flow in the cabin, because this was the minimal combination that was able to fulfil all development tasks in the most integrated and automated way. Moreover, both tools have been proficient in this area for more than two decades and are technically mature. The final deciding factors were the possibility for both simulation programs to extend their application to adjacent development areas and their aptitude for customising.

2 THE DEVELOPMENT PROCESS

This should always be dependent on the targets. The main objective of automotive air-conditioning is still the guarantee of thermal comfort, which not only depends on the temperature level but also clothing, air quality, humidity, draft risk, noise level and dynamic performance of the system [4].

Beside these key criteria, various economic, ecologic, ergonomic, physiologic and safety optimisation tasks have to be taken into account too against a background of climatic, regional, legal, financial, cultural and individual boundary conditions. Ultimately, the passengers are the measure of all things.

Due to different interdisciplinary organisation of responsibilities, the development process is different at each company, but can be described in principle by the five main steps described below. A further split of the development process is possible but would go beyond the scope of this paper.

At the beginning of the development process very quick response times and system level simulations are essential to evaluate and judge the wide range of possible solutions and concepts. This is the key strength of 1D simulation methods. Later on, designed CAD models and prototypes are available, both of which can be improved in all respects by 3D simulations. Eventually, both methods have to come together for the inspection of all effects at vehicle level. Ideally, testing takes place in parallel and provides a continual source of improved input data for the simulation models.

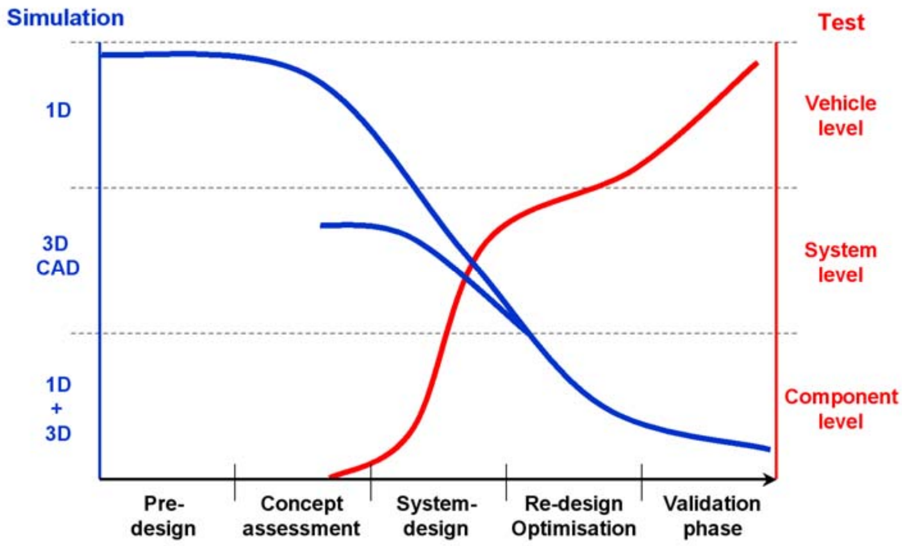

Figure 1: Use of 1D and 3D simulation v development stages

Figure 1 shows that virtual product engineering is obviously the only method of improvement during the decisive first phases of development, where no test data or prototypes are available. At the end of the development process, simulation helps to restrict considerably the increasing costs of testing.

This statement is supported by the following chart:

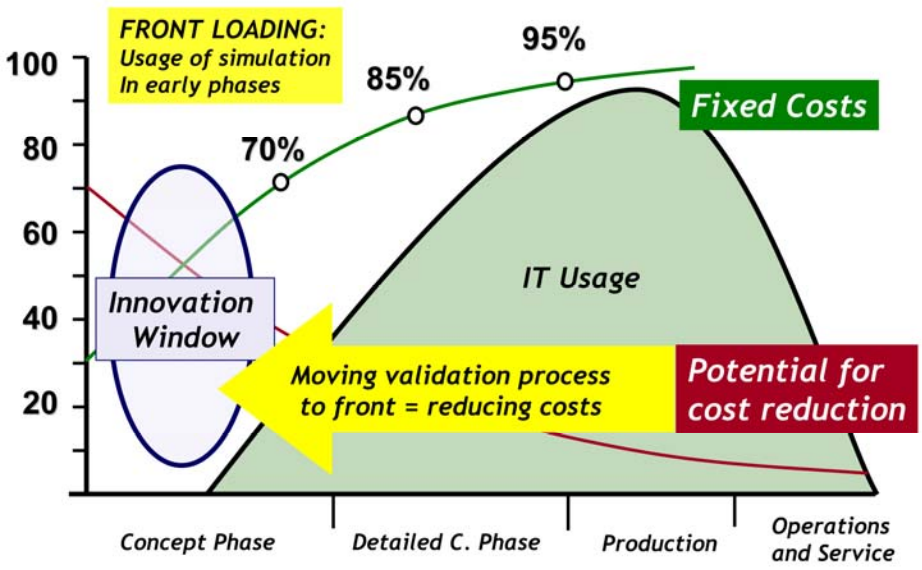

Figure 2: Potential of cost reduction v product lifecycle [3]

Figure 2 clearly states that with onward progress of the developments the total costs are increasing in an exponential way and due to this fact the potential for cost reduction is decreasing towards the end of the process. Therefore a so-called “front loading” of the process has to take place to exhaust the full potential of cost savings. Moreover at the beginning of the developments there is also the most time and best place to introduce and check any application of innovations.

2.1 Pre-development Phase

The first task is to specify and fix all targets. Often the targets are not very well defined, which is a first potential risk of future development costs. The preferred simulation method in this phase of development is analytical; either 1D or simple parametric 3D simulation.

In general during pre-development no CAD models or hardware prototypes are available, which makes it somewhat difficult to obtain the right input data for the simulation; parametric studies are an appropriate method to overcome these uncertainties.

In this context a very effective auxiliary method is to predict the required heat load of the vehicle by inverse calculation at different climate conditions. That means the designer specifies the desired air temperature inside the cabin for a given climate or driving cycle and gets the necessary ventilation temperature and the required power of the A/C system as a result. This helps very much to get an initial starting point for economical and reasonable dimensions of the system. THESEUS-FE is able to do such inverse calculations considering all effects of heat transfer, air humidity and lumped masses in a transient way. An appropriate example is shown in sub-section 2.1.1.

Another need in this phase is to check the possible use of predecessor models and components to save time and money, but compare this with the advantages of applying the latest innovations and technologies.

2.1.1 <u>Example: Heat Load Prediction of the Vehicle by Inverse Simulation</u>

An experienced designer in principle has a rough feeling about the required power of an AC system for a given car type. But how can you be sure this is the optimum dimension and not oversized? Therefore it is worth the effort to execute an inverse calculation at least for the worst cases under summer and winter conditions. The following example shows the results of such an evaluation.

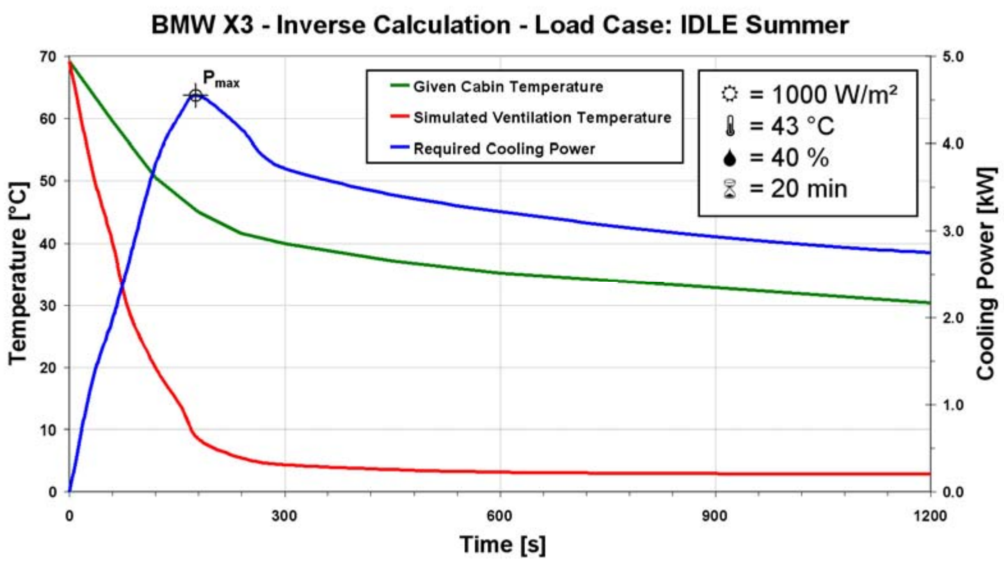

Figure 3a: Calculation of summer load in a BMW X3 setup

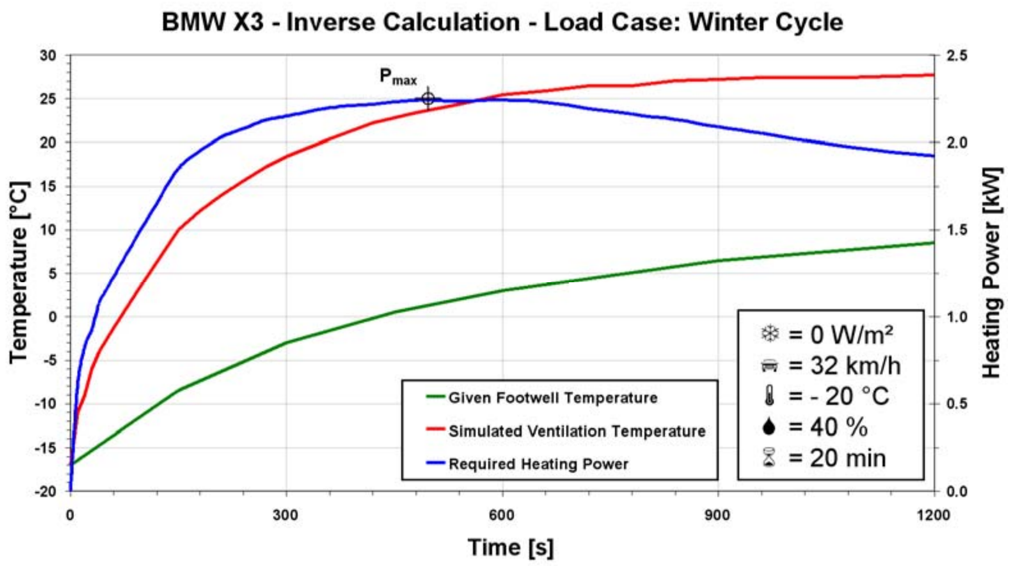

Figure 3b: Calculation of winter load in a BMW X3 setup

The figure illustrates that a cooling capacity of about 4.5 kW and a heater with a power of about 2.3 KW would be enough for the chosen setup to fulfil the specified air temperature targets inside the cabin. Naturally such simulations have to be carried out on all variants, vehicle setups and for all possible and regional climatic conditions. Afterwards the designer has to find the best compromise out of all results for the final system's sizing.

2.2 Concept Assessment

Together with the previous pre-design phase, the concept stage offers the most cost saving potential versus required development costs and effort (compare Figure 2). For this reason, it is decisive in working out clearly the main form of the later system, always with respect to the final targets.

The right procedure to find an adequate concept is the V-approach described in many publications (e.g. [3]). The V-approach cuts down the task from vehicle through system to component level and starts modelling vice versa.

At this stage the designers perform:

- Detailed component selection and sizing
- Sensitivity studies
- Refinement of the system specification

The simulations used to do these tasks incorporate geometry-based heat exchangers prior to obtaining actual performance maps for the chosen design and dimensions. It is then possible to create a virtual assembly of all selected and evaluated parts into a complete 1D AC system coupled with a 1D cabin model.

2.2.1 <u>Example: Geometry-based evaporator</u>

At this stage, detailed performance characteristics for components such as heat exchangers are not available (unless the design is unchanged from a previous model). In order to assess the likely performance of new designs and to perform sensitivity studies on different shapes, sizes and designs of evaporator, for example, the user needs a tool that will predict approximate performance from basic configuration and geometry, such as:

- Number, alignment and connectivity of tubes
- Type and dimensions of tubes and fins
- Number and size of louvers, if any.

In Flowmaster, tube arrangements of any complexity can easily be built up in a simple schematic diagram, with step-by-step guidance provided by a wizard:

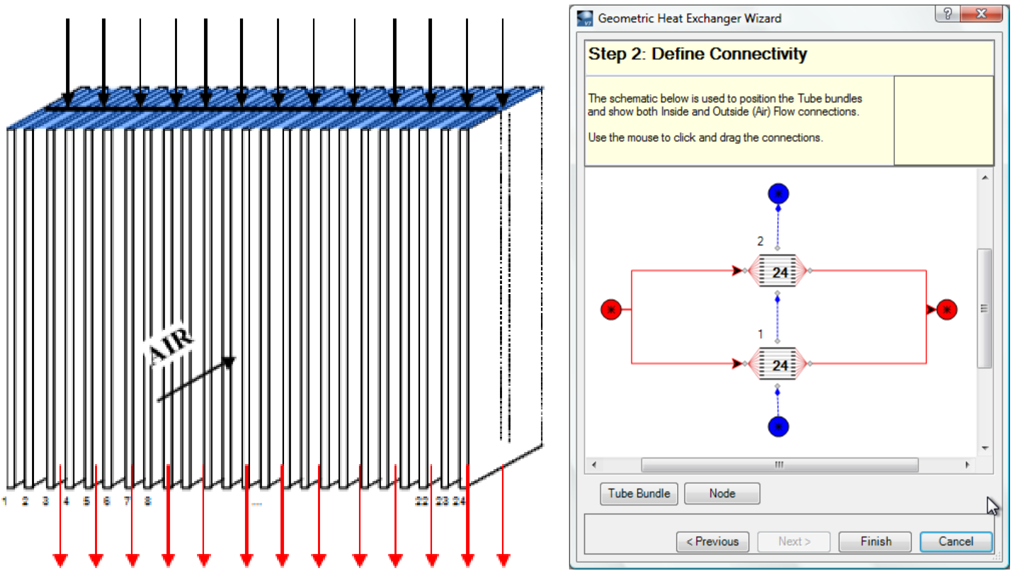

Figure 4: Defining the evaporator configuration

2.2.2 Example: Sensitive study of a full AC system including 1D cabin

Once the main elements of the conceptual design are in place, it is possible to start to build up a 1D model of the fluid systems that directly affect the passenger environment. This will include the cooling system and the AC circuit with all air paths.

The model will start as a very simple representation of the key components with a large number of assumptions based on past experience. As the design develops so will the model, with the most influential assumptions gradually being eliminated. Other parts of the total vehicle, which have a direct influence on the cooling and AC systems, but an indirect effect on the passenger compartment, will still be represented by highly simplified models or statistical data gathered from past designs. This enables the 1D model to remain “light and agile” so that the designer can perform a wide range of sensitivity studies in a short time. This helps to identify which assumptions need to be replaced with a realistic model or representative data, as well as revealing opportunities for performance gain and cost saving.

In due course, a model will be developed that contains the following elements at a level of detail appropriate to the need:

- The engine heat rejection including contributions from the lubrication system and other relevant sources – This may be represented in a transient simulation either as a heat flow to the coolant dependent on engine speed and load, system temperatures and coolant flow rate or as a time-dependent rate of heat generation in a lumped mass model with conduction, radiation, etc.

- The engine compartment temperature based on the cooling pack air-off temperature or on an assumed temperature history

- The key elements of the cooling circuit, including the pump, thermostat, main flow passages, heat exchangers (initially as geometric models, but later using actual or estimated performance data) control valves (e.g. for the cabin heater) expansion tank, etc.

- The complete AC circuit – The effect of the condenser on the radiator should be modelled and the air velocity profile at the cooling pack inlet may also be important at a later stage. At this stage, the cooling fan(s) may be represented literally or as a simple imposed flow rate (dependent on vehicle velocity and sometimes on engine speed).

- The cabin air circuit including the fresh air inlet, recirculation valve and ducting, blower, heater bypass and the cabin itself – The cabin model may start off quite simply, with a small number of panel, glazing and interior elements, and be refined as the design details are settled.

The diagram below shows a concept model in an intermediate state of development.

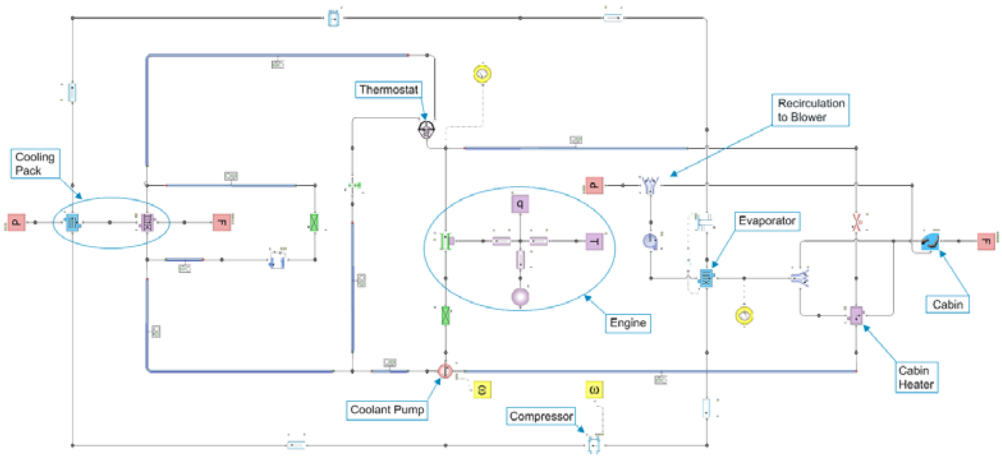

Figure 5: Cooling and AC system with 1D cabin model

2.3 AC Application Design

Today, component development often has to follow the strict requirements of already fixed styling, which again bears a high risk of mistakes. A more efficient process attaches importance to a close collaboration and interdepartmental understanding of art designers and engineers. Of course design space is always rare in a vehicle, but additionally AC systems are sometimes seen as a low priority accessory, which places their development at the end of the VPD chain. This often leads to faulty design of air ducts, wrongly placed vents, high pressure drop plumbing systems, weakly dimensioned HVAC units, unbalanced heat exchangers, etc.

Therefore it is important in this stage to focus on:

- Design and packaging by CAD tools according to the needs of the concept
- Creation of the human interface device and control unit
- Physical component prototyping and/or supplier selection
- Real and virtual component tests, which lead to performance maps. This may be done using a selection or combination of 1D, 3D and CFD tools.
- Real assembly of a first prototype of the AC system

2.3.1 <u>Example: Correlation of test results with simulation at component level</u>

As performance data for individual components becomes available from their manufacturer or from test, these may be used to validate and update the components used in the existing models.

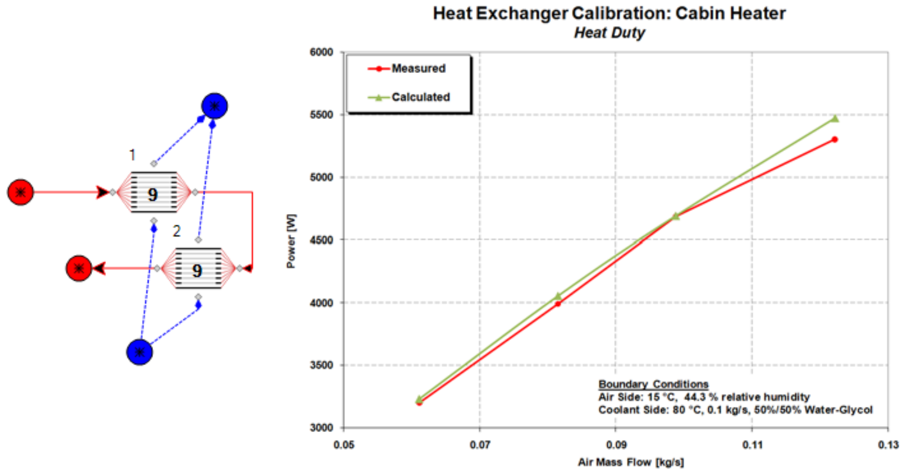

Figure 6: Performance calibration for a geometric cabin heater

2.4 Optimisation Phase and Redesign

Optimisation is by definition the key task of VPD. For a couple of years now this phase has been mainly achieved by simulation. Indeed, sometimes the industry makes the mistake of using virtual engineering *only* in this phase of the process and forgets about previously mentioned “front loading” – the better the pre-design and the more sophisticated the concept, the less you have to optimise. Speaking in the strict sense of Figure 2, optimisation at this advanced stage of the process is already too late and inefficient for a real benefit. Ideally, only a few local effects and some smaller improvements should require optimisation at this level of development. Unfortunately, reality looks completely different and troubleshooting as well as complete component re-design often takes place here.

Nevertheless this part of the development process in general includes:

- Identification of system improvements by 1D and/or 3D CFD simulation
- Air flow balancing using 1D and/or 3D CFD simulation
- System control studies combining 1D with MATLAB/Simulink®
- Redesign, if necessary, and optimisation of the designs from earlier stages
- Troubleshooting by 1D and/or 3D CFD simulation
- Real assembly of all parts as the final system
- Calibration of the various (1D, 3D and co-simulation or combined) models against test results
- Checking progress and results against targets

2.4.1 Example: Coupled optimisation with third-party tools

The benefits of customisable and extendable software tools can be seen at this stage, where other best-in-class tools can be linked to the 1D or 3D thermo-fluid simulations to enable control studies or systems optimisation. A link to MATLAB/Simulink® is particularly powerful in this context, because it gives access to a range of tools that operate in this software environment, such as AVL ADVISOR 2004. This enables the passenger compartment development process to be viewed in the context of whole-vehicle optimisation and design targets.

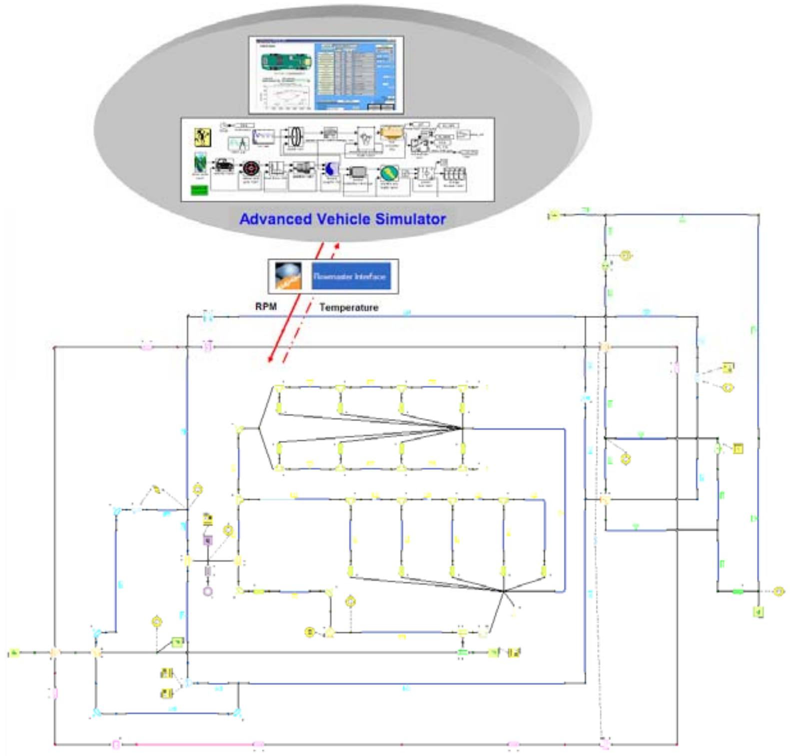

Figure 7: Co-simulation of multi-fluid 1D model with vehicle simulation

2.4.2 Example: Model and Target Check by Test Comparison

Again the BMW X3 is taken for illustration purposes. This example shows the 20 minutes cool-down of the cabin after passively heating up the vehicle in the artificial sun of a climate chamber with 1000 W/m² from above for a period of 90 minutes (see Figure 8). The air temperature in the chamber is set constantly to 40 °C. During cool-down the car is idling, which certainly is a worst case scenario for the AC system. The target after 10 minutes shall be maximum 35 °C in the head level area.

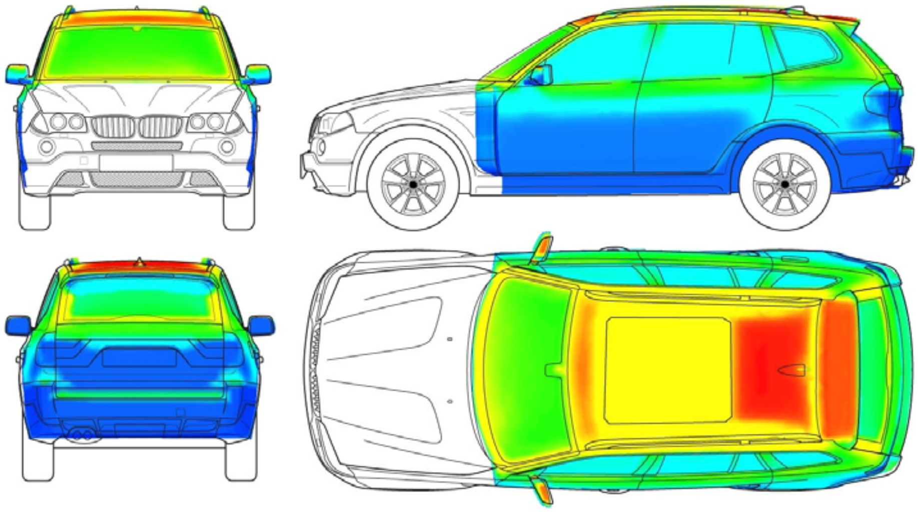

Figure 8: Temperature distribution on the vehicle body after sun soak

A steady-state CFD calculation of the air flow inside the cabin at maximum fan level in recirculation mode is executed and used as a boundary condition for the thermal cabin simulation. The thermal finite-element cabin model holds about 60.000 elements and 47 PIDs and is displayed in Figure 9.

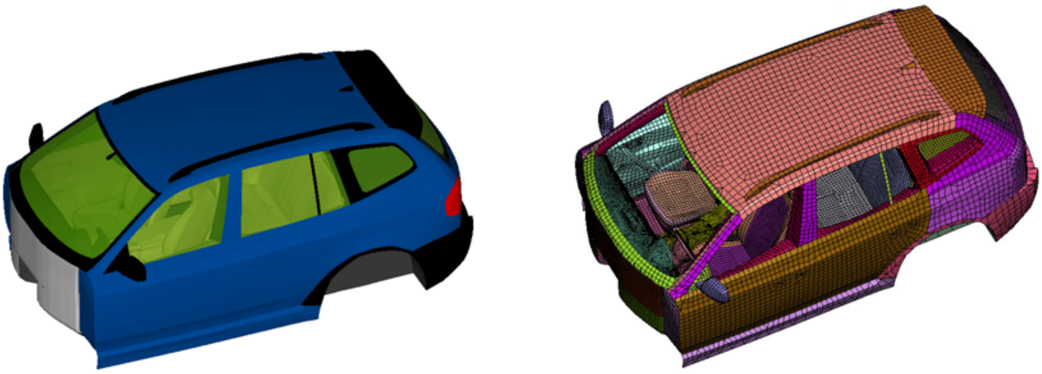

Figure 9: Thermal Cabin Model of the BMW X3

In addition a real climate chamber test was executed and the head level temperature was measured. Afterwards the correlation between simulation and test was evaluated and both results are checked against the given target (see Figure 10).

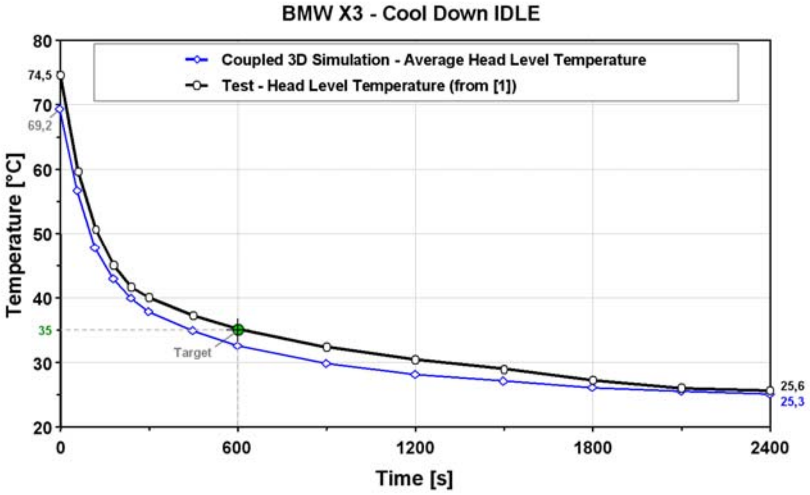

Figure 10: Comparison between Test and Simulation for X3's IDLE Cool-Down

In contrast to the test, the initial temperature after the soak cycle was a bit too low in the simulation. For this reason the simulated head level temperatures are always lower than the test results. But the differences are within the testing uncertainty and the qualitative shape of the curve fits perfect to the test as well as the "steady-state" value at the end of the cool-down cycle. The target will be hit by both independent methods, which is the key statement for the process reached by an optimised VPD.

2.5 Validation phase

The designer will employ only fully coupled 1D+3D analysis of the complete system during this phase, for the purposes of:

- Virtual sign-off of the full system – Before Start of Production (SOP) numerous expensive sign-off tests are required. These can be better targeted and the risk of failure greatly reduced by simulating the test conditions in the virtual world, before committing to the actual test. In this way, a much wider range of cases can be studied and assurance can be gained that failures will not occur with unusual combinations of conditions.

- Virtual outdoor winter and summer tests under real conditions (e.g. with moving sun) – In reality, all vehicles are extensively tested under extreme climatic conditions before SOP. This is a time consuming and very expensive procedure, because the cars and the full test team with all their equipment need to be shipped to the world locations where such extreme weather conditions are available (like Death Valley, Kalahari Desert, Arjeplog, Alaska, etc.). Frequently the test teams have to wait several days or weeks for the perfect weather and have to be well prepared for a one-and-only test window. Thus a full day-cycle simulation with a moving sun is a relatively low-cost instrument to save a lot of money or at least to assist the test engineers in placing the thermo-couples at the pre-evaluated hot spots of the car.

- Judging overall performance and thermal comfort – This topic deals with a very subjective area, but one that has been quantified to a degree by detailed and painstaking research. It is not practical to repeat that research on every vehicle model, but a virtual model is able to apply the techniques developed to obtain a reliable prediction of the likely response of users.

- Validation of targets – Many different targets for the system are set individually by OEMs very early in the design process. Moreover, numerous industrial standards and legal regulations have to be fulfilled by the AC system. But at present there is unfortunately no unique global standard target or testing cycle available. Nevertheless, at this point in the VPD it is time to review if all targets have been met for all the cases.

- Verification of test results – Physical tests, no less than virtual models are subject to limitations of accuracy and a comparison between the two can reveal both systematic errors and individual failures in the tests.

- Cost reduction by virtual testing of variants – Because of the cost of physical testing, only cases of known importance can be examined in that way. The lower cost and time required for virtual testing enable the designers to explore the response of the system (or parts of it) to a very wide range of different combinations of operating conditions. Any of these that indicate a potential failure can then be examined further, by physical tests if necessary.

2.5.1 Example: Field Test Simulation

Figure 11 displays the results of an outdoor simulation, again calculated on the X3 model, of a measurement in Phoenix/Arizona. In contrast to the real 24-hour test, the simulation time on a standard PC just took 3 hours in this case.

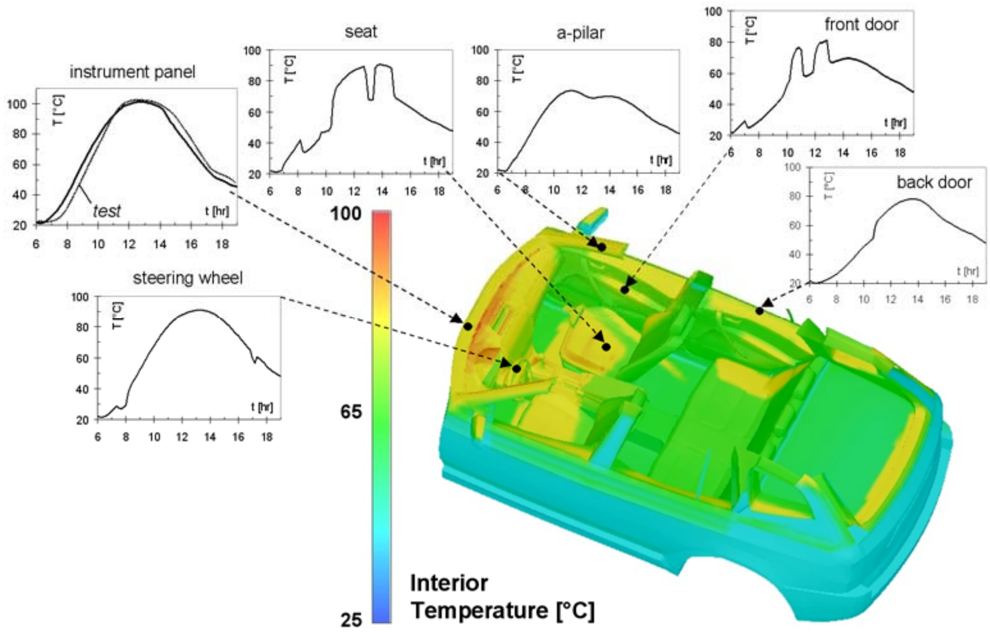

Figure 11: Day-cycle Outdoor Test Simulation on a BMW X3

Knowing the temperatures at the interior parts is important to judge material failure, creep, overheat, de-bonding and ageing.

2.5.2 Example: Local thermal comfort evaluation of passengers

Finally, the target check of occupants' thermal comfort is an important task. Again, a similar virtual cool-down test of 20 minutes on the BMW X3 like that described in sub-section 2.4.2 is executed, but with an active human model [5, 6] of the driver inside the car. Moreover, the car is now driving at a speed of 32 km/h, so that the AC system has a chance to achieve comfortable air temperatures inside the cabin. The fan level is also set to maximum speed and a repeated CFD analysis of the air flow inside the cabin has to be simulated first to get the convective boundary conditions (see Figure 12).

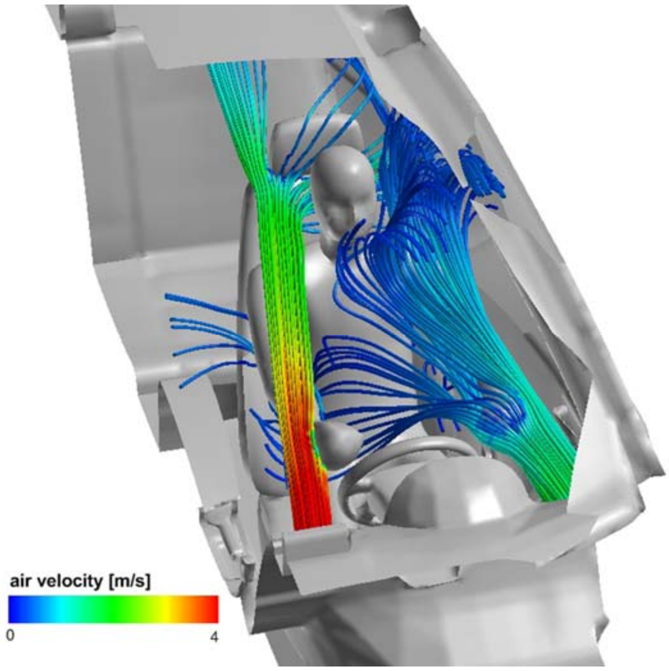

Figure 12: Air flow around the driver

Evaluating the driver's local thermal comfort according to ISO 14505-2 at the end of the simulation (i.e. at time 20 min) leads to the following 5-scale comfort indices and equivalent temperatures (ET) at the body parts of the occupant shown in Figure 13.

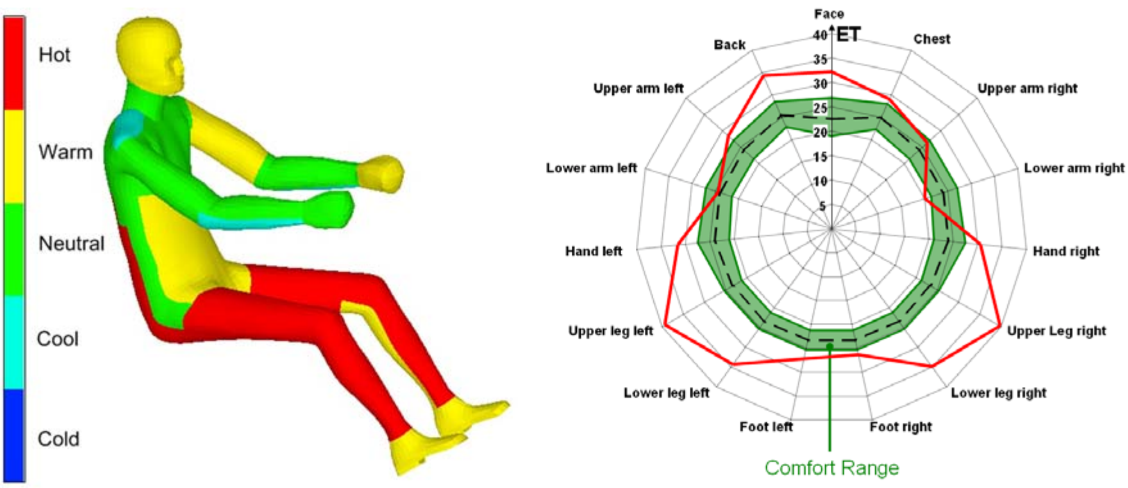

Figure 13: Local Thermal Comfort Evaluation

The diagram shows that not every body part of the driver is within the comfort band. Some of the body parts are still too hot (especially the contact zones to the seat and the sun-impinged legs) whereas others are already slightly too cool due to the ventilation flow. All in all it is still too warm for the driver but thermal neutrality is reasonably close.

3 CONCLUSION

It was shown that development of air-conditioning systems can be evaluated in a fully virtual manner by a variety of methods and tools in every phase of the process. These are even able to assess the local comfort rating targets by active human sensation models.

Energy-optimised air-conditioning systems have to be investigated with regard to the thermodynamic behaviour of the whole system, including the effects of the cabin composition and human occupants, using preventive measures and well-balanced strategies.

Given the financial pressures in today's automotive industry to achieve tough time and quality targets, virtual techniques have become essential in order to examine the many load case scenarios and large number of model variants.

The proper use of a limited number of simulation methods and tools appropriate to the task is seen as the key to success.

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