THE FUTURE OF CAR DESIGN

SYSTEMS ENGINEERING BASED OPTIMISATION

Features and functions of a passenger car can be combined arbitrarily according to a modular system. As a solution interdisciplinary skill and systems engineering can be offered. AVL presents a multi-disciplinary tool chain to support the design of a city vehicle which describes how an design process looks like which is optimised with the principles of systems engineering.

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BEYOND BORDERS

A modern vehicle may be considered a technical „work of art”. Its features and functions go far beyond the sum of its individual components that can be combined together as a modular system. The interdisciplinary approach of systems engineering uses this fact and provides an appropriate framework for successful vehicle development. Customer needs are at the centre of any product development. Phrasing customer requirements are used since starting the development process. The degree of their realisation defines the measure of progress throughout the entire development process.

AVL demonstrates here a typical development task as an example (design of a city car) to optimise the vehicle development process using systems engineering principles. This process copes with two fundamental challenges simultaneously: searching for the best vehicle architecture of a given target use case and proof of concept before implementation work has been started.

To support this method an innovative and efficient tool chain is presented: Potential vehicle architectures are developed systematically; their associated properties are made “driveable” in manoeuvres; and the degree of target achievement of customer needs is quantified. This leads to a significant improvement in the dialogue between product managers and system architects about the “trade-off” of target indicators against design variants.

VIRTUAL SYSTEM PROTOTYPING IN VIRTUAL ROAD TESTS

An increasing diversity and complexity of vehicles arise not least with modular systems of the OEMs who provide a range of tested alternatives for individual vehicle modules. The trick is to combine these modules in a constructive manner. A capability need arises to understand early how building blocks interact on system level as compared to the criteria relevant for the customer.

Virtual Systems Prototyping (VSP), meaning the design of a virtual vehicle on system level, plays a key role in this context. The VSP methodology requires a integration, simulation and testing environment that assesses (virtual) vehicle features against customer-relevant criteria [1]. The VSP methodology is well established and represents the state of the art in development processes [2]. It allows vehicle architectures to be created and tested before they are actually implemented.

However, there is still a question of whether the architecture studied in a VSP approach is in fact the best architecture to meet customer needs. Previously, answers to this question have not been conclusive. However, by integration of the VSP methodology into the Design Space Evaluation (DSE), as described more precisely in [2], this has now become possible. In the following sections this is illustrated clearly by a demonstrative example.

PRODUCT MANAGER MEETS SYSTEM ARCHITECT

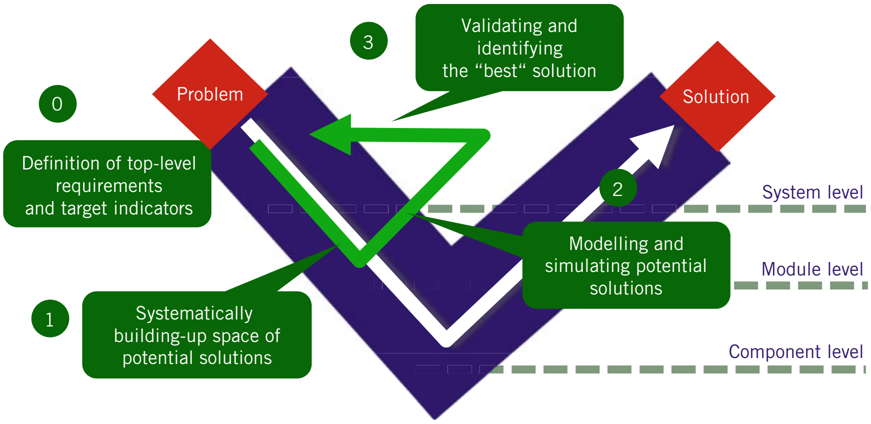
The product manager (PM) is responsible for the economic success of a vehicle. He represents the external customers’ needs and is the client for any development project. Competing in an open market, he must make decisions on the “trade-offs” between quality (customer expectations of the specific vehicle), time (to market) and costs (of development and subsequent production) while simultaneously taking into account all related risks. He needs to know the customer expectations and technical alternatives that can be implemented and their trade-offs.

The system architect (SyA) is responsible for the architecture of the vehicle. He defines the top-level design of a vehicle and breaks it down into sub level designs. In our example, the SyA follows the new development process of DSE based VSP methodology, described in [2]. ❶ shows the development process as V-model. It consists of four parts of steps:

0. definition of top-level requirements and target indicators
1. systematic build-up of possible solutions (“design space”)
2. modelling and simulation of possible solutions
3. identification of the solution most suitable for a defined use-case.

An example given is: Phrasing the requirements for the development of a future battery electric vehicle (BEV) the PM stipulates a vehicle that shall:

- mainly be used in an urban city cycle
- be suited for short motorway trips



❶ The DSE based VSP methodology consists of four steps 0 to 3

- "keep up" in typical urban city scenarios
- have a minimum range of 200 km
- show the lowest possible energy need.

The SyA translates the PM´s requirements into measurable target indicators and values as summarised in ❷. He uses the "AMS combined cycle", as defined by the "Auto, Motor und Sport" magazine [3], as a typical application case and fixes a requirement profile of the target values wanted according to the basis of the PM.

For the continuous development process, further module or component application cases and test scenarios (for example for battery, engine, and chassis dynamometer etc.) may be derived from the parent application to continuously verify the target values [4].

According to the system modules available, the SyA now looks at the set of possible solution architectures ("design space"). If the SyA or those engineers in his working environment are experienced enough, the most suited target variant may be quickly identified. However (and particularly related to BEV or hybrid vehicles), the available experience base is limited and often not sufficient to fully assess the potential for in some cases never tested variants.

The SyA, therefore, chooses the DSE based VSP methodology. Consequently, in the next step he systematically builds up the space of possible solutions. In our example, vehicle modules are available that allow him to address alternatives by varying the design variables shown in ❸. Please note, other design variables may be added, but are neglected here for the sake of clarity. This describes the space of possible solutions. However, the question still remains as to which of the solutions is really the best?

LEVERING FOR SYNERGY POTENTIALS

The SyA has a VSP tool chain at his disposal. In the next step he searches for the best solution according to a „brute force" method by varying the design variables, building up all model variants while assessing their target indicators based on the AMS cycle simulations. In practice, this approach is not constructive. The number of possible combinations increases exponentially with the number of design variables.

In the specific example shown in ③, more than one hundred thousand variations might be derived. This would lead to a computation time of several weeks. The amount of data generated would neither make the decision-making process between PM and SyA any simpler nor more efficient. A reduction of data points in the space of possible solutions is necessary, for example by DoE-based optimisation algorithms (Design of Experiments). The models systematically derived by this technique, fed into a mathematical analysis, enable an understanding of the target indicator versus design variable impacts while requiring significantly less computational time.

❹ shows interactions of the tool chain: A multi-domain authoring tool environment provides the powertrain model, which is linked into the IPG CarMaker integration platform. Other authoring tools can be similarly integrated via a standardised FMI interface (functional mock-up interface) [5]. The integration environment facilitates the "virtual test drive", that means a complete 3-D vehicle with interchangeable modules, the driving environment (roads, traffic, environment etc.) as well as driving manoeuvre characterisation which allows time-efficient implementation, simulation, and analysis of complex motion tasks.

A model-based optimisation [6, 7] is superimposed on the motion tasks, which are planned, controlled and evaluated by the Cameo tool of the company AVL according to the DOE principle. In the following three workflow steps supported by Cameo are described which are used by the SyA.

VIRTUAL FLEET ON TEST

The first step consists of planning the tests and implementation. Here, the design space is sampled with the assistance of a test plan which offers the possibility to create mathematical (meta) modelling with the needed accuracy for the following steps [7]. On this basis, the variants are controlled with Cameo and simulated in CarMaker. ❺ shows the DoE test plan derived from ③ for all variants to be investigated for the powertrain. The coverage for the design space may be recognised intuitively.

TARGET INDICATOR	TARGET VALUE	COMMENT
v_{MAX}	120 km/h	Reference: short trips on the freeway
t_{A50}	≤5 s	Time for acceleration 0 to 50 km/h; typical urban scenarios
$v_{AVERAGE}$	Close to AMS-fastest speed	Average speed in the AMS combined cycle; typical urban scenarios
v_{UPHILL}	≥79 km/h	At a defined point (uphill) out of town
RANGE	≥200 km	Requested by PM
E_{NEED}	≤10 kWh/100 km	Reference: the least possible fuel consumption

❷ Target indicators and target values "translated" by SyA based on PM requirements

DESIGN VARIABLE	VARIATION RANGE	COMMENT
$m_{VEHICLE}$	500 to 1000 kg	The mass of the vehicle is influenced amongst others by battery mass and the use of lightweight design components
P_{MAX}	18 to 100 kW	Motors with different power ratings are available
$NUMBER_{GEARS}$	1 or 2	The motor can be connected to the transmission directly or via a gearbox
$RATIO_1$	3.88 or 6 to 12	In the two-speed option the gear ratio of the 1st gear may be varied. In the single speed transmission, and for 2nd gear with the two-speed transmission the ratio is already given at 3.88 for v_{max} = 120 km/h.
$SHIFT_{UP}$	50 to 200 rad/s	The gearshift threshold in the case of a two-speed transmission can be varied.
$SHIFT_{DOWN}$	350 to 450 rad/s	

➌ Design variables that describe the envelope of possible solutions (top-level architecture)

MODEL-BASED EVALUATION OF THE ROAD TESTS

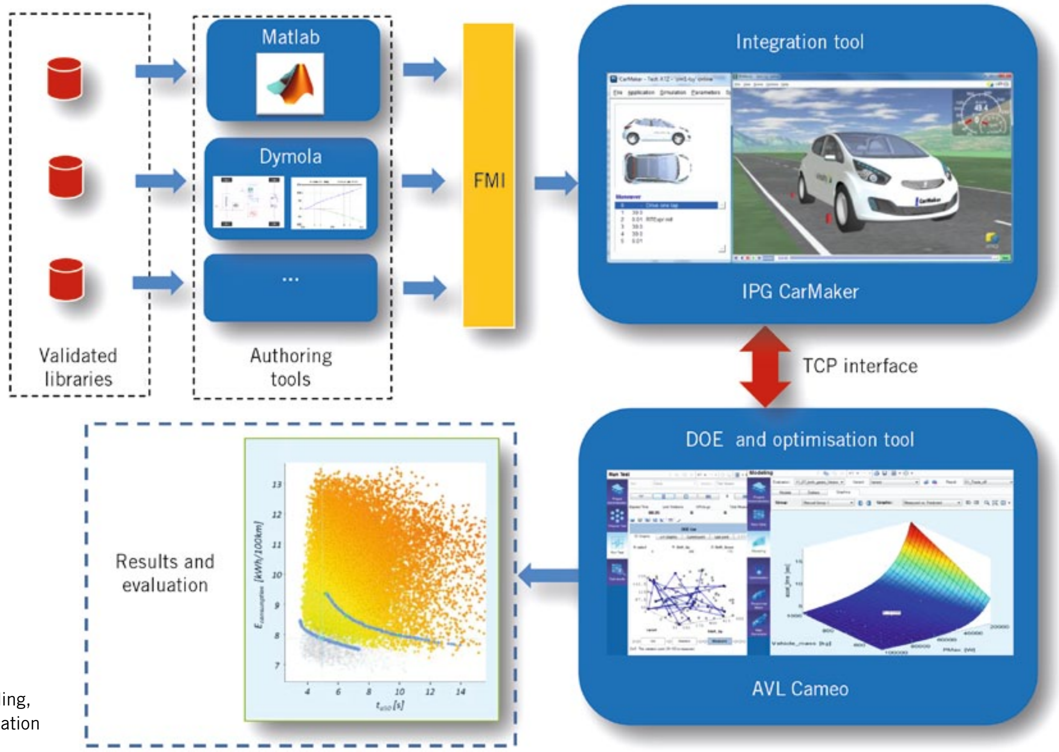
The (meta) model building occurs in step two: Based on the results of simulation, a model of the relationship between the target indicators is built up as algebraic functions of the design variables. An appropriate visualisation leads to a deeper, yet rapid understanding of the relationships. Only 840 simulation runs provide an accurate modelling in a significantly shorter computation time as compared to the „brute force“ method. The “empirical modelling” in this case permits a valid assessment of all variants within the 6-D design space via ③. The quality of the modelling is tested and validated at verification points.

PARETO OPTIMISATION

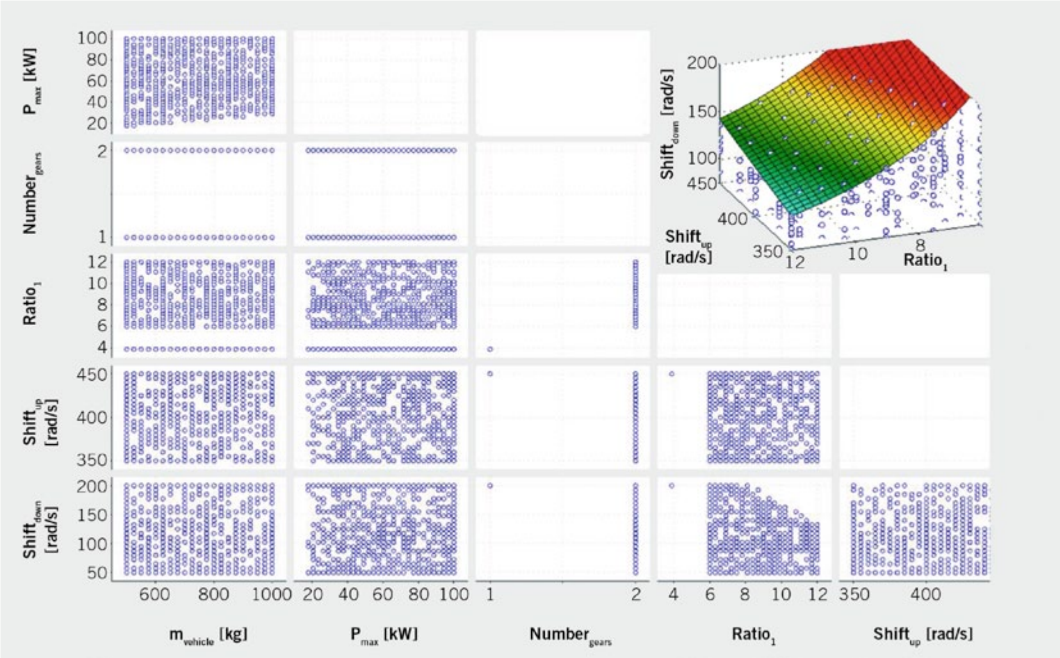
Last step three involves optimisation: The models are “interrogated” by a multivariable optimiser algorithm to show the user the choice of Pareto optimised variants. Seen from the mathematical side this is a multi-dimensional optimisation with constraints. The optimisation tool Cameo uses an algorithm based on NSGA-II [8]. In particular, the critical “levers” (design variables) relative to the target indicators are identified, quantified and visualised.

The example shows a typical result for the SyA: The alternative indicating minimum energy need is not the same as the variant providing best acceleration performance; the alternative with best traffic flow behaviour is not the same as that with maximum mileage range and so on. In other words, choosing the “best” model is a trade-off decision. How can the results of the tests now be presented in a way that supports a goal-oriented trade-off discussion between the PM and the SyA?

In other words, there is an optimisation problem with a multiplicity (n) of targets. We consider the trade-off between acceleration and energy need (n = 2) for example. The so-called Pareto front determines those n–1 = 1 dimensional hyper surfaces in which an improvement of one target function value may be only achieved by deterio-



➍ Tool chain for automated modelling, design of experiments (DOE), simulation and trade off analysis



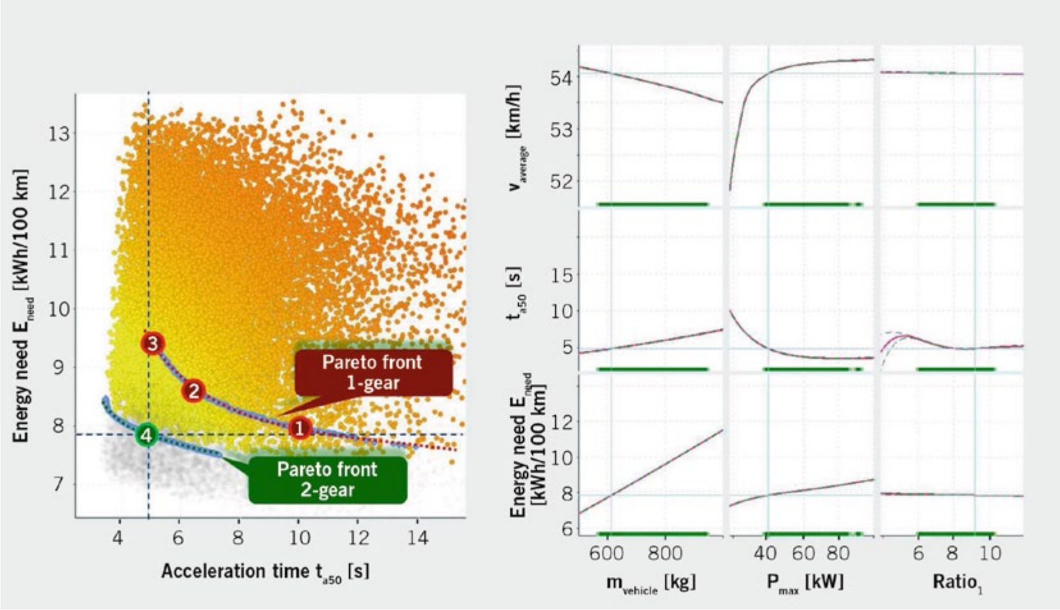
❺ Reduction of the data points within the design space according to ③ by design of experiments based optimisation algorithms

ration of another. For multi-variable optimisation, the optimisation tool can automatically calculate and visualise important areas and thus facilitate an open and efficient discussion between PM and SyA. ❻ shows diagrams of the Pareto front as well as the trade-off analyses:

- On the left, the trade-off representation of the independent targets is illustrated: The "cloud" of possible alternatives for the energy need E_{need} versus their associated time t_{a50} meeting top level constraints (such as minimum range) is marked in yellow. Grey shaded areas indicate alternatives that do not meet at least one of the top level constraints. The two Pareto fronts for the single and two-speed transmission are shown in blue.

Depending on the position in the right side of ⑥ – shown here for variant 4 – the right-hand graph shows design variable sensitivities at the specific position in the model. The tool allows the choice of model variants interactively. In the example, only dependencies of three strongly influential design variables are shown: Vehicle mass $m_{vehicle}$, engine power P_{max} and gear ratio ratio1 for first gear. The latter is only a free parameter for the two-speed transmission and is fixed for the single-speed transmission variants at 3.88.

Given the constraints for optimisation of the target values, the methodology reduces



❻ Four optimal Pareto positions within the target indicators space and their positions within the design space the design space of possible solutions to four representative alternatives and their trade-offs. ❼ summarises these variants.

The benefits of a strongly reduced engine power requirement and significantly better energy need balance the effort of a two-step transmission variant. DSE based VSP allows the quantification of these trade-offs. Thus, valuable and quantitatively assessed foundations are available for the design decision “should we choose architecture with or without a two-step transmission?” The gear shift thresholds have been assessed to be of little influence and do not need to be explored in depth. This saves time and allows focussing on the key issues.

	DESIGN VARIABLES			**TARGET INDICATORS**	
NO.	P_{max} [kW]	$Number_{gears}$ [-]	$m_{vehicle}$ [kg]	t_{a50} [s]	E_{need} [kWh/100 km]
1	40	1	616	10.06	7.97
2	65	1	625	6.73	8.50
3	100	1	640	5.12	9.40
4	40	2	612	4.89	7.86

❼ The four Pareto optimal results from ⑥

SUMMARY

Around the topics development methodology, modular system and systems engineering AVL provides solutions to following questions that may be encountered in any design process:

- How can design decisions be systematically assessed against customer related criteria already during concept and design phase?
- How can the space of possible architecture solutions be systematically built up and the “best solution” be identified?
- How can the described design process be supported by appropriate tools and at least partially be automated?
- How can quality-critical information be extracted in an efficient and quantitatively resilient manner for architectural decisions?

The methodology from [2] extends the established VSP technique (Virtual System Prototyping) by the Design Space Evaluation (DSE). The workflow presented is based on “road test” simulations and experiences of design space variants. Design alternatives are systematically derived from design variables. The use of DoE allows a highly efficient reduction of required alternatives to quantify the target indicator versus design variable relationship. The results establish a new level of collaboration between system architects and product managers: The most suitable alternative for a given use case can be accurately identified by the trade-off of customer-oriented target indicators within the design space. Thus, a partially emotion based decision process may be replaced by a more effective and target oriented approach. In addition, a proof of concept of the chosen best alternative may be demonstrated well ahead of the technical vehicle implementation.

To successfully implement the method, in an integrated vehicle development process, validated models of the individual components and a validated manoeuvre catalogue are required. The proposed tool chain supports the following actions:

- integration of individual components to an overall vehicle model
- simulation of manoeuvres
- DoE and automated execution
- model-based analysis
- trade-off analysis.

Use of the proposed method provides significant competitive advantages to a car manufacturer of highly innovative automotive systems.

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