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Parametric Modeling of Car Body Structures

Enabling Efficient Optimization / Sensitivity and Robustness Analysis for Crashworthiness, NVH, and Multi-disciplinary Concept Assessments

White Paper
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CONTENT

1. INTRODUCTION AND MOTIVATION

This white paper gives an overview of modern technologies for efficient and effective concept development of car bodies in early design phases. It shows the potential of advanced parametric modeling enabling simultaneous variation of geometry and simulation data. Special techniques are available allowing a very high flexibility and versatility either for interactive development or automated optimizations and sensitivity studies. Today, it is hence possible to integrate efficiently numerical assessments of the required functionalities, e.g. crashworthiness, NVH (noise, vibration, and harshness), durability, manufacturability, into early phase development strategies.

2. CHALLENGES IN CONCEPT DEVELOPMENT FOR CAR BODIES

Today, concept development for car bodies requires advanced virtual techniques to consider as early as possible not only expert knowledge and results from numerical assessments or optimizations, but also insights from automatic explorations of design options and concurrent design strategies via set-based development. This altogether contributes to realize upfront CAD-CAE engineering (Fig. 2.1) to reduce costs and improve designs, which is more and more necessary to address a high number of legal and consumer requirements related to crashworthiness, NVH (noise, vibration, and harshness) and other functionalities.

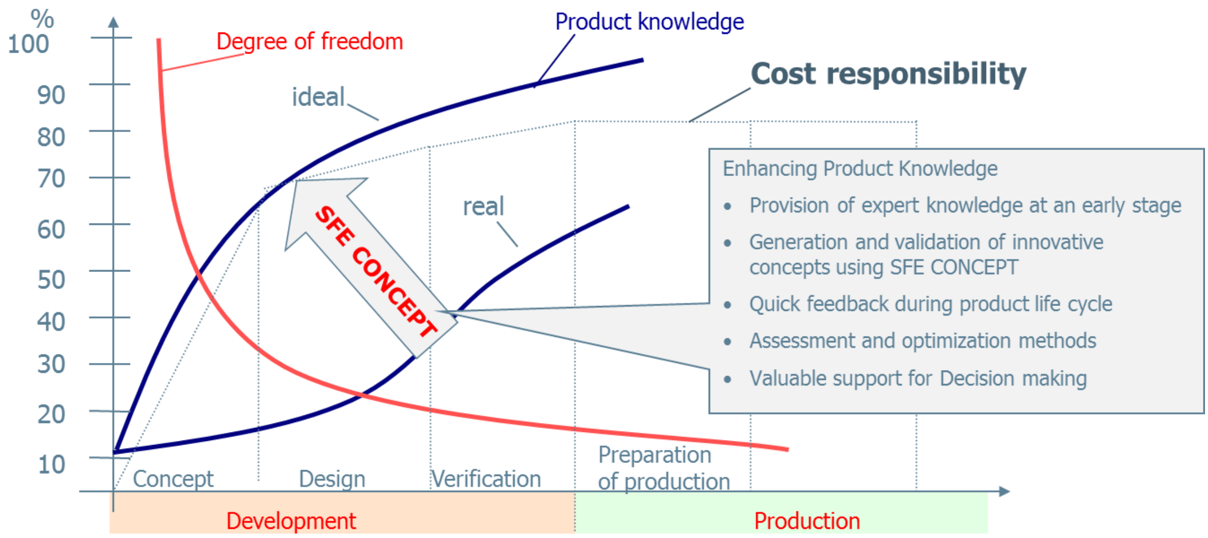

Fig. 2.1: *Upfront engineering: parametric modeling enables integration of product knowledge earlier in the development processes reducing development time and costs.*

In early development phases, it is necessary to work concurrently on a set of designs (i.e. realize so-called set-based approaches). Several concepts have to be derived exploring sufficiently well the available options. Communality and platform approaches have to be assessed where components have to be fitted into different vehicle concepts increasing overall complexity. Parametric modeling is therefore mandatory where components can be combined and varied automatically and where components adapt automatically to changes. This is challenging because of the required detailedness of the geometric and computational (mainly finite element) modeling. Material, joining and manufacturing information has to be considered and geometry has to be adapted to the computational analysis. At the very early stages, package changes may be still addressed such that a parametric representation of the design spaces for the structures is needed as well. All these things should be embedded into simulation data management systems, which are integrated into CAD-CAE software.[1]

[1] CAD = Computer Aided Design; CAE = Computer Aided Engineering.

A system engineering approach should be employed to break down full vehicle requirements to sub-system and component level, see Fig. 2.2. Ideally, this is combined with a decoupling of the components such that first conceptual decisions and investigations are enabled within a distributed development environment.[2] For this, a library approach providing parametric models not only for component geometry but also for numerical simulations is beneficial. A pre-defined hierarchisation of the parameters based on their influence and sensitivity is then possible and contributes strongly to the efficiency of the overall concept development.

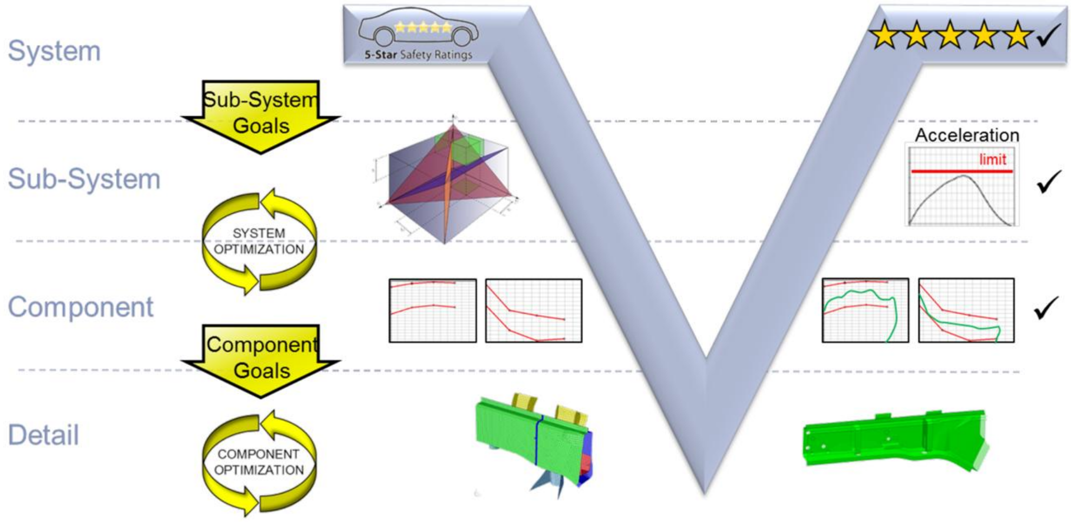

Fig. 2.2: *System engineering approach (solution space methodology) to break down full vehicle requirements to objectives on component level enabling parametric component development*[2]

These advanced technologies, the parametric modeling and the library approach, together with the solution space methodology, or a comparable approach, enable now automatized assessments of functionalities and especially derivations of sensitivities. Numerical optimization becomes possible allowing a true exploration of design possibilities. Topology, shape and size optimizations can be established in a wider sense than discussed normally such that discrete topological changes can be considered as well. Layout, positioning and geometric relations between components and connectors can be evaluated and optimized.[3]

All these aspects require a parametric representation of the structural geometry covering the full range of design possibilities together with the automated generation of the corresponding numerical models (normally based on finite element methods).

3. EFFICIENT TECHNOLOGIES FOR PARAMETERIZATIONS

There are several approaches for parametric modeling and automated finite element (FE) variation. They either work directly on the FE model or they use a geometry model from which the simulation model is generated after the realization of geometrical changes. A first

[2] Zimmermann M, Edler von Hössle J: Computing solution spaces for robust design. *Int. Journal for Numerical Methods in Engineering* 94(3):290-307 (2013);
Fender J, Duddeck F, Zimmermann M: On the calibration of simplified vehicle crash models. *Structural and Multidisciplinary Optimization* 49(3):455–469 (2014);
Fender J, Duddeck F, Zimmermann M: Direct computation of solution spaces. *Structural and Multidisciplinary Optimization* (accepted in 2016).
[3] Moldering F: Development of a method for computer-based optimization of positions and relations of structures and components for vehicular lightweighting (in German). PhD thesis, University of Stuttgart, Germany (2016).

group of methods (vertex morphing) moves the nodes of the FE mesh directly. The number of design parameters is here very high and can only be handled if an additional adjoint solver is available. This is not the case for very complex assessments, e.g. for crashworthiness. In addition, mesh regularity has to be assured, which is not always possible. Topological, lay-out, and positioning changes are also not possible.

A second group realizes shape modifications by direct morphing. Special control points (handles) have to be defined additionally to the FE model and shape functions are used to couple mesh changes to these points. This makes the variation non-transparent and often not sufficiently controllable. Mesh regularity has to be maintained and for larger changes a re-meshing is necessary. More complex geometrical changes can be realized by defining morphing boxes. The FE mesh assigned to the boxes will follow the changes of the control points of these boxes. Again, the changes of the FE mesh are not transparent and for more complex problems, the definition of morphing boxes becomes difficult.

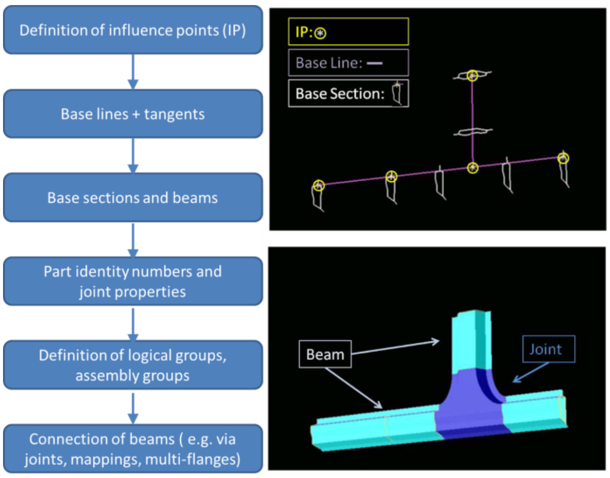

Fig. 3.1: *Beam parameterization (SFE CONCEPT)*

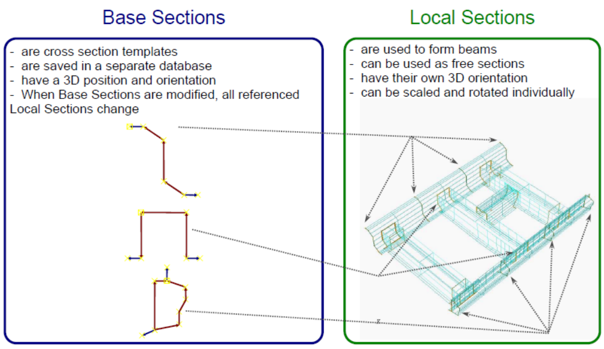

Fig. 3.2: *Cross-section parameterization (SFE CONCEPT)*

An alternative to parameterizations based on FE meshes or morphing-boxes is offered by geometry-based (also called implicit) parameterizations. Here, an additional model is used, which defines the geometry. FE models are then generated automatically from these models. The concept model is established by defining first influence points and base lines connecting these points with parametric joints, Fig. 3.1. On these lines, parametric cross-sections are defined (Fig. 3.2) such that a vehicle beam model is established (Fig. 3.3). As can be seen in Fig. 3.2, it is possible to define parameters for the different cross-sections of the beam model using again influence points and connections / tangents. Mappings can be used, which allow a more flexible definition of design spaces. Both together, the parameters of the cross-sections and of the lines enable a very precise and flexible parameterization of the geometry. They also allow defining a parameter hierarchy, which increases efficiency of parametric changes and optimizations. Joints follow the changes of the beams and have their own parameters (tangents). To obtain the full vehicle model, free form surfaces can finally be defined together with geometric details like depressions, beads, holes, etc. For optimization and structured development, these parameters can be organized hierarchically to enable handling of the complexity.

The geometry representation obtained by this approach has several advantages. First, the continuity between components can be controlled directly via tangent parameters modifying, for example, the base line curvatures. Both, a continuous transition as well as a transition with a certain angle following the overall changes can be defined problem-dependent. A required orientation might be hence maintained during the modifications, see e.g. Fig. 3.3. An additional advantage is the ability to control geometrical dependencies directly avoiding geometrical clashes. In Fig. 3.4 an interior structure is modified simultaneously with the outer structure (here a cross-section of a bumper). The clash between variation of variable D and H1 at the same time, i.e. the overlapping, can be avoided by using a mapping-based parameterization. Via this approach, a larger design space can be defined exploiting the full potential of the structure.[4]

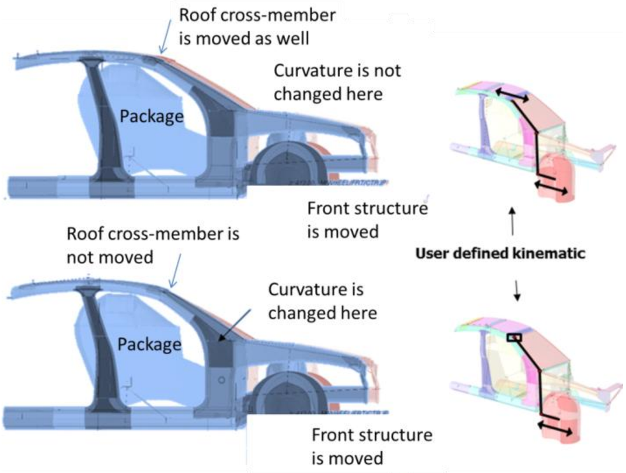

Fig. 3.3: *Example for user-defined control of geometry changes. Blue: original structure, red: modified structure (here: SFE CONCEPT)*

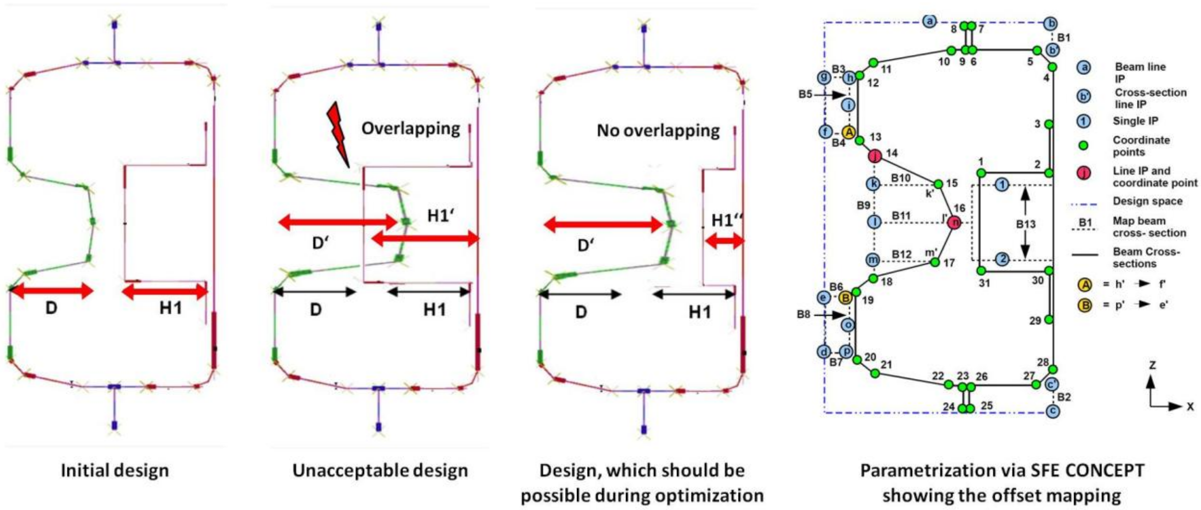

Fig. 3.4: *Parameterization of a cross-section using mapping to enlarge design space (SFE CONCEPT)*[4]

Connectivity is maintained via the implicit parameterization (Fig. 3.5) and it is not lost if one component is moved over several other components (Fig. 3.7). The mapping also allows the implicit definition of joining information (e.g. spot welds, adhesives, Fig. 3.6). Hence, flexible joints are possible connecting either two or three components depending on the geometrical changes.

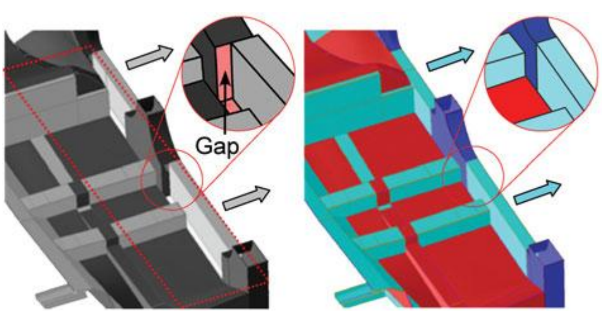

Fig. 3.5: *Left: Gap occurring due to failing connectivity; right: maintenance of connectivity via implicit parameterization (SFE CONCEPT)*

[4] Rayamajhi M, Hunkeler S, Duddeck F: Geometrical compatibility in structural shape optimisation for crashworthiness. *Int. Journal of Crashworthiness*, 19(1): 42-56 (2014).

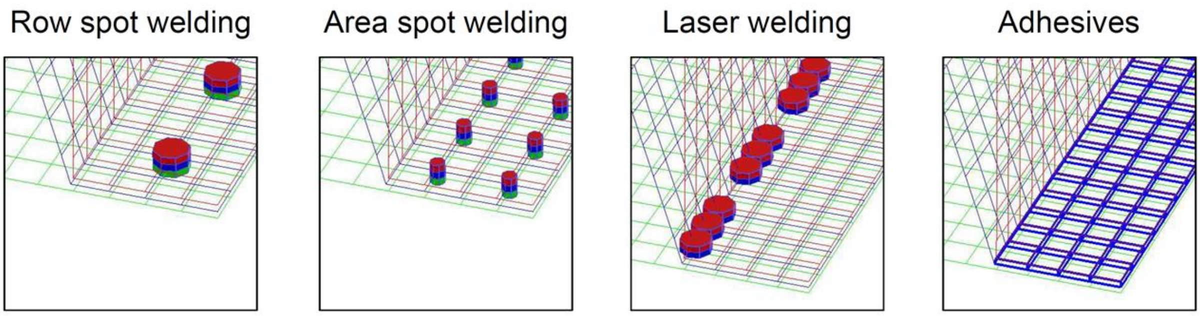

Fig. 3.6: *Parametric definition for variation and optimization of joining elements*

The techniques described so far enable as well that a structure from a predecessor vehicle is taken and integrated into the new design. Because of the stored connectivity information in the geometry model, it will adapt shape and size automatically.

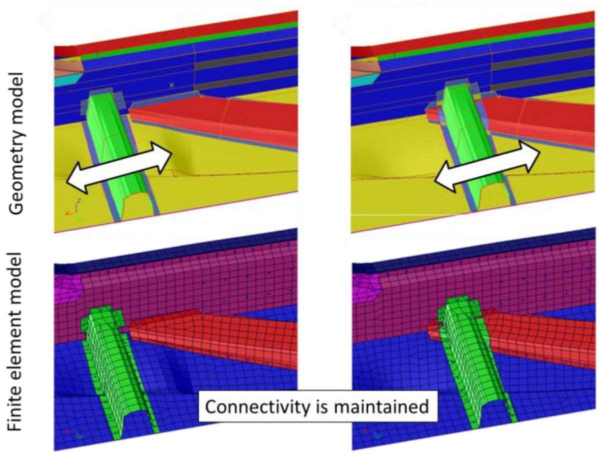

Fig. 3.7: *Sliding of a component over several other components maintaining connectivity (SFE CONCEPT)*

Hence, a library can be established where parameterized geometries of components are stored as pre-defined modules. They can be then used for development of a single vehicle or of a family of vehicles considering communality requirements. An example of such a library is shown in Fig. 3.8 where a vehicle model is built from a sub-assembly library and assembled components are then stored in an assembly library. This library-based approach also allows a combined topology-shape optimization with discrete parameters, i.e. full components. Although the algorithmic part for this type of optimization is challenging, it can be realized here if a hierarchic approach is chosen where optimization progresses from coarser to finer features.

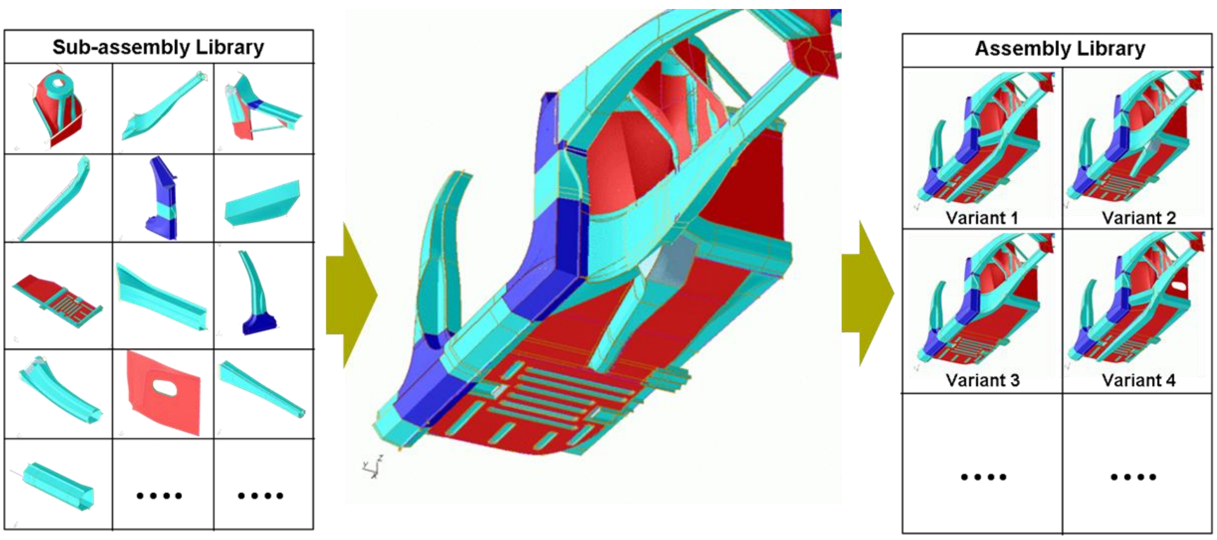

Fig. 3.8: *Example for a library approach using implicit parameterization (SFE CONCEPT)*

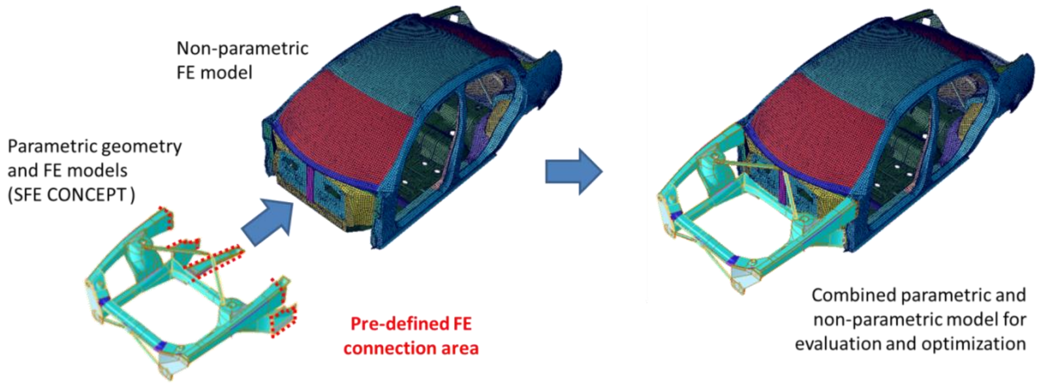

Fig. 3.9: *Combined parametric modeling – non-parametric modeling (SFE CONCEPT)*

To reduce modeling effort, it is possible to embed the FE model generated from a parametric geometry model into a non-parametric FE model (Fig. 3.9). Hereby, it is necessary to assure that a transition zone is not modified. This approach is especially attractive for component, sub-structure or sub-assembly optimizations via the novel solution space approach enabling component and sub-structure optimizations.[2] If this is then combined with a parametric representation of the package using the same approach for parameterization, parametric concept development is made possible, Fig. 3.10. The CAE parameterized modeling is also embedded into a Computer Aided Design (CAD) representation (see Fig. 3.11).

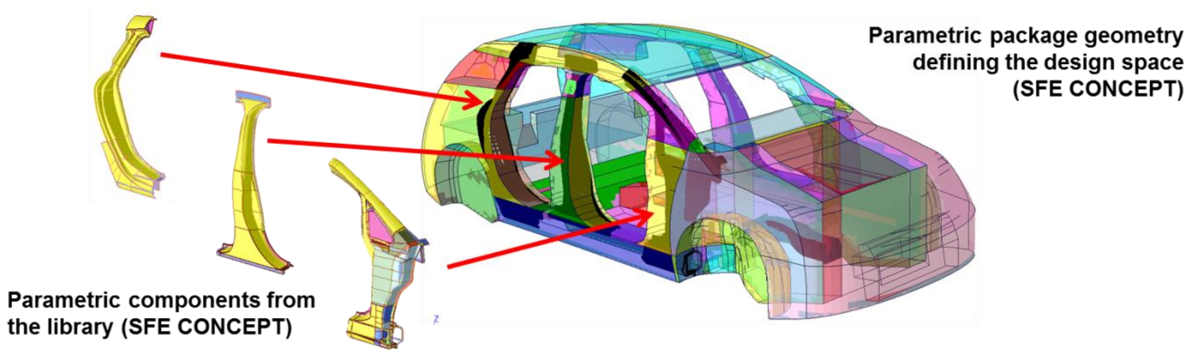

Fig. 3.10: *Modular and library-based approach mapping parametric geometry models into a parameterized package geometry defining the design space of a new concept (SFE CONCEPT)*[5]

To summarize: Geometry-based parameterizations enable

- efficient and transparent parametric representation for package and structures;
- maintenance of connectivity between components during variations;
- flexible geometry parameterization via mapping technology;
- usage of a modular component library with pre-defined parameter hierarchies;
- realization of designs for platform and communality approaches;
- embedding of parameterized models into non-parametric (FE-) models;
- integration of CAE techniques into CAD environments; and hence
- a very efficient and effective parametric concept development.

[5] Zimmer H: Parametrischer Bauraum – synchronisierter Fahrzeugentwurf. *FAT-Schriftenreihe* 251, Ed.: Forschungsvereinigung Automobiltechnik e.V. (FAT); Verband der Deutschen Automobilindustrie VDA (2013).

All these achievements via geometry-based parameterization allow reducing the number of manual design iterations as illustrated in Fig. 3.12.

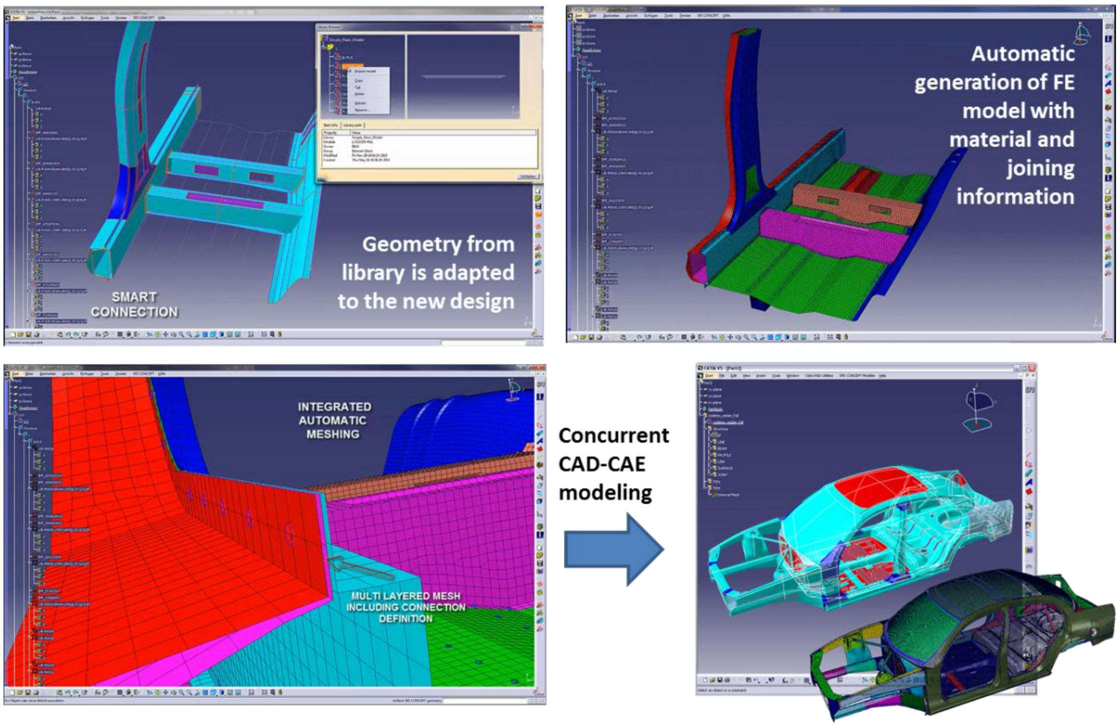

Fig. 3.11: *Integration of geometry-based parameterization modeling into CAD (here CATiA-V5).*

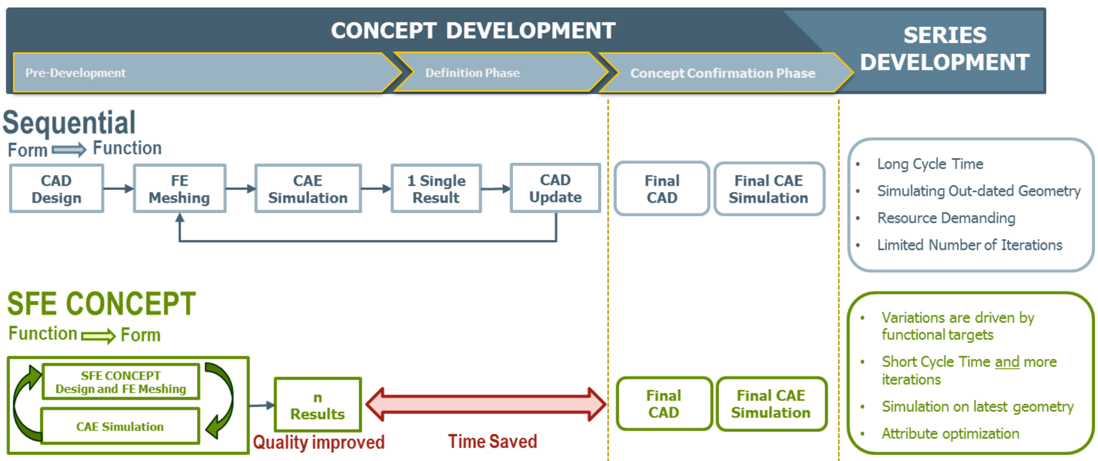

Fig. 3.12: *Top: Sequential development with a high number of manual iterations between CAD-driven changes and CAE-based analyses; bottom: CAE-CAD integrated approach driven by geometry-based parametric modeling enabling set-based concept development with final CAD representations.*

4. APPROPRIATE PARAMETERIZATIONS FOR CRASH OPTIMIZATION

Today, numerical optimization is very well-developed even for highly non-linear cases like design for crashworthiness[6]. While linear functionalities or cases using implicit time step schemes for finite element simulations can be optimized via local sensitivities exploiting gradient information from adjoint solvers, non-gradient methods are normally required for

[6] Duddeck F: Multi-disciplinary optimization of car bodies. *Structural and Multidisciplinary Optimization* 35(4): 375-389 (2008).

crashworthiness. Hence, FE mesh-based approaches with their high number of design variables cannot be used.

The geometry-based parameterization with the mapping definitions and the implicitly defined connectivity discussed above allow for a wider range of variations maintaining correctness of numerical modeling and enable therefore a better exploitation of the design space. A morphing box-based approach cannot handle the discrete changes occurring in the automatic adaptations when a modular library is used to realize optimizations within the context of communality and platform technology. For optimization, parameterizations should fulfill the following requirements:

- The number of parameters should be small enough to enable optimization but large enough to realize relevant geometrical changes;
- For this, a hierarchic approach should be possible where the parameters are structured with respect to their importance for the different functionalities;
- Ideally, sensitivities in the full design space can be used; these are global sensitivities and not local ones because of the non-linearity of the crash physics;
- Dependencies between the parameters should be realizable, for example based on symmetry requirements or required correlations;
- Discrete parameters should be possible not only related to material selection or manufacturing (discrete thickness availability), but also due to discrete topology changes and joining variations;
- Positioning as well as variations of relationships between components should be possible; this also often leads to discrete optimization problems where gradual changes using morphing are not appropriate;
- Parametric results should be transparent; i.e., the sensitivities and changes should be directly linked to distinct geometrical modifications;
- Definition of parameters and their ranges should be user-friendly;
- Ideally, the parametric results are also comparable between different stages in the development and between different vehicles; this is also important to identify a best overall concept for communality.

The geometry-based parameterization is hence a very attractive option to fulfill these requirements on parameterization for crashworthiness (or other) assessments of car bodies.

5. EXAMPLES AND BENCHMARKS

For crash optimization, the case studied most often is the crash box. In Fig 5.1, an example for possible parameterizations using SFE CONCEPT is given. Beside parameters like thickness, material and angle, the position, cross-section and tapering of the main structure can be used. Additionally, parameters for holes and depressions can be defined. These features are ideally pre-defined and pre-evaluated in a library. It is important to control overlap of shape design variables ranges maintaining at the same time sufficient design space by incompatibility control and mapping (see Chapter 3).

This parameterization approach can be transferred to more complex structures, e.g. for the optimization of a front rail shown in Fig. 5.2. Here, the focus is set on optimal cross-sectional shape for energy absorption. This simple component example is proposed as a benchmark and was presented in a study on parameterizations for combined optimization and robustness analysis.[7] A similar approach was used in a more industrial study with more complex conditions in a full vehicle context, Fig. 5.4.

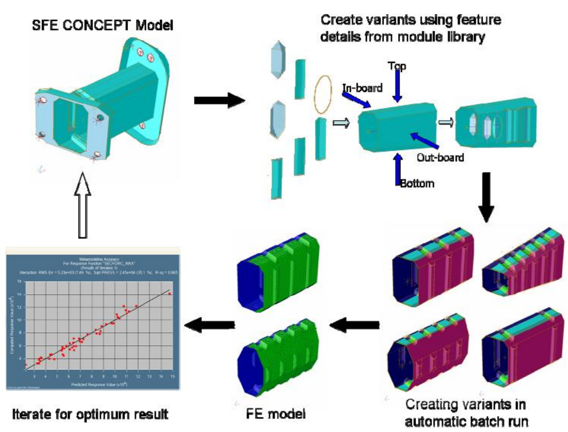

Fig. 5.1: *Crash box parameterization (SFE CONCEPT)*

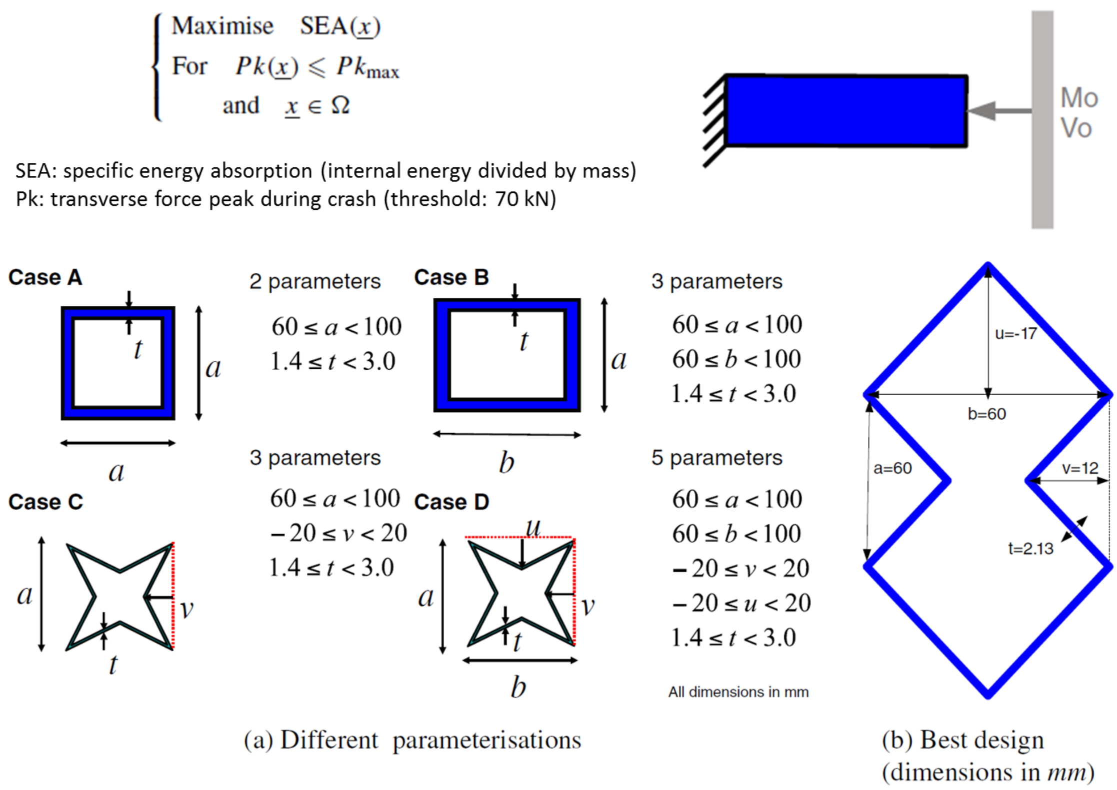

Fig. 5.2: *Proposed benchmark for a front rail optimization (SFE CONCEPT)*[7]

For structures under transverse impact, a comparable approach was developed. Beside cross-sectional parameters, design variables defining size, shape and position of internal reinforcements were optimized. Here, the flexibility and user-friendliness of the geometry-based parameterization and the corresponding mapping (SFE CONCEPT) enabled the definition of a sufficiently large design space, see Fig. 5.3.

[7] Hunkeler S, Duddeck F, Rayamajhi M, Zimmer H: Shape optimisation for crashworthiness followed by a robustness analysis with respect to shape variables. *Structural and Multidisciplinary Optimization* 48: 367–378 (2013).
Duddeck F, Zimmer H: Modular Car Body Design and Optimization by an Implicit Parameterization Technique via SFE CONCEPT. *FISITA Conf.*, Beijing, China, Springer, DOI: 10.1007/978-3-642-33835-9_39 (2012).
Duddeck F, Zimmer H: New Achievements on Implicit Parameterisation Techniques for Combined Shape and Topology Optimization for Crashworthiness based on SFE CONCEPT. *ICRASH Conf.*, Milano, Italy (2012).

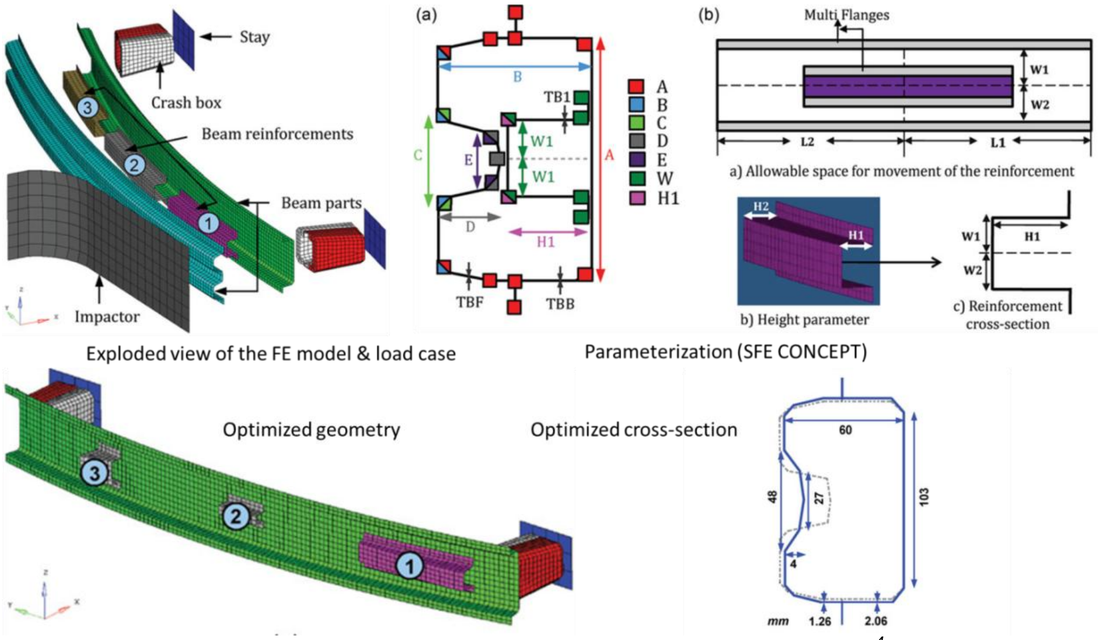

Fig. 5.3: *Example for a bumper optimization (SFE CONCEPT)*[4]

As mentioned above, the industrial component optimization of the front rail was part of an embedded shape optimization, i.e. parametric changes of structural components were realized within the full vehicle model. The geometry-based parameterization allowed here the definition of geometrical changes in a complex environment. Interior reinforcements were as well modified as cross-sectional parameters and connection points of structural components. The initial result was inspired from a topology optimization and the final results were validated against a reference model from standard industrial development showing improved crash behavior after the optimization, see Fig. 5.4.[8]

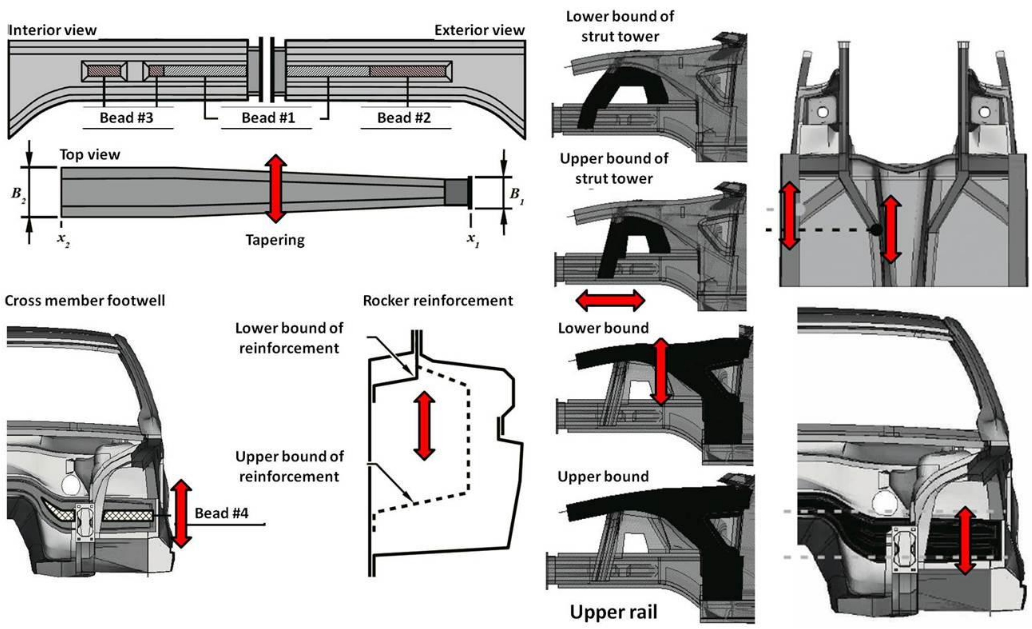

Fig. 5.4: *Example of shape variations used for crash optimization (full vehicle)*[8]

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[8] Volz K: Physical Surrogate Models for Crash Optimization of Car Body Structures in Early Design Phases (in German). PhD thesis, Technical University of Munich, Shaker Verlag, Germany (2011).