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Multi-objective optimization of a vehicle body by combining gradient-based methods and vehicle concept modelling

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ABSTRACT

In the automotive field, size optimization procedures can be combined with concept modelling approaches, in order to design a vehicle Body-In-White (BIW) model with optimal static and dynamic performances already in the early design stages. However, this specific optimization problem, with hundreds of design variables, limited design space and often conflicting objectives, makes the choice of the appropriate optimization method really difficult. The aim of this paper is to show an industrial case study, where two different implementations of the classical gradient-based (GB) method are used in combination with a technique for vehicle body concept modelling to achieve a multi-objective BIW optimization of a passenger car.

1. Introduction

Concept modelling and structural optimization methods are becoming increasingly important in the vehicle development process. The goal is to achieve and improve various functional performance requirements (such as static stiffness, NVH, crashworthiness, etc.) of a concept BIW model, already in the early design phases. Some of the most widely used concept modelling methodologies are based on predecessor Finite Element (FE) models: a simplified structure layout of an existing vehicle FE model is created starting from the detailed model [1–4]. The result is a small-size and parameterized concept model, ready to be optimized. In this process, geometric parameters of cross-section (i.e. thickness, width and height) of concept beams, which can be represented as 1D beam elements, are the design variables; the design space defines geometrical boundary constraints, while targeted values for static and dynamic performances, together with the achievement of minimum weight, define the objectives.

In this paper, a problem of size optimization of a vehicle body concept model is addressed. The amount of design variables, constraints and performance targets makes the choice of the best optimization method, able to find a good trade-off between quality of results and reasonable computational time, a non-trivial problem. In 2008, Duddeck suggested a GB approach to multidisciplinary optimization of car bodies [5]. Different performance attributes, including, static behaviour, NVH, crashworthiness and lateral impact, have been taken into account for the optimization. Recently, Mihaylova et al. [6]

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proposed the use of a global-search method, based on Differential Evolution, to achieve the optimisation of vehicle body concept models.

The main objectives of the research work presented here are: (i) to provide a comparison of the performances of two different existing methods for GB optimization, applied to this highly complex industrial case; (ii) to show the potential and applicability of the concept modelling technique developed at the BMW NVH Department in problems of vehicle body multi-attribute optimization. The first formulation, which will be referred to as “Hard Constraint” (HC) method, uses a basic implementation of the GB algorithm [7], to solve a constrained optimization problem. In a second, more advanced formulation, referred to as “Beta” (BT) method [8], a relaxation of the constraints is achieved by defining additional design variables, the so-called beta values. By providing a measure of constraint violations, these functions allow combining car body weight and functional targets into the objective function, in which the relative importance of the different performance criteria can be adjusted and balanced by specifying relative weighting factors.

Both HC and BT methods are used in combination with a technique for vehicle body concept modelling. Starting from an existing body of a commercial passenger car in steel material (reference model), a new model is created with the same geometry but with typical aluminium material properties (lightweight model), with the aim of reducing the vehicle weight. The objective is to optimize the geometric properties of the lightweight model in such a way that static and dynamic performance indicators of the optimal model are as close as possible to those of the reference one, while keeping its weight as low as possible.

The paper is organized as follows: Section 2 describes the main steps established at BMW to model and optimize concept BIW structures. Section 3 describes the optimization procedure, based on coupling commercial software and dedicated design and analysis tools. Section 4 illustrates a case study, useful to compare the performances of the two GB methods. Concluding remarks are provided in Section 5.

2. Vehicle body concept modelling and optimization at BMW

At the BMW NVH department, FE concept modelling and optimization are widely used in the initial phases of the vehicle development process. Fig. 1 shows the three main steps of the entire process, consisting of model creation, definition of load cases for functional performance assessment and model optimization. Starting point for the design process are customer relevant performance requirements. In the area of NVH, examples are sound pressure level at driver's ear, seat vibrations or steering wheel vibrations. These phenomena are influenced by the static and the dynamic stiffness of the carrying structure of the car body, which represents the connection between the excitation sources (road, power train, driveline) and passengers.

Target values for optimization (e.g., static and dynamic stiffnesses) are derived from the customer relevant performance expectations. The setting of these values requires the deep understanding of the physical mechanisms and is also based on experiences from predecessor cars.

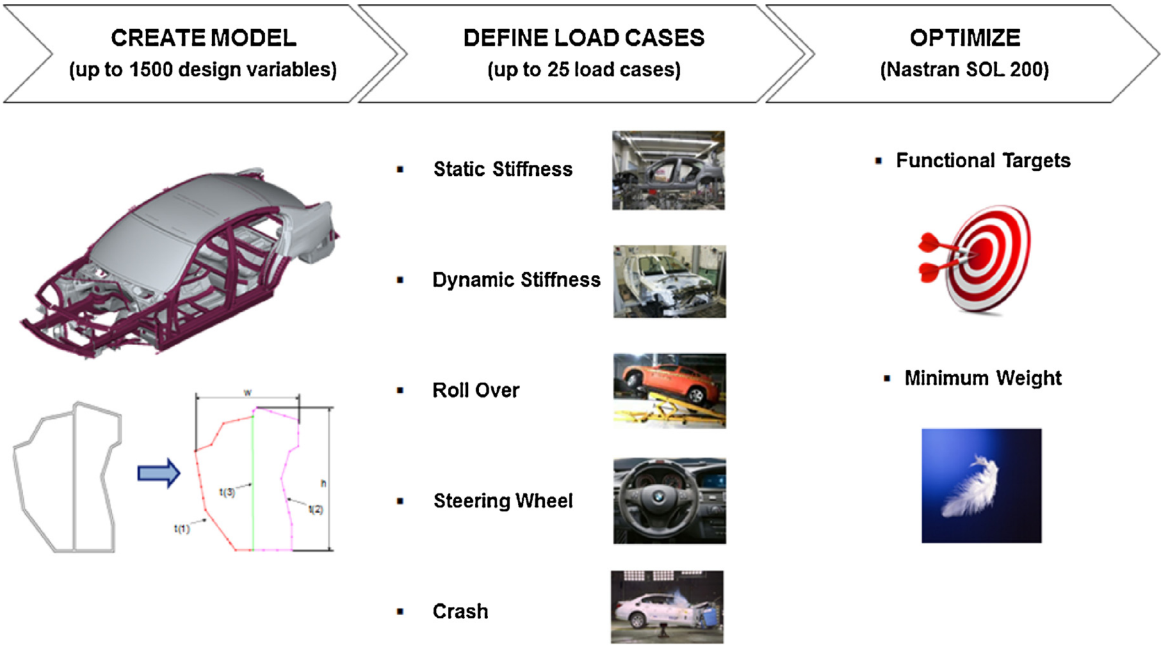

Fig. 1. Modelling and optimization process at BMW.

The definition of the design region and of the available construction space depends on the specific optimization targets. The range here is from general statements on the feasibility for a new car or architecture under certain given specifications up to modifications in a restricted region of a car (e.g., front cradle) for a specific improvement by taken into account all available inputs from other disciplines.

A typical FE concept model of a vehicle body consists of panels, modelled by 2D shell elements, and concept 1D beam elements representing load-carrying structures, with parameterized cross-sections. The latter can be defined by means of the Arbitrary Beam Cross-Sections (ABCS) method [8]. Following this approach, each detailed beam-like structure is divided into a series of 1D beam segments, each having an almost constant cross-section. Then, height and width of the bounding box including the cross-section shape, as well as the wall thickness values, can be changed during the size optimization process [1] to modify the cross-section geometry and, consequently, the beam stiffness and mass properties. Fig. 2 shows an application example of the proposed approach for ABCS parameterization.

By using the pre-processor ANSA [9], a software equipped with dedicated modules for beam cross-section representation and analysis, one can cut shell structures and automatically calculate equivalent geometric properties of cross-sections, such as cross-sectional area and inertia moments. Furthermore, in recent years, the BMW NVH department, in collaboration with IABG company, developed specific tools by means of dedicated ANSA scripts, which allow to create and modify ABCS data [1].

Once the concept BIW model is created, the multi-objective optimization process can start, by using the geometric parameters of beam cross-sections as design variables. The goal is to minimize the body weight, while ensuring that different functional targets are met. Various functional performance cases, addressing vehicle ride, handling and passive safety behaviour, can be taken into account.

Different optimization algorithms can be employed to explore the design domain in order to find an optimal body model. In the research work described here, the numerical algorithms suitable for structural optimization, available in the commercial software MSC Nastran [8], have been exploited to implement two GB methods, namely HC and BT methods, with the aim of optimizing the vehicle body concept model.

3. Size optimization problem

A problem of structural optimization can be formulated as a general constrained optimization problem, described as follows:

$$\begin{array}{ll} \text{Find:} & \mathbf{X} = [x_1, x_2, \ldots, x_D] \\ \text{that minimizes the Objective Function:} & OF(\mathbf{X}) \\ \text{subject to constraints:} & c_l(\mathbf{X}) \geq 0, \qquad l = 1 \ldots L \\ \text{and boundary constraints:} & x_j^{(LB)} \leq x_j \leq x_j^{(UB)}, \qquad j = 1 \ldots D \end{array} \tag{1}$$

where $x_j^{(LB)}$ and $x_j^{(UB)}$ are the lower and upper bounds of each design variable x_j.

In the size optimization problem addressed here, $\boldsymbol{X}$ represents the vector of design variables, i.e. height, width and thickness values of each concept beam element, for which the admissible region is defined by the given lower and upper limits; OF($\boldsymbol{X}$) is represented by the weight of the body structure, while constraints $c_l(\boldsymbol{X})$ are related to the functional targets set by the designer.

Such a basic formulation of the size optimization problem, which will be referred to as HC method, can be implemented by using the GB optimization sequence available in MSC Nastran (Nastran Solution 200 [8]), but has a main disadvantage in that the optimizer tries to fulfil constraints while minimizing the OF. Then, if the starting point is a highly infeasible design, convergence towards an optimal solution that fulfils the design constraints can be difficult to achieve. This concept is schematically illustrated in Fig. 3 for the optimization problem that is addressed in this paper and that will be described in the next section.

For highly constrained optimization problems, a relaxation of constraints is then advisable to help the optimizer to move from infeasible to feasible design regions. A possible approach to handle constrains is based on the use of penalty functions [10]. The basic idea is to incorporate the design constraints into the objective function by adding penalty terms to the OF. In

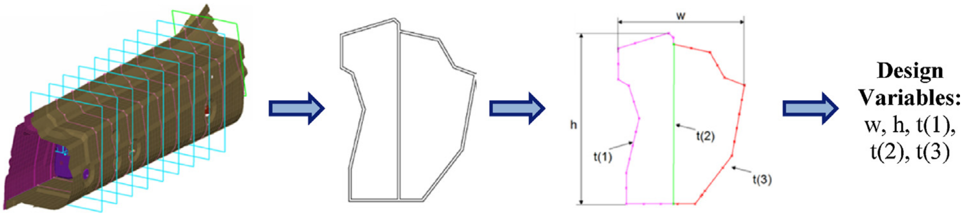

Fig. 2. Parameterization of Arbitrary Beam Cross Section (ABCS).

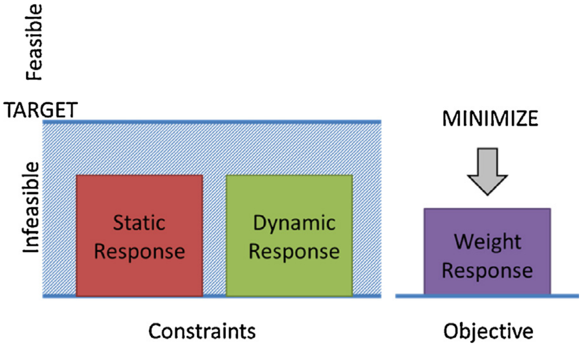

Fig. 3. Schematic of the structural optimization problem according to the HC method.

general, these additional terms consist of penalty parameters, multiplied by a measure of the violation of each constraint in the actual design. By adjusting the values of such parameters, which has the effect of weighting the different performance indicators and differentiating their relevance, it is also possible to establish different priorities in the optimization strategy.

A possible approach to relax the optimization problem defined above is known as BT method. For each functional target or group of functional targets, an additional design variable, called beta value, is defined. In addition to the weight response, new responses are created as a sum of each functional response and of the related beta value, and the constraints are defined on these new responses, as shown in Fig. 4. The initial value of the beta design variables can be set so that the optimization starts in the feasible region even if the targets are not fulfilled. As shown in Fig. 4, the OF to be minimized is not only the weight itself but a sum of penalty terms that additionally contains all beta values. The latter are multiplied by weighting factors to allow balancing of the different performance criteria and body weight.

Beneath the benefit of a well-conditioned optimization problem inside or near the feasible region, the user has various options to tune the optimization problem. For example, by setting very low weighting factors for static and dynamic stiffnesses, the optimization is forced to focus very much on weight reduction and it will end the iterations in a still feasible status, even if functional targets are not met. Of course with the BT method the setup of the optimization problem becomes more complex and more experience and understanding is required to create a well-defined design model with reasonable settings for initial beta values and weighting factors.

In the research work presented here, the optimization problem, which includes the steps of design variable identification, constraint and cost function definitions, is set by using a BMW in-house tool, named "*OptiCenter*". Nastran Solution 200 is used to implement the two size optimization approaches described above. Several performance targets can be defined. For static stiffness performance, target values are evaluated according to different bending and torsional load cases. Regarding dynamic performances, the user can set up to four natural frequencies, along with the allowed tolerance ranges, as dynamic stiffness targets. Additionally, pseudo frontal and rollover crash load cases can be defined and monitored during the optimization sequence in order to minimize strain values in the beam structure of the vehicle greenhouse. Finally, frequency response functions and steering wheel vibrations can be added as performance targets for ride comfort optimization.

Weighting factors for the different performance indicators can be defined in order to differentiate their relevance in the optimization strategy.

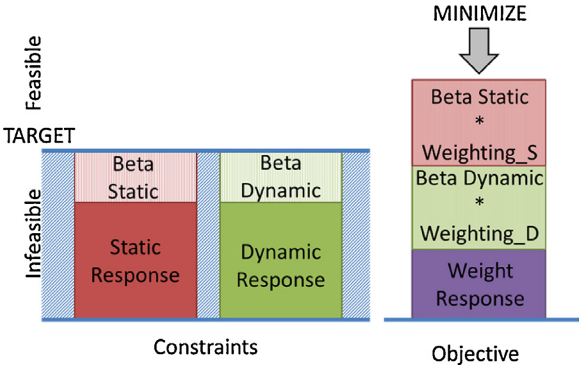

Fig. 4. Schematic of the structural optimization problem according to the BT method, where "Weighting_S" and "Weighting_D" are weighting factors related to static and dynamic performances, respectively.

4. Case study

A case study has been analysed with the aim of comparing the two optimization algorithms described in the previous section. Computations were made on a Linux workstation, with following technical characteristics: CPU Intel Xeon@2.5 GHz, 32 GB RAM. Size optimization was applied to the FE concept model of the BIW of passenger car (Fig. 5). The model consists of about 500 beam cross-sections, modelled as concept 1D beam elements with ABCS. For each cross-section, at least three design variables, i.e. width, height and one or more wall thickness values, were defined.

Before starting the optimization process, two static load cases, one for torsion and one for bending, and a modal analysis in free–free conditions, have been implemented and analysed to set the optimization functional targets, i.e. the static and dynamic stiffness values of the vehicle body with steel material properties (reference model). A second concept model of the same vehicle has been created by using material properties that are typical for aluminium structures (lightweight model). The aim of the optimization process was to modify the geometry of the beam cross sections, in such a way that an optimal design is obtained for the lightweight model, with minimal weight and with static and dynamic performance as close as possible to the values estimated for the reference model.

The first torsional frequency was taken into account as indicator of the dynamic performance, while the static performance was monitored by considering the static stiffness of the vehicle body under torsional, vertical bending and lateral bending load cases. A total of 1414 design variables have been defined, for which an admissible design space has been set in the range 70–150% of their value in the reference model. As the objective was to outline the differences between the investigated methods, the whole car was chosen as design region without the restrictions that are usually taken into account by crash or fatigue requirements. Furthermore, the available construction space is given for the complete design region, whereas in the real development process much more effort would be spent on partitioning the structure into different regions with different settings.

The conversion of the original steel parts into aluminium structures lead to a 61% mass reduction of the vehicle body, but the static performance of the lightweight model, reported in Table 1 as the average of the three static stiffness values, was about half as compared to the reference model. In the same table, the optimization results achieved by using HC and BT methods are also summarized. For the latter method, four different optimization strategies have been implemented, where the relative importance of mass reduction and both the static and dynamic performance targets in the objective function has been varied in the range of factor 0.2–5 relative to the weight term.

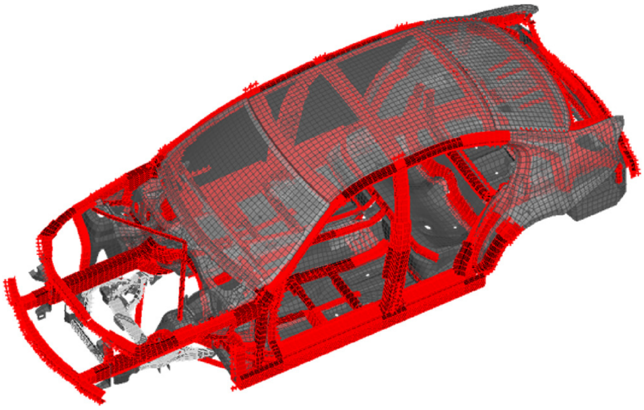

Fig. 5. The BIW of a passenger car, with 1D beam elements (in red) subject to the size optimization.

Table 1
Optimization results.

	Initial model	HC method	BT method Weighting stiffness vs. mass reduction			
			1:5	1:2	1:1	5:1
Mass reduction [%]	61.0	51.1	52.7	50.7	48.8	46.7
Dynamic performance [%]	1.0	1.0	0.7	3.8	4.9	5.2
Static performance [%]	−56.5	−14.5	−38.8	−22.2	−13.6	−8.3
Computational time [h:m]		3:55	1:10	0:53	0:53	0:35
Cycles		50 (max)	16	12	12	8
Status		Infeasible	Feasible	Feasible	Feasible	Feasible

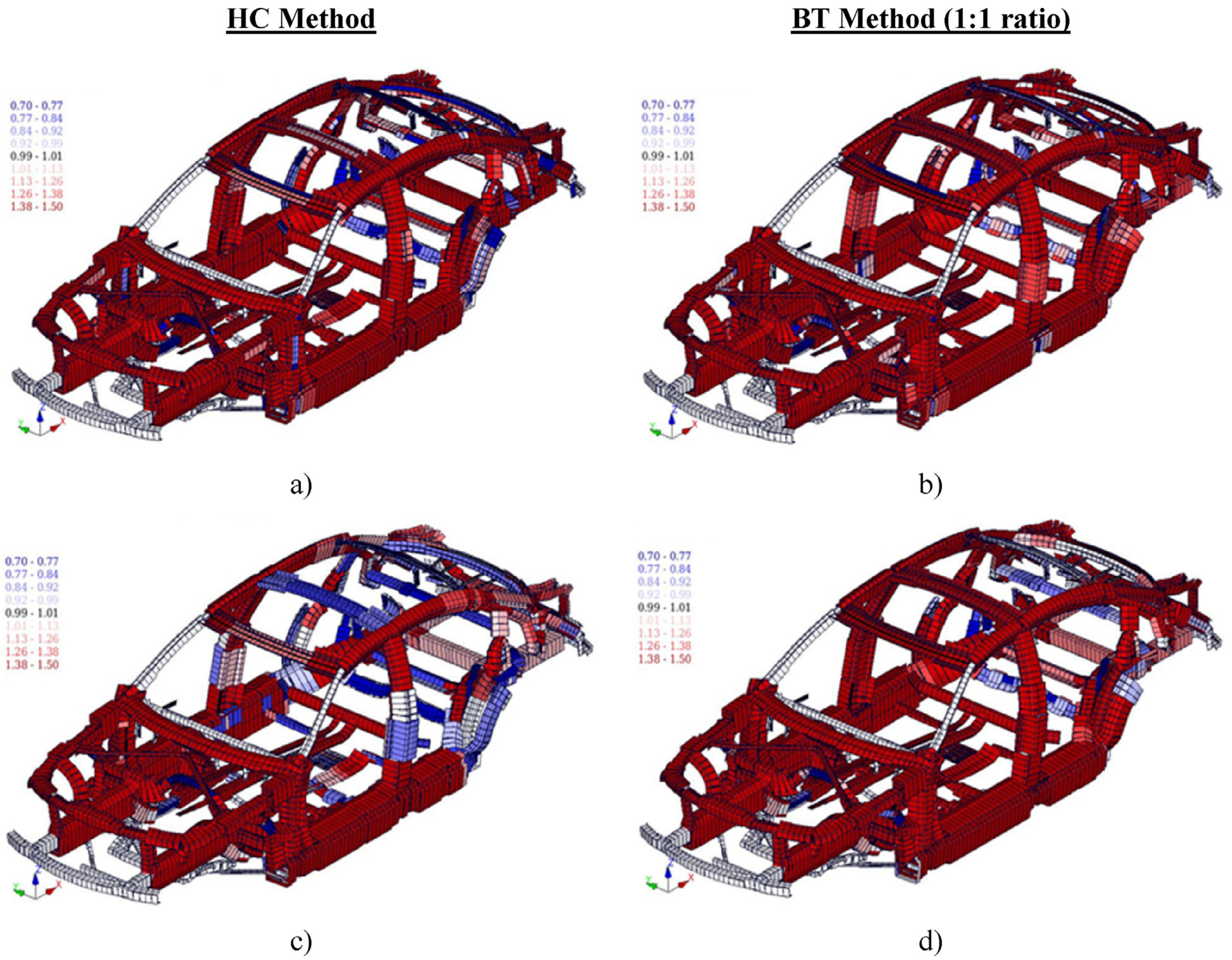

Fig. 6. Graphical solutions of size optimizations; in the upper part, design space variations (a–b), in the lower part, wall thickness variations (c–d).

The results summarized in Table 1 show that after 50 iterations the HC method gives an optimal solution, which is marked as infeasible since at least one of the design constraints is violated. The BT method, instead, always finds a feasible optimal solution after a much smaller number of iterations, which results in a reduction of the required computational time ranging between 70.2% and 85.1% with respect to the HC method. It is also worthy to point out that the BT method allows to adjust the relative importance of functional targets and mass reduction, enabling a more sophisticated optimization procedure in which mass reduction can be maximized at the cost of penalizing functional performance and vice versa. Usually, in the real development process, the main objective is to reach the given functional target values. If the optimization shows that this would result in a significant increase of mass, the next step would be to think about other approaches like modifications on topology or material. Even if the designs with the strong focus on mass reduction will not be implemented, they will give a deeper understanding of the structure as they show the sensitivity for the different functional requirements and their influence on the resulting structural mass.

Fig. 6 shows variations of design space (a–b) and thickness (c–d) for each of the two methods, obtained by using GNS Animator4 software [11]. Increments with respect to nominal values are indicated in red, decrements in blue. While the BT method (with 1:1 ratio) gets strong increments in almost all parts of the BIW, the HC method realizes decrements for central and rear beams, especially with regards to thickness values.

5. Conclusion

In this paper, two different implementation of the GB optimization method, namely the HC and the BT method, have been used in combination with a vehicle body concept modelling technique with the aim of addressing a case study of vehicle body light-weighting. The optimization results show that the more sophisticated BT method allows to find different optimal solutions, based on the relative importance of functional targets and mass reduction objective, in a considerably shorter computational time as compared to the HC method.

A limitation of the proposed optimization approaches lies in the local search nature of the optimization algorithms employed. Next steps of the work presented here will concern the assessment of global search techniques, such as evolutionary algorithms, used as standing alone or in combination with GB methods, in problems of size optimization of vehicle body concept models.

Acknowledgements

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