

CASE STUDY // AUTOMOTIVE INDUSTRY

OPTIMIZATION OF CRASH RELEVANT VEHICLE STRUCTURES DURING THE CONCEPT PHASE

A reduction in time spent for early phase product development can cut costs significantly. Using RDO methodology, safety related simulations can be carried out a lot earlier than in conventional processes.

In optimization applications used for novel product development methodology, crash behavior evaluations are involved during the early stage of the product development process to save time in later phases. In conventional processes, vehicle safety related simulations like crashworthiness tests, insurance tests and pedestrian safety related tests are carried out separately at a later stage. Furthermore, FEM models used for engineering analyses do not permit easy changes in terms of geometry and topology of the vehicle structures. Therefore, to answer basic questions about the crash behavior of different concepts, a simplified model at concept stage is needed. The method involves usage of implicit parametric CAD models, providing necessary flexibility to the FE mesh. By using a powerful implicit parametric CAD Model, manifold concept studies can be carried out and evaluated based on objective criteria, such as crash behavior, weight or classification tests. Furthermore, selected designs can be optimized to achieve specific goals.

Objectives

The main objective is to develop a methodology which can be used to predict crash behaviour of vehicle structures. The generated knowledge is to be used for ratings of the various

concept studies. Furthermore, this methodology should offer potential for optimizations during the early stage of the product development process using simplified structures.

Methodology

General approach

The shown product development process (PDP) on the left hand side of Figure 1 is based on the planning and design process by Pahl/Beitz. The typical PDP begins with an idea followed by the product planning, conceptual design, embodiment design and the detailed design phase. The difference between the Pahl/Beitz and the proposed methodology is the usage of design phase elements, such as FE calculations and optimizations that are usually carried out in the embodiment and detailed design phase of the conceptual planning. The new methodology proposes the use of implicit parametric CAD to illustrate design concepts and support initial FE calculations.

Independent of the product development time schedule, a simplification process (Figure 1) has been carried out to generate three different highly parametric models which

can be used for initial crash calculations to demonstrate the capabilities of the presented methodology. By simplifying (abstraction and idealization) detailed vehicle models (FORD Taurus and TOYOTA Yaris), crash relevant structures can be extracted. Within the verification process, the limitations of the models are defined and finally validated with typical crash configurations to ensure the correct response of the simplified models. Due to the parametric setting, these simplified models can be adopted and used for further development processes. At best, the simplification process does not have to be repeated.

Batch process

Figure 2 shows the general batch process of the optimization loop used for the studies. At the first stage, an implicitly parametric CAD model was created using SFE CONCEPT. The

mentioned CAD package has powerful auto-mesh functionality with welding and multi-flange definitions to handle relatively complex actual vehicle FE models. A FE mesh of the geometry was exported from SFE CONCEPT in the format to suit LS-Dyna input deck. The boundary conditions, material properties and other inputs were assembled in SFE CONCEPT. Calculations were performed using LS-Dyna solver, MADYMO solver or a combination of both. The critical output parameters of the calculations were identified and processed using MATLAB or combination of LS-Prepost with MATLAB. The whole process was controlled using optiSlang. The software is capable of performing the design of experiments, sensitivity analysis, robustness evaluation and single and multi-parameter optimizations.

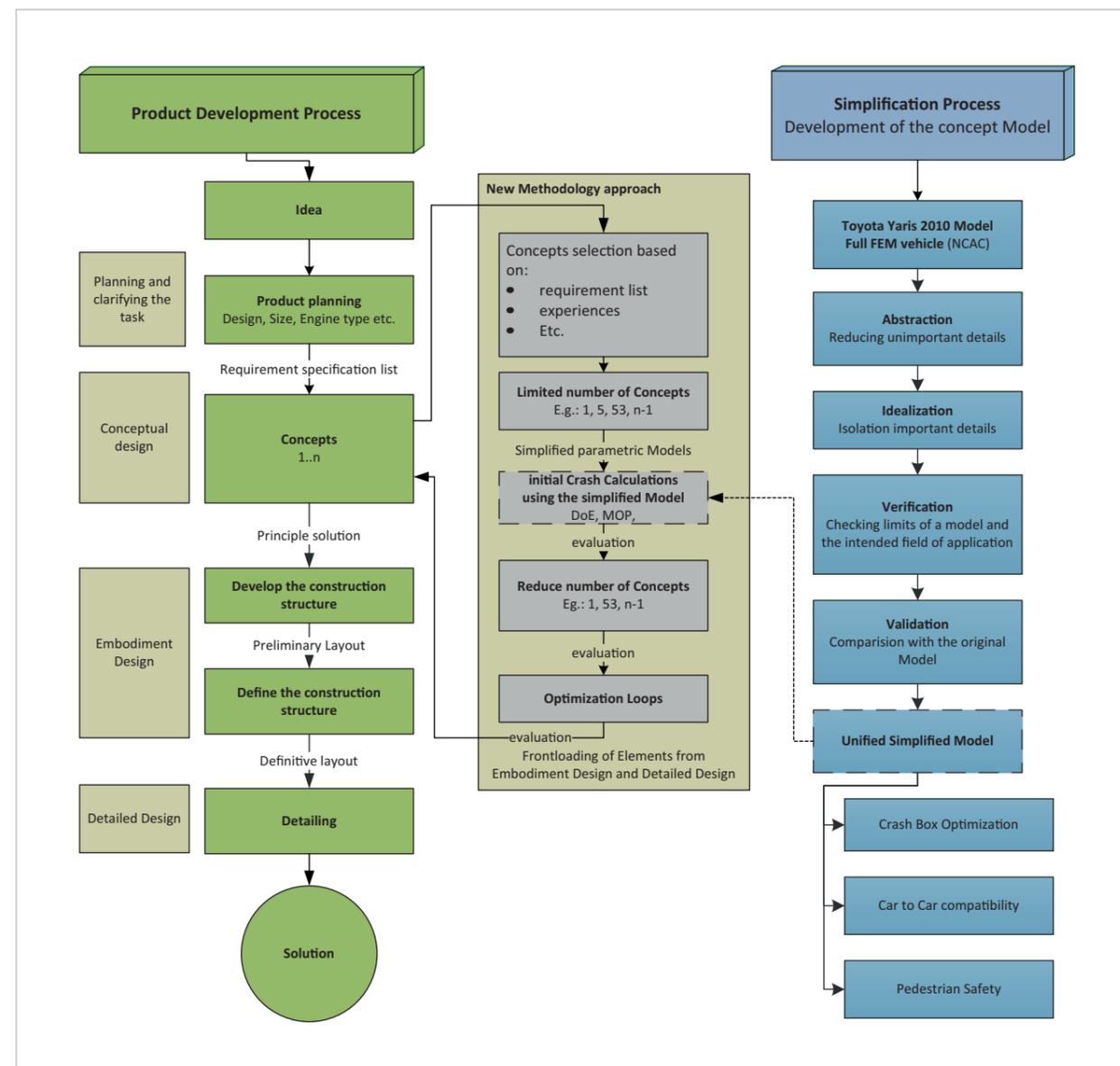


Fig. 1: Methodology for the front end Optimization during the early stage of the product development process

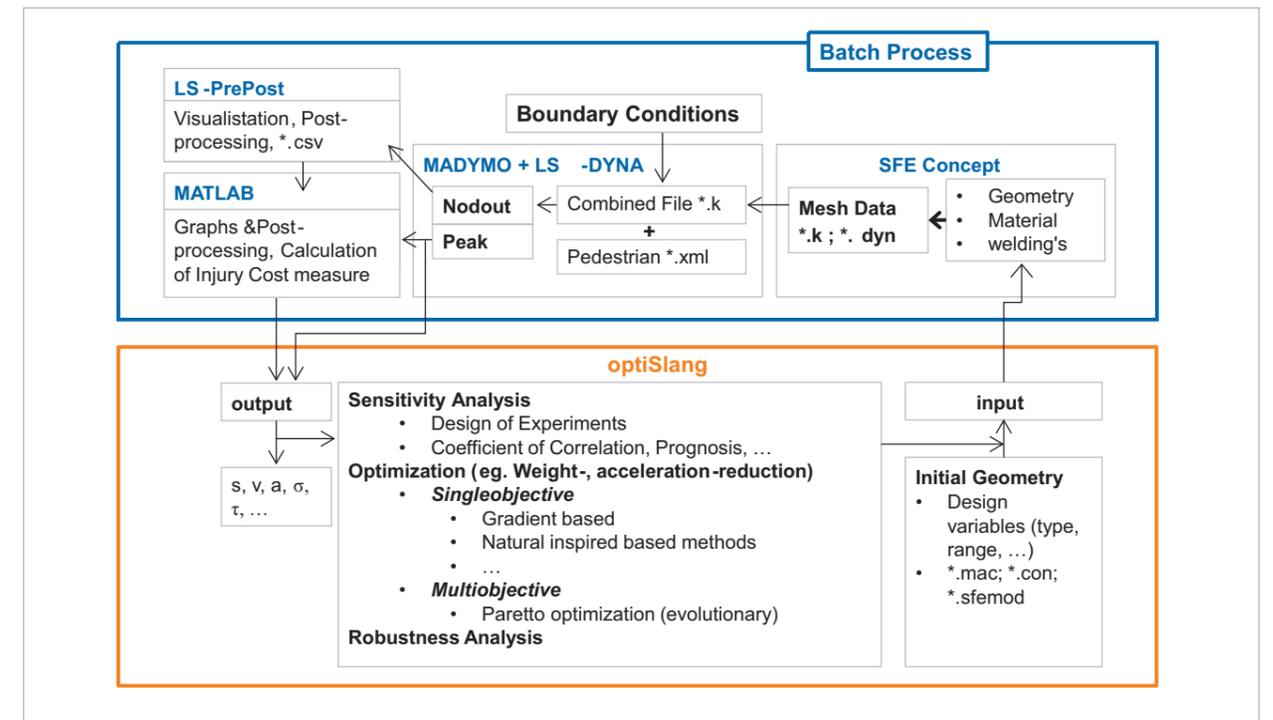


Fig. 2: possible batch process

Example 1 – Crash-box

Low energy vehicle car crashes

The aim is optimizing the front end structures, in particular the crash-box, to absorb the energy of low speed crashes with a velocity of 15 km/h. Here, the crash-box shall absorb major parts of the excess energy, thereby other parts will be exposed to forces within their elastic limits. The deformation and energy absorption of the crash-box is essential especially concerning repair cost reduction and, thus, minimizing insurance contribution. Therefore, reduced models, which replicate the critical output parameters effectively, are crucial to establish a development process within a desired time range.

Simplified Model and Validation

A TOYOTA Yaris has been used as a reference car. The model was validated by NCAC for US regulatory frontal impact load conditions. The internal energy over time distribution of the bumper and the crash-box (inner and outer) was used as the reference value (see Figure 3). The structure test barrier, according to the Research Council for Automobile Repairs (RCAR), was used as an obstacle and the vehicle speed was set to 15 km/h. The number of parts in the Yaris model has been reduced step by step and the crash-box performance of the original Yaris crash-box has been checked regarding to its crash performance in terms of absorbed energy. Figure 4 shows the different simplified models with the calculation time on one workstation. With decreasing number of nodes and parts, the calculation time was reduced sig-

nificantly. For comparison of the results, the internal energy of the inner crash-box has been plotted. The plot shows the internal energy results of the part concerning the full vehicle calculation and, for comparison, also the reduced version. Furthermore, the absolute difference of the internal energy between the original vehicle and the reduced vehicle was plotted, as well as the absolute difference on the

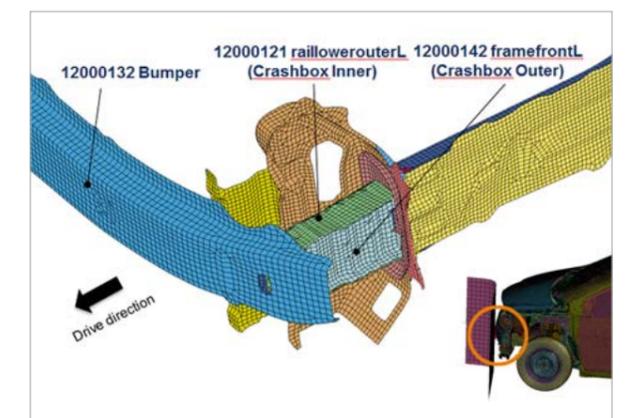


Fig. 3: Relevant TOYOTA Yaris front end parts

second ordinate. Additionally, every plot shows a box with the mean difference of the original Yaris model and the reduced model in terms of the percentile deviation and mean energy deviation. The simplified model had an overall calculation time of 1.5 h and was used for an initial optimization. The deviations from the original model indicated the

need for optimization processes for fine tuning parameters of the simplified model and to achieve similar prediction capability as the original model. Therefore, an optimization was started to modify the three different weights and the appending inertias, which were 27 variables in total.

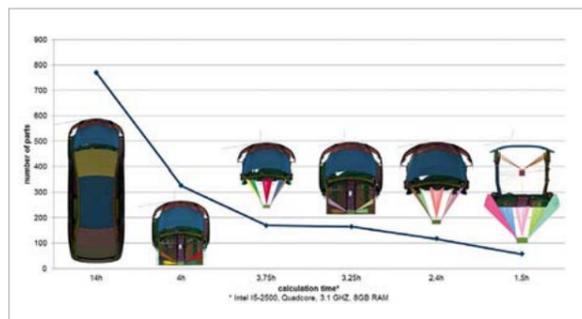


Fig. 4: Simplified model simulation time

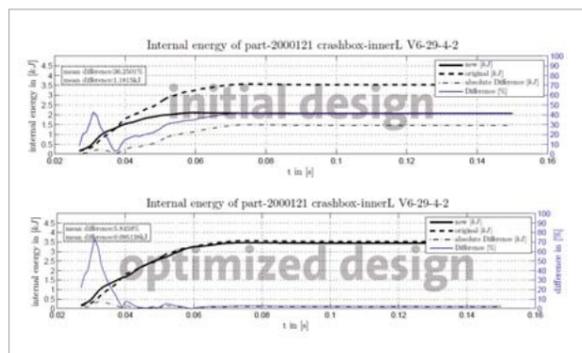


Fig. 5: Comparison of Initial and optimized design of the simplified model (extract)

After 183 calculations, a significant improvement was achieved. The average deviation of the internal energy of the three parts decreased from 17% to 6% (see Figure 5). This result was within desired limits of accuracy to permit the simplified model to run further simulations with highly parametric crash-boxes.

Example 2 – Pedestrian Safety Model

Introduction to pedestrian safety and vehicle front-end design

Pedestrians are the most vulnerable road users. Therefore, their safety needs to be in the focus. Most crash database analysis show that the most frequent pedestrian-to-vehicle crash scenario is a vehicle-front one striking the pedestrian laterally. For a typical sedan shape, the adult pedestrian crash kinematics were observed as leg to bumper, pelvis to bonnet leading edge, torso to bonnet or head to windshield types. For children, leg to bumper, torso or head to bonnet leading edge types were observed. In case of flat front vehicles, the secondary crash injuries were found to be more severe than the primary injuries. The variation of pedestrians from a 6 years old child to 95th percentile male is almost

two times in weight and more than twice in height and anthropometric features. With such a manifold requirement for safety, a pedestrian friendly design at concept stage is necessary.

Objective of this Study

A pedestrian crash scenario was shortlisted from crash data base studies, indicating that lateral collisions are recorded statistically more often. The objective was to discover the position with the highest risk to pedestrians. A DoE was planned to study the worst position for lateral pedestrian impact. The possible variations shortlisted for study were the angle of pedestrian to car and the gait positions as shown in figure 6 (A) and (B).

Input Set up (MADYMO) for study

Four pedestrian models having the size of 95th %le male, 50th %le male, 5th %le female and 6 year old child models from TNO are considered as representative for the pedestrian population. The inputs to this study are three joints namely “Human_jt” (referred as angle_6c for child model in statistical figures) in MADYMO, representing the angle of the human being with respect to the car. The rotation of the human is limited to 45° on the left and right, as indicated in figure 6 using notation. A 50th percentile male human model is shown representing a similar position and being used for all other models.

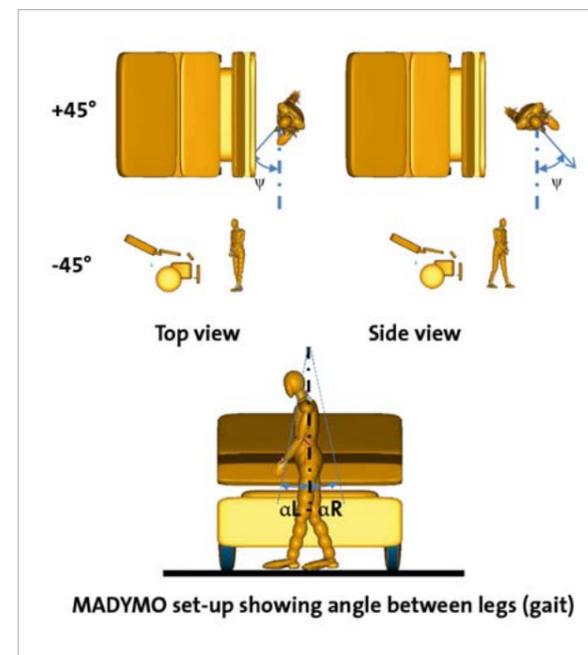


Fig. 6: Pedestrian simulation input set up (Angle with car - ψ)

“HipR_jt” for right leg and “HipL_jt” for left leg (referred to as HipR_6c and HipL_6c for child model in statistical figures) were the two joints in TNO pedestrian model for modifying the gait. The leg angles (gait) are limited to 14.32°

positive and negative for adults and 11.46° on either side for child models, as shown in Figure 6 using notation ‘ α L’ and ‘ α R’. The total number of variables is 12 (3 per pedestrian model, 4 models).

Pedestrian to vehicle interaction characteristics were modelled based on force deflection characteristics obtained from crash reconstruction studies. Also, body form characteristics concerning vehicle test data were used. An optimization loop with optiSlang, MADYMO and MATLAB was set up similarly to the one explained in Figure 2. To understand the injury risk to a pedestrian by a vehicle profile, the injury to the whole body was considered. Rating and regulatory tests use linear acceleration based criteria for the head, acceleration and displacement based criteria for the chest and penetration based criteria (peak force) for the abdomen. Peak force is also used for pelvis. A combination of bending and compression force factors is applied to long bones of the lower extremity and displacement based criteria is used for knees.

Studies related to the optimization of safety for pedestrians showed a single objective function as more effective to address the correlation of the different injuries. An injury cost based measure represents the hospitalization and medical expense with provision of high penalty for potential impairment or death. The injury cost calculation is shown in Figure 8. The threat to pedestrian was calculated based on Injury Cost (IC) measure using MATLAB based on output from MADYMO simulations.

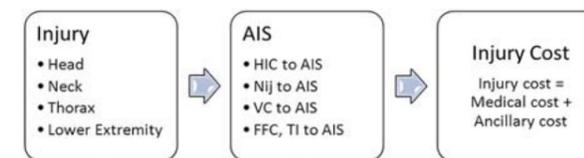


Fig. 8: Calculation of injury cost (abbreviations at end of paper)

DoE results analysis

The preliminary DoE was run with a total of 1000 loops consisting of 4000 simulations (4 pedestrian models x 1000 simulations). The measure computed for output was IC for 4 separate scenarios simulated in series one after another. The total IC represents the sum of all scenarios. Henceforth, 5 outputs and 12 inputs form the tables of statistics explaining them effectively. Figure 9 shows the ranking of the three variables relating to the IC of the child model. The same trend was also found on the other pedestrian models for the respective IC measure. The figure shows an angle of the child model inclination having the highest influence on the outputs, followed by the angle of struck leg and the non-struck leg.

Figure 10 shows the variation of linear and quadratic correlation coefficients for the child scenario. Both the correlation value matrices show a weak relationship between any of the inputs with the output. The same trend was observed in other scenarios with varying levels of correlation but not strong enough (>0.9) to establish some correlation.

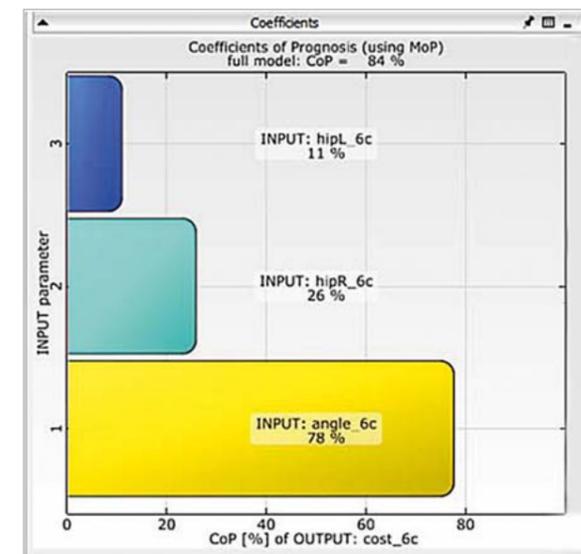


Fig. 9: Coefficient of Prognosis child model

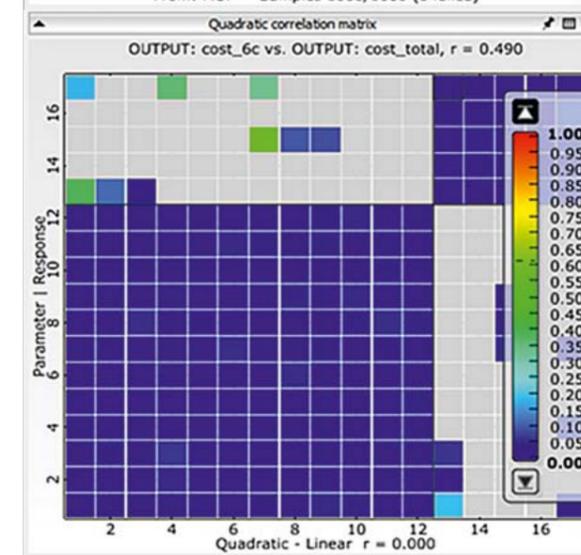
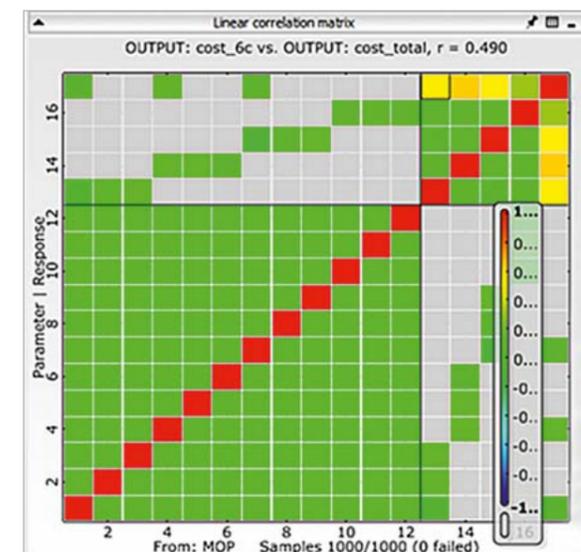


Fig. 10: Linear and quadratic correlation matrix

Figure 11 shows the variation of meta-models based on the simulation of 1000 samples and 4536 samples run. The Coefficient of Prognosis increased from 84% to 93%. The approximated model was generated for three variables with 3% variation allowed. The identical three variables and their order of influence were involved in the generated models.

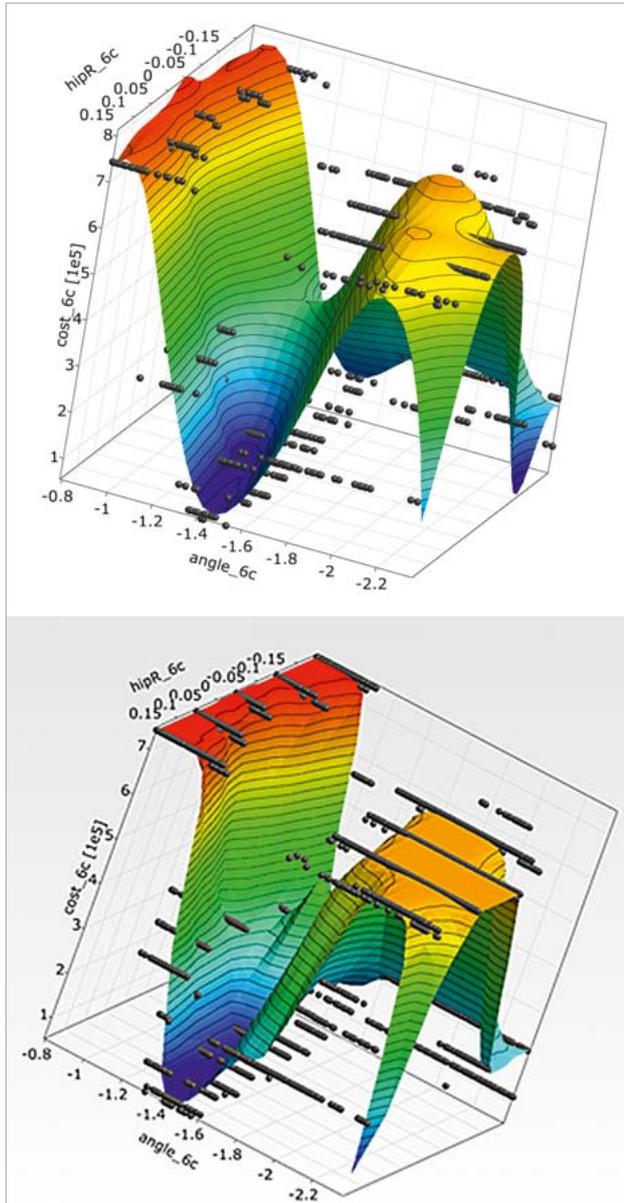


Fig. 11: Meta model with 1000 Samples (top) and 4536 samples – 6yr child (bottom)

Summary and Conclusions

The methodology using multiparameter optimization during the early stage of the product development was shown and two applications have been described. It was shown that the methodology is suitable for the early stage of the PDP in combination with high parametric simulation models, either to simplify FE Models or to identify crucial parameter sets using DoE and MoP.

The simplified crash-box model was found suitable to be used for optimizations. The calculation time reduced significantly with a deviation of 5% compared to the original Model. Further investigations with respect to other important parameters such as accelerations and others have to be carried out. The found optimum has to be reviewed regarding its robustness. The model itself is verified for this specific load case, other load cases have to be verified.

The pedestrian safety results from DoE and the approximated meta-model show that the angle of impact remains an important factor to the injuries sustained especially for children. The perpendicular hit had higher IC indicating it to be a worst case scenario. The variation in leg angles show struck leg backward to be having higher threat to the pedestrian than the struck leg forward. With the input on pedestrian gait and angle, pedestrian simulations for the simplified vehicle front model can be built up to optimize for pedestrian safety.

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