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Methodology for multiparameter optimization during the concept phase for crash relevant vehicle structures

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Abstract

This paper discusses optimization applications used for novel product development methodology. It involves crash behaviour evaluations during the early stage of the product development process to save time in later phases.

Two applications of OptiSlang to the process are described in this work. One application involves optimization using a combination of LS-DYNA solver with post processing using MATLAB. In a low energy model, this process was used to fine tune a simplified crash box model to match performance characteristics with an evaluated reference full vehicle model.

The Second application is a study to understand the role of position of pedestrian impact on pedestrian safety during a crash with vehicle front measured as potential Injury Cost. MADYMO solver is used for calculation and MATLAB for the post processing. The application involves a Design of Experiments (DOE) process followed by a generation of approximated models (MOP) to understand the significance of the parameters.

Keywords: simplified vehicle models, insurance classification, pedestrian safety, front end optimization, implicit parameterization, SFE CONCEPT, MADYMO, LS-DYNA, DoE, Meta models, OptiSlang

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1 Introduction

A reduction in time spent for early phase of product development process (PDP) can cut the development costs significantly. In conventional process, vehicle safety related simulations like crashworthiness tests, insurance tests and pedestrian safety related tests are carried out separately and 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 a simplified model at concept stage, to answer basic questions about the crash behaviour of different concepts 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 Models manifold concept studies can be carried out and evaluated based on objective criteria's such as crash-behaviour, weight, classification tests, etc. Furthermore selected designs can be optimized to achieve specific goals.

2 Objective

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.

3 Methodology

3.1 General approach

The shown product development Process on the left hand side Figure 1 is based on the planning and design process by Pahl/Beitz [1]. 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 [1] methodology and the proposed methodology is that during the conceptual design phase Elements, such as FE calculations and optimizations usually carried out during the Embodiment design- and detailed design phase are used. 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 [2].
By simplifying (Abstraction and Idealization) detailed vehicle models (FORD Taurus and TOYOTA Yaris [3]) crash relevant structures are extracted. Within

the verification process the limitations of the models are defined and finally the models are 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. Possibly, the simplification process must not be repeated.

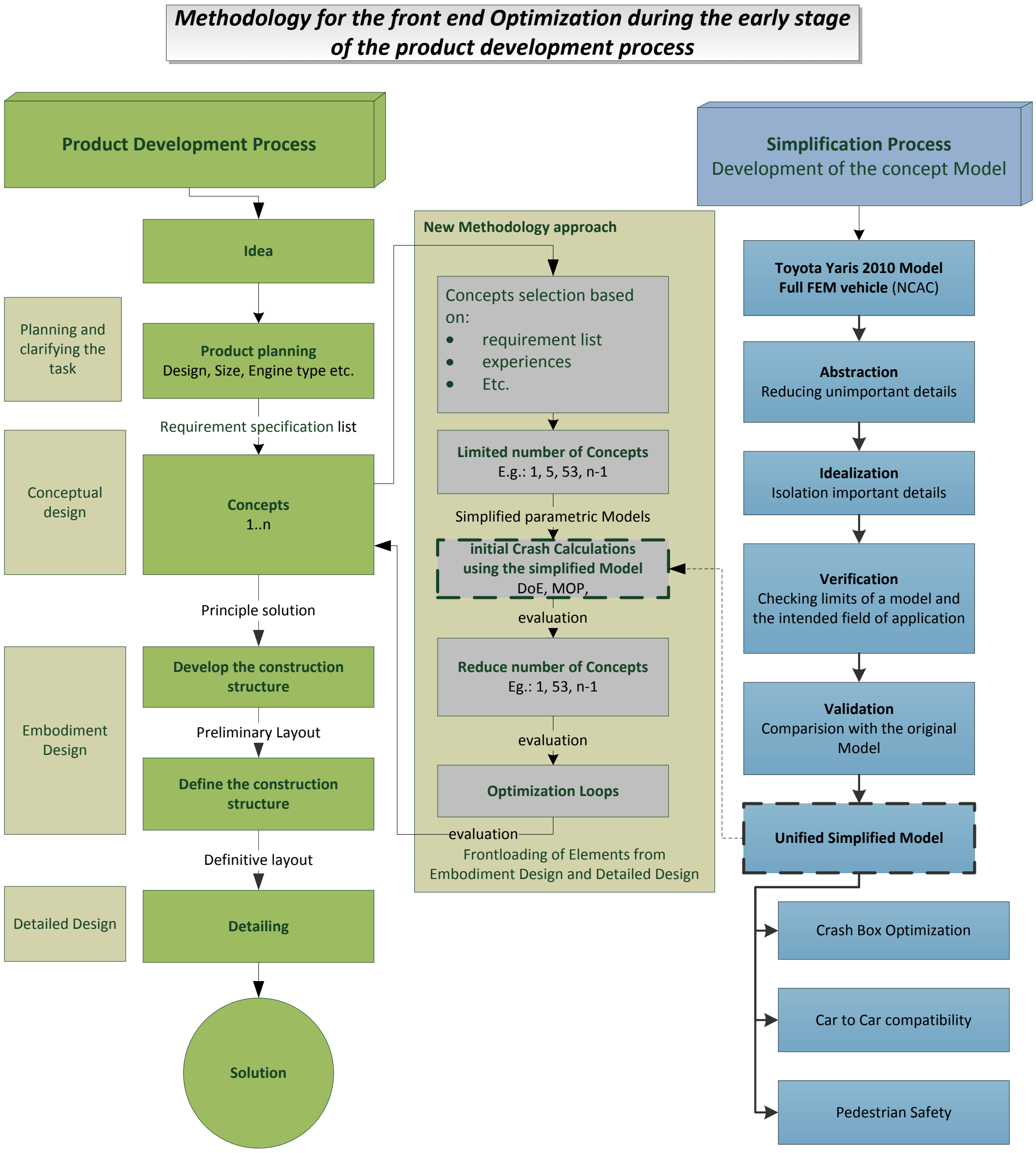

Figure 1: Methodology for the front end Optimization during the early stage of the product development process

3.2 Batch process

Figure 2 shows the general batch process of the optimization loop used for the studies.

At 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.

With boundary conditions, material properties and other inputs assembled with SFE CONCEPT exported mesh for LS-Dyna input deck, was added an include file to it. Calculations were performed using LS-Dyna solver, MADYMO solver or a combination of LS-Dyna and MADYMO solver.

With critical output parameters of the calculations identified, the output files were processed using MATALB or combination of LS-Prepost with MATLAB.

The whole process was controlled using OptiSlang. It is capable of performing design of experiments, sensitivity analysis, robustness analysis and single and multi-parameter optimizations.

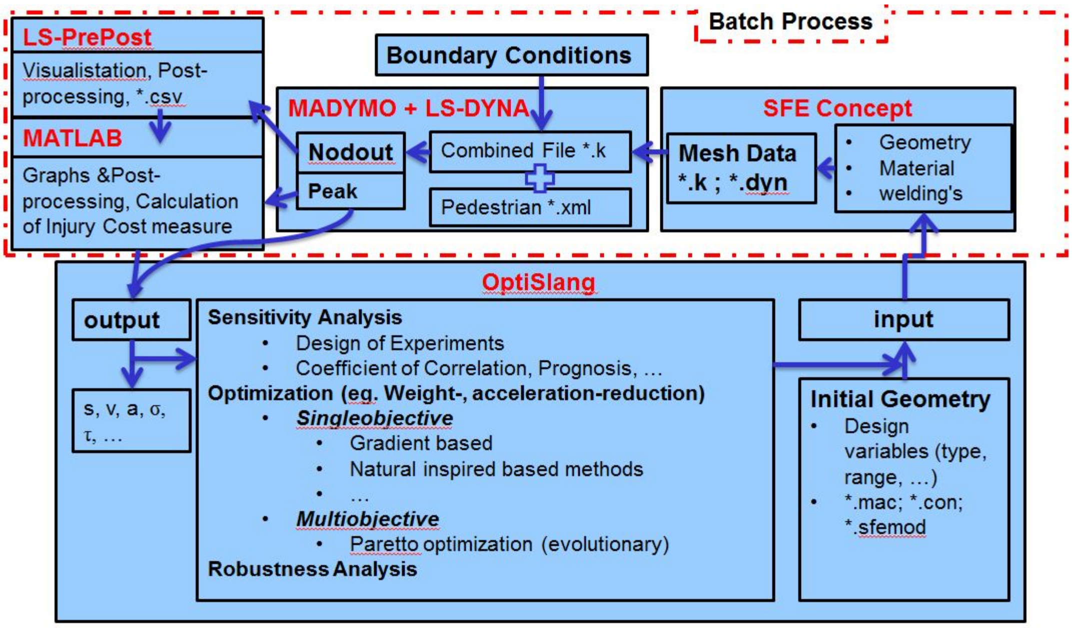

Figure 2 possible batch process

3.3 Example 1- Crashbox

3.3.1 Low Energy Vehicle Car crashes

The aim is to optimize front end structures in particular the crash-box to absorb the energy of low speed crashes with a velocity of 15 km/h. The aim of the crash-box is to absorb major parts of the excess energy thereby that other parts ideally experience force within elastic limits. The deformation and energy absorption of the crash-box is very useful especially in terms of repair costs reduction and therefore minimizing the insurance contribution [4].
Reduced models which replicate the critical output parameters effectively are therefore crucial to establish a development process within a desired time range.

3.3.2 Simplified Model and Validation

As reference car the TOYOTA Yaris [3] has been used. 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 reference value, see Figure 3. The Research Council for Automobile Repairs (RCAR) structure test barrier was used as obstacle and the vehicle has a speed of 15 km/h [4][5].

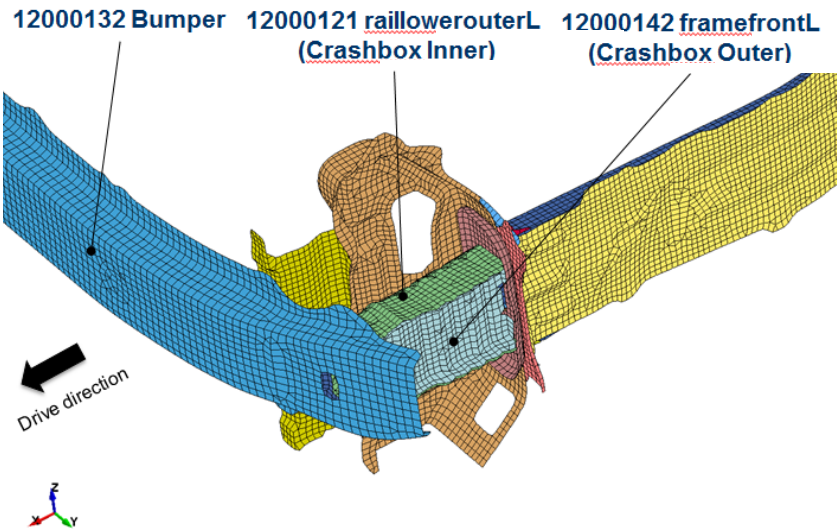

Figure 3 Relevant TOYOTA Yaris front end parts

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 their crash performance in terms of absorbed energy.
Figure 4 shows the different simplified models with the calculation time on one workstation. With a decreasing number of nodes and parts the calculation time was reduced significant. For comparison of the results, the internal energy of the inner crash-box has been plotted. The plot shows the result of the internal energy of the part in the full vehicle calculation and for comparison the reduced vehicle calculation. 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 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.

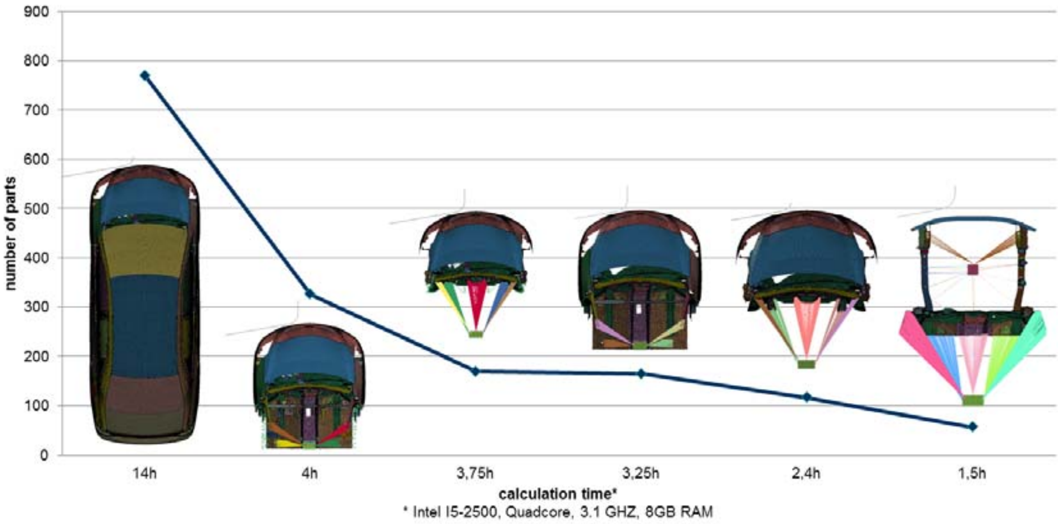

Figure 4: Simplified model simulation time

The simplified model had an overall calculation time of 1.5 h and has been used for an initial optimization. The deviations from original model indicated the need for optimization process to fine tune parameters of the simplified model to achieve similar prediction capability as the original model.
Therefore an optimization has been started to modify the three different weights and the appending inertias, 27 variables in total.

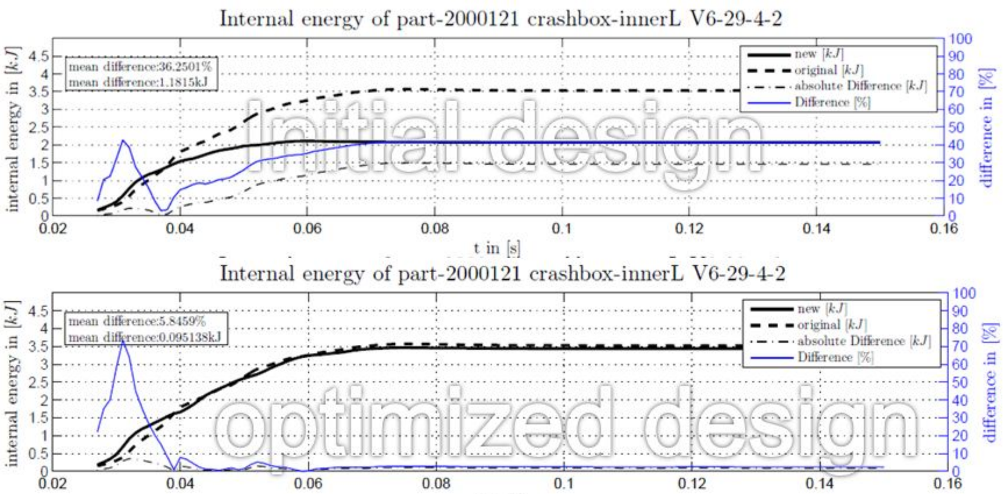

Figure 5 Comparison of Initial and optimized design of the simplified model (extract)

After 183 calculations a significant improvement was achieved. The average deviation of the internal energy of the three parts has been reduced 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.

3.4 Example 2 Pedestrian Safety Model

3.4.1 Introduction to Pedestrian Safety and vehicle front-end design

Pedestrians are the most vulnerable road users therefor the safety on road needs to be in focus [6], [7]. Most crash database analysis show that the most frequent pedestrian-to-vehicle crash scenario is a vehicle-front striking the pedestrian laterally. For a typical sedan shape, the pedestrian crash kinematics was observed as leg to bumper, pelvis to bonnet leading edge, torso to bonnet and or head to windscreen type of crash for adults. For children it is leg to bumper, torso or head to bonnet leading edge [8]. 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 6 year old child to 95^{th} percentile Male is almost two times in weight and more than twice in height and anthropometric features. With such a manifold requirement for pedestrian safety, a pedestrian friendly design at concept stage is necessary.

3.4.2 Objective of this Study

A pedestrian crash scenario was shortlisted from crash data base studies, pointed that lateral collision are recorded statistically more often. The objective was to discover the position with highest risk to pedestrian. 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 Figure 6 (A) and (B).

3.4.3 Input Set up (MADYMO) for study

Four pedestrian models of size 95^{th} %le Male, 50^{th} %le Male, 5^{th} %le Female and 6 year old Child models from TNO is considered representative of the pedestrian population. The inputs to this study are in the form of three joints namely “Human_jt” (referred as angle_6c for child model in statistical figures) in MADYMO, representing the angle of the human with respect to car. The limits rotation of human is limited to 45° on left and right indicated in Figure 6 using notation ‘ψ’. A 50^{th} percentile Male human model is shown which represents similar position used for all other models.

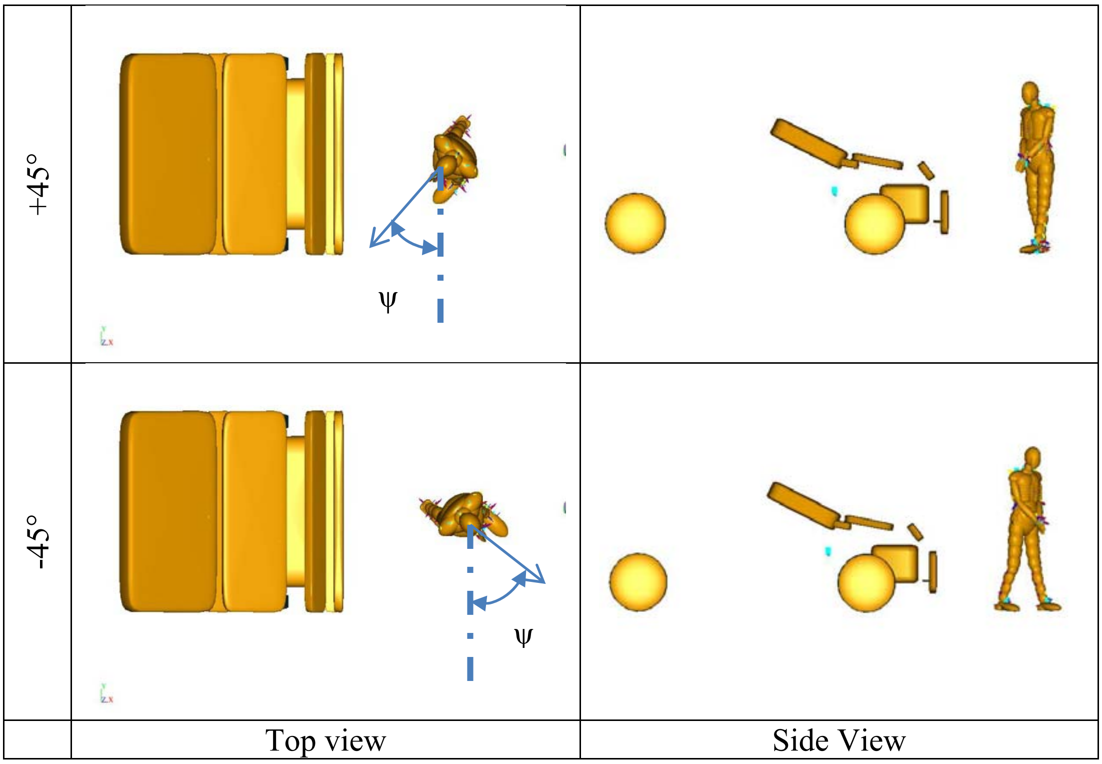

Figure 6 Pedestrian simulation input set up (Angle with car -ψ)

"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 model as shown inFigure 6 using notation 'α_L' and 'α_R' . The total number of variables is 12 (3 per pedestrian model, 4 models).

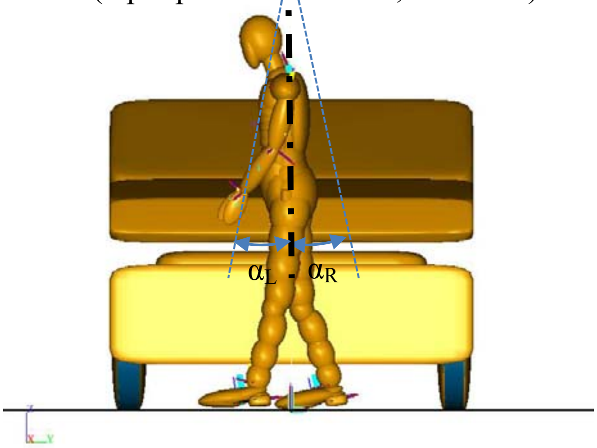

Figure 7 MADYMO set-up showing angle between legs (gait)

Pedestrian to vehicle interaction characteristics were modelled based on force-deflection characteristics obtained from crash reconstruction studies and body form with vehicle test data applied in [9]. An optimization loop was set up similar to the one explained in Figure 2 with OptiSlang, MADYMO and MATLAB.

To understand the injury risk to a pedestrian by a vehicle profile, Injury to whole body was considered. Rating and regulatory tests use linear acceleration based criteria for head, acceleration and displacement based criteria for chest, penetration based criteria (peak force) for abdomen, peak force for pelvis, combination of bending and compression force factors to long bones of lower extremity and displacement based criteria for knees.
For studies related to optimization for pedestrian safety, it was found that a single objective function was more effective to address the relationship between injuries. An injury cost based measure was a representative number involving hospitalization and medical expense with provision of high penalty for potential impairment or death [9]. Injury cost calculation is shown in Figure 8.

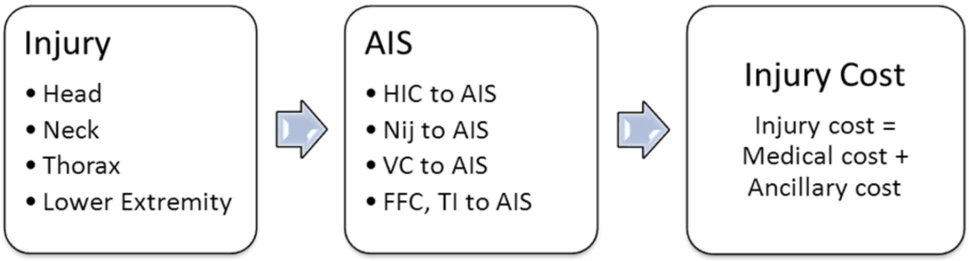

Figure 8 Calculation of injury cost (abbreviations at end of paper)

The threat to pedestrian was calculated based on Injury Cost (IC) measure using MATLAB based on output from MADYMO simulations.

3.4.4 DoE results analysis

The preliminary DoE was run for a total of 1000 loops consisting of total 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 and total IC as sum of all the four. Effectively 5 outputs and 12 inputs form the tables of statistics explained henceforth.

Figure 9 shows the ranking of the three variables relating to the IC of child model. The same trend was also found on the other pedestrian models for respective IC measure. The figure shows angle of inclination of the child model to have higher influence on the outputs, followed by the angle of struck leg and then the non-struck leg.

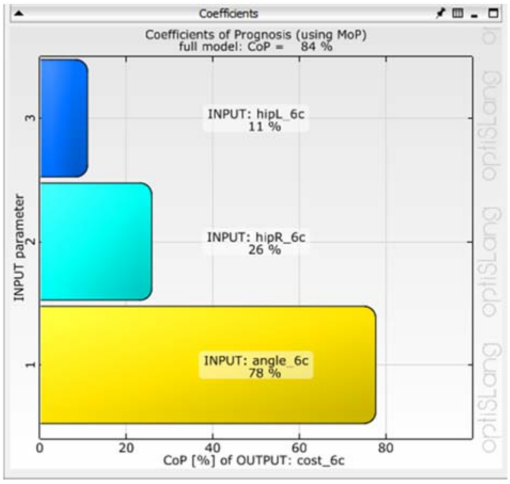

Figure 9 Co-efficient of Prognosis child model

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.

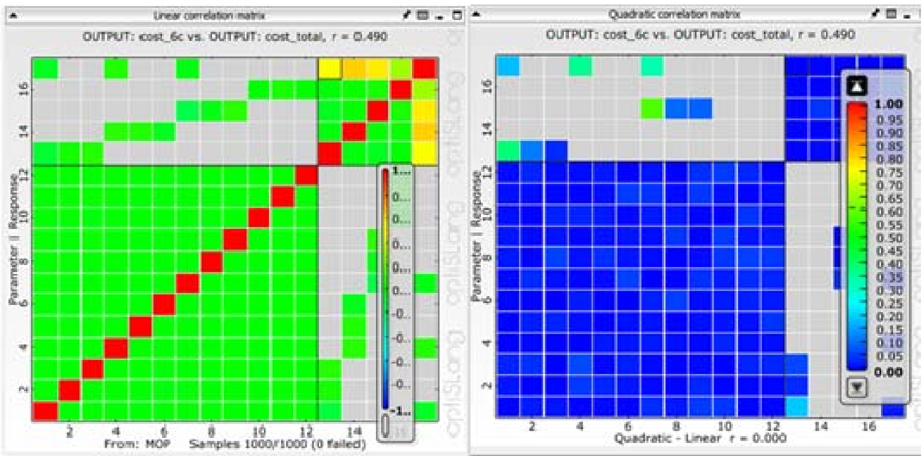

Figure 10 Linear and Quadratic correlation Matrix

Figure 11 shows the variation meta-models generated based on the simulations in 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 models generated also had the same three variables involved in the same order of influence.

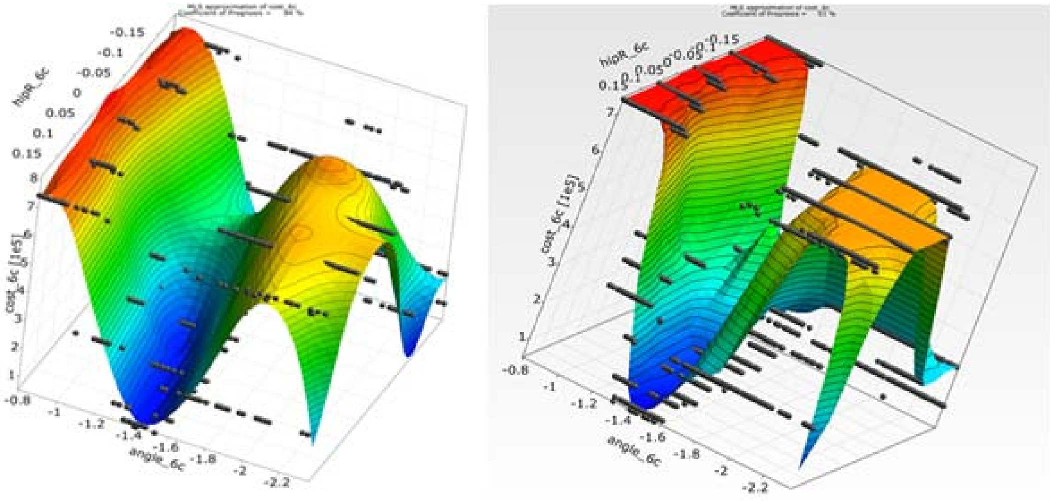

Figure 11 Metamodel with 1000 Samples and 4536 samples (6yr child)

4 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 their 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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Abbreviations

AIS – Abbreviated Injury Score
HIC – Head injury Criterion
Nij – Neck Injury criterion
VC – Viscous Criterion
FFC – Femur Force Criterion
TI – Tibia Index