The World Congress of Structural and Multidisciplinary Optimization, May 20-24, 2019, Beijing, China

Submodel-based Multi-Level optimization of crash structures using statistically generated universal correlations of the different levels

Axel Schumacher*, Harman Singh, Sven Wielens

** Corresponding author: schumacher@uni-wuppertal.de*
Chair for Optimization of Mechanical Structures, University of Wuppertal, Wuppertal, Germany

Abstract
This contribution shows the necessary activities for a submodel based multi-level optimization of crash structures. For a computer-time saving optimization scheme, it is necessary to find universal correlations between optimization functions of the different levels. Based on a wide range of vehicle architectures, these universal correlations are calculated and ready to use in the optimization loop. We obtain a compromise between all involved vehicles. This universal correlation can be used in the development of a new car, without having to evaluate new experiments. Exemplary for vehicle front car scenarios, first optimization results are shown.

Keywords: Multi-level optimization, submodel, correlation, crash simulation, automotive development

1. Introduction

When developing large and complex structures, optimization calculations should be carried out on different levels with associated simulation models of the overall structure and the substructure. For example, the creation of the best possible global layout of the structure can be done in level 1, the design of main components in level 2 and the detailed construction of the individual components in level 3. In each of the three levels, different simulation models are used and individual objectives and constraints have to be considered. Also the nature of the design variables can be different. In an automatic optimization process, the different levels of detail must be interlinked. Such multi-level optimization processes make it possible to optimize large systems with appropriate computational resources.
In this paper, we focus on the optimization of vehicle structures for frontal crash events and we look at two levels:

Level 1: the whole vehicle architecture with evaluation points for the acceleration of the occupants in case of a crash
Level 2: the detailed design of the structure in the crash zone (side rails, crash boxes, etc.)

In level 1 global design variables are considered. In level 2 regional design variables for sizing, shape and topology optimization are considered. Figure 1 shows a whole vehicle architecture for level 1 together with a possible submodel for level 2.

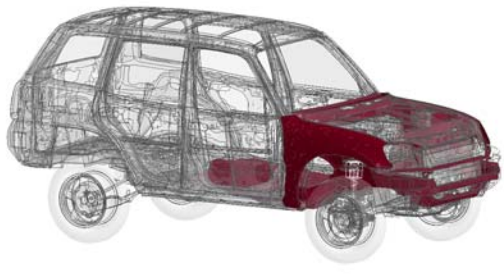

Figure 1. Vehicle architecture of a Toyota RAV4 (level 1) together with a possible submodel (level 2, in dark red)

2. Submodel-based Multi-Level optimization

2.1 Automatic generation of submodels

In preliminary works [1,2], we have developed a hierarchical multi-level-optimization scheme for crashworthy structures using automatic generated submodels including all loads and boundary conditions. The submodels are generated using the so called “connecting island” algorithm. The algorithm helps to effectively and intelligently reduce the size of the finite element main model into a submodel. A detailed description is written in [1]. Based on the finite element calculation results of the main model, a defined evaluation function together with a predefined threshold limit provide the information to collect the important regions or parts of the model. One simple evaluation function is the internal energy of car body parts during the crash event. This function only considers the highest energy absorbing regions or parts. In order to connect the collected parts, the above named connecting island algorithm finalizes the submodel by connecting the considered parts. The whole process runs automatically with all common model description possibilities of LS-DYNA®, the keywords. If the main model is generated by additional keywords, the main model has to be cleaned by hand, before starting the automatic process. Figure 2 shows two automatically generated submodels of the same vehicle. The user defined threshold limits TR are varied, while the same connecting island limits CI are used.

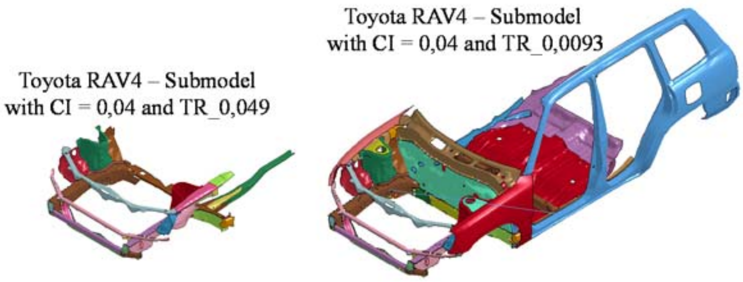

Figure 2. Automatic generation of submodels for the optimization of the front module in a front crash scenario

2.2 Multi-Level optimization scheme

In Figure 3, the Multi-Level-Optimization process for two hierarchical levels with use of submodel technique is shown [2]. The level 1 refers to the optimization of the main model and level 2 refers to the submodel optimization. The process starts with the start design in level 1 which is the main model. An initial finite element simulation of the main model is required to evaluate and generate a submodel. This submodel is used as the start design in level 2. To simulate a submodel it is necessary to define the interface boundary conditions. These boundary conditions are located at interface nodes where the submodel is cut from the main model and are in form of displacements. Nodal forces or user defined boundary conditions would also be conceivable.

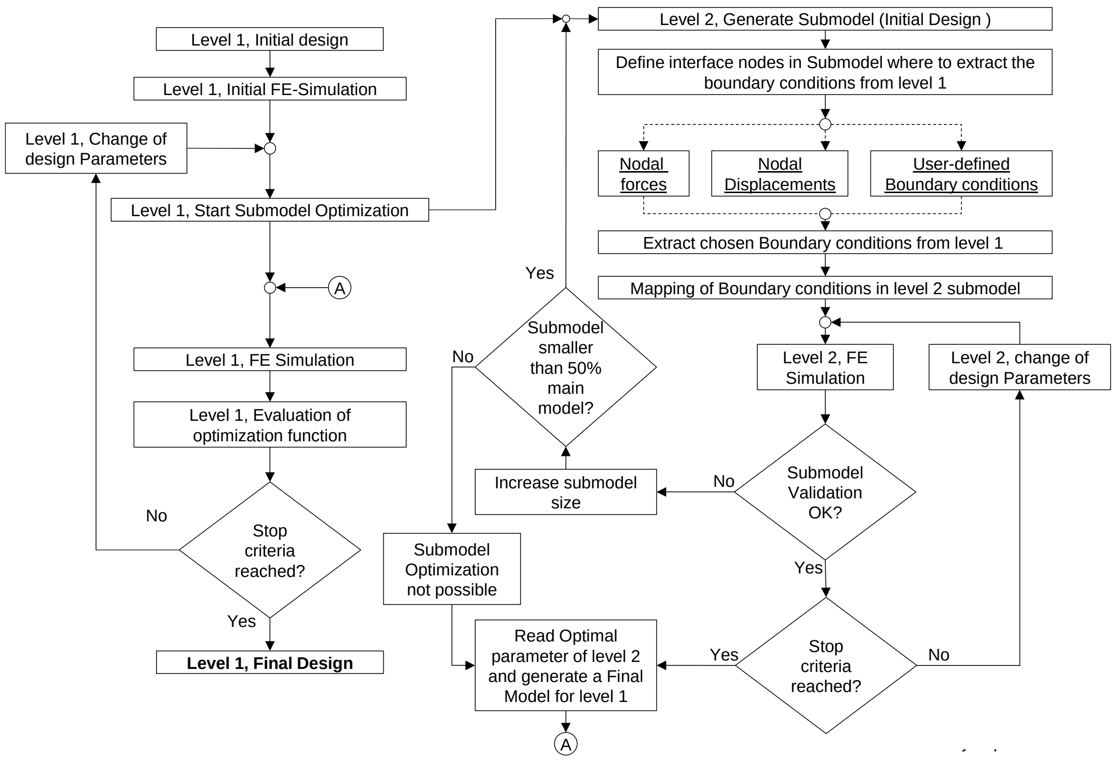

Figure 3. Nested Multi-Level optimization loop with submodel technique [2]

The standard approach uses the interface boundary conditions in form of time dependent nodal displacements which are extracted from the finite element simulation of the main model and mapped on the interface nodes of the submodel. Using these boundary conditions the submodel is simulated in level 2. Afterwards the submodel is validated in an automatic process, in order to determine the exactness of the submodel. If the submodel is not validated, its size will be increased. In a next step the optimization with LS-OPT® will be started. After a successful optimization in level 2, the optimal design of level 2 is transferred to level 1. The loops are repeated until the optimization in level 1 reaches the stop criteria and the final design is delivered.
The pictured scheme needs a preparative process for correlating the objective functions and the constraint functions of the two hierarchical levels, which is carried out with the specific models of the respective vehicle. This requires a great effort before the actual start of the optimization. In this paper we want to show how the statistical correlation on many different vehicles can be done far in advance of the actual optimization. By analyzing various vehicle models we create statistically proven universal correlations that are valid for investigated load cases for a wide range of vehicle types.

3. Development of substitute functions for the optimization in the submodel level

3.1 Possible structural responses in the submodel level

Based on typical structural responses for the whole car, we have to find responses, which can be analyzed inside the much smaller submodel. Therefore, we have to correlate the possible responses in the submodel with those of the whole car. Exemplary, in this paper we look to front crash scenarios. In order to evaluate the frontal crash accelerations with respect to the occupant safety, the so-called Occupant Load Criterion (OLC) [3] is used. The OLC checks accelerations at different positions of the whole car body. Table 1 summarizes the considered design criteria in level 1for front crashes.

Table 1. Front crash criteria in level 1

Criterion in level 1	Abbreviation
Mass of the car	MASS_L1
Average acceleration from L1_F2 to L1_F7 (OLC)	L1_F1
Acceleration at the vehicle center	L1_F2
Acceleration at the tunnel	L1_F3
Acceleration at the left B-pillar	L1_F4
Acceleration at the right B-pillar	L1_F5
Acceleration at the left rocker	L1_F6
Acceleration at the right rocker	L1_F7
Deformation of the left side rail	L1_F8
Deformation of the right side rail	L1_F9
Deformation of the passengers door	L1_F10
Deformation of the driver´s door	L1_F11
Force in the right wall or NCAP barriers	L1_F12

Most of the criterions in table 1 are not detectable inside the submodel geometry. We have to find alternative structural responses and criteria to analyze inside the submodel geometry. Table 2 shows the exemplary criteria for level 2. The mentioned sections i are located in the side rails, 3 sections in the left side rail and 3 sections in right side rail (see figure 4).

Table 2. The most relevant structural responses in level 2

Criterion in level 2	Abbreviation
Left side rail av. nodal displ. y-direct.	L2_D3P_NDy_L_AVG
Left side rail max. nodal displ. y-dir.	L2_D3P_NDy_L_MAX
Left side rail av. nodal displ. z-direct.	L2_D3P_NDz_L_AVG
Left side rail max. nodal displ. z-dir.	L2_D3P_NDz_L_MAX
Right average nodal displ. y-direct.	L2_D3P_NDy_R_AVG
Right side rail max. nodal displ. y-dir.	L2_D3P_NDy_R_MAX
Right side rail av. nodal displ. z-direct.	L2_D3P_NDz_R_AVG
Right side rail max. nodal displ. z-dir.	L2_D3P_NDz_R_MAX

Criterion in level 2	Abbreviation
x-Force in section i	L2_SF(i)_1
y-Force in section i	L2_SF(i)_2
z-Force in section i	L2_SF(i)_3
Result force in section i	L2_SF(i)_4
x-Moment in section i	L2_SF(i)_5
y-Moment in section i	L2_SF(i)_6
z-Moment in section i	L2_SF(i)_7
Result moment in section i	L2_SF(i)_8

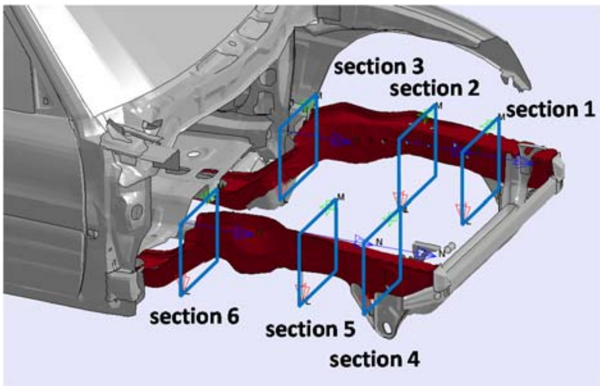

Figure 4. Sections for detecting the section forces in the submodel level (level 2)

3.2 Universal correlations of vehicle crash criteria and typical structural responses in the submodel level

For the criteria L1_F(i) level 1 we have to find a good substitute function L2_F(i), which is detectable in level 2. Therefore, L2_F(i) is calculated by the sum of all possible responses in level 2 $resp_k$ corrected by the correlation values c_k and $corr_k$:

$$L2\_F(i) = \sum_{k=1}^{n} c_k * corr_k * L2\_resp_k \qquad (1)$$

The correlation between the structural response from level 1 and level 2 is described by $corr_k$, whereas c_k is used as a weighting factor. This factor is adjusted by optimization in such a way that the best possible overall correlation between the replacement function L02_F(i) and the criterion L02_F(i) is found. In order to consider the different units and dimensions, we have to normalize the structural responses in eq. (1). The coefficients are also normalized, so that the influence of the individual coefficients is easier to compare:

$$L2\_F(i) = \sum_{k=1}^{n} \frac{c_k * corr_k}{\sum_{l=1}^{n} c_{kl} * corr_{kl}} * \left(1 + \frac{L2\_resp_k - L2\_resp,min_k}{L2\_resp,max_k - L2\_resp,min_k}\right) \qquad (2)$$

Normalization of the structural responses is done by feature scaling and is increased by one, so that no zeros can occur. The coefficients, on the other hand, are normalized by the sum of all correlations found. These correlation activities are necessary before the multi-level optimization is started. In order to get a universal equation, it is essential to involve as many different vehicle architectures as possible. Then these universal correlation can be used in the optimization of a special design task.

4. Universal substitute functions based on the results of many different cars

In this study, we analyzed crash models of state-of-the-art passenger cars of different car manufacturers. Also we consider the open to public crash models of the NHTSA [4], which are shown in figure 5.

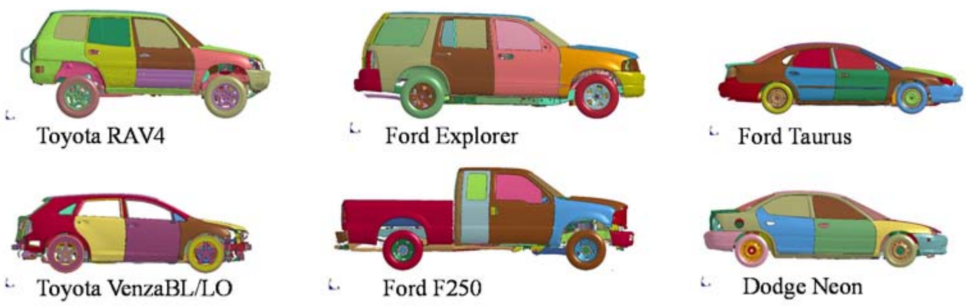

Figure 5. Some of the considered crash models [4]

These models are the basis for the automatic generation of the submodels like the models in figure 2. For every model a substitute function is generated. We have to find a compromise between all involved vehicles and get a correlation which we can use in the development process of a new car. To find this, each substitute function was tested in every vehicle. The correlation calculation between the criteria and the substitute function is done by a hybrid scheme of Pearson and

Spearman approach models [5]. In table 3 and table 4 are examples of the correlation between the level 1 responses and level 2 responses after optimizing the coefficients.

Table 3. Correlation between L1_F1 (acceleration) and L2_F1 after optimizing the coefficients

	Explorer	F250	Neon	RAV4	Taurus	VenzaBL	VenzaLO
Explorer	0,9847	0,9613	0,8622	-0,4021	0,9501	0,7202	0,7928
F250	0,8496	0,9616	0,5583	0,2704	0,4328	-0,4965	0,4457
Neon	0,8611	0,8282	0,8972	-0,2688	0,7816	0,9377	0,7801
RAV4	-0,3285	-0,2479	-0,2914	0,9461	-0,2329	-0,1816	-0,5943
Taurus	0,9094	0,7229	0,6690	-0,1567	0,9239	0,8261	0,5987
VenzaBL	0,8346	0,7816	0,6986	-0,3170	0,6769	0,7576	0,6917
VenzaLO	0,5934	0,4051	0,6354	-0,3063	0,8080	0,6235	0,8109

Table 4. Correlation between L1_F9 (deformation) and L2_F9 after optimizing the coefficients

	Explorer	F250	Neon	RAV4	Taurus	VenzaBL	VenzaLO
Explorer	0,9282	0,8959	0,8713	-0,2942	0,7477	0,7621	0,5131
F250	0,8680	0,8913	0,9071	-0,4117	0,7708	0,8014	0,7787
Neon	0,7395	0,6561	0,8330	-0,1078	0,8172	0,4361	0,8973
RAV4	-0,3961	-0,1974	-0,3849	0,8403	-0,5307	0,0474	-0,1272
Taurus	0,8323	0,7441	0,7312	-0,3714	0,8113	0,6374	0,6186
VenzaBL	0,3953	-0,1413	0,1771	-0,3792	-0,3913	0,8149	-0,1087
VenzaLO	-0,3036	0,4308	0,4318	-0,3141	0,4308	0,2757	0,9297

The correlations shown in table 3 and table 4 are highlighted according to their grade. Green areas have a higher correlation than the red or yellow ones. The RAV4, which shows hardly any useable correlations, is conspicuous. Probably a bug in the model is responsible for it. It is remarkable that both an acceleration in table 3 and a deformation in table 4 show good correlations for a variety of vehicles. A universal substitute function should have most areas highlighted green in one row, e .g. in table 4 the F250 is promising.

5. First optimization results

As a first attempt we optimized the sheet thickness of the side members. We used the same design variables in level 1 and 2. The used vehicle is the Dodge Neon, which crashes with an initial velocity of 56 km/h into a rigid wall. The optimization objective is the minimization of the OLC. Multiple responses like the deformation of the doors or side members are chosen as constraints. Also the mass is a constraint, which should not exceed its initial value. Table 5 provides an overview of the considered responses.

Table 5. Considered responses in the optimization of the Dodge Neon

	Structural response
Objective	Minimize OLC
Constraint 1	Mass lower or equal to initial value
Constraint 2	L1_F8 <= 425 mm
Constraint 3	L1_F9 <= 425 mm
Constraint 4	L1_F10 <= 100 mm
Constraint 5	L1_F11 <= 100 mm

The Adaptive Simulated Annealing optimization algorithm in LS-OPT® is used with a radial basis function network metamodel [6]. The optimization results are shown in table 6. For benchmarking, some single-level optimizations of the vehicle are done are started. First the full vehicle model with level 1 objective and constraint functions is optimized. Next the optimization is done again, but with level 2 functions. In the third run, an optimization is carried out with only the submodel. After those benchmarks a multi-level optimization is done.

Table 6. Optimization results

Optimization	OLC	Constraint violation	Computational time	Function calls
Full model with level 1 functions	4,042	L01_F9: 1,58 mm	170,85 h	153 in level 1
Full model with level 2 functions	5,007	L01_F11: 5,082 mm	144,05 h	129 in level 1
Submodel	5,177	L01_F11: 4,868 mm Mass: 0,53 kg	62,5 h	3 in level 1 275 in level 2
Multi-level	4,643	No violations	123,78 h	41 in level 1 360 in level 2

The results show that a submodel optimization alone is not sufficient. Also the level 2 objective and constraints alone are not enough for a viable optimization. We need both levels for adequate results. With the possibility of such a high number of simulations in level 2 and the verifications in level 1, computational time can be saved and useful results are possible.

6. Conclusions

The research in the field of submodel-based multi-level optimization in such highly non-linear application is still at the beginning. But, in order to apply mathematical optimization schemes in development process, activities to reduce the computer-time for one function call is necessary. Actual, the computer-time for one crash simulation of a vehicle is 12 hours with 64 CPU. In the next time, the following research activities are planned:

- The considered linear correlation are not sufficient for this application.
- Modularization of the kind of submodel generation in the optimization scheme: In addition to the connecting island algorithm, we have to integrate other approaches.

Acknowledgements

The authors thank C.J. Falconi and A.F. Walser for providing the connecting island algorithm and C.L. Benito and C. Schöne for providing the GENERATOR4®-tools for the automatic generation of the the finite element submodels.

References

[1] Falconi, C.J.; Walser, A.F.; Singh, H.; Schumacher, A. (2018): “Automatic generation, validation and correlation of the submodels for the use in the Optimization of crashworthy structures", in: Schumacher, A., Vietor, T., Fiebig, S., Bletzinger, K.-U., Maute, K. (Hrsg.): Advances in Structural and Multidisciplinary Optimization, Proceedings of the 12th World Congress of Structural and Multidisciplinary Optimization (WCSMO12), Springer Nature, 1558-1571, 2018

[2] Singh, H.; Schumacher, A.; Falconi, C.J., Walser, A. F., Trentmann, S., Leyre Benito, C., Foussette, C., Krause, P. (2017): „Hierarchical Multi-Level-Optimization of crashworthy structures using automatic generated submodels”, Proc. of the 11th European LS-DYNA Conference 2017, 9. - 11. Mai 2017, Salzburg, Austria, 2017

[3] Kübler, L.; Gargallo, S.; Elsäßer, K. (2008): Characterization and Evaluation of Frontal Crash Pulses with Respect to Occupant Safety, Proceeding of the Airbag 2008 – Intl. Symp. And Exhibition on Sophisticated Car Occupant Safety System

[4] NHTSA: Crash Simulation Vehicle Models, www.nhtsa.gov/crash-simulation-vehicle-models

[5] Härdle, W. K.; Klinke, S., Rönz, B. (2015): Introduction to Statistics, Springer, 2015

[6] LSTC (2015): “LS-OPT® User´s Manual. A design optimization and probabilistic analysis tool for engineering analyst”, California, 2015