CAE-based robustness evaluation in virtual prototyping – luxury or necessity

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Summary:

Today one of the greatest challenges is the rising number of numerical simulations of large test and analysis programs including CAE-based optimization and CAE-based robustness evaluation while reducing the number of hardware tests. Also, the increasing usage of structural optimization may require CAE-based robustness analysis of “optimized” designs. In many cases, the optimization of cost, performance and weight lead to highly sensitive designs which can lead to substantial robustness defects especially in nonlinear systems. It is no surprise that the increase of virtual prototyping in conjunction with the reduction of hardware tests and development times combined with a very high innovation speed of new materials or electronic components do have some risks. This can be seen in the statistics of product recall, which have increased significantly in the last few years. Therefore, the topic of CAE-based robustness evaluation assuring serviceability, safety and reliability should be considered in virtual prototyping as early as possible.

Looking to the obvious necessity of CAE-based robustness evaluation in virtual prototyping the fact that still only a rare number of publications about successful introduction suitable for daily use exist may surprise. Is the CAE-based robustness evaluation seen to be a luxury? Or if not, where are the bottlenecks at implementation.

In the paper we discuss the status of application at three industrial examples including barriers, bottle necks and challenges.

Keywords:

robust design, robustness evaluation, Coefficient of Prognosis

1 Introduction

Due to a highly competitive market, the development cycles of increasingly complex structures must be constantly reduced while the demand regarding performance, cost and safety is rising. The development of innovative, high-quality products within a short time frame which can succeed in international car producer competition is only possible by using CAE-based virtual prototyping. Herein one of the greatest challenges is the rising number of numerical simulations of large test and analysis programs including CAE-based optimization and CAE-based stochastic analysis while reducing the number of hardware tests.
Also, the increasing usage of structural optimization may require CAE-based robustness analysis of “optimized” designs. In many cases, the optimization of cost, performance and weight lead to highly sensitive designs which can lead to substantial robustness defects especially in nonlinear systems. It is no surprise that the increase of virtual prototyping in conjunction with the reduction of hardware tests and development times combined with a very high innovation speed of new materials or electronic components do have some risks. This can be seen in the statistics of product recall, which have increased significantly in the last few years. Therefore, the topic of robustness evaluation assuring serviceability, safety and reliability should be taken into account in virtual prototyping as early as possible.
Looking to the obvious necessity of CAE-based robustness evaluation in virtual prototyping the fact that still only a rare number of publications about successful introduction suitable for daily use exist may surprise. Is the CAE-based robustness evaluation seen to be a luxury? Or if not, where are the bottlenecks at implementation. In the paper we discuss the status of application at three industrial examples including barriers, bottle necks and challenges.

2 Robustness evaluation

Robustness characterizes the sensitivity of all relevant system responses in respect to the scatter of all relevant input variables, like environmental conditions, material or production tolerances. Of course, designing a robust structure was always a goal in engineering. Therefore, design rules were established which ensure a safe distance from failure. Safe in a sense, with a sufficient probability the scatter of design responses not oversteps critical limits. To cover all possible uncertainties the designs rules, need to be very conservative and the formulation of design rules needs sufficient experience and experimental validation.

But today we are driving often into situations where design goals like saving material or going to the boundaries of material performance conflict with conservative safety distances or where safety factors are not available. Here we need to verify the design robustness using real world test matrixes or combinations of real world and virtual test matrixes or rely purely on CAE-based robustness evaluations.
Having large time and cost pressure from the market in our point of view consequently, probabilistic methods using CAE-based stochastic analysis become mandatory in virtual prototyping to quantify robustness, safety and serviceability.

Dependent on the robustness evaluation criteria, variance-based robustness evaluation (robustness evaluation) or probability-based robustness evaluation (usually called reliability analysis) have to be utilized [1]. In variance-based robustness evaluation procedures, a medium sized number (100 to 150) of samples of possible realizations of input variables are generated by Latin Hypercube Sampling (LHS). After calculating the sample set, the variation of important system responses and their correlation to input scatter is investigated. By running a sample set of around 100 Latin Hypercube samples, reliable estimation of event probabilities up to 1 out of 1000 (2 to 3 Sigma range) is possible.

For rare event probability estimations like 1 out of 1.000.000 (4 to 6 Sigma range), probability-based robustness evaluations using gradient (FORM) or sampling based (ISPUD, adaptive sampling, asymptotic sampling) stochastic analysis methodology [2] becomes necessary. Because effective algorithms of reliability analysis try to learn where the rare event failure points are in the space of uncertainties and may fail to learn, we recommend using multiple algorithms to proof the forecast of rare event probabilities. Therefore probability-based robustness evaluations usually require significant more design evaluations than robustness evaluations especially in case of many scattering variables. For computational expensive simulation in the past the required large number of simulations was a significant barrier to start. But with rising CPU power and the availability of intelligent load sharing systems that barrier melts away and will not be the main bottle neck in the future.

From our experience, the key to a successful integration of robustness evaluation in the virtual product development cycles is the balance between appropriate introduction of input uncertainties, appropriate stochastic analysis methodology and appropriate post processing. If we miss the balance of one of the three, the main results of the stochastic analysis, the variation or correlation estimation may become misleading, wrong or useless. For example, if we miss the most important input scatter, the variation prognosis is useless. If we use the wrong sampling (like 100 Monte Carlo Sample), the reliability of correlation measurements is very low or if we test linear correlation only, we may miss the most important correlation between input and output scatter.

Consequently, the best possible translation of all knowledge about input uncertainties and the contribution of all potentially influencing uncertainties are very important. Therefore, in real world applications we need to contribute large numbers of uncertain variables. A result of a robustness evaluation of full car applications may contain several hundred scattering inputs. Because the reduction to smaller sets of variables is only possible from reliable knowledge of the variable unimportance the use of objective measurements of variable importance like Coefficient of Prognosis (CoP) [3] is mandatory.

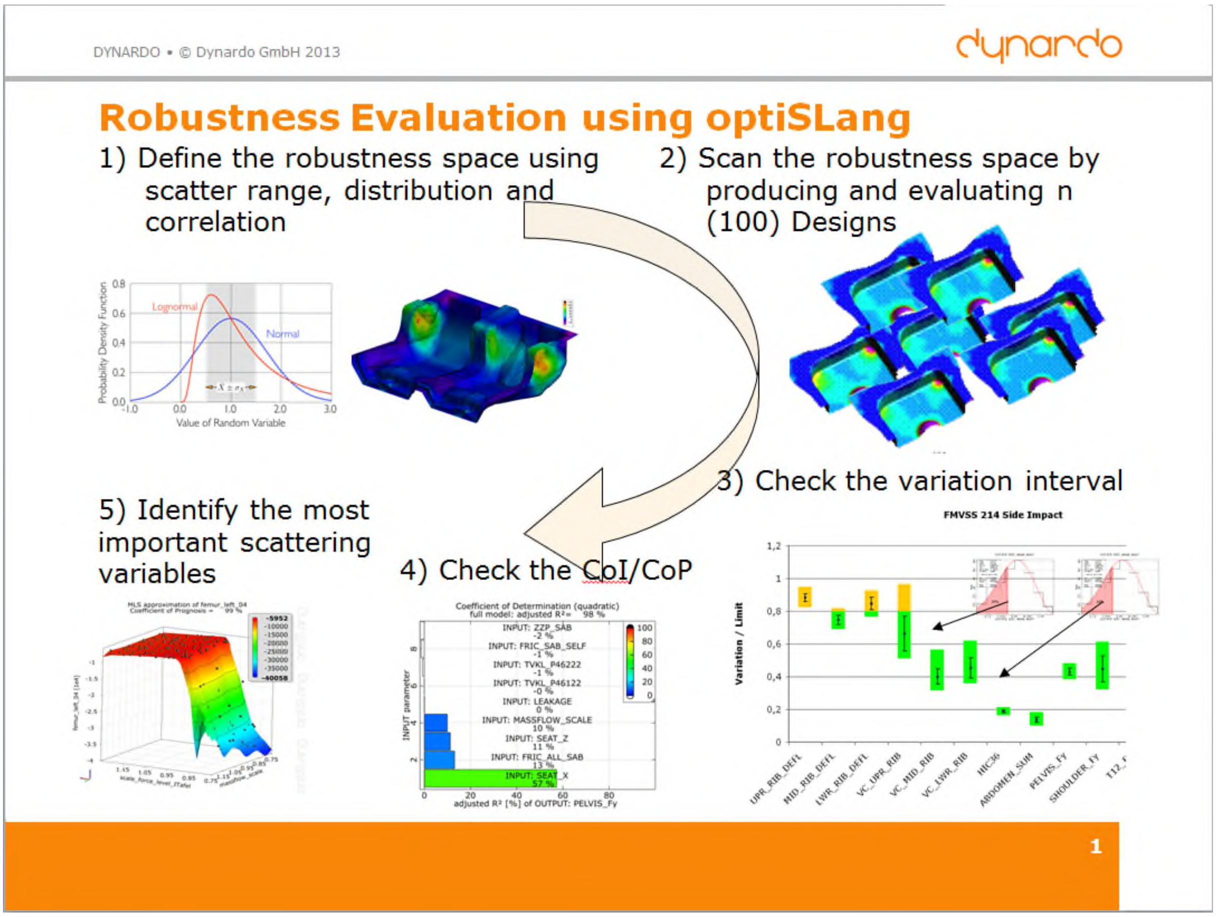

Figure 1 Diagram of CAE-based robustness evaluation workflow

3 CAE-based robustness evaluation in passive safety [4]

Robustness evaluations are performed by the car producer as soon as possible after assembly of the numerical car model and calibration of the most important passive safety test load cases to previous car lines. Important scattering input parameter which needs to be considered are the definition of uncertainties regarding test conditions (dummy positioning), environmental condition (friction), uncertainties of airbag system (time to fire), uncertainties of car interior and other components of the restraint system and load transmitting due to the car front represented by a “puls” loading.

Implementation challenge: One of the main challenges during implementation at daily use is the parametric definition of the variation of dummy seat position. Using multi body dynamic modeling approach it was necessary to implement a dummy positioner, which after moving the seat position of the dummy corrected the position of legs and feet’s as well as arms and hands to represent a valid dummy position. Using finite element modeling approach, it was necessary to run a “sit-in” simulation for every different seat position. Here finally a matrix of different seat positions which covers the test set uncertainties was used for the robustness evaluation.

Implementation success keys: Most important success keys were the process automation including preparation of all necessary parametric and the standardization of the post processing using normalized criteria status. Due to process automation and introduction of model parametric no further modifications to the model or the process chain were necessary when a robustness evaluation was performed.

Customer benefits: The main benefit is the identification of critical load cases where in the current design of the restraint system important criteria overstep limits as early as possible. For these responses the responsible input variations are identified. Part of the post processing is the ranking of numerical robustness of the model using the Coefficient of Prognosis (CoP). These identification of modeling errors as well as response values having large amount of numerical noise were used to rank the model. Finally, there was a ranking for design robustness – Does important response stay within the limits as well as a ranking for the numerical robustness of the simulation model. With that knowledge necessary investments in design modifications or modeling efforts to improve the quality of the numerical models can be allocated. Numerical robustness evaluations help to reduce the number of hardware tests. For load cases having sufficient safety margins virtual robustness evaluation are good enough to prove passive safety and no hardware tests are performed.

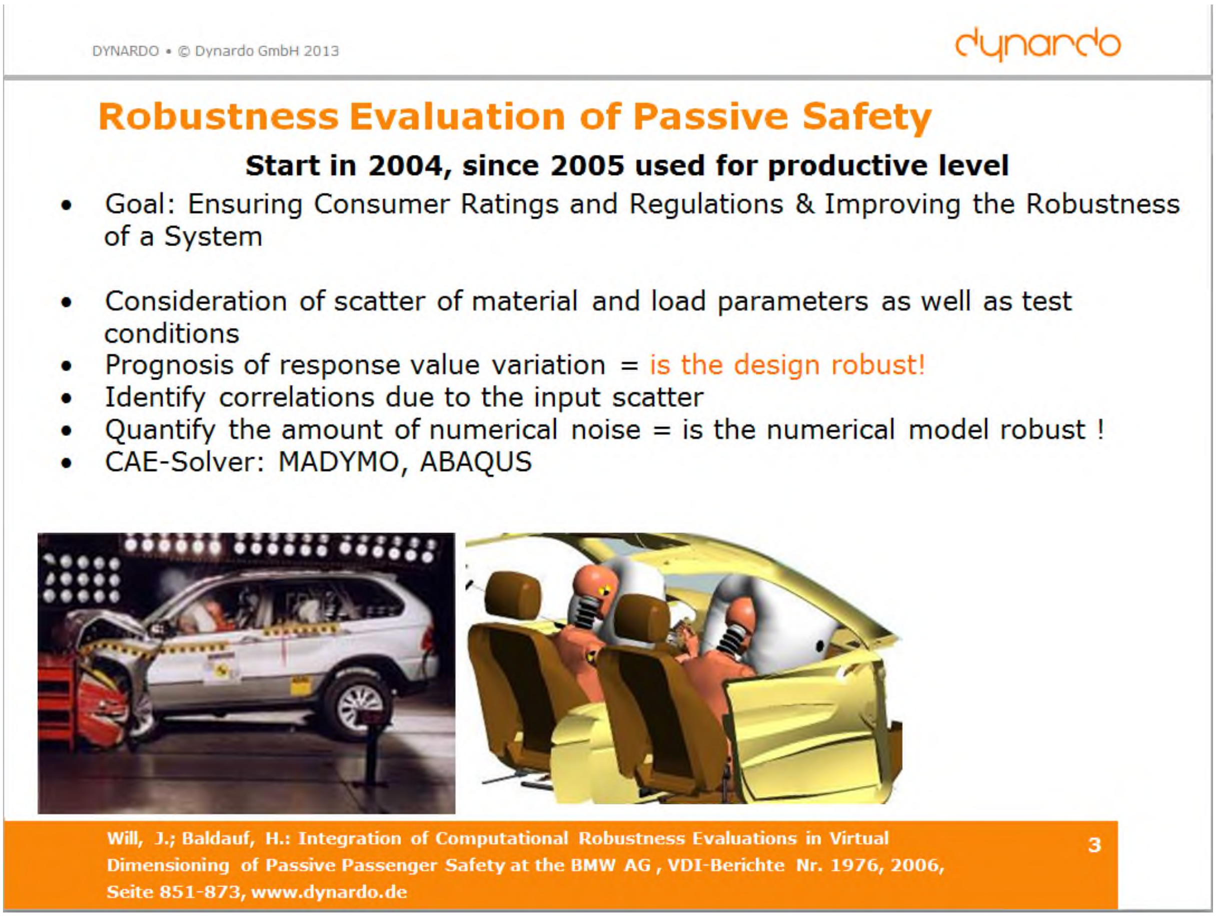

Figure 2 Robustness evaluations for passive safety

Bottlenecks: Unless there are several milestones in the development process defined for which robustness evaluation should be performed the parametric model setup, the numerical model robustness and the status of limit violation sometimes moves the robustness evaluation at later stages. If the CAE engineer does not see a chance to demonstrate robustness or if he still wants to improve the model or the design before starting the robustness he may miss the time gates, and the robustness evaluation is skipped or moved to the next milestone.

Future challenges: The main input to the robustness evaluation is the definition of uncertainties, therefore the verification of the assumptions about uncertainties is an ongoing process. A very important part to improve is the calibration with all available test results. Of course, the main findings of the CAE-based robustness evaluation need to correlate to the test results and the tests should be in the forecasted window of variation. Like every step in the virtual prototyping optimizing of costs and number of virtual robustness evaluations will be an issue. Here optimal process automation and parametric modeling are the keys. To further shorten design cycles performing the robustness evaluations as early as possible also in component level will be the next challenge.

4 CAE-based robustness evaluation of brake squeal [5,6]

Robustness evaluations are one of the most important quality criteria for the brake system. Braking noise results from instability in the dynamic behavior if energy is moved from one mode to another. Thereby the brake system has to function is a large variation range defined by large variation in the environmental conditions, production tolerances as well as due to fading effects on the brake pads. At the same time the dynamic performance of the brake components interacts with many other parts in the car assembly and a completely “noise free” brake wasn’t achieved so far. With a test matrix of different pressure and friction conditions the brake performance is testing with hardware and in the virtual world today. Because quality requirements rise the challenge is to design brake system with less and less noise, which seems to be prohibitively expensive and time wise impossible to achieve with hardware tests only. Therefore, OEM’s and brake producers worldwide are pushing CAE-based robustness evaluation into virtual prototyping as a part of CAE-based robust design optimization strategies. The analysis method CEA (Complex Eigenvalue Analysis) is “linearizing” the system with the definition of contacts between the rotation parts of the brake system. These “linearization” needs to be verified with test, which means the critical Eigenfrequencies which show negative damping ratios larger than 2% needs to be verified to be critical in the real-world using hardware tests. Only when the numerical model is validated against hardware test results does the model is qualified enough to be used to forecast robustness against brake squeal and forecast minimization of the probability of brake noise because of geometric modification.
Important scattering input parameters which need to be considered are uncertainties regarding production tolerances, material tolerances, fading and temperature effects for different load scenarios of pressure and friction conditions.

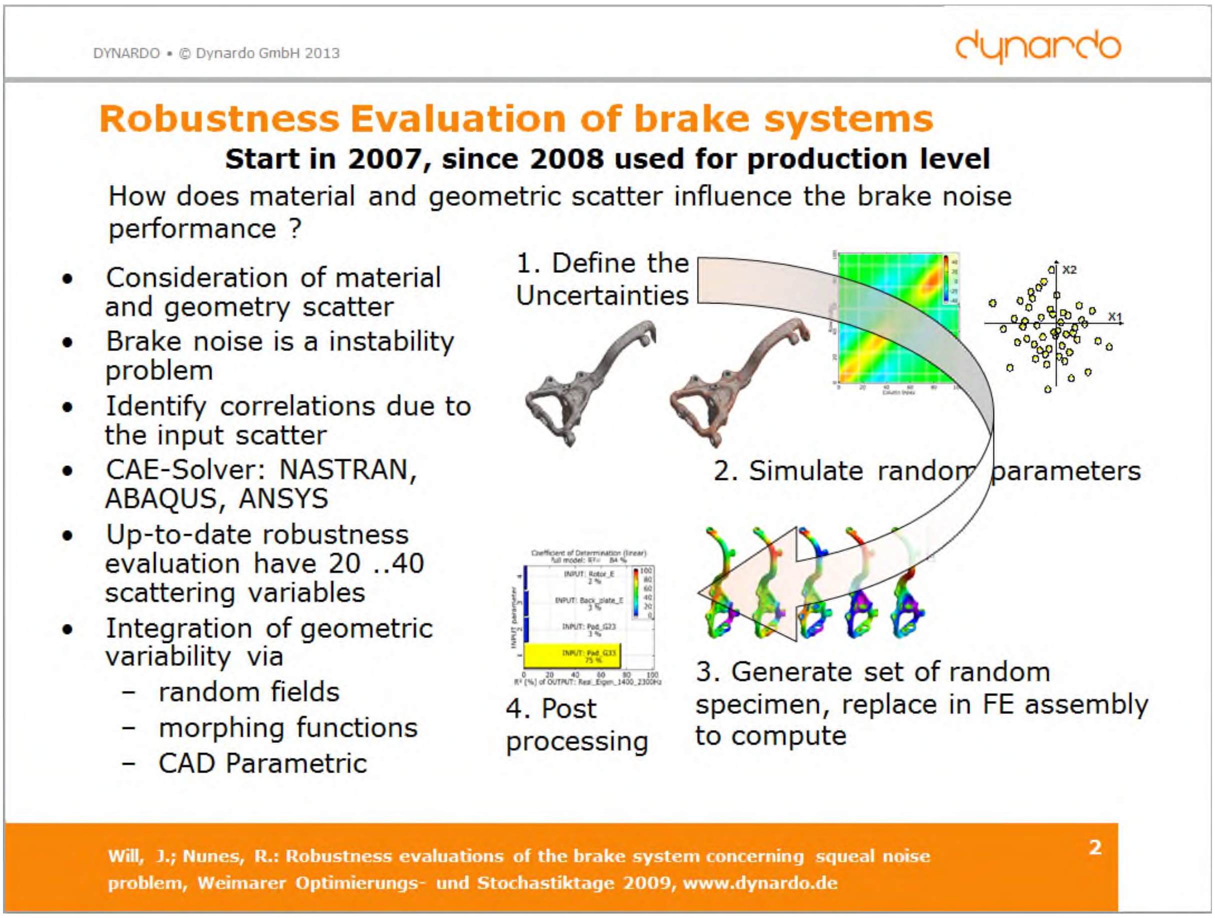

Figure 3 Robustness evaluations for brake systems

Implementation challenge: One of the main challenges during implementation at daily use is the parametric definition of production tolerances of the cast brake parts as well as parametric definition of the brake pad geometry fading.

Implementation success keys: Again, first the process including parametric variation of geometry of brake parts needs to be automated and a standardized post processing needs to be established. If system robustness needs improvement the necessary geometry modifications define additional requirements for parametric geometry. Due to the significant CPU requirements of every design evaluation a most effective procedure needs to be established for the combination of robustness evaluation with optimization procedure.

Customer benefits: Numerical robustness evaluations help to reduce the number of necessary hardware tests. Geometric modification of brake components to reduce brake squeal can be investigated effectively and fast in the numerical world and can be optimized to be weight neutral.
Bottlenecks: Current numerical brake models which are used in the car assembly to demonstrate the brake performance do not contain parametric geometry suitable to be used for investigating sensitivity to production tolerances or geometry modifications. Therefore, additional manual work is necessary to provide parametric of the geometry. Often the parametric is pure and opens small optimization potentials only or is not suitable to represent tolerances good enough for robustness evaluation.

Future challenges: The main input to the robustness evaluation is the definition of uncertainties, therefore the verification of the assumptions about uncertainties is an ongoing process. Current investigations try to find suitable parametric modeling for fading effects of the brake pads as well as for representing geometric tolerances of the casted parts. As a result, there will be the challenge for the suppliers to provide CAE models of brake components with inbuilt geometric parametric for robustness evaluation and optimization.

5 CAE-based robustness evaluations in crashworthiness [7]

Robustness evaluations are performed by the car producer as part of the development process to fulfill passenger car crash test requirements. Important scattering inputs which need to be considered are the definition of uncertainties regarding test conditions (speed, barrier positioning), environmental condition (friction) and uncertainties of crash relevant structures considering sheet metal thickness and material energy absorption including damage and failure as well as spot welds and other connection between the body in white structure.

Implementation challenge: Unless the process automation of running crashworthiness, load cases is no problem the parametric definition of scatter of crash relevant structures is a real challenge. Almost all crash codes use a part structure where material definitions can be shared with multiple parts. But of course, if we introduce material and production uncertainties every physical part needs to have his own material definition including thickness definition, stress strain curves and failure strain parameters. Because many parts will play an important role within the crash loafing it results in hundreds of scattering parameters and correlated values. To be ready for daily use it became mandatory to have an automatic parameterization tool. Starting from the current crash deck and a list of parts for which uncertainties need to be introduced, the parameterization tool modifies the crash input deck and introduced all uncertainties based on a database of material variation definitions.

Implementation success keys: Beside process automation the standardization of post processing is very important. First again limit violations need to be investigated. If limits are violated, minimal and maximal values and statistics need to be post processed, for some results on the finite element structure. Part of the post processing is the ranking of numerical robustness of important response values using the Coefficient of Prognosis (CoP) to quantify the numerical noise at response values.
Customer benefits: Numerical robustness evaluations help to reduce the number of hardware tests. If experience from previous car line and CAE-based robustness evaluation show no robustness problems hardware test for that load cases can be minimized. Because the goals in different disciplines like NHV, crash and weight optimization are conflicting, there will be crash load cases where criteria are in danger of being violated. Here numerical robustness evaluations are necessary to evaluate the robustness as early as possible, to help to improve the design and finally prove design robustness as early as possible in the virtual prototyping.

Bottlenecks: If the CAE engineer does not see a chance to demonstrate robustness or if he still wants to improve the numerical model or the design before starting the robustness he may miss the time gates, and the robustness evaluation is skipped or moved to the next milestone.

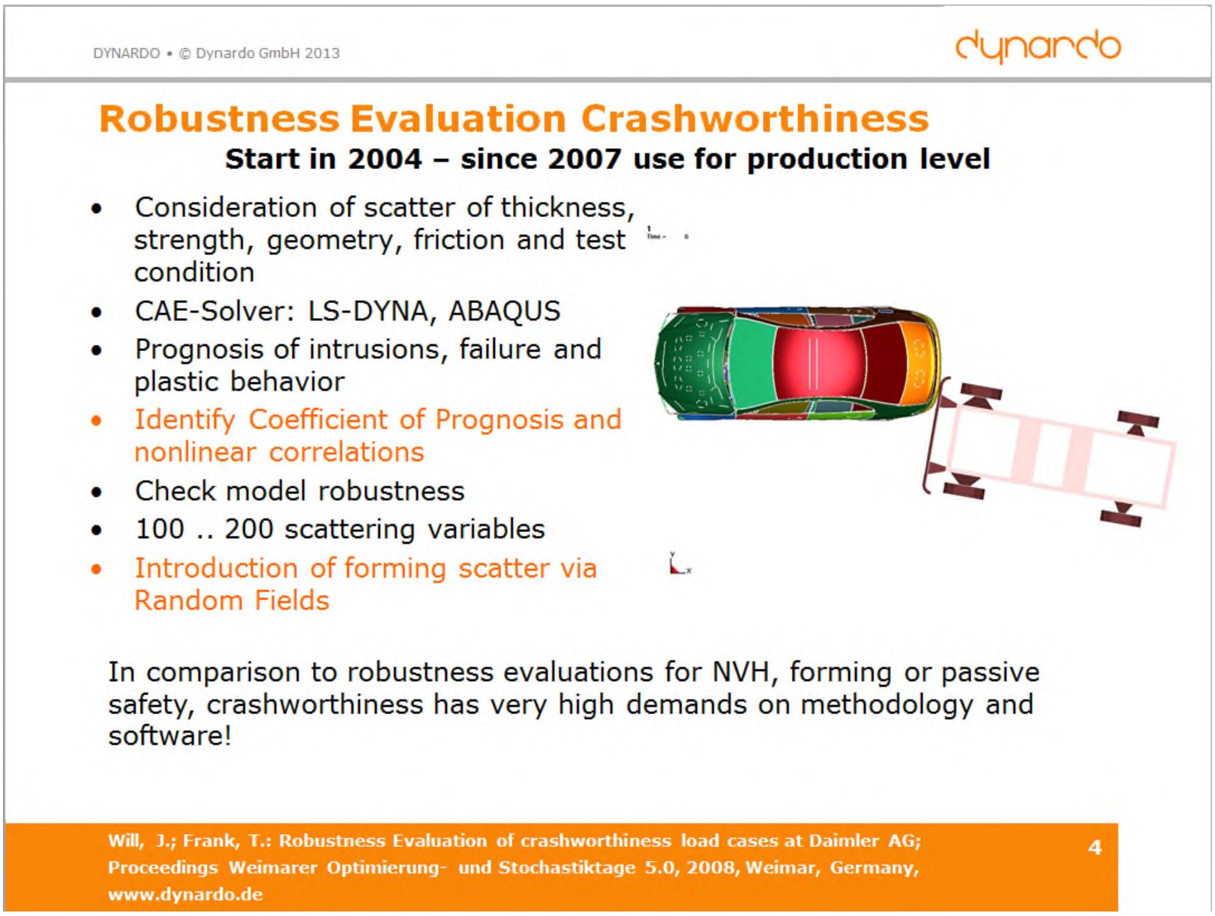

Figure 4 Robustness evaluations for crashworthiness

Future challenges: The main input to the robustness evaluation is the definition of uncertainties, therefore the verification of the assumptions about uncertainties is an ongoing process. For some high-speed front and rear load cases the forecast quality of the variation of important responses quantified using the CoP is very low. That indicates that either a different mechanism which finally results in the response variation cannot be identified with the current number of runs (100-150 designs) or that numerical noise or extraction noise overlay the results. Here improvements in numerical modeling of cars and barriers to reduce the numerical noise or alternative response values which are less sensitive to numerical noise need to be investigated.

6 Summary

CAE-based Robustness evaluation needs significant additional input in terms of definition of the variation of the uncertainties of the system. In addition, CAE-based Robustness evaluations require parametric CAE-models to automatically generate and evaluate possible design configurations as well as standardized post processing procedures to quantify robustness in terms of variation and identify correlations which explain most of the variation using CoP measurements.

From our experience, the key to a successful integration of robustness evaluation in the virtual product development cycles is the balance between appropriate introduction of input uncertainties, appropriate stochastic analysis methodology and appropriate post processing. If we miss the balance of one of the three, the main results of the stochastic analysis, the variation or correlation estimation may become misleading, wrong or useless. Consequently, the best possible translation of all knowledge about input uncertainties and the contribution of all potentially influencing uncertainties are very important.

The validation of design robustness with experience and experiment are necessary to prove the reliability of the CAE-based Robustness evaluation. Therefore, the connection between the CAE-based robustness evaluation to the experiments is very important to increase the acceptance of CAE-base robustness evaluation and to establish the methodology in daily use.

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