

Applying Sensitivity Analysis and Robustness Evaluation in Virtual Prototyping on Product Level using optiSLang

Alexander Ptchelintsev⁽¹⁾, Gerald Grewolls⁽¹⁾,
Johannes Will⁽²⁾, Marcus Theman⁽¹⁾

(1) – Nokia Corporation, (2) – Dynardo GmbH

Abstract: Reliability of portable devices becomes a serious issue as complexity of the devices grows and miniaturization trend continues. In case of dynamic applications durability against impact on hard surfaces is a standard requirement for mobile electronic devices, verified in drop tests. Computer Aided Engineering (CAE) methods and tools are used as means to accelerate the overall design cycle and to reduce time to market. In case of drop test simulations it is an important task to assess quality of simulation models and effect of different input parameters on results. Strong nonlinearities (contact, material, geometric) and large number of parameters involved make such sensitivity studies more difficult. It is also necessary to include effect of stochastic nature of input parameters which requires a robustness evaluation of the simulation models. This paper describes first results of a research project on development of an automated procedure of sensitivity analysis and robustness evaluation of product level simulation models used for drop test simulation. Several goals have been pursued with development of the methodology: to estimate the scatter of important design responses, to find out the most important input variables affecting important design responses both in sensitivity and robustness evaluation studies; investigate quality of simulation models in terms of explainability of the response scatter with correlations to scattering input variables. First results of the sensitivity and robustness evaluation studies have shown that the methodology can be used by Nokia at the product level. Additional verification with test results is required.

Keywords: Drop Test Simulation, Sensitivity Study, DOE, Robustness Evaluation, Stochastic Analysis

1. Introduction

Reliability of portable devices becomes a serious issue as complexity of the devices grows and miniaturization trend continues. Virtual prototyping helps companies like NOKIA to reduce the overall design cycle and time to market. There is a strong pressure to reduce number of physical tests and to rely more on results of simulation. In case of dynamic applications durability against impact on hard surfaces is a standard requirement for mobile electronic devices, verified in drop tests. Computer Aided Engineering (CAE) methods and tools are used during all phases of design as means to accelerate and shorten the design cycle. In case of drop test simulations it is an important task to assess the quality of simulation models and the effect of different input parameters on results. Strong nonlinearities (contact, material, geometric) and a large number of

parameters involved make such sensitivity studies more difficult. Stochastic variation of input parameters like material properties, parts thicknesses, load cases, etc can significantly affect results of simulations, obtained at nominal values of input parameters. This problem can be tackled using a robustness evaluation (Will, 2007).

2. Robust Design Process for Nokia Drop Test Applications

As a first step a numerical sensitivity analysis against variation of drop test setup (drop angle) as well as variation in design parameters (material, geometry,..) are carried out, with the following objectives:

- determine "worst case" drop test orientations;
- evaluate most efficient optimization variables to influence important response values;
- estimate optimization potential to allow effective, specific tuning of the design by simulation-based optimization algorithms.

In the second step, the robustness evaluation is made in order to check the sensitivity of the product performance at critical drop test position against material scatter and production tolerances as well as small deviations in drop positions. With the estimation of scatter, quantity safety margins can be extracted and implemented in the design process to ensure robust structures.

For drop tests, the orientation of the device at the moment of impact is crucial for the loading on the device after impact. Therefore it was required to identify those drop orientations which lead to high loading in different parts of the phone. Based on experience, the critical range for the orientation was selected to vary around the horizontal position with angles of $\pm 10^\circ$ about the longitudinal and the transverse axis of the phone. To identify the worst case drop position in the first sensitivity study the drop angles as well as all design parameters available for optimizing the design are varied. After detecting the most critical orientation, further sensitivity analyses were set up without variation of the drop angles, in order to quantify the influence of design parameters at this "worst case" orientation.

By use of the identified "worst case" orientation, the sensitivity of important design responses for this drop direction needs to be determined to carry out a robustness evaluation which allows to check the sensitivity against manufacturing tolerances, material scatter and scatter sources.

During sensitivity analysis and robustness evaluation a large number of designs are evaluated. Therefore the whole process is automated and integrated into optiSLang, which drives the sensitivity analysis and robustness evaluation. The process automation is shown in Figure 2. Due to the high number of analyses the result extraction process was significantly accelerated by use of Python scripts for the automatic extraction of the essential results.

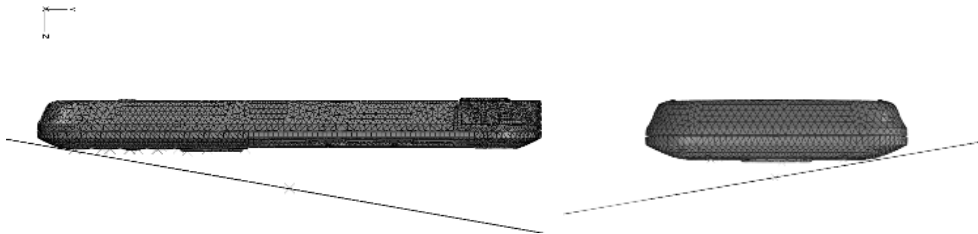


Figure 1. Example for drop test configurations, drop with phone inclined about “angle x” (left), “angle y” (right).

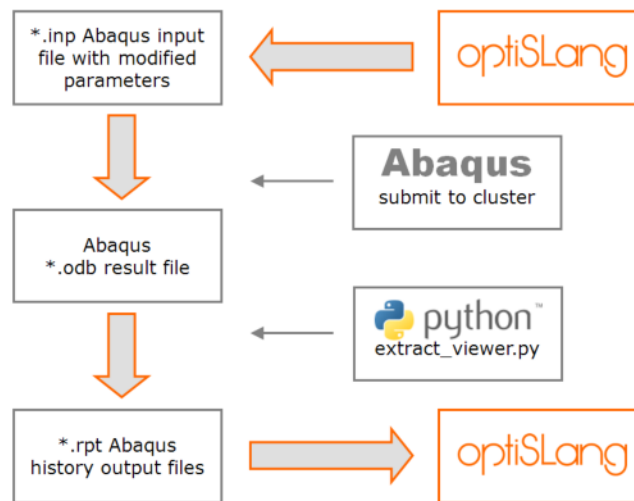


Figure 2. Process automation.

3. Statistical Measures to Evaluate Design Spaces

For the evaluation of statistical design spaces, there are different measures with graphical representations available:

- **Histogram:** Investigation of response variation and limit violation probability.
- **Coefficient of Determination (CoD), Coefficient of Importance (CoI):** What proportion of the variation of a response is explainable by linear, quadratic and monotonic non-linear (Spearman) correlations to the input parameters?
- **Anthill-Plot:** 2D representation of a pair wise relation between inputs and responses.

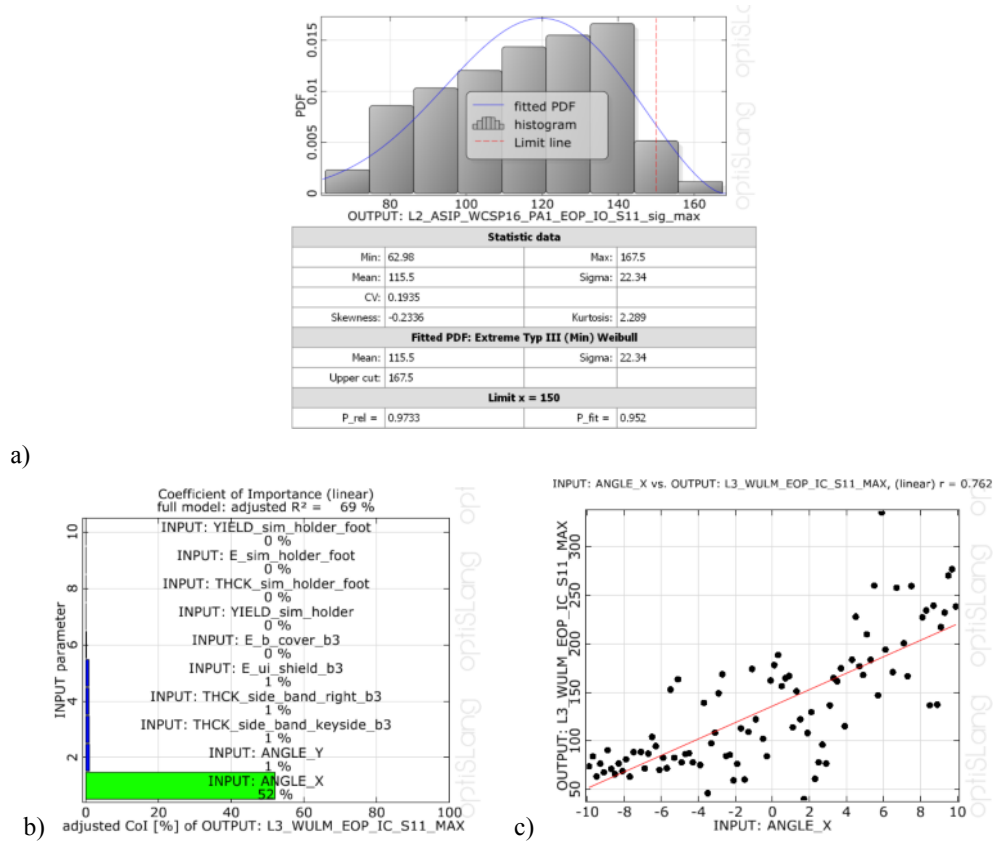


Figure 3. Statistical measures to evaluate design spaces:
a) histogram, b) Coefficient of Importance (Col) graph, c) anthill plot.

Further, **Coefficient of Prognosis (CoP)** is of interest (Figure 4). It is applied to predict what proportion of the variation of a response can be **forecasted** with identified arbitrary non-linear correlations to the input parameters. In contrast to CoD and CoI the Coefficient of Prognosis checks the forecast quality at an independent sample test set. It has three benefits:

- reduce the variable space with different filter
 → best subspace
- check multiple non-linear correlations by checking multiple MLS/polynomial regression
 → best Meta Model
- split sample set and check forecast (prognosis) quality at the test samples
 → Metamodel of optimized Prognosis (MoP)

Find more details to the statistical measurements of sensitivity analysis in (Will, 2009).

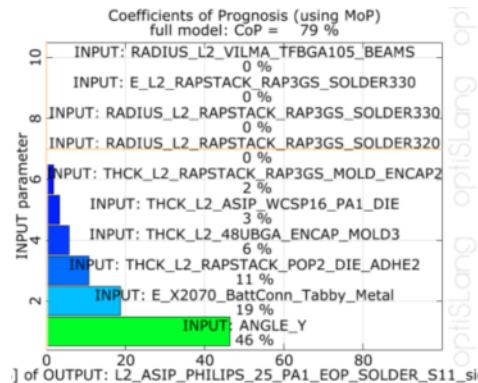


Figure 4. Coefficient of Prognosis (CoP) for the phone drop simulation.

4. Sensitivity Analysis: Drop Test of a Mobile Phone

To identify the most critical drop test position and for better understanding of the influence of the selected design parameters on the results, a sensitivity study was carried out in the first step. The sensitivity study aims to investigate how the variation of test setup and design parameters will affect the output responses.

For the study, the optimization software optiSLang, Version 3.0.0 is applied (Dynardo, 2010). 51 design parameters were selected, including geometric dimensions, material and friction parameters. A range of orientation angles which define orientation of a phone related to a rigid surface have been selected to study effect of clattering. Several previous internal and external studies like (Goyal, 1998), (Shan, 2006) have shown that clattering has an important effect on performance of portable devices in drop tests. One of the tasks of the study was to quantify the effect.

An effective method to investigate the parameter range for all 51 input parameters is Latin Hypercube Sampling (LHS). By this method, a statistically representative result of response scatter for the complete parameter space of a high number of input parameters can be produced by a relatively small number of samples. Each input parameter range is divided into N intervals with equal probability and from each interval one random value is used for one sample set of parameters. By combining these parameter values, N different samples are generated. This method provides a good representation of the real variability in the randomly selected samples. Of course beside the response scatter the correlations to the scattering input variables are of interest. Therefore the necessary number of samples is depending on the number of important scattering variables as well as on the nonlinearity of the design responses. To minimize the necessary amount of samples we use input correlation error minimized Latin Hypercube sampling, significance filter and CoD, CoI and CoP values. We decided to start with 100 samples, thus 100 variants of the FEM model were created. It could be shown that 100 simulations are good to estimate variation, correlation and explainability for the mobile phone drop test simulation.

The statistical analysis of the results included the variation of responses, linear, quadratic and monotonic non-linear correlation between input and output. Further, the coefficients of determination, importance and prognosis were determined; the latter two are measures in optiSLang to quantify the amount of explainable scatter. As an additional value with estimation how much scatter can be explained we estimate the scatter which can not be explained. The amount of unexplained scatter most likely results from numerical noise or from the procedure how the result values are extracted and is an important measure for the quality of the simulation model and for that of post-processing as well.

The example in Figure 5 shows CoI and anthill plot of the most important correlation for the front side drop, here it was found that angle x is most significant within the parameter range between -10° and 10°. A second analysis with fixed drop angle x of 3° showed that the mass density of the battery and the thickness of the UI shield (a metal sheet near the display) are the most important design parameters at worst case drop test position.

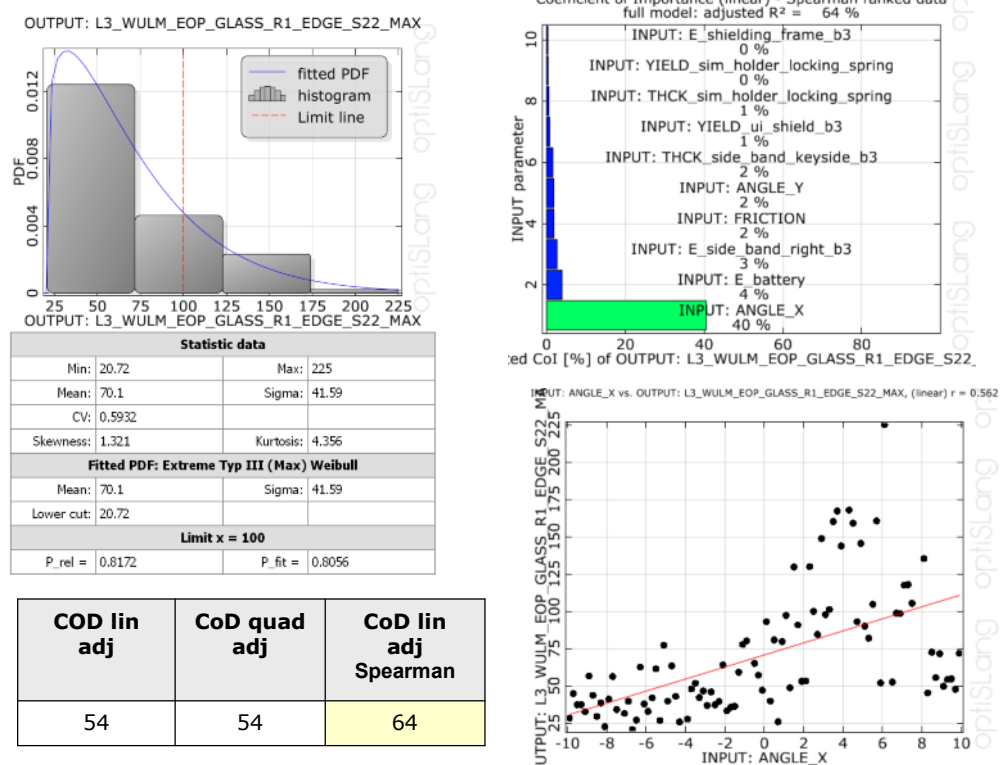


Figure 5. Example: sensitivity of stress maxima in the rear glass panel of the display (angle x between -10° and 10°).

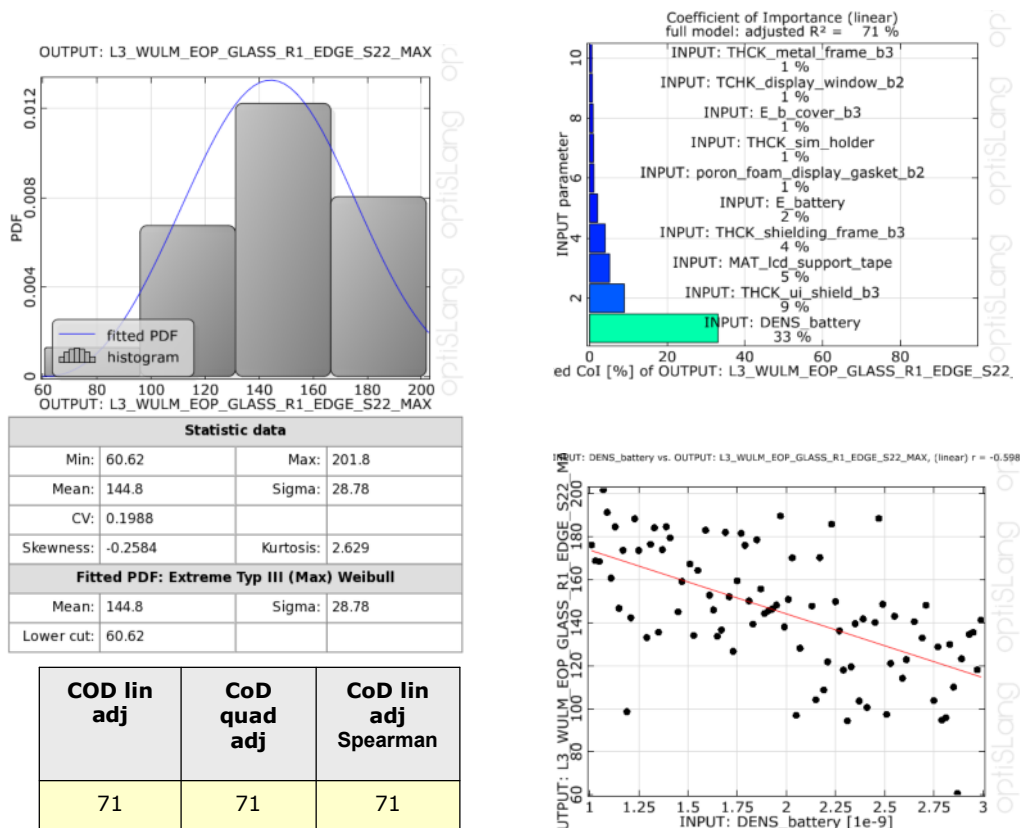


Figure 6. Sensitivity of rear glass stress for the “worst case” orientation (equal drop orientation for all simulations).

In Figure 6, the evaluation for one fix drop orientation is shown. The display stress in rear glass panel shows a variation between 61 and 202 MPa, the maximum CoD is 71%. The mass (mass density) of the battery (variable DENS_battery) has the most significant influence on the stress in the rear glass of the display.

The sensitivity result for orientation angles (impact point and direction) indicates high probability that the highest stress in the display glass occurs in drop cases on one front corner at angles of 2 ... 6 °. Critical design load cases for the glass component lie in this range. Within the investigated design modifications, battery weight and UI-shield thickness are the most effective design parameters to reduce glass loading.

5. Robustness Evaluation

A robustness evaluation is a so-called global variance-based stochastic analysis which addresses the question how much the response values scatter under the consideration of input parameter

scatter. The input scatter is defined by different types of distributions i.e. uniform, normal and truncated normal. Besides the response variation the correlation between input and output scatter is investigated. The process automation workflow is presented in Figure 4. Robustness evaluation was conducted in order to check sensitivity of product performance against material scatter and production tolerances as well as small deviations in drop positions. With the estimation of scatter quantity safety margins can be extracted and implemented in the deterministic design process to ensure robust structures.

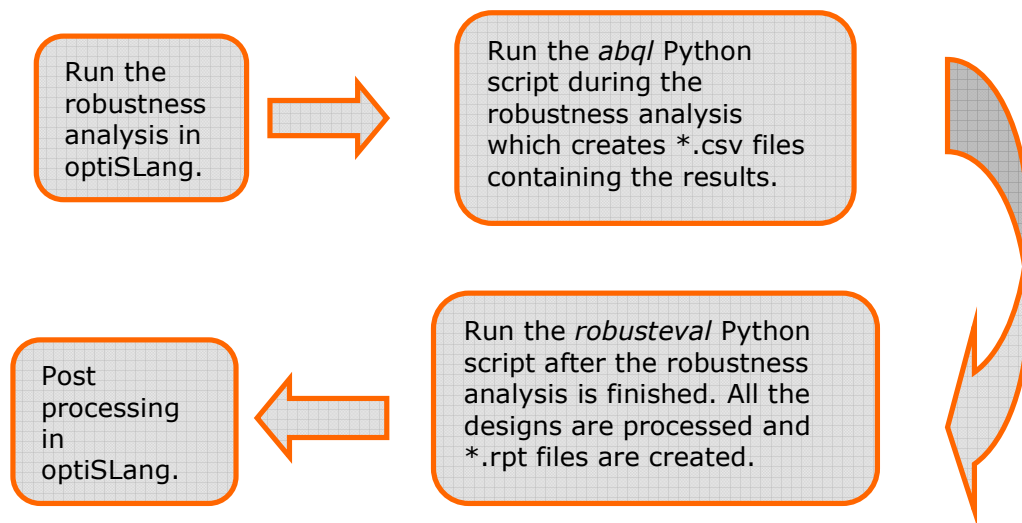


Figure 7. Robustness evaluation workflow.

209 scattering input parameters were selected, taking into account results of the sensitivity study, lower and upper bounds of the orientation angles angle x and angle y were defined in the ranges of $[-1^\circ, 1^\circ]$ and $[-1^\circ, 1^\circ]$ respectively. Other input parameters included geometric dimensions (shell thicknesses), material properties (linear and nonlinear) and friction parameters. 36 outputs parameters were defined and Latin Hypercube Sampling (LHS) was selected with 150 designs. Statistical post-processing of the 36 output parameters included variation of the responses, coefficient of determination/importance, checking linear and non-linear correlation, coefficient of prognosis.

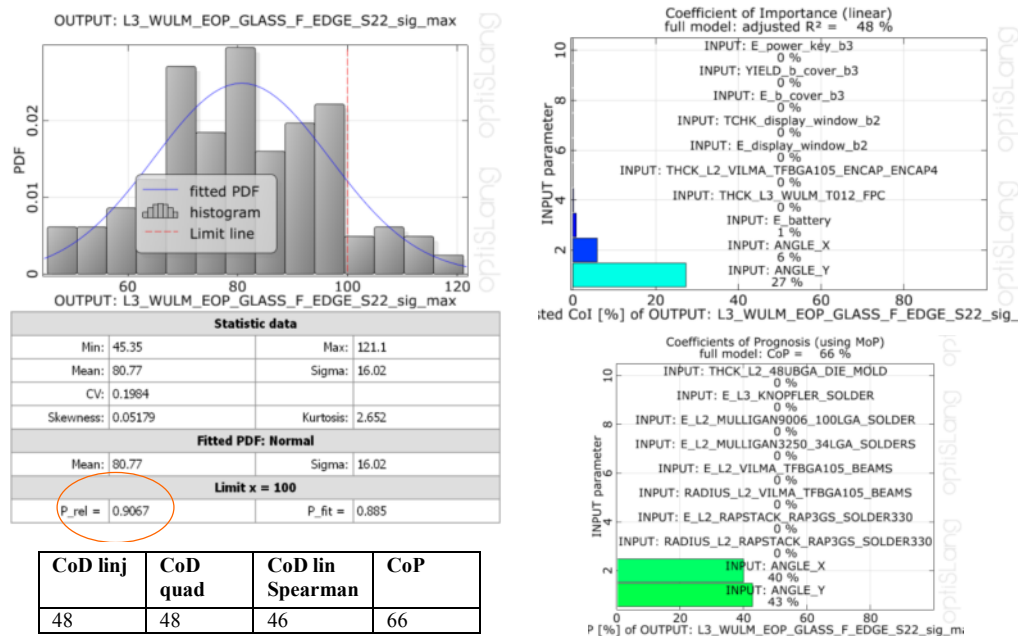


Figure 8. Post-Processing Robustness Evaluation of Drop Test Simulation.

An example of statistical post-processing which was done for each output parameter is shown in Figure 8. The histogram on the left side shows a variation between 45.35 and 121.1 MPa. The probability of violating the limit is 9.33 % ($1 - 0.9067 = 0.0933$). Maximum CoP is 66 %, inputs angle y and angle x have the most significant influence. Comparison between the CoI and CoP clearly show the difference between those two measurements of correlation. The very nonlinear correlation due to variation in x-angle (which was already shown in the sensitivity analysis) cannot be identified with linear, quadratic and monotonic nonlinear correlation which is used at the CoI. Only the arbitrary nonlinear correlation capabilities of CoP identify and quantify that correlation. Anthill (scatter) plots were used to study 2D representation of a pair wise relation between inputs and responses, as shown in Figure 9.

Of course, evaluation of 36 important design response values may not be the full picture in terms of design robustness. Maybe some other locations which are not properly treated by the result extraction of 36 scalar values show critical values within the scatter range. To address that issue it becomes necessary to project statistical values of variation onto the finite element discretization level. Then we have a full picture of variation at every finite element and can check hot spot locations for critical loading. That post-processing capability is addressed with the software tool Statistics on Structure (SoS). Therefore the Abaqus results for the most important design parts are extracted and imported and post processed in SoS. At the element level then hot spots of variation can be identified and the correlation analysis for hot spot elements can be performed. Figure 10 shows the variation of stresses at a glass component in the 150 design evaluations. Two hot spot

areas of peak stress can be located and using optiSLang the correlation analysis at hot spot element level is performed. The CoP values show explainability values over 80%, which mean the variation can be explained very well and the scatter of the drop angles ($\pm 1^\circ$) is dominating the stress scatter. All other scattering variables have no influence on the stress scatter at the glass component.

Therefore it could be shown that projection of statistical values adds significant benefits to the post processing capabilities of robustness evaluation:

- Visualization of min/max and scatter range on FE structure.
- Visualization of spatial distribution of variation and correlation on FE structure.
- Selecting and visualizing important regions and calculation of their correlations.

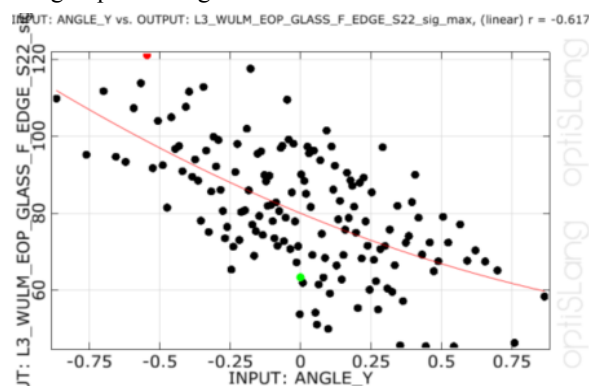


Figure 9. Example of an Anthill (scatter) plot.

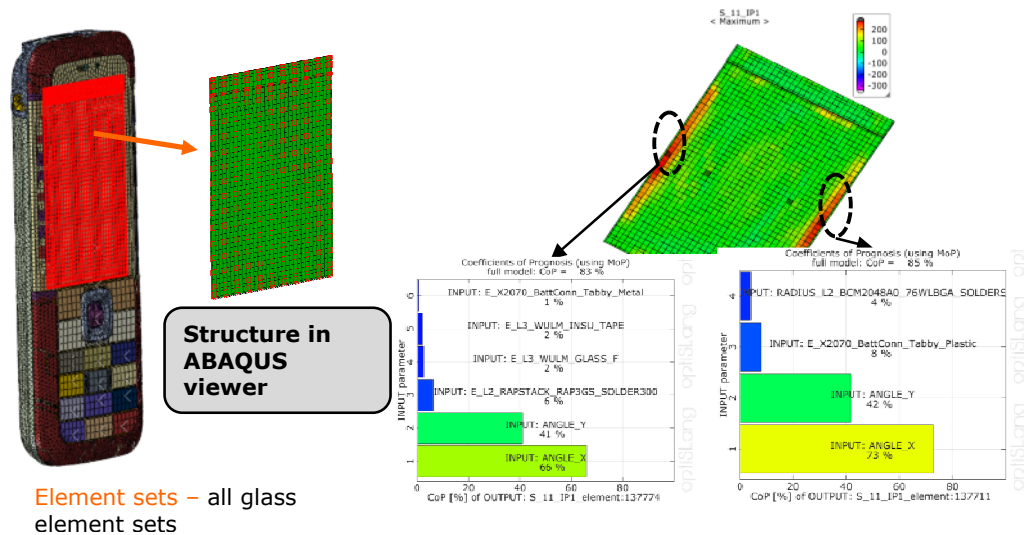


Figure 10. Statistics on structure.

6. Conclusions

Sensitivity study and robustness evaluation have been conducted for a typical simulation model at product level complexity. The number of input parameters in the sensitivity study included drop test position and all possible design parameters which were of interest for designers in order to estimate their relative importance. We can conclude that it is possible to use such sensitivity studies to identify design drop positions and main design parameters to optimize the structure. As an example, interesting results have been obtained for display glass. The sensitivity study indicates high probability that the highest stress in the display glass occurs in drop cases on one front corner for drop orientation angles of 2 ... 6 °. Critical design load cases for the glass could be identified. Within the investigated design modifications, battery weight and UI-shield thickness are the most effective design variables to reduce glass loading.

Robustness evaluation at a drop angle of 0° shows very small influences of manufacturing tolerances or material scatter on the maxima of glass loading compared to small deviations of the drop angle (+1°). Therefore the main task of improvement (more robust design) is to reduce glass loading sensitivity to drop position. The safety margin due to deviation of worst case drop positions can be extracted and compared to safety margins which are used today in the virtual design process from scatter estimations of robustness evaluation. That is a very efficient method in order to avoid over-engineering by using too large safety margins and on the other hand to avoid robustness problems by using too small safety margins.

For a robust design of mobile devices sensitivity and robustness studies can provide an extended insight into the complex non-linear nature of the reliability against mechanical loading. At the current state-of-the-art in numerical simulation and with current simulation hard- and software it is feasible to perform such types of investigations. Due to fast increase in hardware and software performance, FEM analyses can go to the next level today: statistically relevant numerical analyses with a sufficient number of design simulations. The simulation time for a corner drop test of a mobile phone has been reduced significantly in the last 5 years. Due to this development, developers of complex, mechanically sensitive devices can benefit from software like optiSLang or Statistics on Structure to evaluate the reliability of their products.

Further improvement of model parametric, hardware and numerical methods will allow introducing the assessment of tolerances in material parameters and geometry in numerical simulations of mechanical performance as a standard. This development is very beneficial to increase the quality and reliability of electronic consumer products via virtual prototyping.

7. References

1. Goyal. S., Papadopoulos, J. M. and Sullivan, P.A., "The dynamics of clattering I: equation of motion and examples," ASME J. of Dynamic Systems, Measurement and Control, 120 (1998), pp 83-93.

2. Goyal. S., Papadopoulos, J. M. and Sullivan, P.A., "The dynamics of clattering II: global results and shock protection," ASME J. of Dynamic Systems, Measurement and Control, 120 (1998), pp 94-101.
3. optiSLang - the optimizing Structural Language, DYNARDO GmbH, Weimar, 2010, www.dynardo.de.
4. Shan, H., Su, J., Badiu, F., Zhu, J., and Xu, L, "A Modeling Study of Clattering Impacts of Falling Electronic Device," Mathematical and Computer Modeling, 43 (2006), pp.592-611.
5. Will, J.: "Variation Analysis as Contribution to the Assurance of Reliable Prognoses in Virtual Product Development", Proceeding NAFEMS Seminar "Reliable Use of Numerical Methods in Upfront Simulations" , 2007, www.dynardo.de.
6. Will, J.; Most, T.: "Metamodel of optimized Prognosis (MoP) – an automatic approach for user friendly design optimization", Proceedings ANSYS Conference & 27. CAD-FEM Users Meeting 2009, Leipzig, Germany.