

Efficient Stochastic Analysis of Process Chains

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Abstract – In this paper, a novel strategy (PRO-CHAIN) and software modules (DesParO, DIFF-CRASH, SCAIMapper) for the statistical ensemble analysis of sensitivity and stability as well as multi-objective robust design-parameter optimization of process chains are discussed. Results are presented for the process chain forming-to-crash for a formed part of a B-pillar, which has a potentially critical influence in car crashes. The PRO-CHAIN strategy consists of several coordinated modules, solving different tasks such as stability analysis, parameter sensitivity analysis, reduction of design space, ensemble compression, robust design-parameter optimization of a step and/or the chain, and mapping of ensembles. The novel software modules can handle large ensembles of simulation data efficiently, even ensembles of full simulation results on highly resolved grids. This way, large random fields can be analyzed directly and fully locally and can be mapped including detailed information on variations from step to step.

1. Motivation

It is known that material and process parameters, geometry and also external influences can vary substantially during the fabrication of products. These variations can have a substantial, even critical influence on the robustness of production processes and the quality of resulting products. Analyzing governing influences of the variations and possibly minimizing them belongs to the most challenging research and development tasks today. This is especially true for the consideration of whole process chains. Exemplary applications in automotive engineering include the forming-to-crash and casting-to-crash process chains, and in semiconductor simulation the process-to-device simulation and device-to-circuit simulation chains.

Commonly, the last step of a process is still considered separately. Partly, at least first information from the history is integrated, but without variations. However, considerably better forecasting quality of numerical simulation and optimization can be achieved if not only the history of the process is included in the simulation of the last step as completely as possible, but also variations of decisive parameters are taken into account and transferred over the steps. Therefore, statistical analysis and robust optimization have to start as early as possible in the process.

A strategy with coordinated, efficient software modules for statistical analysis and multi-objective robust design-parameter optimization of whole process chains is necessary. In Section 2, we describe the PRO-CHAIN strategy and software modules DesParO, DIFF-CRASH, SCAIMapper. PRO-CHAIN performs different analysis steps addressing stability, sensitivity, robustness, and optimization aspects. The methods are based on appropriately constructed ensembles of simulation results. An important goal is keeping the number of ensemble members as small as possible while maintaining user-controllably accurate results. In Section 3, we discuss results obtained by PRO-CHAIN for a ZStE340 micro-alloyed metal blank of a B-pillar, a decisive part with a potentially critical influence in car crashes. Section 4 concludes the paper with an outlook on future developments.

2. Strategy for Analysis and Robust Optimization of Process Chains

The PRO-CHAIN strategy [1-4] consists of the following main analysis steps and accompanying software tools (in brackets):

- Process step 1
 - A stability analysis of the simulation model is carried out optionally (DIFF-CRASH, [7]). Physical bifurcations and/or numerical instabilities in simulation packages can cause extremely sensitive dependencies of simulation results on even the smallest model changes. Among other things, DIFF-CRASH allows the engineer to find critical structural regions and potential sources of instabilities.
 - A parameter sensitivity analysis (DesParO, [5,6,8]) is performed, based on a “thin” and adaptive design-of-experiment strategy (DoE). The first DoE consists of just $2n+1$ simulations, with n being the number of design parameters. This is sufficient if parameter variations show only a weakly nonlinear behavior. DesParO offers an estimator for that. The DoE can iteratively be extended in order to handle stronger nonlinearities efficiently. Computational effort for the sensitivity analysis is mainly determined by reading and writing the ensemble of simulation results. The data are processed “on the fly”. This way, the software modules can handle huge data bases efficiently, even on highly resolved grids.
 - Both, the design space (design parameters) and the ensemble of simulation results are compressed (DesParO). The user can control both the reduction of the design space as well as the accuracy of the compression.
 - The novel DesParO Geometry Viewer supports an efficient analysis via direct visualization of appropriately interpolated results. This way, an interactive exploration of the design space with a “preview” on simulation results is enabled.
 - A robustness analysis and/or a multi-objective robust optimization (DesParO) are performed optionally.
- Transfer
 - The data base for the mapping process is prepared. In particular, for the forming-to-crash chain, it includes local variations of thicknesses, strains, pre-damages.
 - The resulting data base is mapped (SCAIMapper, [9]). The local quality of the mapping is validated. In particular, it is evaluated against local variations stemming from the first process step.
- Process step 2
 - A stability analysis of the simulation model (DIFF-CRASH) is performed optionally. Note that especially for a crash scenario a detailed stability analysis and identification of possible sources of instabilities is very recommendable.
 - A parameter sensitivity analysis and corresponding efficient reduction of the design space is carried out (DesParO). The influence of parameter variations on simulation results as well as on global criteria, as specified by the user, is analyzed. Parameters can stem from the first process step and, where applicable, additionally from the second process step.
 - As a last step, a robustness analysis and/or a multi-objective robust optimization of the whole process chain is performed, based on user-defined robustness measures.

Novel software modules, integrated into DesParO and DIFF-CRASH, can handle large ensembles of simulation results efficiently, even on highly resolved grids. In this way, large random fields can be analyzed directly and more realistically. Therefore, global as well as fully local influences can be characterized efficiently. Main PRO-CHAIN steps are represented schematically for the process chain forming-to-crash in Figure 1.

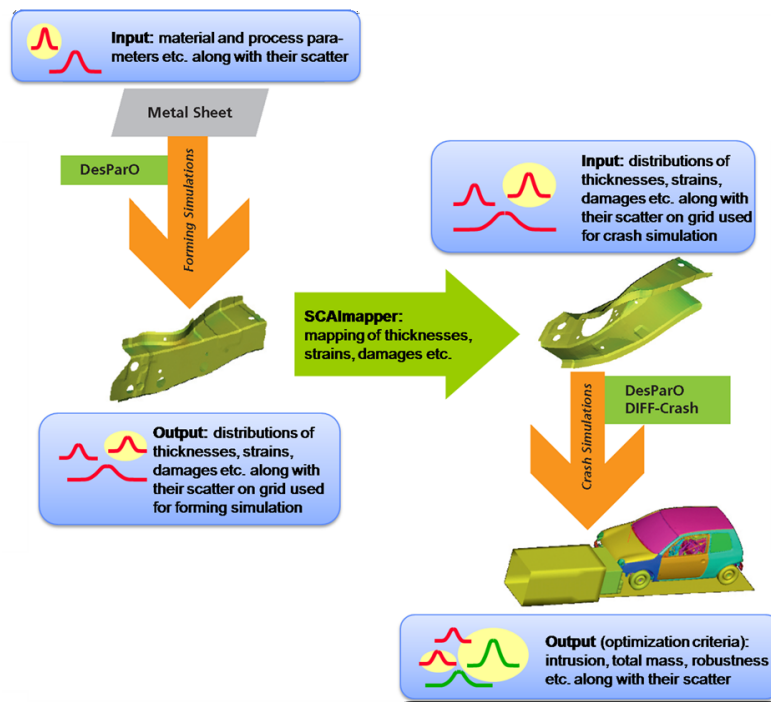


Figure 1: Process chain forming-to-crash: simulation types (in orange), typical kinds of variations to be dealt with (in blue), software tools (in green) supporting sensitivity and robustness analysis as well as multi-objective robust optimization (DesParO), mapping (SCAIMapper) and a backtracking of instabilities in crash simulations (DIFF-CRASH). For forming and crash simulations, LS-DYNA is employed, for instance. Material models such as BI-FAILURE [2,3] can be integrated there.

3. Results for a Micro-alloyed Metal Blank of a B-Pillar

The PRO-CHAIN strategy has successfully been tested on a micro-alloyed steel (ZStE340) blank of a B-pillar, see [1-3,10] for first discussions. Several results are presented in the following. In the first process step, namely the metal forming (deep drawing), several material and process parameters have been considered. In total, 15 design parameters have been varied for a detailed analysis, see Table 1. The range of variations is also indicated there. Per parameter, a distribution function was approximated, based on experimental results.

The forming simulations have been carried out by means of LS-DYNA. The sensitivity analysis shows two important material parameters and three important process parameters. The data base can be reduced to a size of three to eight times the size of one simulation result, depending on the desired accuracy. The relevant simulation data for the mapping consist of local distributions of thicknesses, strains and damages. In particular, taking local damages and their variations into account has turned out to be a crucial point in order to achieve simulation results considerably more realistic compared with physical experiments.

The mapping has been carried out by means of the SCAIMapper. A mapping is necessary because the crash grid is usually much coarser than the adaptively refined forming grid; additionally some parts are cut out. Several mapping scenarios have been compared, in order to analyze the effect of taking local distributions of thicknesses, strains and damages of the forming step into account in a step-wise fashion.

class	parameter	range of variations
damage	d_1	$\pm 20\%$
	d_2	$\pm 20\%$
	d_3	$\pm 20\%$
	d_{shear1}	$\pm 20\%$
	T_{trans}	$\pm 10\%$
hardening	k	$\pm 10\%$
	n	$\pm 10\%$
	e0	$\pm 10\%$
shell thickness	t	$\pm 10\%$
anisotropy coefficients	r00	$\pm 10\%$
	r45	$\pm 10\%$
	r90	$\pm 10\%$
friction	mue	$\pm 50\%$
binder force	FORCFN	$\pm 10\%$
drawbead force	DFSCL	$\pm 10\%$

Table 1: Overview on design parameters along with their range of variations (minima/maxima; distribution not shown) for the metal blank and its forming process.

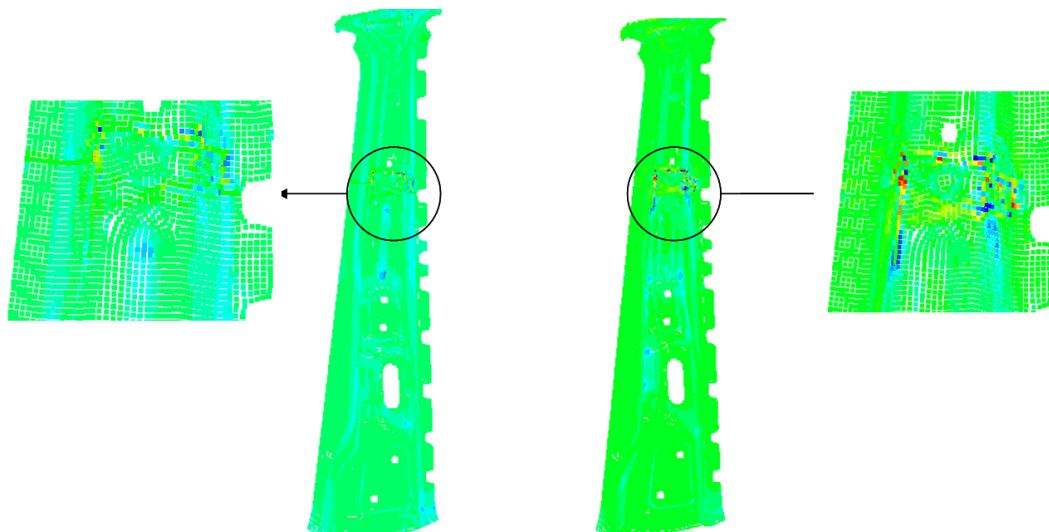


Figure 2: Differences between crash results for the scenarios “without mapping” and “with mapping of local thicknesses, strains and damages”, exemplarily for a variation of the d_3 parameter by +20%. Differences in effective plastic strain (left) and differences in damage (right) are shown.

The crash simulations have been performed by means of LS-DYNA again. Fraunhofer IWM’s BI-FAILURE damage model [2,3] has been used in addition. A comparison of the scenarios with and without consideration of thicknesses, strains and/or damages of the forming process has shown a high influence of the fully mapped data and their variations, especially in critical regions of the B-pillar blank, see Figures 2 and 3. The force-displacement diagrams show a good agreement between physical experiment and crash simulation, but only if the forming history is taken into account, see Figure 3. To be more specific, not only resulting local thicknesses and strains have to be obtained from the deep drawing process and mapped to the crash step, but also local pre-damages.

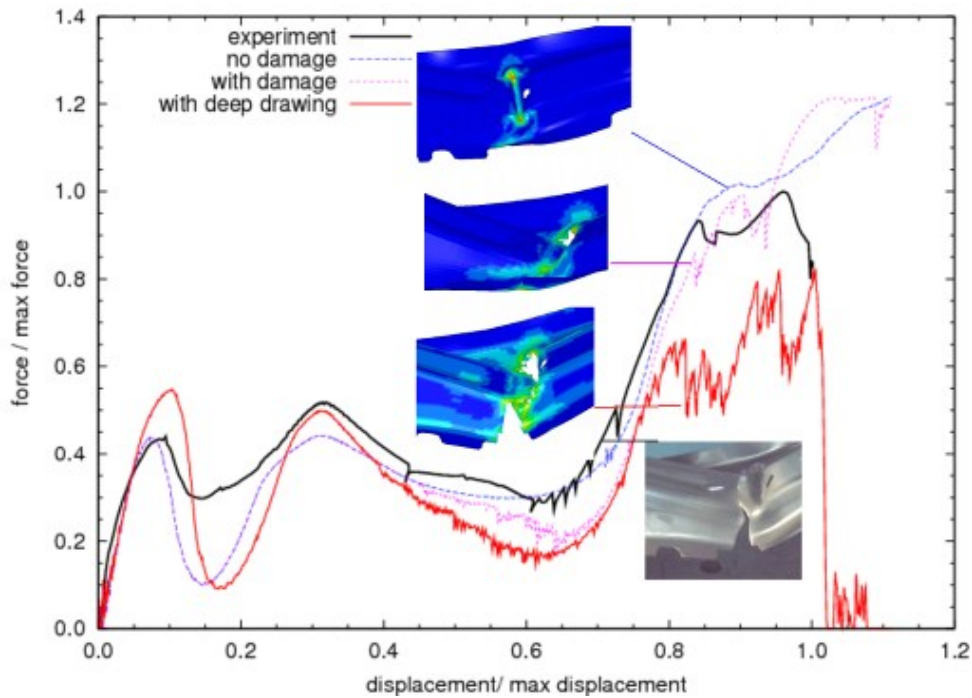


Figure 3: Comparison of experiment with simulation of the initial model (without parameter variations) with and without the forming history. “with damage” means using an estimation for the initial damage (without mapping), “with deep drawing” means taking mapped local thicknesses, strains and pre-damages into account, as obtained from the forming simulation. Courtesy of Fraunhofer IWM.

The sensitivity analysis of the crash step adds three parameters to the original set of five important parameters stemming from the forming step. The influence of the latter five is somewhat weaker now. All impacts are nonlinear.

Figures 4 to 6 exemplary show the influence of variations of one of the most important design parameters, namely d_3 , which controls a part of the BI-FAILURE damage model [2,3]. Its behavior is very nonlinear. In particular, Figure 5 shows the “corridor” of force-displacement diagrams resulting from the variation of d_3 over the whole forming-to-crash process chain. Together with Figure 6, a large effect of variations of d_3 is can be observed. This is true also in smaller ranges (e.g. $\pm 5\%$) around the center.

Qualitatively similar results are obtained when analyzing other influencing parameters. The entirety of parameter variations yield a force-displacement corridor similar to the one shown in Figure 5. The corridor is not reduced considerably for smaller parameter variations, cf. also Figure 6. Even relatively small parameter variations thus influence the crash results substantially here.

Additionally, PRO-CHAIN could detect an intense nonlinear interplay of a crack with a dent. This compensation effect is also present in the physical experiment. Its dependency from parameter variations and its relationship to corresponding extreme simulation results, as shown in Figure 7, could be characterized.

Note that a part of the resulting variations is due to a slightly instable behavior of the simulation model itself even if a fixed set of parameter values is used – scatter is triggered by just permuting the compute nodes in a parallel simulation run, as results of a DIFF-CRASH analysis reveal. Locally on the simulation grid, the scatter is limited. However, resulting maximal forces are influenced considerably. The influence per fixed set of parameter values is smaller than the influence of parameter variations for a fixed number of parallel processes along with a fixed order of compute nodes. A combination of

varied parameter values and permuted order of compute nodes does not enlarge the corridor considerably compared to considering parameter variations alone.

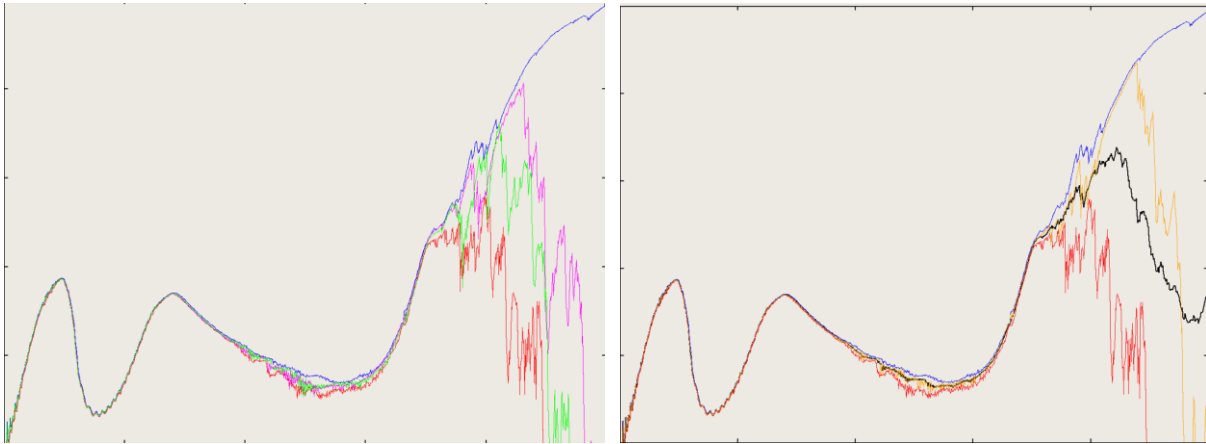


Figure 4: Variation of the d_3 parameter, taking the forming history into account, leads to a high variation range of results, as shown in the force-displacement diagrams above. Exemplarily, $d_3 + 20\%$ (pink), initial d_3 (yellow), $d_3 - 20\%$ (green), minimum per displacement-value (red), maximum per displacement-value (blue), and all results weighted w.r.t. the distribution (black) are shown.

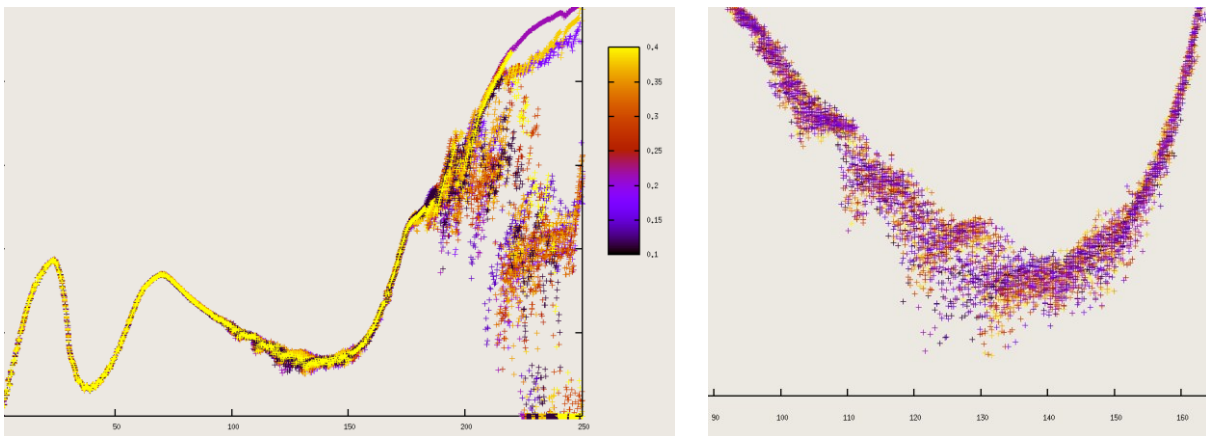


Figure 5: Corridor of results: Force-displacement diagrams for variations of the d_3 parameter; color coding indicates weighting w.r.t. a Gaussian distribution for the d_3 distribution. Original data points without interpolation are shown.

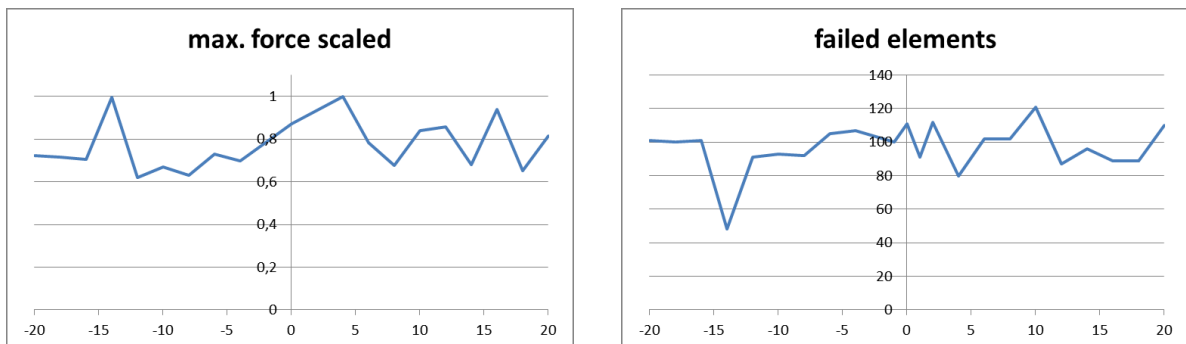


Figure 6: Maximal force, divided by overall maximum, against variation of the d_3 parameter (left); number of failed elements against variation of the d_3 parameter (right).

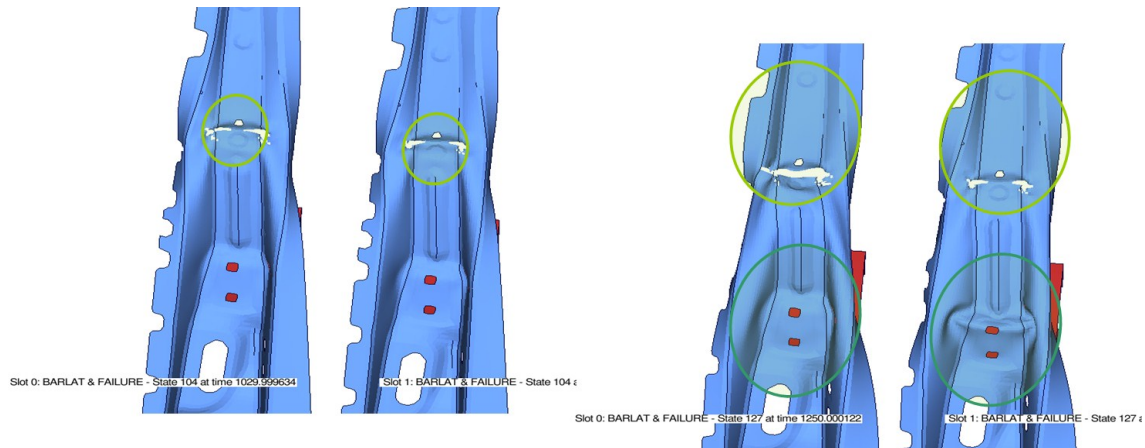


Figure 7: Interplay of a crack with a dent in an early (left) and later (right) time step, found by PRO-CHAIN. Shown are extreme simulation results caused by (non-extreme!) parameter variations.

The large corridor arising in the most decisive part of the ensemble of force-displacement diagrams clearly shows that an optimization process taking global criteria such as maximal force or number of failed elements (Figure 6) into account cannot be expected to produce reasonable results here. The development of a novel set of optimization criteria including robustness measures seems mandatory.

The results for the blank can be summarized as follows. Including the pre-damage information from the forming step as well as variations of thicknesses, strains, damages caused by parameter variations increases the forecasting quality of numerical simulation considerably here. Furthermore, analyzing impacts of these variations gives valuable insight into local behavior of the part considered. In particular, numerical and/or physical instability as well as compensation effects could be studied in detail. In addition, the large impact of variations, stemming from different sources (parameters, numerical/physical instabilities of the model), shows that novel optimization criteria have to be developed. Variations should be taking into account by means of robustness criteria added to a “classical” set of optimization criteria.

4. Conclusions and Outlook

The PRO-CHAIN strategy for statistical analysis of stability, sensitivity and robustness aspects was presented. Its efficiency was demonstrated for analyzing a forming-to-crash process chain for a ZStE340 micro-alloyed metal blank of a B-pillar. Important influences of parameter variations as well as local pre-deformation and pre-damage, as caused by the forming, on the crash behavior could be explained. The PRO-CHAIN strategy already provides efficient tools for analyzing the forming-to-crash process chain.

Several directions will be pursued in future research. First, the statistical methods employed and the design-space reduction will be further enhanced by even more efficient nonlinear methods. In addition, the development of appropriate optimization criteria will be continued. Second, PRO-CHAIN is applicable in a lot of different areas. Another application example in automotive engineering is the casting-to-crash process chain. Several aspects can already be analyzed with PRO-CHAIN. For an exemplary crank, the influence of local shrinkage porosities, coming from the casting process, on crash simulation results could be analyzed successfully [10]. Other application classes include the semiconductor process-to-device-simulation and device-to-circuit simulation chains. PRO-CHAIN can handle also several aspects of these application classes in first examples [11].

References

- [1] Clees, T.; Steffes-lai, D.; Helbig, M.; Roll, K.; Feucht, M.: "Process Chain Forming to Crash: Efficient Stochastic Analysis", Procs. 7th European LS-DYNA User Conference, Salzburg, May 14-15, 2009. Dynamore GMBH.
- [2] M. Helbig, F. Andrieux, D. Steffes-lai, T. Clees: „ Development of a material model for the process chain forming to crash taking stochastic and deterministic influences into account“, Procs. ANSYS Conference & 27th CADFEM Users' Meeting, Nov. 18-20, Leipzig, Germany, 2009.
- [3] Clees, T., Steffes-lai, D., Helbig, M., Sun, D.-Z.: "Statistical analysis and robust optimization of forming processes and forming-to-crash process chains", Procs. 13th ESAFORM Conference on Material Forming, Apr. 7-9, Brescia, Italy, 2010. Springer. Accepted for publication.
- [4] Clees, T., Steffes-lai, D.: "PRO-CHAIN: Efficient Statistical Analysis of Process Chains", in: ERCIM News 81, Special Theme "Modelling and Simulation for Research and Industry", Trottenberg, U., Poutré, H.L., eds., pp. 29-30, 2010.
- [5] Steffes-lai, D., Thole, C.-A., Nikitin, I., Nikitina, L.: "Interactive optimization with DesParO", in: ERCIM News 73, Special Theme "Maths for Everyday Life", Väänänen, J., Trottenberg, U., eds., pp. 29-30, 2008.
- [6] Clees, T.: "Computer-Aided Robust Design for Multi-Disciplinary Processes", Procs. 10th MpCCI Userforum, Feb. 17-18, 2009, Fraunhofer Institute for Algorithms and Scientific Computing SCAI, Sankt Augustin, German. Fraunhofer Publication Series, ISSN 1860-6296, pp. 20-29, 2009. Available from www.scai.fraunhofer.de/mpcci.
- [7] www.scai.fraunhofer.de/diffcrash.html
- [8] www.scai.fraunhofer.de/desparo.html
- [9] www.scai.fraunhofer.de/scaimapper.html
- [10] FhG Internal Program "CAROD – Computer-Aided Robust Design", Grant No. MAVO 816450, www.carod.fraunhofer.de
- [11] FhG Internal Program "HIESPANA – Hierarchical Simulation of Nano-Electronic Systems for Controlling Process Variations", Grant No. MAVO 817759, www.hiespana.fraunhofer.de