INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

DESIGN 2010

CUSTOMIZED DESIGN PROCESSES OF POLYMER PARTS BY COMPUTER AIDED TOOLS

J. Zapf, B. Alber-Laukant and F. Rieg

Keywords: CAx, FEA, simulations, workflow

Preface

To remain competitive in global markets most product development processes are conducted by computer-aided tools (CAx-tools) to accelerate product design. But because of missing simulation strategies and procedure guidelines the development process is constricted and hence slowed down. Main topic of article is to show a methodical approach to handle complex processes supported by computer-aided tools. By detailed analysis of these programs, their functionalities and complex interactions can be disclosed. Product development as a whole consists of many sub-processes that have to be performed in specific orders, iterations and linked to certain product-specific data. Depending on their relations single sub-processes can be composed to complete process-chains as this contribution will explain. In the second part of this article, this procedure, supplying the developer on different process levels and steps, is to be shown by means of a practical example of product design, the elastomer damping elements of claw couplings. The usage of polymers has successfully been established even in high performance fields. But application in these areas assumes correct dimensioning of the polymer part. It is possible to predict material behaviour by computer-aided tools, such as finite element analysis. Nonlinear material properties can be mapped and scaled to a computer model by skilled combination of virtual product design and prototype testing using the method presented.

1. Introduction

By consistent use of computer-aided tools crucial advantages in competition can be achieved in product development process. Commonly synthesis and analysis software are used to anticipate part behaviour matching experimental data with material models. Creating virtual prototypes is an efficient scheme to avoid mistakes and unnecessary iterations in early stages of design process which helps lowering efforts and hence costs (Figure 1).

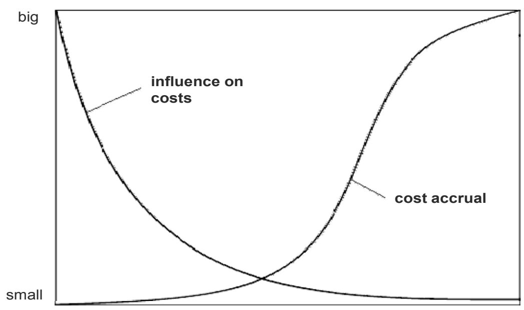

Figure 1. Cost influence in design processes (according to: [Ehrenspiel 2005])

But due to rising product complexity several programs have to be used to completely comprehend the products' design. One methodical approach for targeted linking of CAx-tools among themselves is the ICROS-method (Intelligent CROss-linked Simulations) [Alber 2006] to exploit full capabilities of modern CAx-tools [chapter 2.1]. Another issue shown in this contribution is consideration of nonlinear material properties especially of thermoplastic polyurethanes (chapter 2.3).
Chapter 3 shows the applied combination of both methodical approaches at an example of power train engineering.

2. Theoretical foundations

2.1 ICROS

The origins of the ICROS-approach were based on the interdependencies of computer-aided strength determinations and manufacturing tools like finite-element simulations and injection moulding for fibre-reinforced polymers [Alber 2007]. Furthermore attribute-property-coupling has been added [Vajna 2009]: Parts' attributes can only be generated by synthesis tools, such as CAD (Computer-Aided Design) software. Their properties have to be verified by analysis tools like CAM (Computer-Aided Manufacturing) programs. Therefore these tools were classified in adequate categories within the scope of the Bavarian research cluster FORFLOW [Zapf 2009] (Figure 2, Figure 3).

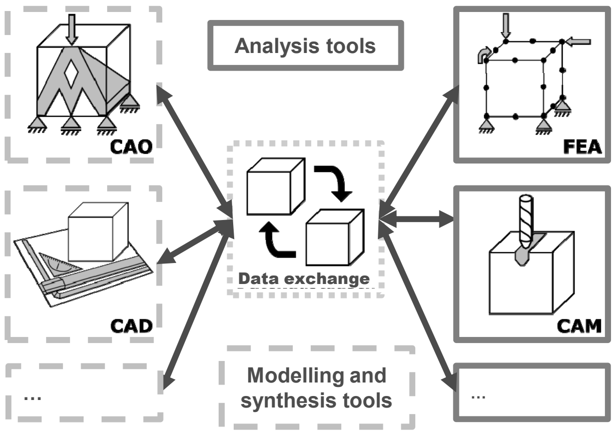

Figure 2. CAx-tools categorized in synthesis and analysis tools

CAx-tools sorted in that way can properly be linked to complete process chains. These chains are to be provided with well defined flybacks: if required properties are not fulfilled, preceding predefined synthesis steps are reexecuted without having to pass through the whole development process again.
The support of simultaneous and concurrent engineering is a crucial point concerning an efficient product development [Vajna 2009]:

- Simultaneous engineering (SE) involves products' synchronized itemization and linking the appurtenant manufacturing method including their interactions.
- Concurrent engineering (CE) marks the parallel and contemporaneous implementation of simultaneous executable working stages.

An essential preference to provide a fully integrated design process is widespread knowledge about programs' capabilities, interactions and interdependencies [Troll 2008]. Determining realistic stresses and displacements, for example, of parts mostly comprise nonlinear material behaviour. Hence an appropriate tool capable of matching material model calculation has to be chosen. Except for simplification of the model, linear approaches are selected wilfully. Consequently modelling and calculation strategies can be developed, standardizing workflows [Hackenschmidt 2009].
Therefore the ICROS-method is a multi-layer approach, containing overall process-level information such as properly linked tools, as well as direct user support on lower process levels. On top level the ICROS-method is located, providing information about proper linkage of CAx-tools. To support the developer on sub process layer the right piece of information is required at the right time, such as

necessary input documents and output to be generated, but also tutorials and experiences of former projects. This data has to be linked to the project as well as to the process and exact sub process e.g. by a PDM/PLM-system such as for example the ProcessNavigator, which has been derived from the FORFLOW research cluster, too [Faerber 2009, Jochaud 2009].

	CAD	CAM	FEA	ERP	PDM
Category	Synthesis	Analysis	Analysis	Organization	Organization
Task	modelling of mechanical parts	manufac-turing and feasability safeguarding	numerical analysis of e.g. strength	work, logistics and production planning	computer aided data management
Result	virtual prototype with additional information	machining time, costs and feasability	reproducable part evaluation	work processing sheets, …	integrated documen-tation

Figure 3. Overview on CAx-Tools (selection)

Unnecessary iterations and rework can be reduced significantly by this modus operandi. Via consistent application of computer aided tools from the beginning of the design process this methodical approach can support the whole procedure and accelerate it to lead to competitive products. Pushing processes to a preferably abstract level, reutilization potentials for similar demands can be tapped, as discussed later on in chapter 3.

2.2 Shaft couplings

An example in the field of drive systems and components is shown - torsionally flexible claw couplings - to break down and adapt this technique to praxis-relevant stages, These machine elements are used as shaft joints to provide low-grade oscillations, and low-loss torque transmission. Furthermore axial, lateral and angular displacements can be compensated to a certain degree. These parts are available in different sizes, dimensioned up to torques of 600 Nm and 28.000 revolutions per minute.

Impact and vibration damping is realized by star like damping elements, made of elastomeres, located between two halves of the coupling. Available in several shore hardnesses these damping elements can be used for several different operation purposes. Those polymer parts are considered for further examinations.

2.3 Material properties

Due to their widespread properties polymers have proven successful in wide ranges of product design. Their low specific weight, combined with manifold shaping technologies and low cost raw material makes them a popular choice as design material, even in highly stressed domains, though manufacturing and moulding processes have a major influence on the strongly nonlinear material behaviour. These aspects render calculations complex, but they prove nevertheless solvable by the means of modern computer-aided tools.

The damping components examined, are made of thermoplastic elastomers (TPE) - in this case thermoplastic polyurethane (TPU). With properties located between thermoplasts and elastomers this material class combines both their advantages avoiding most of their disadvantages. The thermoplastic part renders possible injection die moulding as manufacturing method which is a means of mass production helping to lower manufacturing costs. Elastomer material properties provide the elastic

damping capacity. Another characteristic is the irregular physical interlacing of the macromolecules: this physical effect is based on van der Waals forces and dissolves at rising temperature. Physical interlacing strongly depends on and varies with manufacturing constraints, such as mould filling, age and predrying of the synthetic granules. A cold mould causes faster cooling of the melt, which prevents crystallisation, equally as mould-release agents on silicone basis.
Therefore no norm specimen like tension rods can be used for strength determination, as the shape of the damping elements differs too much. So a special holding tong was designed to determine tensile strength. By this, the maximum force needed to tear one lobe apart can be measured. For the examinations three different materials were available, with different Young's modulus and Shore hardness (Table 1).

Table 1. TPUs

material name	Young's modulus, N/mm²	Shore hardness
material 1	25	85 (A)
material 2	256	96 (A)
material 3	948	98 (A)

Corresponding series of tests have been executed on a Zwick tensile testing machine for each material and force-displacement curves have been converted in stress-strain-diagrams.

2.4 Calculation tasks

To represent real material behaviour in computer simulations several material models implemented in common FEA software are possible:

- First of all linear-elastic FEA can be used, to simplify material data needed an to keep computation times low. The main disadvantage is the lack of nonlinear effects which cannot be considered.
- The second model procurable is the elastic-plastic approach. As resulting stresses of tensile strength test refer to the original profile but don't yet consider necking effects, true stress and plastic strain values have to be ascertained. Remaining deformations also can be accounted for in opposition to linear calculations.
- As quite elastic materials can bear high deformations also hyperelastic material models are suitable.

Table 2 recapitulates the respective input data required, depending on the material model chosen.

Table 2. Input data for linear-elastic, elastic plastic and hyperelastic material models

material model	Young's modulus	Poisson ratio	nominal stress	nominal strain
linear-elastic	yes	yes	no	no
elastic plastic	yes	yes	yes, converted into true stress	yes, converted into plastic strain
hyperelastic	yes	yes	yes	yes

CAx-tools to fulfil requirements for comparative calculations though have to support nonlinear FEA as well as the three material models selected.

2.5 Workflow

The issue "workflow" has to be contemplated ambilateraly. On one hand there is the product design process - in this case injection moulding - based on attribute-property-couplings; on the other hand the corresponding simulation strategies for similar calculation tasks are needed.
Synthesis programs interplaying with analysis software to safeguard the design are the common tools used for the design process as a whole. Providing a methodical framework the programs' interactions can be described in a matrix. Depending on the data needed to transfer in between CAx-tools, the derived interdependencies can be pointed out accordingly distinct.

For example CAD software passes geometry, features and parameters to an FEA-software. After strength determination this program returns maximum stresses in certain areas and hence design proposals for possible iterations with the preceding software used. So the FEA-program has a major influence on the CAD design and vice versa, whereas other interdependencies are less incisive (Figure 4).

Inter-action (weak … strong)	CAD	FEA	CAM	Moulding
CAD	geometry, features, parameters, history	geometry, features, parameters	geometry, features, parameters	geometry, features, parameters,
FEA	max. strength, design proposals	safeguarding	design proposals	mechanical safeguarding, parameter proposals
CAM	feasability, design proposals	design proposals	safeguarding, optimization	design proposals for mould
Moulding	quality, feasability, design proposals	mould quality, fiber orientation	design proposals for mould	safeguarding, optimization

Figure 4. CAx-interdependencies (selection)

Using the ICROS-method to compile CAx-tools appropriately alternatingly synthesis and analysis tools are used (Figure 5). The basic shape of the part is generated in a CAD-software [1], followed by moulding simulations [2] for quality prediction and finite element analysis [3] for mechanical safeguarding. CAD-tools are used to design the die casting cavity [4], whose feasibility is checked by a CAM simulation [5]. Having passed all examinations successfully real prototypes and tests under usage conditions can be conducted.

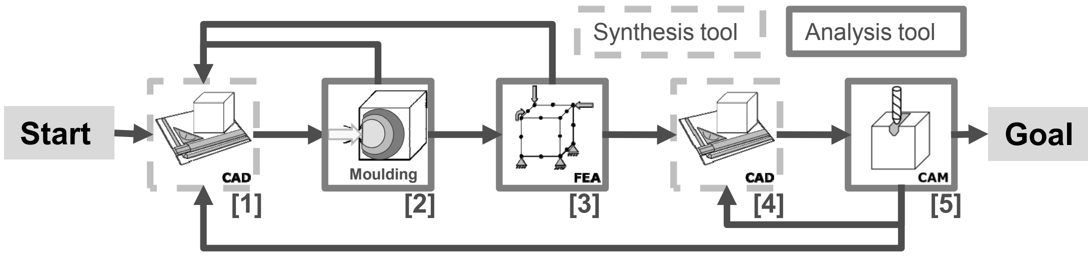

Figure 5. CAx-chain for injection moulding

On a sublevel simulation strategies for each tool used can be deduced a similar way. Given that not only this CAx-chain deals with nonlinear material data a standardized procedure can be derived enhancing follow-up projects to be handled more efficiently.

First of all real material data is to be acquired by material tests such as tensile or compressive strength tests or data sheets of materials' producers. These curves have to be conditioned and converted to fit the corresponding material models. According to the FEA-tool programs specialities must be considered to import the formatted data properly. This procedure is generated in a generic way which renders reutilization for similar projects possible [Figure 6].

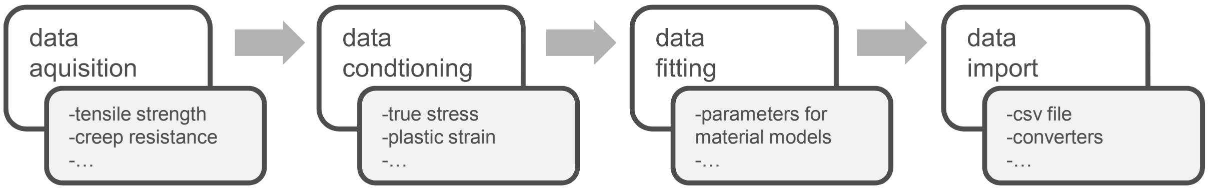

Figure 6. Standardized data aquisition for FEA

3. Practical example

3.1 Simulation

Modern product development implies increasingly usage of computer-aided tools. To evaluate the part behaviour under operation conditions the single loads have to be exposed. Transmitting torque the flanks experience pressure loads and due to high revolutions also centrifugal forces. As opposed to the torque which influences the pressure only linearly, centrifugal forces rise quadratically. To simulate product misuse the revolutions per minute are set to 40000. Containing all modules necessary - linear, as well as elastic-plastic und hyperelastic material models - the FEA-tool Abaqus of DS-Simulia was used to create the virtual prototype, meshed with quadratic tetrahedrons. Material data was prepared according to chapter 2.5 and imported as Abaqus input deck (Figure 7). To emulate bearing between coupling's claws a virtual fixed-point was used.
According to corresponding data sheets loads have been applied. Two different test runs were conducted. First one only complies centrifugal forces whereas the second additionally contains torques (applied as pressure loads).

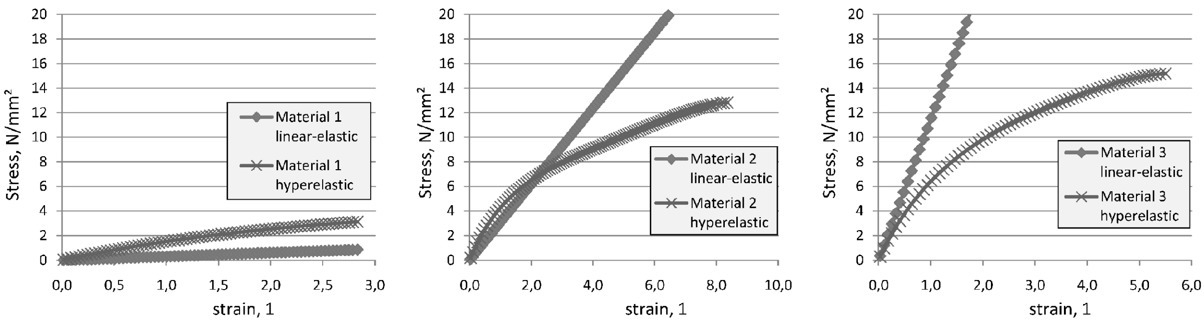

Figure 7. Stress-strain-diagrams for material 1 (left), material 2 (middle) and material 3 (right)

3.2 Results

To be able to compare material behaviour under different load cases, only deformations are contemplated [Alber-Laukant 2008]. These deformations are maximum values of the damping stars' tips (Table 3).

Table 3. calculation results

	Series 1: deformation, mm (centrifugal forces only)		Series 2: deformation, mm (centrifugal forces and torque)	
	linear	hyperelastic	linear	hyperelastic
material 1	2,299	0,332	2,387	0,346
material 2	0,218	0,089	0,264	0,106
material 3	0,062	0,061	0,075	0,077

Table 3 shows only small differences between that at high revolution speeds centrifugal forces outweigh torques. Linear simulations ran without any problems. Elastic-plastic material models aborted due to errors, as the strain increment exceeded fifty times the materials' yield strength, leading to numerical instabilities. Hyperelastic material models, fitted for rubberlike materials, are given the opportunity of numerical stability checks. The Ogden-model order one proved most stable.

3.3 Result

Numerical instabilities of elastic-plastic approach can originate form the fact, that this model being intended for metals: high strains lead to remaining plastic deformation on metals, whereas rubberlike materials reform mostly elastically.
Differences between hyperelastic calculation and linear results can be explained as follows:

- Concerning material 1, the fact that hyperelastic model's deformations are much stiffer than the elastic ones is based on that curve being far above elastic line (Figure 7).
- In case of material 2 both curves intersect. After the intersection point the hyperelastic model computes more supplely than the linear one. Up to that point (approximately at 230% strain) it's stiffer, like in this case, as deformations are below that critical point.
- The hyperelastic curve of material 3, which is the most inflexible material examined, lies below its elastic line. But as both lines are nearly parallel at low strains, values are quite the same.

In areas of maximum revolution rates torque had no significant influence on TPU-damping elements examined. So for continuative research computer models can be simplified containing less loadcases with minor influence on the results, to minimize preliminary efforts and calculation times. The corresponding ICROS-scheme can therefore be adapted and optimized for more efficient procedures. Despite ambitious efforts taken with complex and powerful material models, matching with deformations measured in practical tests show variations by factor two to three. For the area examined (torsionally flexible claw couplings) these predictions are sufficiently precisely, but render moot the usability of material models available for this field of application. This necessitates more research demands.

4. Synopsis

The presented methodology allows a more explicit adaption to the particular development context. The importance of contextsensitive user support for product development to make processes more efficient is one of the main tasks in modern product design. Using design and simulation strategies as proposed in chapter 2, further examinations, as needed in the use case shown, can be conducted more efficiently. By assigning product and process data to projects, profound databases can be created, helping to handle varying design jobs in a more sophisticated way. Well-defined schemes complete the approach by making knowledge available for a wider range of designers throughout the company, rendering follow-up research more standardized and offer hence better methodical procedure. The result TPUs only differing in Shore hardness showing such varying properties is a remarkable, and can be used in further examinations. Concerning the considered material models several conclusions can be derived from this study:

- Due to generally nonlinear material properties linear-Hookean behaviour cannot be assumed without constriction.
- Elastic-plastic material models are not suitable for rubberlike materials with high strains in combination with low Young's modulus causing numerical instabilities in Abaqus.
- To represent thermoplastic elastomers hyperelastic material models are in comparison more adequately fitted, being able to handle large reversible deformations.

This example is proving no general predictions can be made about the suitability of hyperelastic material models for this material class. Hence each case has to be examined individually. Material models implemented in FEA software meet limitations concerning this simulation task. For follow-up research, development of new material models, such as e.g. Abaqus user defined materials (UMAT), would be a proper solution statement. Therefore prediction of thermoplastic polyurethanes still remains an interesting research field. But by consistent application of the ICROS-method, combining synthesis and analysis tools, optimization potentials can be opened up, providing recommendations on proper program usage. Cross linked computer-aided tools, providing simulation strategies on multiple layers, allow efficient design processes. Therefore the ICROS-framework can be regarded as a powerful method combining virtual product design and practical prototype studies.

References

Alber-Laukant, B.: Struktur- und Prozesssimulation zur Bauteildimensionierung mit thermoplastischen Kunststoffen: Validierung von Werkstoffbeschreibungen für den technischen Einsatz. Fortschritte in Konstruktion und Produktion, Band 10, Diss. Universität Bayreuth, 2008.

Alber, B.; Rieg, F.; Hackenschmidt, R.: Product design with high-tech-polymers – Practical use of CAE-Tools with cross-linked simulations and experimental verification. In. Materialpruefung, Carl Hanser Verlag, Volume 49, pp. 402-407, 2007.

Alber, B.; Hackenschmidt, R.; Dolsak, B.; Rieg, F.: ICROS-The Selective Approach To High-Tech Polymer Product Design-Modelling And Experimental Verification. In: Proceedings of the Design 2006, Dubrovnik, 2006.

Ehrenspiel, K.; Kiewert, A.; Lindemann, U.: Kostengünstig Entwickeln und Konstruieren - Kostenmanagement bei der integrierten Produktentwicklung. Spinger-Verlag, Berlin, Heidelberg, 2005.

Faerber,M.; Jochaud, F.; Stöber,C.; Jablonski S.; Meerkamm, H.: Knowledge-oriented process management for DfX. In: Proceedings of the Design 2008, Dubrovnik, 2008.

Hackenschmidt, R.; Troll, A.; Rieg, F.; Dolsak, B.: Optimizing the Use of Multiple Simulation Programs by Intelligent Cross-linked Simulations (ICROS). In: NAFEMS Seminar: „Simulation Data Management - Integration into the Product Development Process“, Wiesbaden, 2009.

Jochaud, F,; Jablonski, S.: Process oriented knowledge management for product development. In: Proceedings of the First International Conference on Integration of Design, Engineering and Management for innovation IDEMI09, Porto, Portugal, 2009.

Krehmer, H.; Eckstein, R.; Lauer, W.; Roelofsen, J.; Stöber, C.; Troll, A.; Weber, N.; Zapf, J.: Coping with multidisciplinary product development – a process model approach. In: International Conference on Engineering Design, ICED'09, Stanford, CA, USA, 2009.

Troll, A.; Zapf, J.; Faerber, M.; Jochaud, F.: Prozessorientierung beim CAD-Datenaustausch. In: CAD-CAM Report, 8th Issue, August 2008, Hoppenstedt Publishing GmbH, 2008.

Vajna, S.; Weber, C.; Bley, H.; Zeman, K.: CAx für Ingenieure: Eine praxisbezogene Einführung, 2. Auflage, Springer, Berlin, 2009.

Zapf, J.: Kopplung und prozessorientierte Verknüpfung der Methoden und Werkzeuge. In: Meerkamm, H.; Henrich, A.; Jablonski, S.; Krcmar, H.; Lindemann, U.; Rieg, F.: Flexible Prozessunterstützung in der Produktentwicklung: Prozesse - Daten - Navigation. Shaker-Verlag GmbH, Aachen, 2009.

Dipl.-Ing. Jochen Zapf
Scientific Assistant
Department of Engineering Design and CAD
University of Bayreuth
Universitaetsstr. 30, D-95447 Bayreuth, Germany
Telephone: +49 921 55 7224
Telefax: +49 921 55 7195
Email: Jochen.zapf@uni-bayreuth.de
URL: http://www.uni-bayreuth.de/departments/konstruktionslehre