Integrative Optimization of injection-molded plastic parts
–
Multidisciplinary Shape Optimization including process induced properties

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Summary:

The Integrative Approach described in this paper incorporates effects of the part's manufacturing process (here: injection molding) into a new workflow for optimization of the part performance. The new approach is able to close the gap between process simulation/optimization and mechanical simulation/optimization.

New classes of design variables linked to the manufacturing process complicate the workflow of the optimization. The newly introduced optimization discipline "manufacturing simulation" acts as a preprocessing step for all other disciplines while it can simultaneously be seen as a full optimization discipline as well. Shape optimization by morphing is included as well and further complicates the workflow. The paper outlines the necessary changes in the workflow and discusses the influence in different optimization scenarios.

In a first example the prototype workflow based on state-of-the-art software packages and newly developed script and interface tools was designed, defined and proved to work. A screening phase as well as an optimization had been done with reasonable results. The part considered in this study is a thermoplastic structure, manufactured by injection molding. The most important process induced changes are based on the anisotropic orientation of short glass fibers in the material during filling. These effects had been taken into account using BASF's ULTRASIM™ software. Filling simulation as well as warpage simulation and a mechanical impact simulation were used as single optimization disciplines.

Keywords:

ULTRASIM™, Integrative Simulation, Morphing, Shape Optimization, Injection Molding, Short fiber-reinforced thermoplastic

1 Motivation – The Integrative Approach

For parts made of short fiber-reinforced thermoplastic, injection molding is a common manufacturing process. To describe the mechanical behaviour of those parts correctly, it is essential to take into account the process induced anisotropy. Many publications in recent years underline this statement [[1]   Glaser, S.; Wüst, A.: "Computer Modelling", Kunststoffe plast europe 3/2005, translated from Kunststoffe 3/2005 pp. 132-136, Carl Hanser Verlag, Munich, 20051[1] Glaser,   S.;   Wüst,   A.: "Computer Modelling", Kunststoffe plast europe 3/2005, translated from Kunststoffe 3/2005 pp. 132-136, Carl Hanser Verlag, Munich, 2005], [2], [3]. Due to the transient melt flow in the injection molding tool the fibers are aligned. This induces mechanical anisotropy. In plastic materials with common glass fiber contents of 30% one can observe a factor of two in the yield stresses. This factor underlines, that the anisotropy effect should not be neglected.

Consequently, if an injection-molded part is subjected to a numerical optimization to improve its mechanical behaviour, the influences of injection molding have to be covered as well. The integration of process induced influences on the mechanical part behaviour shall be furthermore named as the Integrative Optimization Approach or Integrative Approach. On the contrary the term Standard Optimization Approach or Standard Approach stands for an approach which does not cover the process induced property changes (Figure 1).
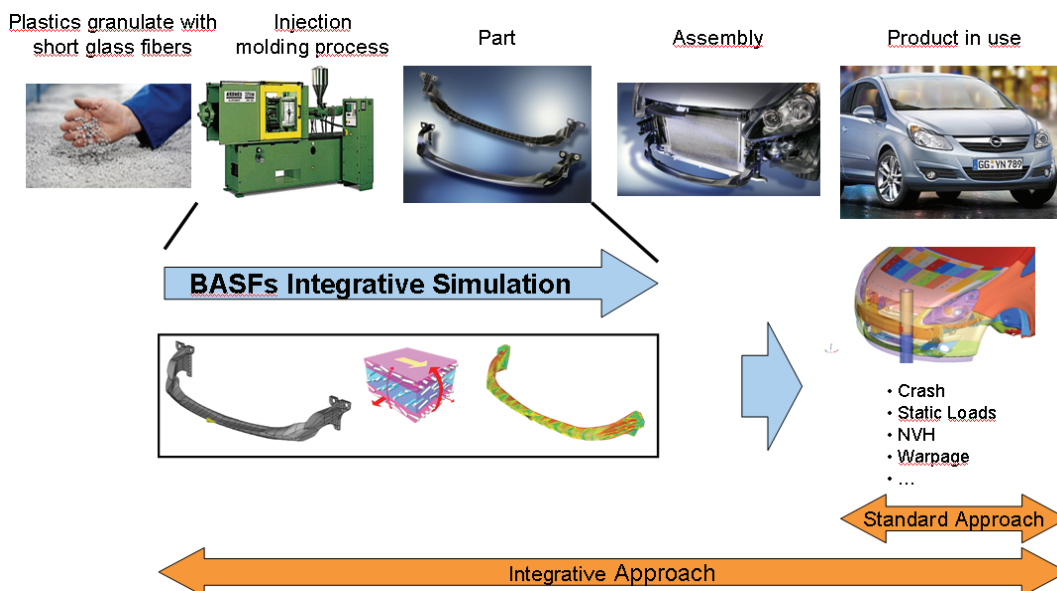

Figure 1: Standard Approach versus Integrative Approach

2 Influence of the Integrative Approach on the design variable vector

The design variable vector (DV-Vector) contains parameters which possibly have an influence on the performance of the part. If no Integrative Approach is used, mostly parameters are used which directly describe the geometry of the part. The most important ones are different part wall-thicknesses and shape parameters (e.g. defined by morphing) which may change part contours or the height of ribs.

By using the Integrative Approach, the influence on the components of the DV-vector in the optimization can be grouped in 3 classes:

- **Standard DVs remain fully unchanged**: An example for this is a DV describing a part of the total structure which is not produced by injection molding, like a metal insert.
- **Standard parameters which were also used in a Standard Approach now have to be also seen as process relevant**: A wall thickness in an injection-molded part is an example for this: Changing it means a change in geometry as well as a change in the melt flow. This will directly affect the anisotropic mechanical behaviour.
- **New, process related parameters will be added to the DV-vector**: The gate location where the melt enters the cavity is one of many examples. It is obvious that the flow pattern, which depends

on the gate location, directly changes the anisotropic distribution of the fibers which affects the mechanical behaviour. Fill time or melt temperature are other parameters belonging to this class.

3 Influence of the Integrative Approach on the optimization workflow

3.1 Workflow for Standard Approach

A simplified Standard Approach optimization workflow is shown in Figure 2.
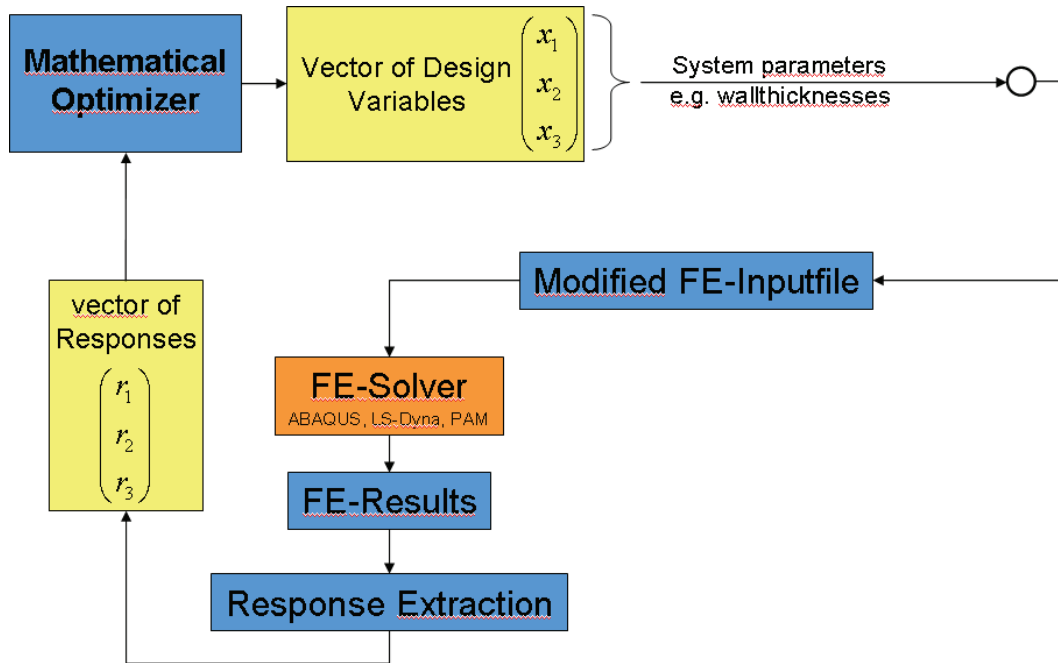

Figure 2: Workflow for Standard Approach

The numerical optimizer writes a DV-vector to the workflow and reads a response vector from the workflow. In a standard CAE based workflow, all parameter values referenced in the DV-vector have to be incorporated in the FE input files. For the sake of simplicity only a single discipline, non-morphing approach is shown in Figure 3.

3.2 Workflow for Integrative Approach – single disciplinary

In the case of the Integrative Approach the workflow has to be redefined according to Figure 3. Now, a preceding step which covers the injection molding process becomes necessary. The extended DV-vector addresses all types of parameters according to chapter 2.
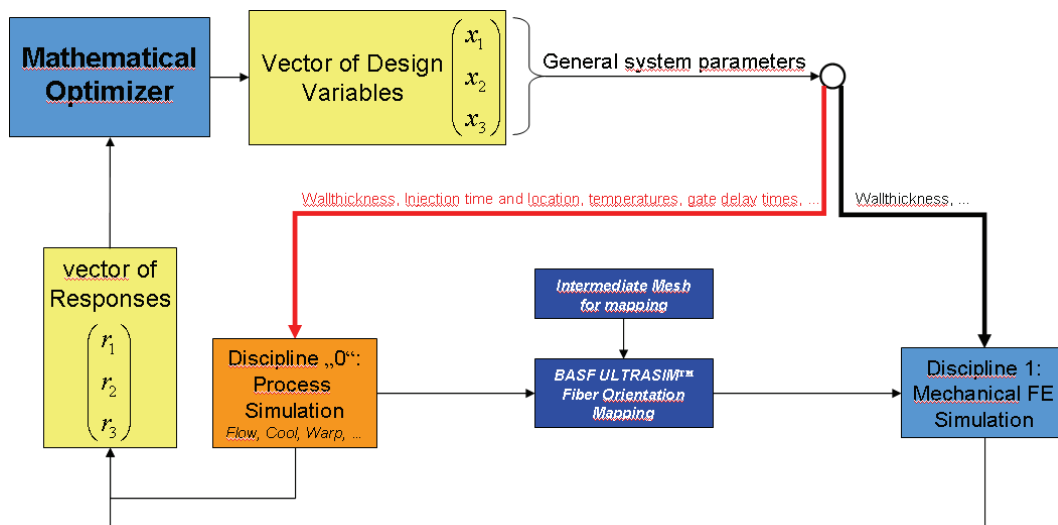
Figure 3: Workflow for the Integrative Approach

Fiber orientation mapping as well as material modelling is done by BASF FIBER, a software developed in BASF. BASF's ULTRASIM™ approach which is based on FIBER, is able to account for all effects which are typical for thermoplastic materials like

- anisotropy induced by the injection molding process
- nonlinearity of stress strain behaviour
- strain rate dependency
- tension compression asymmetry and
- failure behaviour which is able to account for all above mentioned effects

3.3 Workflow for Integrative Approach – multidisciplinary

In case of multidisciplinary optimization, the above mentioned changes due to the Integrative Approach have to be applied to all involved disciplines. This further complicates the workflow (Figure 4). If shape parameters have to be applied defined by morphing, it is crucial to extend the morphing process to the FE mesh used for the injection molding process as well. In addition to that, a mesh mapping procedure - used to map rheological based results from the fluid mesh to the mechanical meshes - normally affords an intermediate mesh which also has to be morphed.
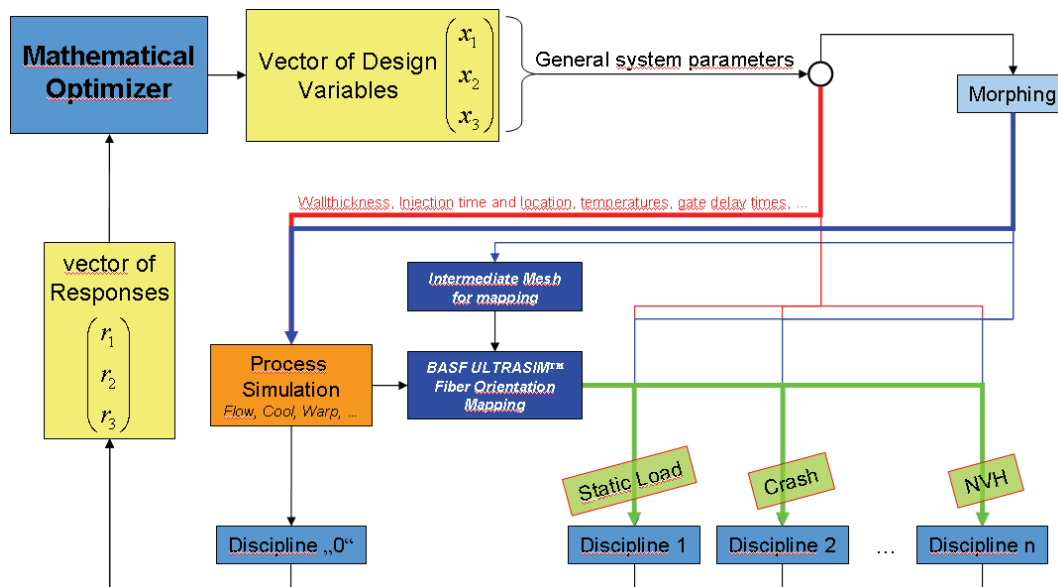

Figure 4: Workflow for Integrative Approach with multiple disciplines

An important fact to be noticed here is that the incorporation of the injection molding process is not comparable to introducing a new discipline. That is because it is only needed once as a preprocessing step, but influences all other disciplines. At the same time it cannot be handled as a pure preprocessing step, because the variables described in chapter 2, class 0, are also subject to change during the optimization. This last, integrative aspect allows to adapt the process conditions to improve the mechanical behaviour!

4 Software used in the workflow for the Integrative Approach

It is obvious, that the implementation of the procedures described in chapter 3 depends on the software available. Currently the following software tools have been used:

Mathematical optimizer:	LS-OPT 3.3
Morphing Tool:	ANSA 12.1.5
Filling Analysis:	MOLDFLOW 6.2
Mechanical Analysis:	LS-Dyna V971 / MOLDFLOW 6.2 Warp
Response Extraction:	C-Shell Scripting, HyperView 9.0 & Templex, META Post
Optimization Visualization:	D-SPEX 0.3.7

In addition to that a tool had to be developed to couple LINUX/UNIX based tools to the Windows based MOLDFLOW software.

A procedure which is able to use and couple all necessary software modules to the workflow described was developed at BASF Performance Polymers in the Simulation engineering group. An example for the use of the workflow and tools will be shown in the next chapter 5.

5 Example: multidisciplinary shape optimization including process induced properties

As a first test example for the workflow, the part shown in Figure 5 is used to illustrate the Integrative Approach. The outer dimensions are approx. 220x220x40mm and the initial wall-thicknesses vary in the range of 1.5 to 3 mm. The part shown only exists virtually as a test geometry. The filling simulation is based on a Ultramid® B3WG6CR, a PA-GF30 with short glass fibers. This material was especially developed for crash applications. Real parts made of this material are the Lower Bumper Stiffeners for the platforms of the current Opel Corsa and the Insignia.
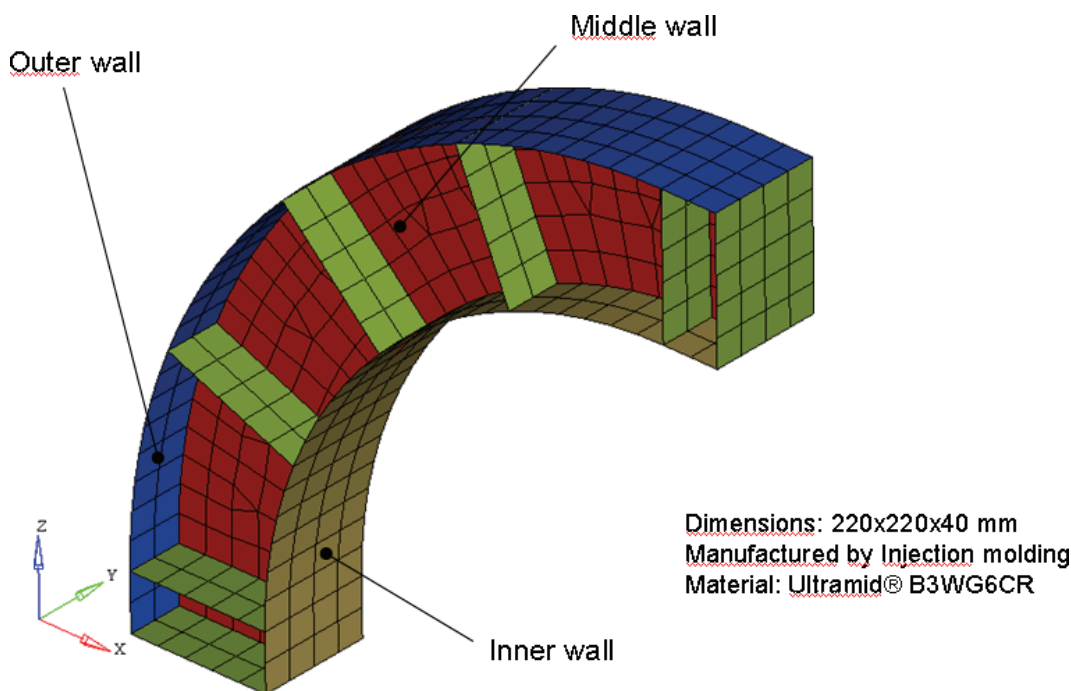

Figure 5: Example to illustrate the Integrative Approach

5.1   Disciplines

The following disciplines A to C are incorporated in the optimization loops:

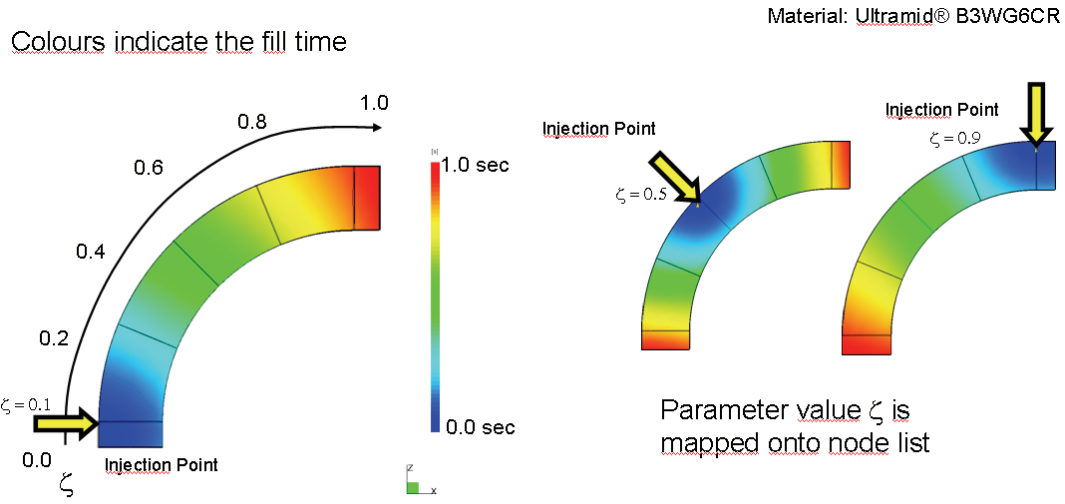A   Filling Study – MOLDFLOW Fill+Pack
The part is filled with varying gate locations according to Figure 6. Other process parameters are not varied for the sake of simplicity. The discrete injection location has to be defined by means of an injection node. The discrete node numbers were parameterized along a geometric line to achieve continuous parameter values.

B   Warpage Analysis – MOLDFLOW WARP
Based on the process conditions and the resulting fiber orientation the part will warp after it is removed from the tool. Warpage is induced by the shrinkage due to the solidification of the material during the cooling phase. It has to be kept in a certain limit which is influenced by manufacturing tolerances. A warpage result based on a fixed lower end of the structure is depicted in Figure 7.

C   Impact Analysis – LS-Dyna
To consider an impact event, a guided impactor (in z-direction) is modelled, which contacts the part with a given energy (Figure 8). The mass of the impactor is 30 kg, the initial z-velocity is set to -1 m/sec.

Colours indicate the fill time

Material: Ultramid® B3WG6CR

Parameter value ζ is mapped onto node list

Additional process DVs which could be used in Filling Simulation:
Melt temperature, tool temperature, injection time, injection location, …
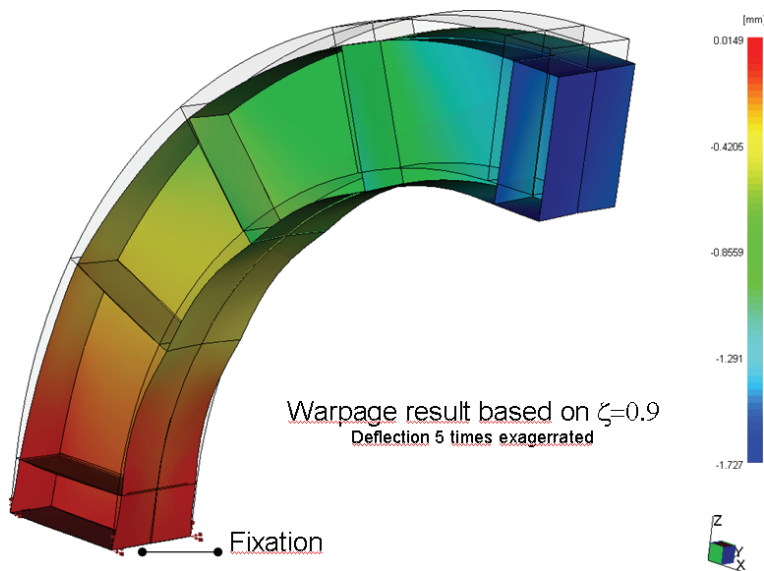
Figure 6: Parametric Definition of Injection Point

Warpage result based on ζ=0.9
Deflection 5 times exagerrated

Fixation

Figure 7: Warpage Simulation with Moldflow

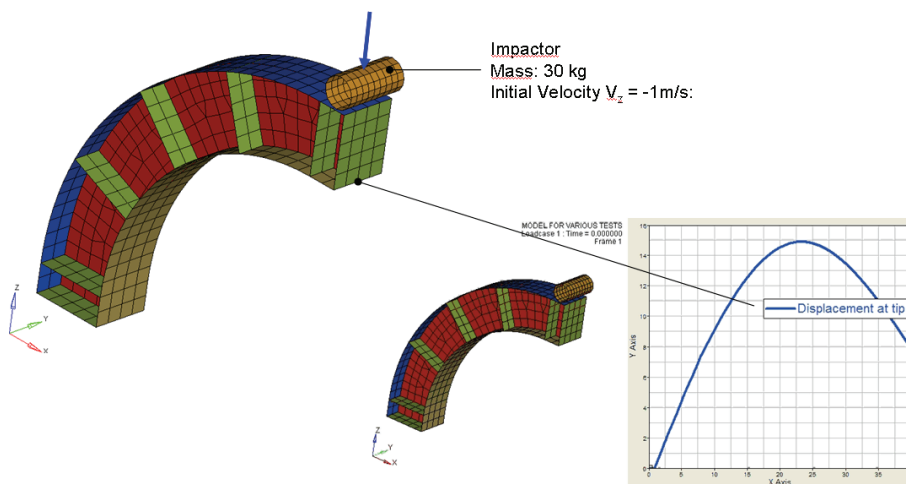

Impactor
Mass: 30 kg
Initial Velocity Vz = -1m/s:

Figure 8: Impact Simulation with LS-Dyna, Impactor guided in z-direction

5.2   Shape change defined by Morphing

Morphing is applied to the structure as depicted in Figure 9. As already pointed out the morphing operation has to be applied on the mesh for fill and warp simulation as well as on the mechanical mesh used for LS-Dyna.
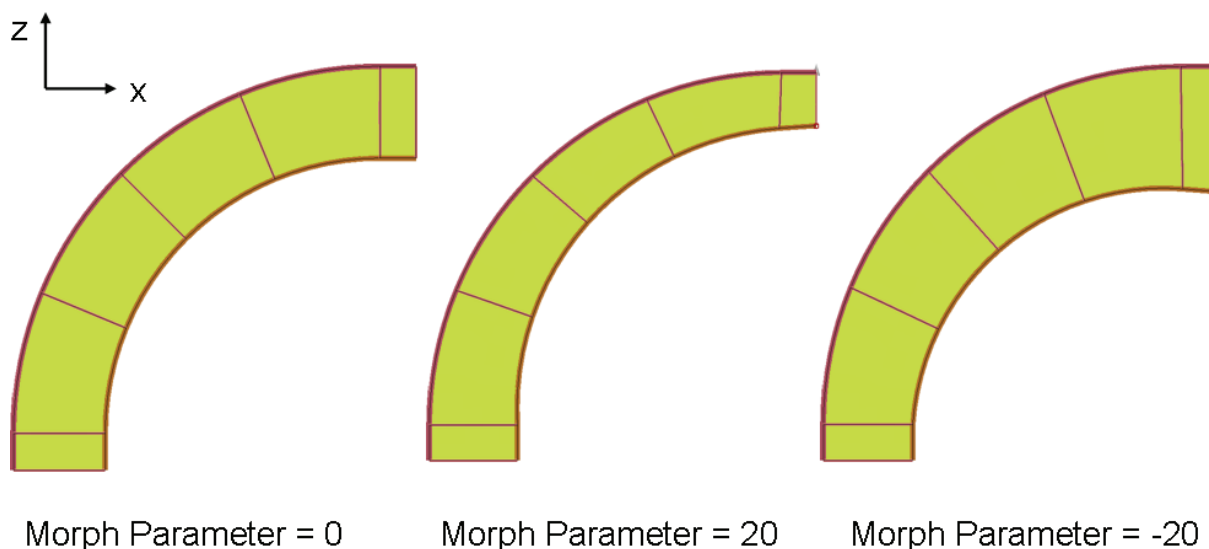

Morph Parameter = 0   Morph Parameter = 20   Morph Parameter = -20

Figure 9: Visualization of shape changes by morphing

5.3   Result mapping

To prepare the FE model for the mechanical run with LS-Dyna, it is necessary to read the orientation distribution values calculated by MOLDFLOW for every new iteration. Then, the material modelling (BASF ULTRASIM™) is applied and the anisotropic material behaviour is determined, based on a user defined material subroutine.

5.4   Summary of design variables and responses

In the following table, the DVs and responses used are listed. The DVs are grouped according to the classification given in Chapter 2. The disciplines to which the DVs and responses are linked are marked to point out the relations in the problem considered.

	Type	Discipline	Initial range
Inner wall thickness	DV	A, B, C	2 mm – 5 mm
Outer wall thickness	DV	A, B, C	2 mm – 5 mm
Middle wall thickness	DV	A, B, C	2 mm – 5 mm
Gate location parameter	DV	A	0.1 – 0.9
Injection Time	DV	A	const. 1.0 sec
Melt Temperature	DV	A	const. 280°C
Tool Temperature	DV	A	const. 85°C
Morph parameter	DV	A, B, C	-35mm … +25mm
Part mass	Response	A or B or C	-
Displacement due to warpage	Response	B	-
Displacement due to impact	Response	C	-

Table 1: Design variables and Responses overview

6 Screening - Optimization results

6.1   Screening Phase

As a first step, the DVs had been varied in a screening step based on a space filling algorithm with 30 jobs. A sensitivity analysis using an Anthill Correlation plot shows the influences of selected parameters on the objective (Figure 10). D-SPEX was used to visualize and explore the data. Two wall-thickness DVs and the morphing parameter turned out to have the highest influence on the

warpage and impact displacement as well as on the mass. The displacement caused by warpage is mainly influenced by the injection location.
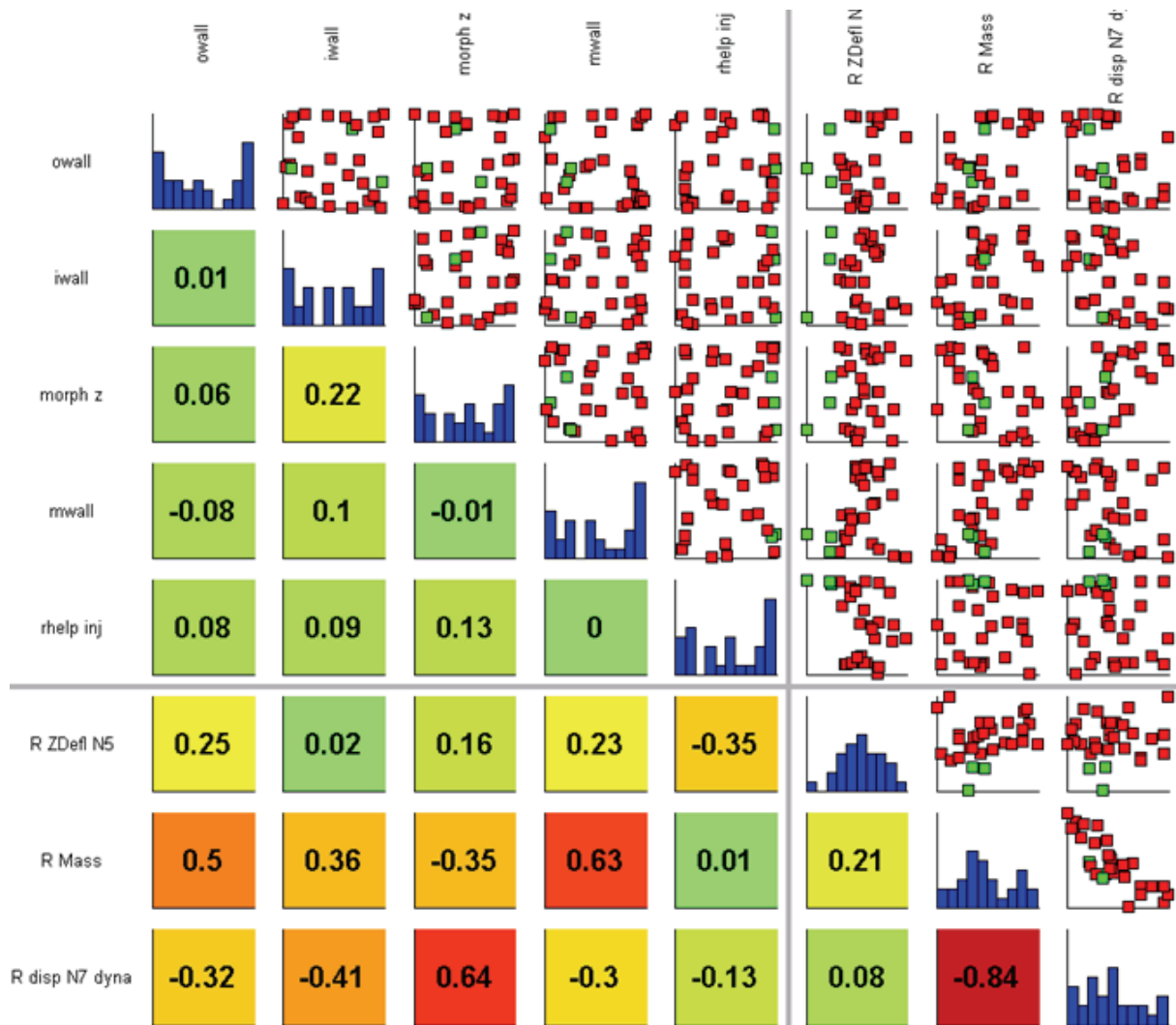

Figure 10: Screening Phase – Anthill Correlation Plot

6.2 Optimization Phase Numbering of figures, pictures, and tables

For numerical optimization the two wall thickness parameters (inner and outer thickness), the morphing parameter and the injection location parameter were used as variable. All other DVs were set to reasonable constant values.

Constraints were set to the displacement caused by warpage (<1.0 mm) and the displacement due to impact (<14 mm). Objective was to minimize the mass.

In LS-OPT a response surface approach was selected based on radial basis functions with 8 jobs per iteration (Space Filling). It converged after 13 iterations with the results listed in the following table.

	initial range	value after optimization
Inner wall thickness	2 mm – 5 mm	2.0 mm
Outer wall thickness	2 mm – 5 mm	3.49 mm
Gate location parameter	0.1 – 0.9	0.9
morph parameter	-35 mm … +25 mm	-18.82 mm

Table 2: Optimization results

The mass could be reduced to 78% of the initial mass while both constraints were satisfied.

As the focus on the paper is the description of the Integrative Approach and its influences on the optimization workflow no further discussion of the optimization and the results is done.

7 Future development

The workflow setup described in this paper needed a relatively high degree of user defined and tailor-made scripting, which complicated the work and increased the time for setting up the process. This process is time consuming, mostly non value adding and error-prone.

Necessary improvements in the optimization software (here LS-OPT) must concentrate on a better definition of the integrative structure of the workflow. A clearer definition of subsequent preprocessing steps is needed as well as a hierarchical definition of the solver processes for the involved optimization disciplines.

Another challenge is the clean integration of shape changes defined by morphing. The morphing tool (here ANSA) has to offer possibilities to apply the necessary morphing processes on different meshes without too much additional user action. A seamless interface to the optimization package concerning design variable transfer and definition is important as well.

The setup of response extractions can also be very time consuming. All postprocessing software tools involved should incorporate specific macro tools for a fast and easy definable access to the mainly used responses.

Last but not least there is a general need for each software which shall be coupled into the workflow to work proper and reliable in batch mode. This affords a fundamental software design which allows a stable, pure solver dominated batch mode in the background, decoupled from a visual, graphical, user interaction based mode which could cause severe stability problems.

The workflow developed and described is used and steadily improved in customer projects in BASF Performance Plastics - Simulation Engineering.

8 Literature

[1]   Glaser, S.; Wüst, A.: "Computer Modelling", Kunststoffe plast europe 3/2005, translated from Kunststoffe 3/2005 pp. 132-136, Carl Hanser Verlag, Munich, 2005

[2]   Glaser, S.; Wüst, A.; Jansen, D.: "Virtual Development of Crash-stressed Parts ", Kunststoffe international 9/2006, translated from Kunststoffe 9/2006 pp. 168-172, Carl Hanser Verlag, Munich, 2006

[3]   Glaser, S.; Wüst, A.; Aumer, B.: "Virtual Development of Crash-stressed Parts ", Kunststoffe international 7/2008, translated from Kunststoffe 7/2008 pp. 88-92, Carl Hanser Verlag, Munich, 2008