Innovative Product Design and Robust Process Layout in Die Casting with Autonomous Engineering

Dr.-Ing. Horst Bramann, M.Sc. Laura Leineweber, Dr.-Ing. Jörg C. Sturm, MAGMA Gießereitechnologie GmbH, Aachen, Germany

Abstract

Innovative automotive lightweight designs lead to a higher demand for the product and process development of die cast components. This is attributed to shorter and shorter product development cycles as well as the rising functional integration and complexity of structural die cast parts. The main objectives of the technically complex processes and tools in aluminum and magnesium die casting are cost and resource efficiency along with the robust fulfillment of the defined high-class requirements of the casting. In this context, casting process simulation is a well-established tool used to support tool design, part design as well as process development.

Using the example of a structural die cast part this paper demonstrates how the new methodology of Autonomous Engineering of MAGMASOFT® 5.4 contributes to the demands of die casting for:

- faster product and process development,
- optimum process and tool design in terms of quality, yield and costs, as well as
- robust process layout with maximum reproducibility of quality

better than ever before.

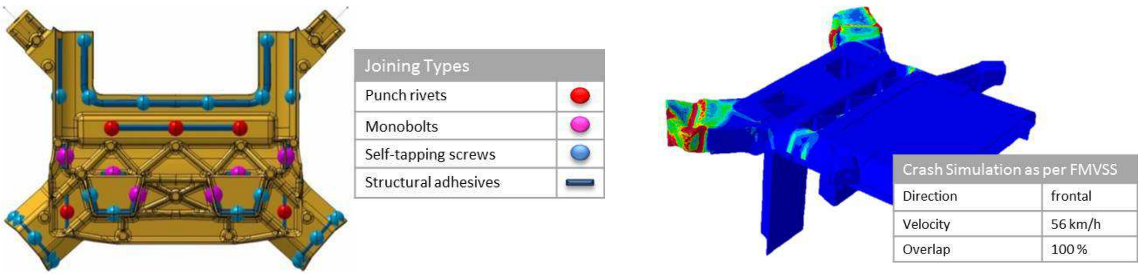
Autonomous Engineering expands on the virtual experiment of casting simulation by defining the quantifiable objectives, critical variable process parameters and their variations as well as relevant quality criteria. In addition to the identification of reliable technical solutions, this new approach provides the best compromise between the quality and economic efficiencies the die caster is always striving for.

Systematic knowledge can be generated without economic or production risks enabling secured decisions to be made early in the development phase of robust, cost-efficient and resource-efficient die cast products and processes.

1. Development Process for Structural Components

The variety of models and strong market competition result in increasingly shorter product development cycles along with increasing time and cost pressures. Therefore, complex parts, for example for the automotive sector, are often only designed functionally with virtual methods such as CAE. The assessment regarding feasibility and potential manufacturing restrictions take place later. At such a late stage, reasonable or necessary design changes can rarely be realized and will most likely be very time-consuming and costly.

The systematic integration of casting process simulation and virtual optimization for the early-stage identification of manufacturing restrictions in the product development process is shown using the examples of the demonstrator components "joint" and "shock tower". The joint is part of the crash load path from the longitudinal beam to the transmission tunnel of a passenger car body structure. A key element for success depends on the feasibility of the four planned connections to the other components of the system as well as in the compliance with the requirements for a frontal crash according to FMVSS, see **Figure 1**.



(a) (b)

Figure 1: Requirements for the structural component "joint": a) realization of different connection types; b) energy absorption and load transmission at frontal crash

Due to the geometrical complexity as well as the planned quantities, high pressure die casting is chosen as the production process. The redesign of the functional geometry for a casting takes place within the framework of the conventional development process. Classical design and construction rules for high pressure die casting have been already taking into account, see **Figure 2.** When possible, the specified requirements are validated virtually by making use of FE simulation tools. The final die casting part often undergoes the parallel virtual validation of the operational load case/ the functional requirement profile. As a rule, the supplier is not involved in this process until the design-freeze status is reached.

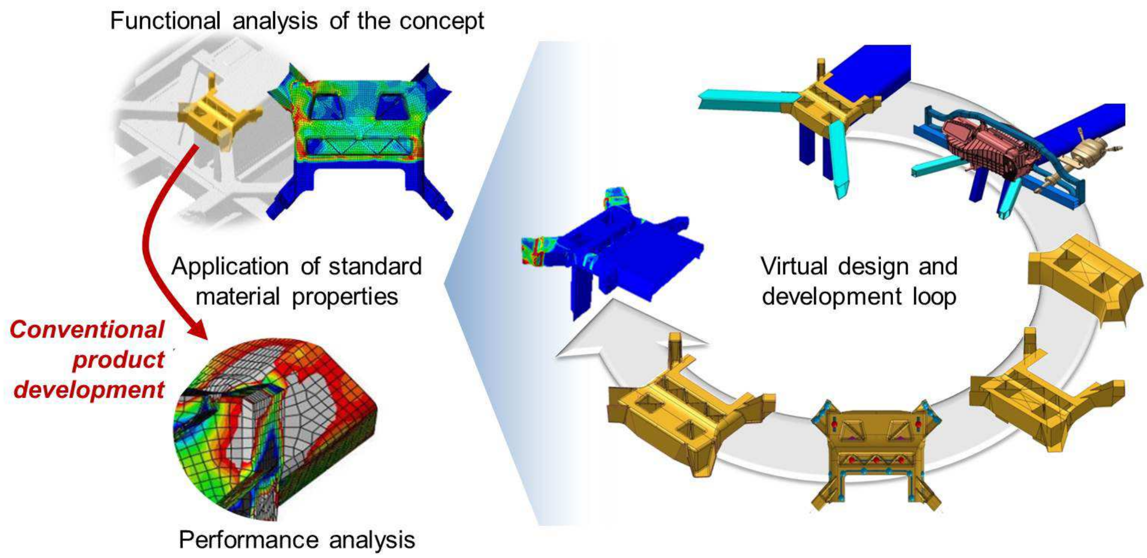


Figure 2: Conventional product development process for cast structural components

In few cases, a detailed analysis and evaluation of the feasibility take place when sending a request for quote. However, often this is only done once the supplier has been chosen. On the supplier side, the robustness of the feasibility commitment during process development is dependent on the ability to meet the casting requirements. In the process of developing the tool layout retroactive design changes are often proposed or deemed necessary. In most cases, however, these changes can only be realized to a certain extent and are frequently time-consuming and costly. Usually, the process development ends with the supplier feasibility confirmation and the approval for production of the costly tools and peripheral resources see **Figure 3**. The result is often a production process that is not very robust, with little transparency, long ramp-up times and often initially high scrap rates.

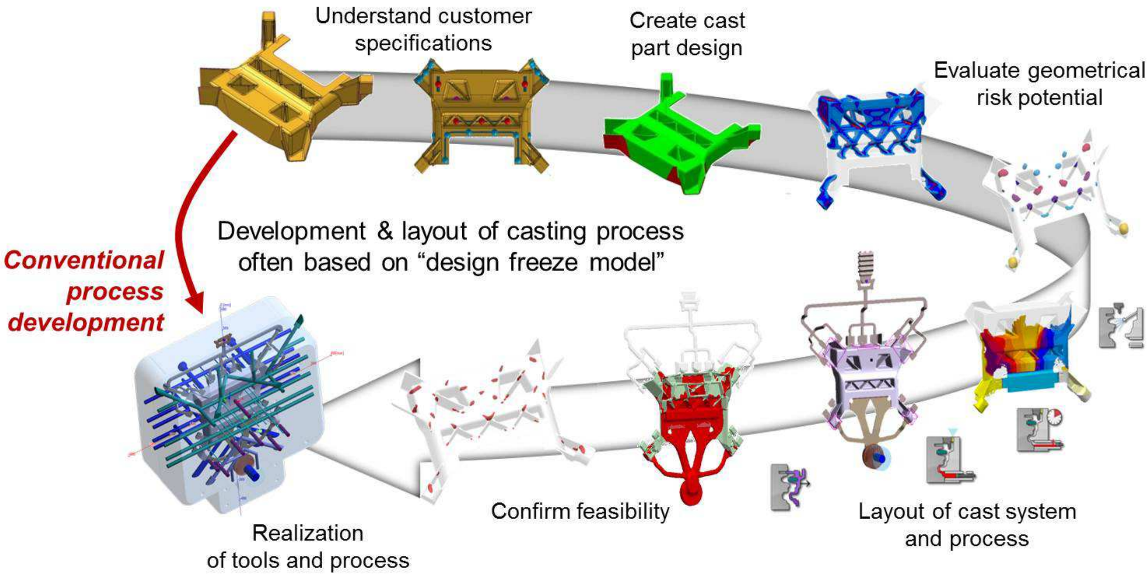


Figure 3: Conventional process and tool development process on the supplier side

MAGMASOFT® 5.4 offers with autonomous engineering a new methodology and a comprehensive tool box of numerous capabilities for the optimization of die casting processes. The software allows to set up different objectives, evaluate a design space of parametrized variables and assess different quantitative quality criteria to identify both an optimum and the robustness of the operating conditions. In combination with the established methods of virtual functional validation during product development this enables early analysis and consideration of manufacturing influences on the casting properties. This virtually generated knowledge is the basis for confident decision-making as well as providing the layout for more robust products and production processes. The following case studies demonstrate the advantages of applying MAGMASOFT® 5.4 autonomous engineering to the entire product and process development of die casting parts.

2. Optimization of the Process and Tool Layout

2.1 Influence of the Shot Chamber on the Gas Porosity

Gas porosity caused by entrapped air or escaping gases is a common cause of scrap. Particularly during the heat treatment process, the defects directly lead to scrap and have a negative influence on the casting requirements for the joining technologies, such as weldability and riveting capability. Moreover, the often large and thin-walled structural components are prone to significant temperature losses of the melt in the course of the filling process. This results in error patterns such as flow marks and surface defects up to unacceptable cold laps in critical connection areas in the casting.

Therefore, within the scope of process development and casting design, the goal should be optimum filling of the die while avoiding air entrapments and excessive temperature loss in the casting system. Today, the analysis and identification of these potential risks routinely take place with a suitably reduced model only considering the biscuit. A special potential for avoiding the risks described above also lie in the corresponding definition of the process conditions for the first phase of the plunger movement in the shot chamber, see **Figure 4**. Inconvenient process conditions will immediately result in air entrapments in the shot chamber. Through further movement of the plunger, these air pockets are then uncontrollably transported into the casting.

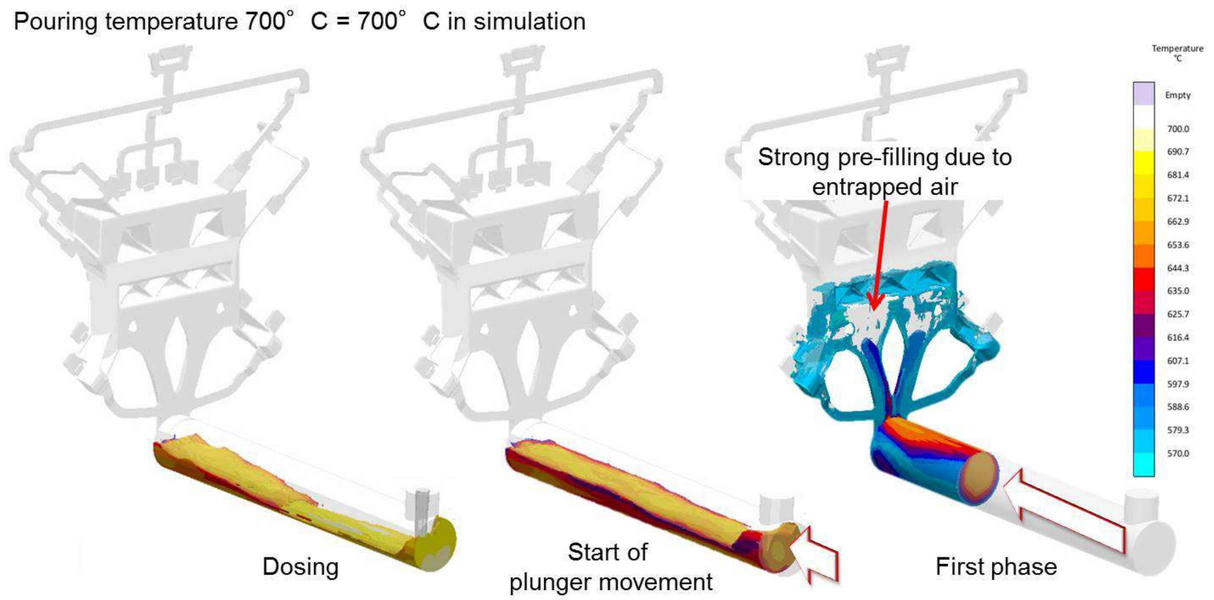


Figure 4: Die filling analysis of the joint with consideration of the shot chamber. The chosen shot profile results in massive air entrapments and a significant temperature loss of the melt during the first phase of the plunger movement.

The following example shows the systematic analysis and optimization of the dosing and shot profiles by making use of the new methodology of Autonomous Engineering in MAGMASOFT® 5.4, see **Figure 5**. The virtual analysis has two objectives:

1. Avoiding air entrapments during the dosing process and the first phase of the plunger movement

2. Preventing significant temperature losses of the melt in the shot chamber.

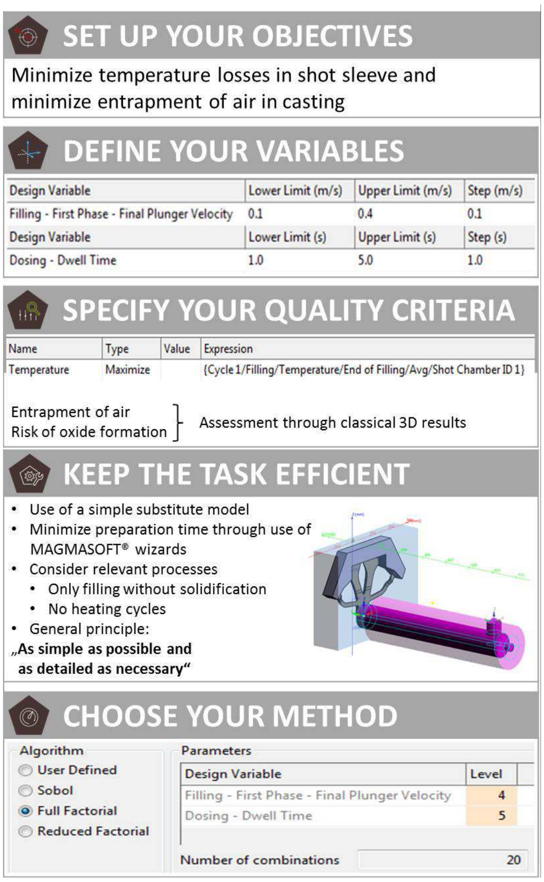


Figure 5: Systematic optimization of relevant process parameters to avoid air entrapments and temperature losses in the shot chamber. The methodological approach supports a targeted and efficient work on casting-related tasks with MAGMASOFT®.

For this purpose, the plunger velocity in the first phase is varied from constant 0.1 m/s to 0.4 m/s in steps of 0.1 m/s; simultaneously, the wait time after the dosing process is varied between one second and five seconds in 1-second steps. Quality criteria/ output variables for the evaluation of the virtual design of experiments include the mean temperature of the melt in the shot chamber at the end of filling and air entrapment in the shot chamber. In some cases, due to the complexity of the task, the evaluation of potential air entrapments in the shot chamber is carried out based on the 3D results.

The efficient simplification of the simulation model plays an essential role when performing systematic virtual process analyses. In the present case, the complex structural part as well as overflows and venting system were replaced by a simplified geometry with the same volume. For the virtual design of experiments in this example, only the die filling without heating cycles for the die is calculated. MAGMASOFT® 5.4 supports the execution of methodological virtual statistical analyses, from the individual simulation, to virtual designs of experiments (DoE), up to the autonomous optimization by making use of a genetic algorithm. The 20 experiments of the virtual DoE resulting from the degrees of freedom were calculated as a full factorial design of experiments.

Figure 6 shows the comparison of the different dwell times for some combinations of the design of experiments with constant plunger velocities from 0.1 to 0.3 m/s. The settling time of the melt in the shot chamber leads to different risk potentials for the formation of air entrapment in the shot chamber due to premature closing of the runner system in the transition to the shot chamber. A wait time of 2 seconds combined with a plunger velocity of 0.2 m/s leads to a continuous displacement of air by the flow front, thus preventing entrapped air in the shot chamber. Basically, it becomes evident that for each plunger velocity, there is a suitable wait time that allows creating an acceptable filling profile in the shot chamber. However, the air entrapment risk tends to rise with increasing plunger velocity.

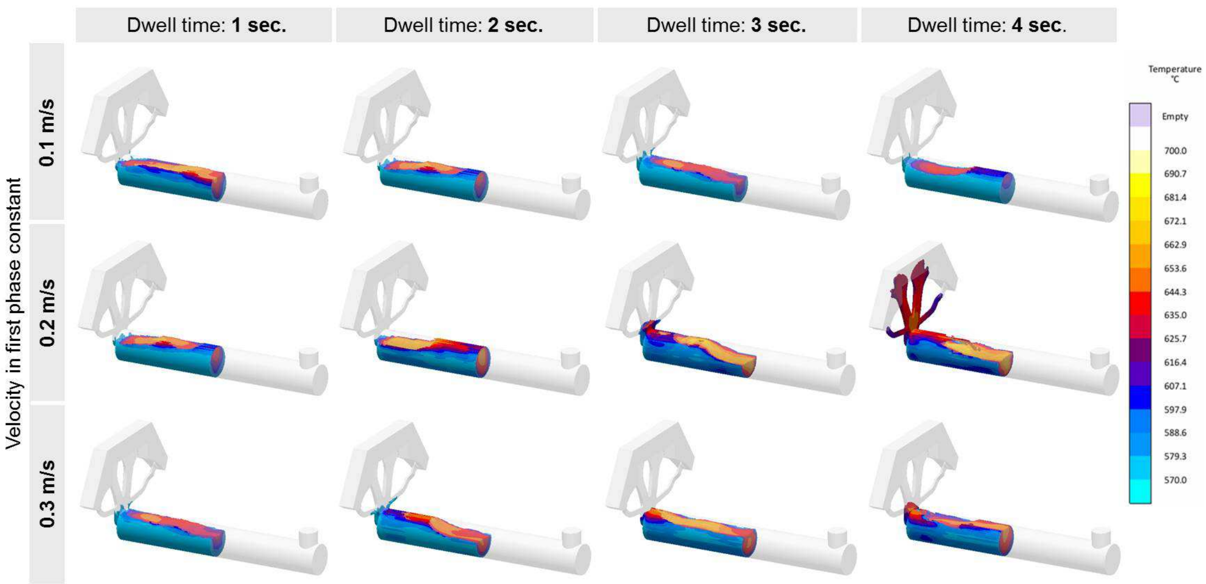


Figure 6: Temperature distribution and position of the melt with constant plunger movement of the first phase for different wait times after dosing in the shot chamber

A correlation matrix allows for the quantitative evaluation of the influence the pouring velocity and wait time have on the temperature loss of the melt in the shot chamber, see **Figure 7.** As expected, the evaluation reveals a clear connection between the two varied process variables and the mean temperature of the melt. Between the fastest parameter combination (wait time of 1 s for a plunger velocity of 0.4 m/s) and the slowest combination (5 s / 0.1 m/s), the temperature difference of the melt in the shot chamber is 55°C. For a dosing temperature of 700°C, the temperature loss in the shot chamber up to the end of die filling is at least 66°C. This corresponds to the shortest wait time and the highest plunger velocity.

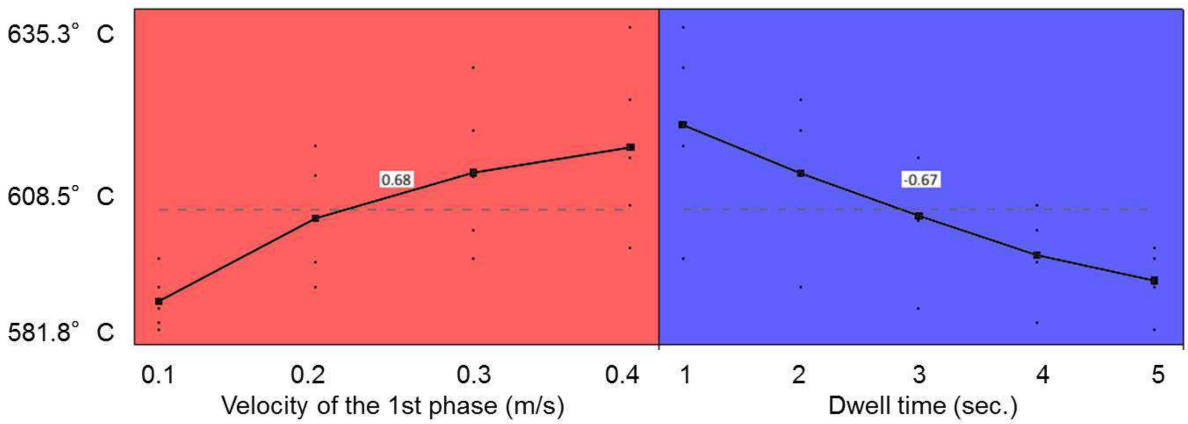


Figure 7: Correlation matrix for the mean temperature of the melt in the shot chamber at the end of die filling for the two variables analyzed

The best compromise when taking into consideration the intended goals is reached with a wait time of two seconds and a plunger velocity of 0.2 m/s. These parameters are analyzed using the complete model for the more complex casting geometry, see **Figure 8.** The results are shown compared to the initial variant. The optimized process conditions display a homogeneous transport of air from the shot chamber through the cavity. The temperature loss in the shot chamber up to the end of die filling is approx. 90°C.

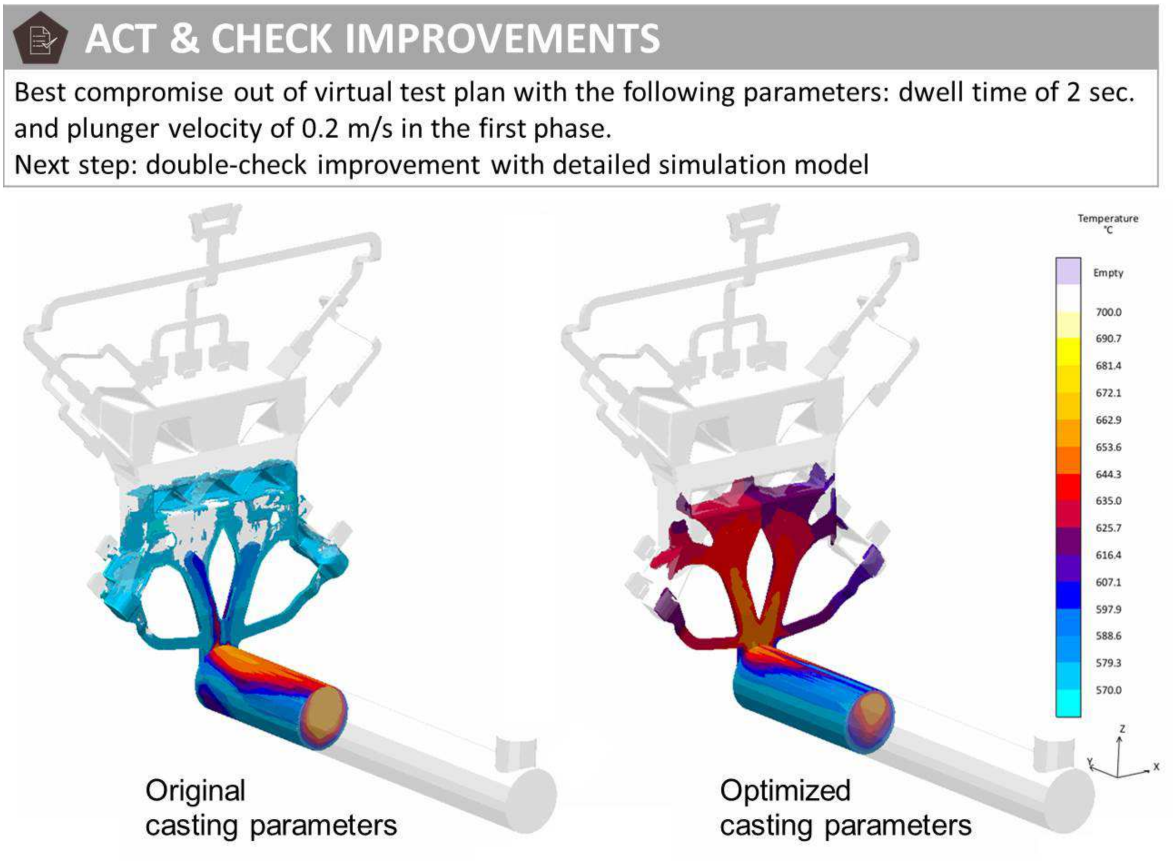


Figure 8: Comparison between the filling of the connecting node with the initial process parameters and for the best compromise of the virtual design of experiments with a wait time of 2 s and a plunger velocity of 0.2 m/s

Figure 9 compares the optimized process conditions to the reduced simulation model without shot chamber. The nearly identical filling behavior of the two models confirms that the reduced (simplified) simulation model without shot chamber is equally suited for the upstream development process of the casting system. If required, the simulation model can be extended for a detailed analysis or process optimization of the processes in the shot chamber.

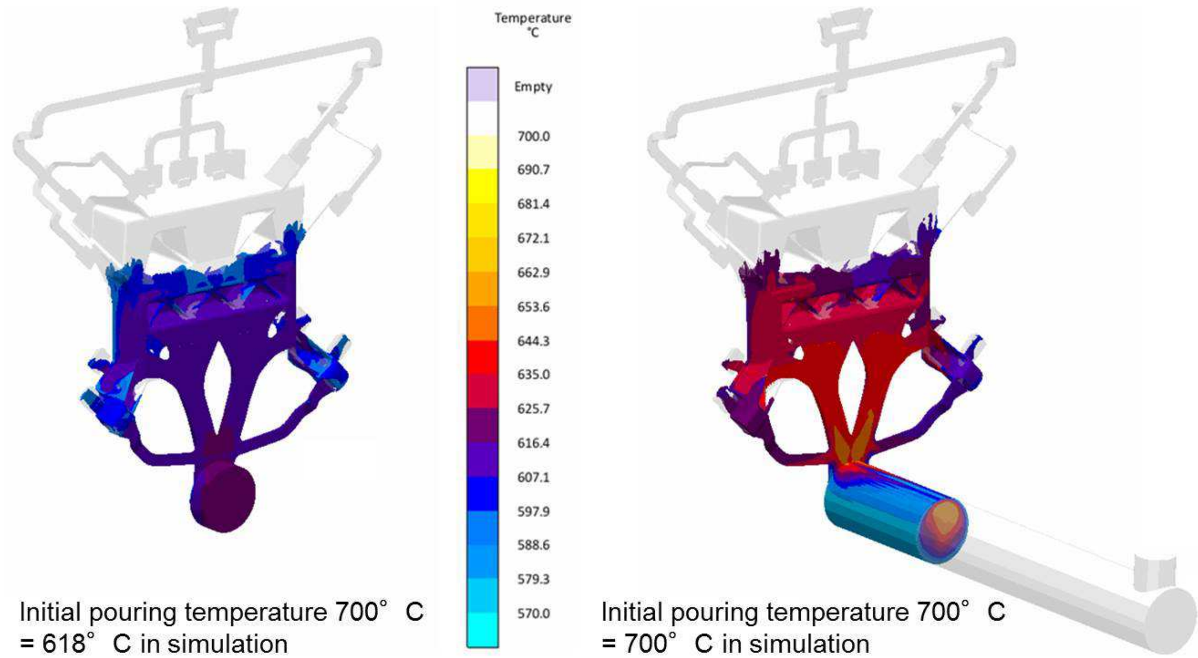


Figure 9: Comparison between filling with and without consideration of the shot chamber for the optimized first phase of the plunger movement

2.2 Optimization of the Spraying Process

Structural components are characterized by large, complex and thin-walled geometries combined with partly thick-walled areas for mounting or fastening points. In this context, minimum draft angles and high demands on the surface quality of the castings present a particular challenge for the spraying process. The prevention of premature tool damages caused by thermal shock due to classical water-based spraying has a high priority.

The new possibilities in MAGMASOFT® 5.4 allow for the detailed optimization of the spraying process. It is possible to carry out a detailed analysis of the surface temperatures of the die or evaluate the wetting of individual die areas for optimizing the casting quality regarding cold laps, porosity and die soldering. MAGMASOFT® 5.4 also allows for the evaluation of the distortion of die components or optimizing the local die lifetime.

For the structural component, the simulation model was extended by a realistic representation of the spraying process including directional spray nozzles with spray cones, spray circuits and spraying cycle, see **Figure 10**.

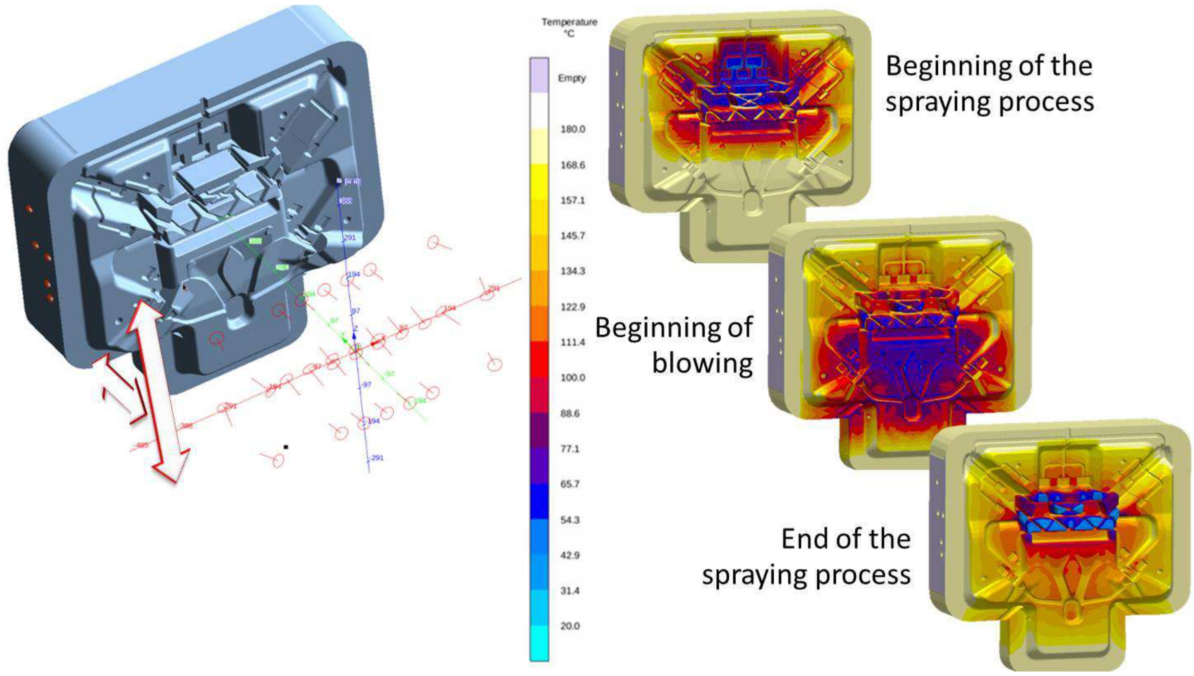


Figure 10: Representation of the spraying process including individual spray cones, spray circuits and spraying cycle with display of the local surface temperatures of the die in the course of the spraying process

The analysis of the temperature measuring points in the area near the surface illustrates the effectiveness of the spraying process combined with the internal die temperature control, see **Figure 11**. Assuming an idealized homogeneous initial temperature of the die, after the heat extraction at the surface caused by the spraying process, a reheating of the surface takes place in areas 1 and 4 due to the energy stored in the die. Particularly in area 3 near the gate, over the cycle, a clear temperature hysteresis takes place, involving the risk of premature tool damages caused by heat checking. The internal spot cooling added in area 2 locally extracts energy from the die and reduces the reheating of the die surface.

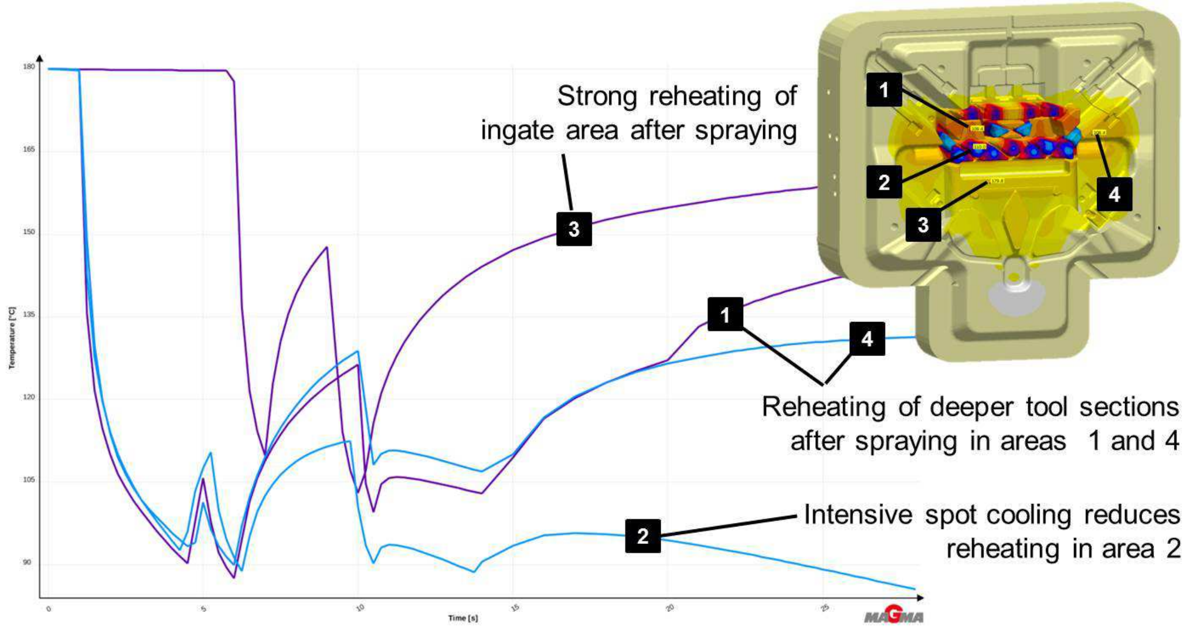


Figure 11: Temperature curves in the die areas near the surface illustrate the effectiveness of the spraying process combined with internal die temperature control. The internal spot cooling in area 2 locally extracts energy from the die and minimizes the reheating of the die surface.

2.3 Quantitative Evaluation of the Die Cooling Lines

Laying out suitable cooling lines is particularly important in the application of minimum spray. Due to the minimum heat extraction through the spray medium, most of the energy introduced by the melt needs to be dissipated by means of internal cooling lines. The cooling lines are supposed to simultaneously ensure the required microstructure quality in the casting, achieve a minimum cycle time along with minimum die erosion as well as ensure a robust die filling with an overall minimum energy consumption.

A solution to meet multiple objectives can be achieved through transparency regarding the local effects of complex cooling lines as well as their dependency on the machine settings available in practice (temperature of the cooling medium and flow rate).

Figure 12 illustrates the flow simulation integrated in MAGMASOFT® 5.4 in a complex cooling line in insert. The flow calculation can be done either simultaneously with the filling simulation or separately. In addition to results regarding the flow direction, velocity, pressures and temperature, the flow calculation primarily provides the effective heat transfer coefficients resulting locally at the interface to the melt.

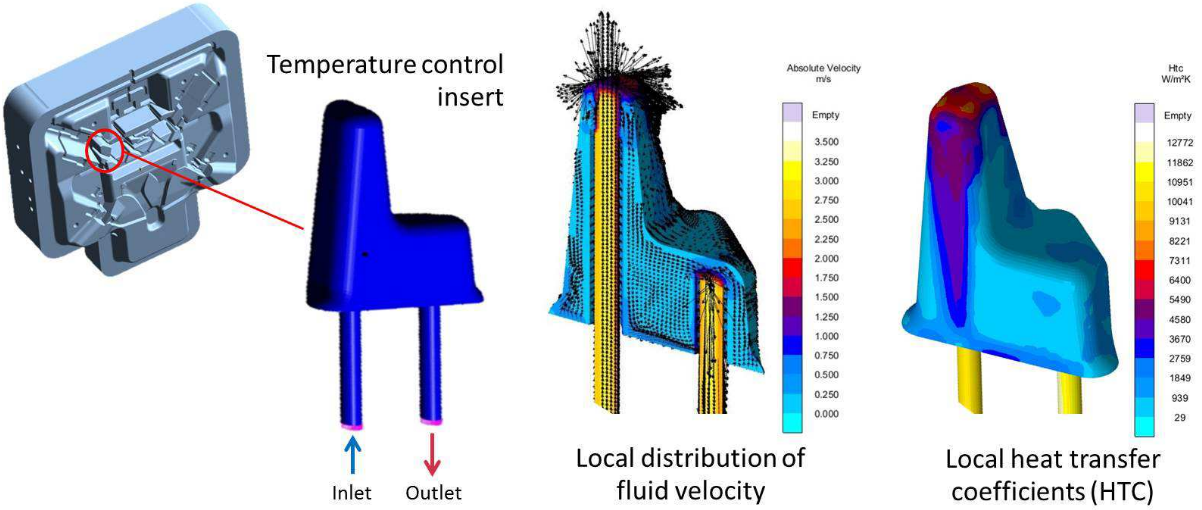


Figure 12: Based on the local flow vectors, the effective heat transfer coefficients resulting at the interface to the melt are calculated.

This extended process knowledge allows for a systematic, automated evaluation and optimization of various cooling lines. Possible objectives to be analyzed include process conditions for improving the casting quality, influencing process times (cycle time) as well as the reduction of die erosion and the evaluation of the energy balance. In this context, possible degrees of freedom may be the variation of the geometry, the cooling line position in the die as well as of all process conditions. **Figure 13** shows the influence different flow situations in the cooling line have on the distribution of the local cooling capacity using the example of the heat transfer coefficient. The use of a tube for flow conduction leads to the desired increase of the cooling capacity in the tip of the insert.

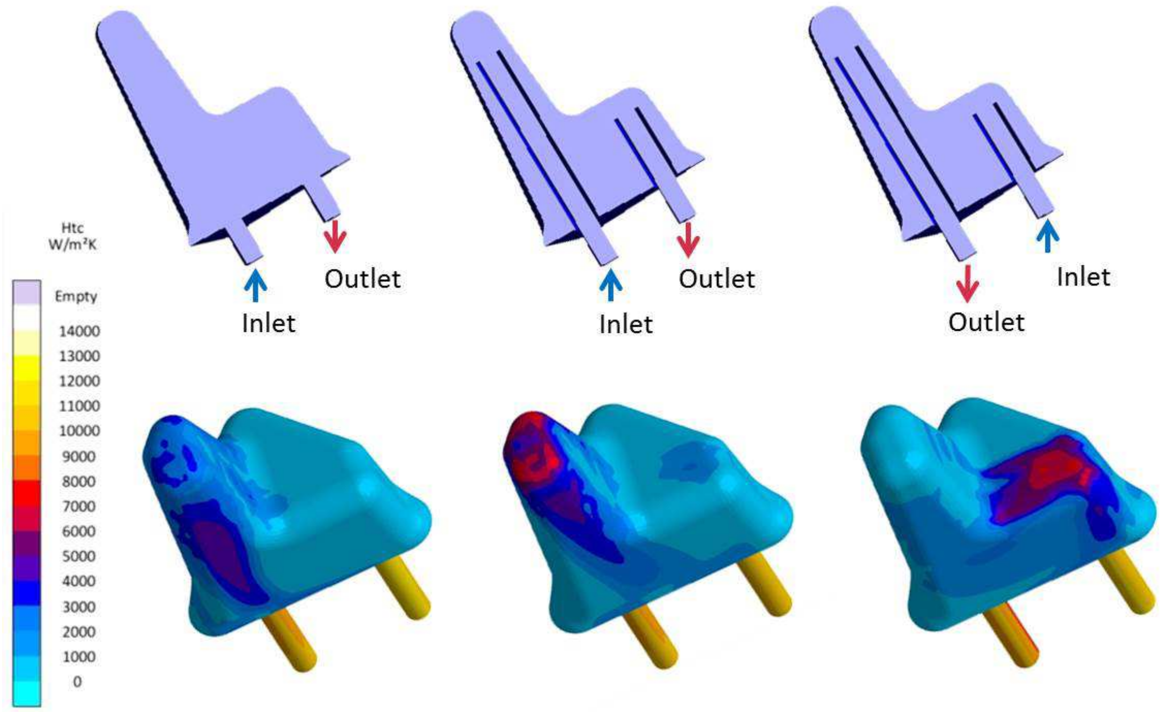


Figure 13: Different flow situations in the cooling line and their local heat transfer coefficients. The capillary tube used leads to an increase of the cooling capacity in the tip of the insert.

To evaluate the process stability, the influence of different flow rates (5 to 25 l/min in steps of 5 l/min) on the local solidification time in the critical casting area is analyzed in a virtual design of experiments. The corresponding main effects diagram in **Figure 14** displays a non-linear reduction of the solidification time with increasing flow rate. A detailed evaluation of the pressure distributions in the cooling line for the different flow rates explains the cause for this. With increasing flow rates, the pressure loss in the system rises, leading to an increasing inefficiency.

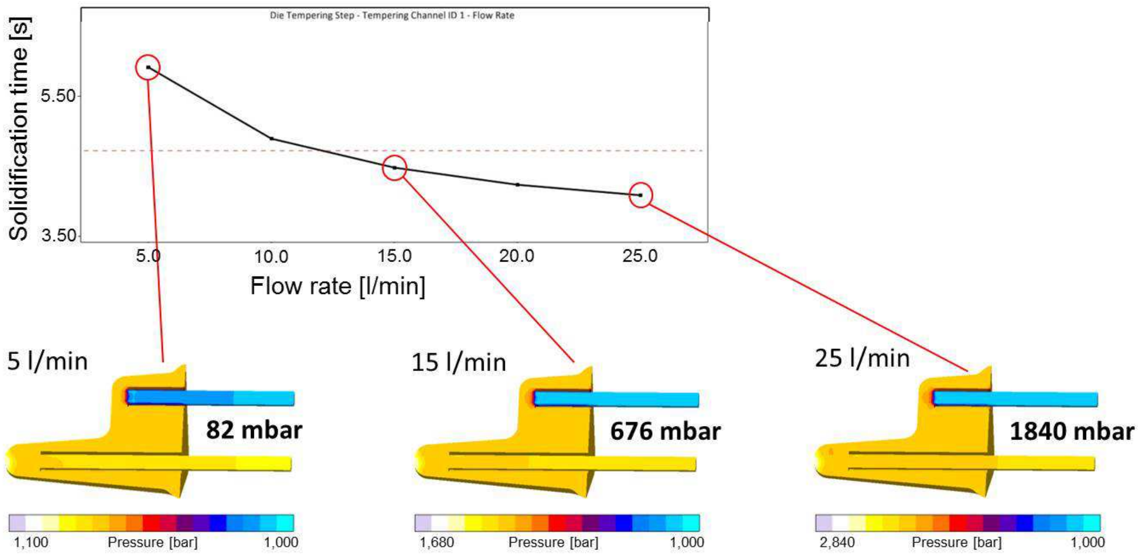


Figure 14: Main effects diagram for the cooling line regarding the effect of varying flow rates on the local solidification time in the critical casting area. With increasing flow rates, the pressure loss in the system leads to an increasing energetic inefficiency.

2.4 Heat Balance of the Die

The heat balance of the die as well as the thermal stability of the complete system can be evaluated with the energy balance integrated in MAGMASOFT® 5.4, see **Figure 15**. The intuitive overview allows analyzing and evaluating the energy exchange between all materials/ material groups (e.g. casting, casting system, part of the die) over the complete process cycle, individual process phases or a defined period of time. For example, it is possible to directly compare and optimize the amount of energy discharged while considering cost efficiency in the course of the process cycle via internal cooling and external spraying.

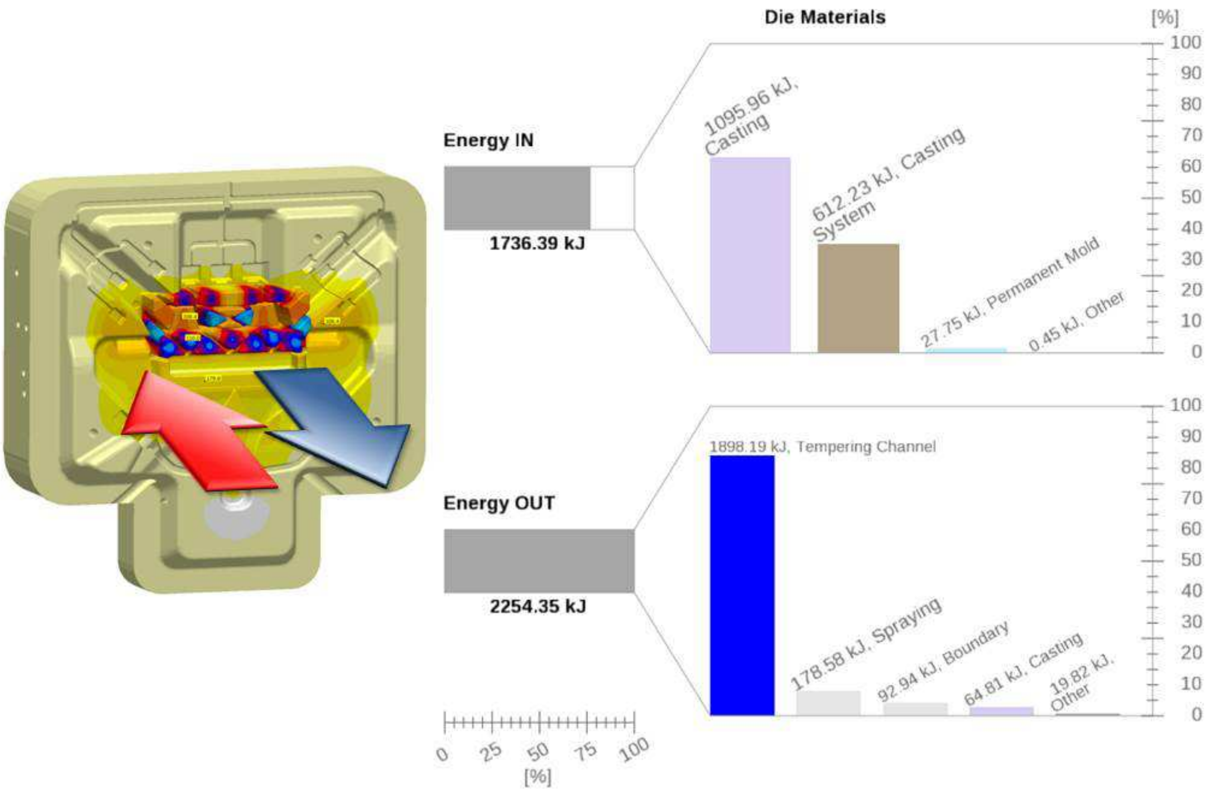


Figure 15: Energy balance – energy exchange between materials/ material groups, for example casting or part of the die, over the process cycle, phases or defined periods of time

The economical and efficient use of casting process simulation requires the use of these options. For each process layout phase, the simulation should be "as simple as possible and as detailed as required". The methodology of Autonomous Engineering with MAGMASOFT® supports the systematic work on detailed tasks as well as the identification of reliable technical solutions. For the systematic analysis of variants or process conditions, a suitable simplification or coarsening of the simulation model is recommended, followed by the validation of the identified solution or alternatives using the detailed model.

3. Robust Products and Processes

In structural components, in addition to the resource and cost efficiency objectives, the robust fulfillment of the defined quality requirements has absolute priority. To evaluate the robustness of the developed casting system and the nominal process parameters defined, the virtual model is extended by critical process parameters as well as their variations. The engineer defines the objectives, the degrees of freedom to be varied and the quality criteria for the evaluation of the improvement. The analysis of the resulting virtual design of experiments or process window in MAGMASOFT® takes place autonomously without requiring further actions of the user, see **Figure 16**.

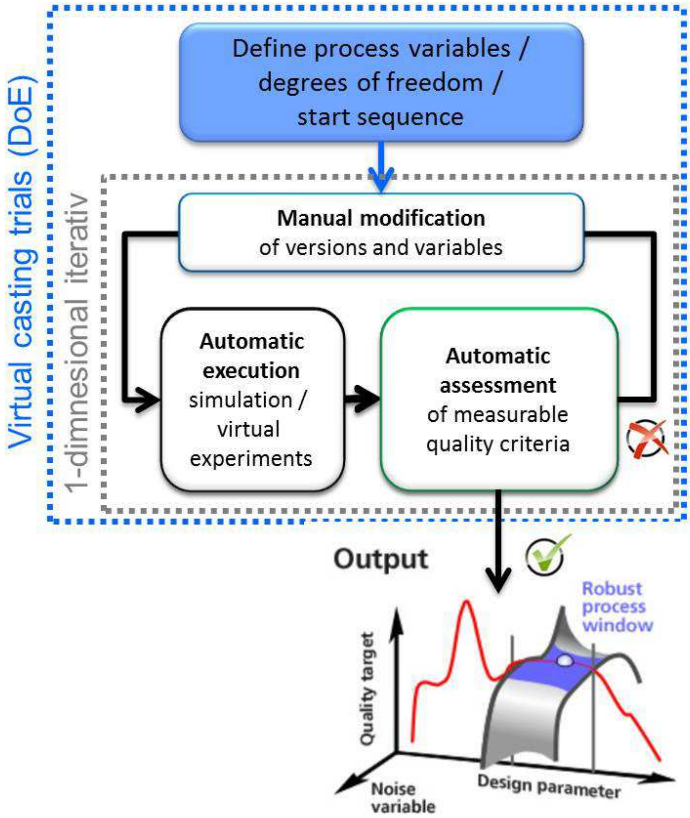


Figure 16: Schematic for carrying out systematic and efficient robustness analyses with the help of virtual process window analyses in high pressure die casting

To enable a more simplified evaluation of the casting quality, the simulation model of the cast node was extended by considering evaluation areas. These evaluation areas measure the calculated quality criteria in areas of particular interest. In the example, this applies to the functionally critical thick-walled connection points in the bottom ("Evaluation Area 1") or a thin wall thickness that is critical regarding the filling process ("Evaluation Area 2"), see **Figure 17**. Based on know-how acquired from experience, the shot curve of the planned target process includes a plunger deceleration at the end of filling to avoid flashing, see shot curve in **Figure 17**.

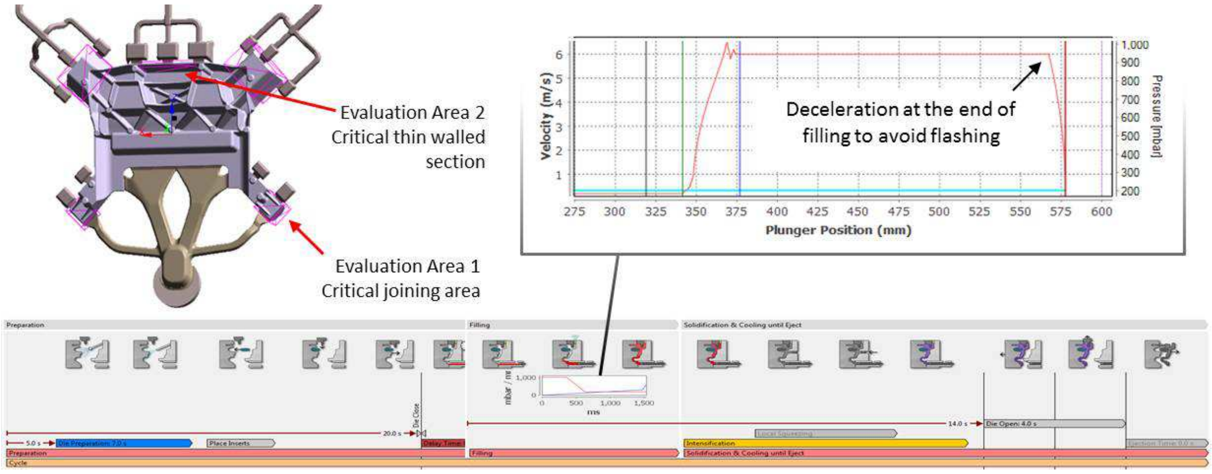


Figure 17: Extension of the simulation model by "evaluation areas" for a purposeful evaluation of critical casting areas. The shot profile of the target process for the connecting node includes a massive plunger deceleration at the end of filling to avoid flashing.

In the next step, the simulation model is extended by the critical process parameters to be varied and analyzed to obtain the relevant process window. In the example, this extensions of the model considers the variation of the dosing quantity (defined as biscuit thickness in the simulation model), the variation of the pouring temperature of +/-15°C, the incomplete squeezing (3rd phase) as well as the variation of the intensity of spot cooling in the area of the functionally critical thick-walled connection points in the bottom. The variables are assigned a lower and upper limit as well as a step size. Qualitative parameters or geometry variations can be defined as being variable, active or inactive, see **Figure 18**.

DEFINE YOUR VARIABLES

Design Variable	Lower Limit (mm)	Upper Limit (mm)	Step (mm)
Geometry hpdc_inlet_001 - Biscuit thickness: h	15.0	30.0	7.5
Design Variable	Lower Limit (°C)	Upper Limit (°C)	Step (°C)
Cast Alloy Class - Initial Temperature	620.0	650.0	15.0
Design Variable	Lower Limit (bar)	Upper Limit (bar)	Step (bar)
Intensification - Working Pressure [p(w)]	20.0	820.0	800.0
Design Variable	Dataset List		
Cover Die ID 1 / Tempering Channel W-20-Sprud	MAGMA/C2000.0 MAGMA/C10000.0		
Ejector Die ID 1 / Tempering Channel W-20-Spr	MAGMA/C2000.0 MAGMA/C10000.0		

Figure 18: The variables of the virtual design of experiments for evaluating the robustness of the production process. The variation of each variable is defined with a lower and upper limit as well as with a step size.

For the cast node, all possible variants of the virtual design of experiments/ process window were analyzed in a full factorial design of experiments. The correlation matrix shown in **Figure 19** is a summary of all main effects, i.e. the influence of the process variables analyzed on the quality criteria defined for the structural component. As quality criteria, all results available in MAGMASOFT® for all materials featured in the model (casting, casting system, die) can be used.

The quantitative comparison of all variants by making use of statistical methods yield reliable results without subjective influences. The steeper the slope and the more intense the color of an individual diagram, the stronger the influence of the considered parameter on the corresponding quality criterion.

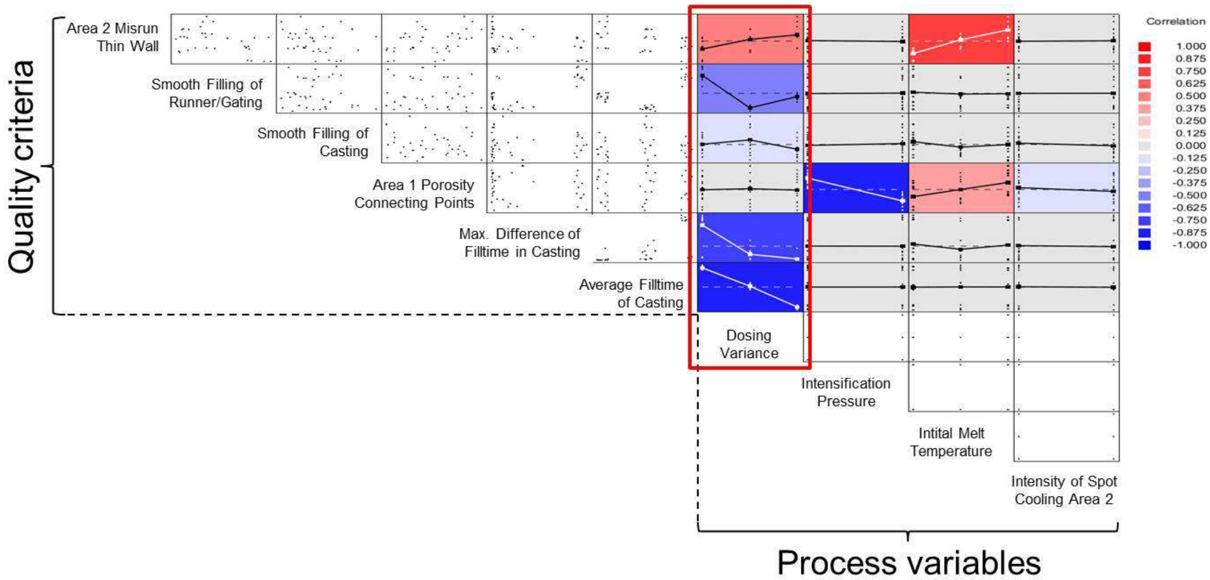


Figure 19: The correlation matrix shows an overview of the main effects of all process variables analyzed on the quality criteria defined. The slope and color intensity of the individual correlations describe the intensity of the effect the corresponding variable has on the quality criterion.

For the casting node, the importance of a precise dosing process for all relevant quality criteria is shown at a glance. The cause for this is attributed to the shift of the shot curve depending on the dosing quantity. A too small dosing quantity will shift the entire shot curve (start of acceleration to the second phase and deceleration point) to earlier times, leading to the shift of the deceleration point from the end of filling into the cast cavity. The result is a considerable increase in filling time along with the corresponding danger of flow marks and cold laps. A too large dosing quantity will inevitably lead to a shift of the shot curve to later times. In the worst case, this will result in the programmed deceleration becoming ineffective as well as an increased risk of flashing.

A systematic virtual analysis of process variations allows generating real process knowledge long before the first parts are cast. Of course, a comprehensive virtual process analysis will take longer than an individual simulation run. However, carrying out such an analysis on the production floor is not feasible or does not make financial sense. The knowledge obtained supports the layout of robust processes and ensures a smooth production.

4. Evaluation of the Complete Process

In addition to the methodological design of the die and process layouts for the casting, a secured and robust quality prediction for structural components requires the consideration of the complete process. For a reliable prediction of the properties and distortion of structural components, this particularly applies to the process steps following the ejection of the casting from the die.

Figure 20 illustrates schematically the continuous prediction of properties and distortion along the casting process up to the heat treatment for an aluminum shock tower. MAGMASOFT® allows for the calculation and evaluation of the residual stresses of the casting that are a result of the production process as well as the corresponding distortion at any time in the process. The early identification of potential risks within the framework of the design phase allows for the implementation of preventive measures with all available degrees of freedom. Such measures may consist in the change of the casting design, in preventive geometrical adjustments to the die or in an adjusted layout of the heat treatment process.

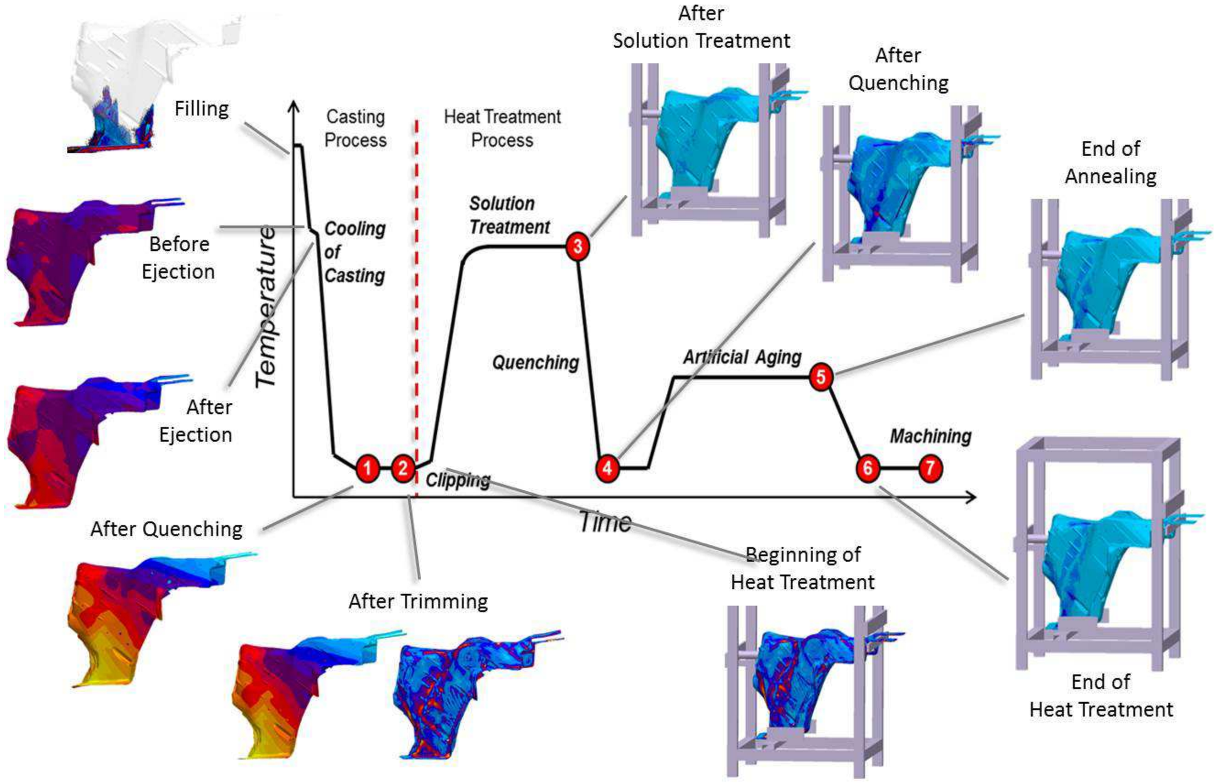


Figure 20: Virtual consideration of the complete process in structural casting including the heat treatment

For complex large structural components, achieving a robust distortion within the required tolerance limits during the heat treatment presents a particular challenge. Normally, the design of the heat treatment racks begin once the first castings from production arrive at the heat treater; it is commonly optimized by trial and error. Virtual heat treatment trials, however, allow for an optimized rack design early in the planning phase.

The prediction of the distortion requires the calculation of the local residual stresses as well as of the effective plastic strains at any time in the casting process. In this context, all relevant process steps are considered: solidification and ejection of the casting, removing the casting system, heating, solution treatment, quenching and tempering during the heat treatment up to the consideration of a final machining step.

Figure 21 shows the distortion of the structural component after a classical T6 heat treatment consisting of solution treatment, quenching and tempering. The simulation of the heat treatment process with MAGMASOFT® makes use of a both temperature and strain rate dependent creep model that considers the loads on the casting caused by gravity particularly during the solution treatment as well as the resulting distortion.

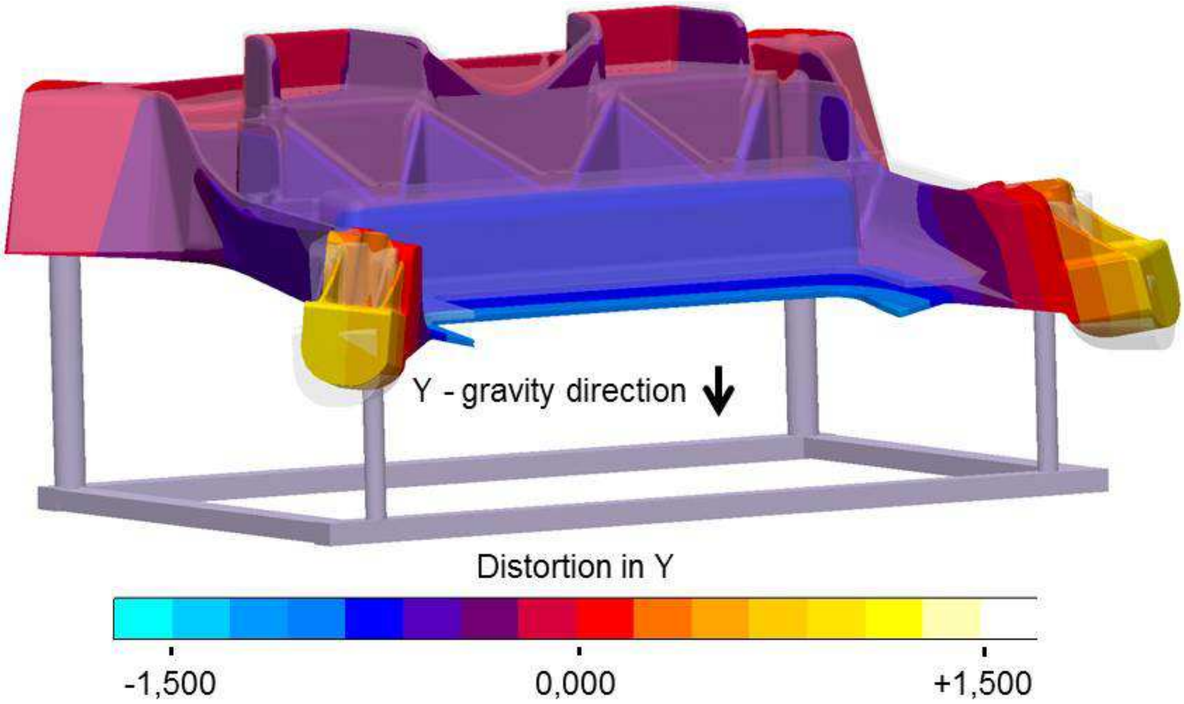


Figure 21: Distortion of the connecting node in the rack in the direction of y at the end of the heat treatment resulting from the influence of gravity during the solution treatment

The local plastic strains and residual stresses predicted with the software for the complete production process extend and refine the description of condition of the structural component before the virtual CAE functional analysis, see **Figure 22**. The local plastic strains arising during the solidification allow for the identification of irreversibly pre-damaged areas of the cast material. Areas subject to significant local von Mises stresses after the heat treatment complement the load spectrum of the FE crash simulation. An inconvenient overlapping of high loads from the functional simulation with locally reduced casting properties can lead to an increased failure risk in case of crash.

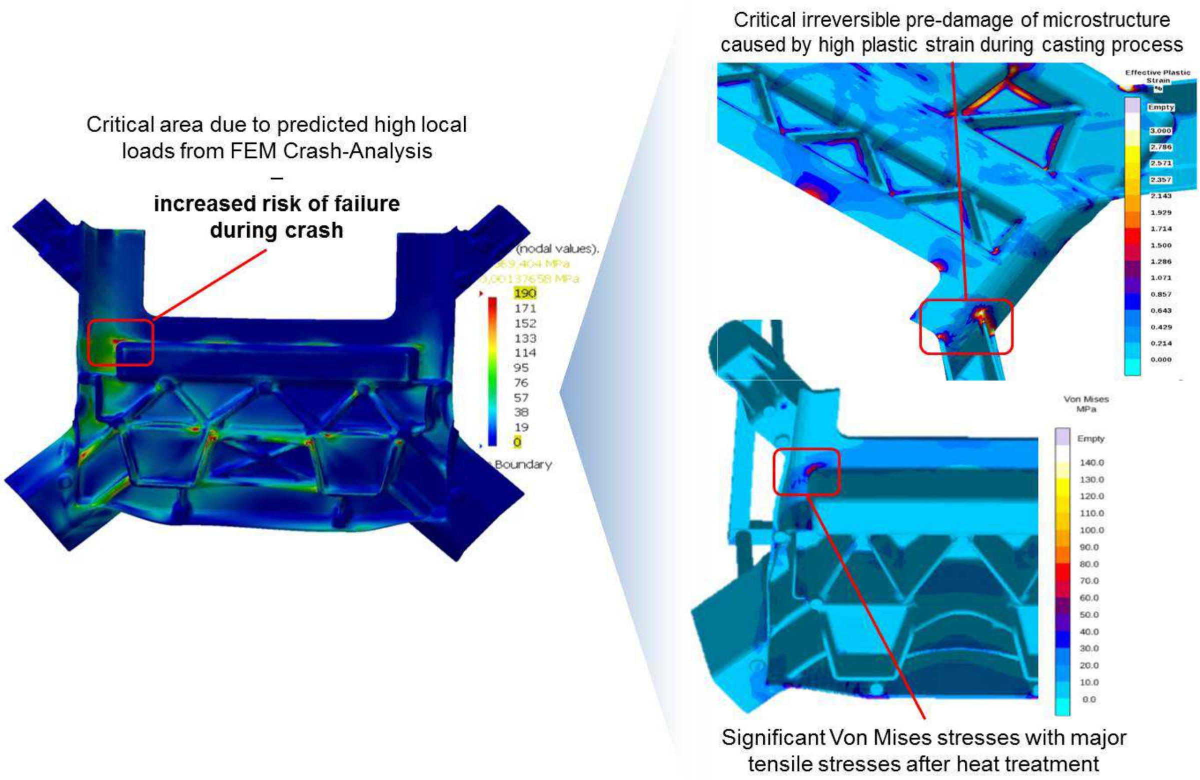


Figure 22: Integration of information (local effective plastic strains and residual stresses) from the casting process simulation into the virtual functional analysis

The systematic integration of the calculated local casting properties from the production process into the virtual functional and risk analysis of the concept development allows for more accurate predictions. The virtually generated systematic knowledge of correlations between production parameters and quality criteria of the casting enables the layout of more robust products and production processes through early secured decision-making.

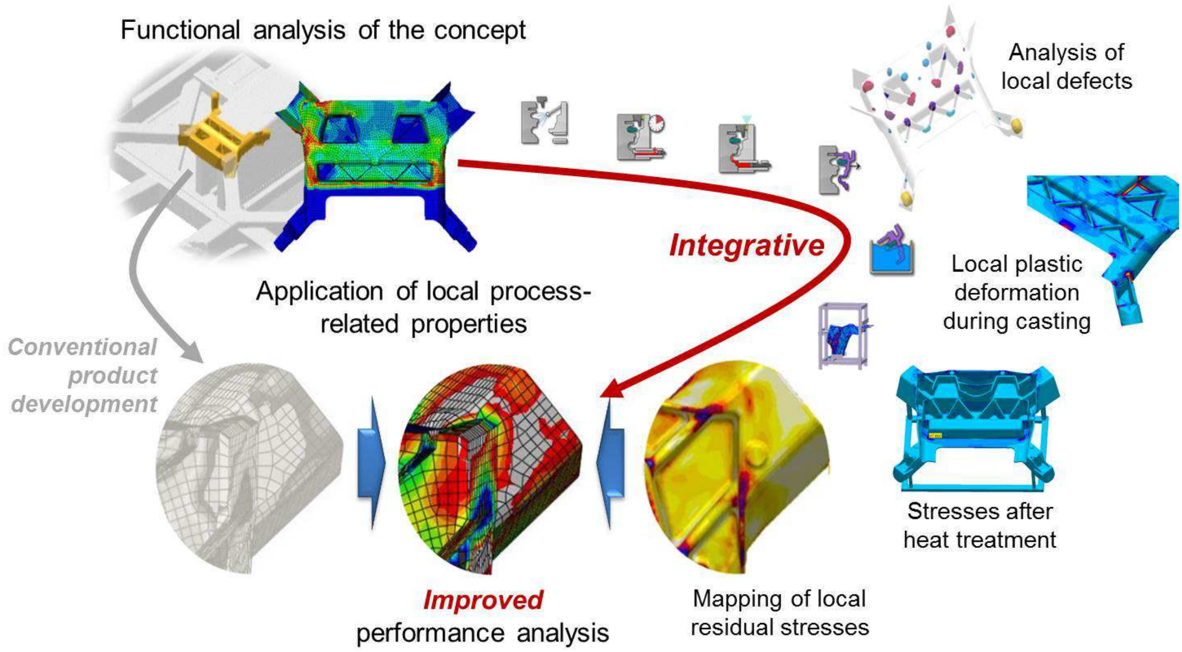


Figure 23: Innovative CAE process: improved functional prediction and risk assessment by making use of local casting properties from the casting process simulation. Virtually generated knowledge as a basis for confident decision-making in the concept and design phases to achieve robust products and processes.

5. Summary

In high pressure die casting, methodological virtual experimentation or Autonomous Engineering with MAGMASOFT® is a breakthrough methodology enabling an optimum and robust layout of dies and production processes through a transparent and quantitative process knowledge. In addition to the identification of reliable technical solutions, this new approach allows defining the best compromise between quality and profitability as targeted by the die caster. It is thus possible to generate systematic knowledge of correlations between production parameters and quality criteria of the casting even for complex tasks early on in the planning phase with nearly no economic or productive risks.

Early-stage secured decision-making supports product developers as well as die casters in designing robust, cost-effective and resource-efficient products and processes. The application of this virtually generated knowledge early in the planning phase is the basis for a CAE development process in which the designer and the die caster simultaneously optimize both the component and the casting process.

Literature:

[1] Casting Process Simulation for Robust and Optimized Castings with Tailored Properties, NAFEMS World Congress (2017),

[2] HTC Conference Venice (2016)

[3] Bachelor thesis Leineweber (2015)