# Systematic optimization of aluminum sand casting gating systems

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## 1. Introduction

Foundries are continuously exposed to ever increasing demands regarding their competitiveness, as well as in developing their specific casting process. This is especially the case for equipment intensive jobbing foundries, which have to develop numerous new parts per year under perpetually increasing economic pressures.

The development process for a new part was in the past determined within the foundry using "experience" as well as "trial and error". Nowadays, however, advanced casting process simulation tools have established itself as very reliable tools in the development process of new parts. Extensive casting trials are avoided, despite ongoing changes to pattern and process layouts, which especially jobbing foundries are forced into due to time and cost constraints. Only at the very end of the development process, once all parameters and design ideas are finalized, a test casting is produced.

That way the equipment utilization of jobbing foundries can be extensively improved, especially when continuous varieties in parts to manufacture and small batch-sizes prevail.

Casting process simulation provides "exact" parameters for the casting process to the foundry. Even with established casting processes, there is still a high amount of variability inherited in them, as process fluctuations are unavoidable. A process window needs to be evaluated and established. The larger and the more robust this process window is, the better the economics and quality of demanding castings can be realized. Hence, the process knowledge of foundry personnel is essential for the practical utilization of casting process simulation results.

If all parameters in a foundry with an impact on the quality of the final casting would be systematically analysed, an enormous amount of experimental effort, as well as calculation effort for simulations, would be required. For such cases autonomous optimization methods were developed, which provide a high degree of confidence despite them providing a limited amount of virtual trial and errors (simulations) in form of a virtual experimental test field. Objective of such virtual experiments is to establish not only an optimal operation point, but to create a robust manufacturing window, as well as defining adequate general casting manufacturing standards for both design and process.

The biggest challenge for the utilization of aluminium alloys remains - aside from the process oriented feeding and gating design - the control of hydrogen content in the melt and the minimization of oxide skin development. The strong tendency of aluminium to create oxide skins while being exposed to oxygen is a well known fact. In the gravity casting environment the relatively slow movement of flow fronts of aluminium can still become turbulent and, therefore, can easily create extensive oxides. These, in return, will create surface defects and may even result in internal defects, which influence casting properties and micro-structures of parts in a negative way [1/2/3].

In the following a specific example is chosen to demonstrate how the minimization of oxide defects in castings can be supported through numerical casting process simulation in a systematic way. For this purpose a defect-inducing gating system of an aluminium gravity sand casting was analysed using the MAGMASOFT® system, providing the automatic optimization of a gating system layout. The numerically calculated solution proposals were implemented in the production of a new sand-casting foundry of Ohm & Haener Metallwerke/Germany.

## 2. Automatic optimization of casting processes

Casting process simulation is calculating the process layout of a casting provided by an expert user. The judgement of the expert on which gating system and process conditions are the best will define the quality of the produced castings. Hence, the success of simulation is strongly linked to the expertise of the simulation operator.
The biggest advantage of the casting process, in being the fastest and most economical way to create near-net-shape manufactured parts, is also its biggest disadvantage: everything happens simultaneously and is interlinked.
The change of individual parameters can influence many quality aspects of castings in different and simultaneous ways. For example, a simple change of the melt temperature in an aluminium gravity sand casting process will not only influence the properties of the melt itself, potentially resulting in cold-shuts, but the inherent increase of its hydrogen content will impact the metallurgical properties and the solidification behaviour. In such inherently complex cases automatic optimization is an ideal tool to create a solution to support the best manufacturing boundary conditions. It utilizes the simulation software by creating a virtual experimental test field to either change casting process conditions or geometries in order to create the optimal result. Individual parameters are independently changed and evaluated. In other words, automatic optimization tools are mimicking the classical foundry expert approach: find the best compromise considering all parameters but do this under the consideration of thermal and physical boundaries.

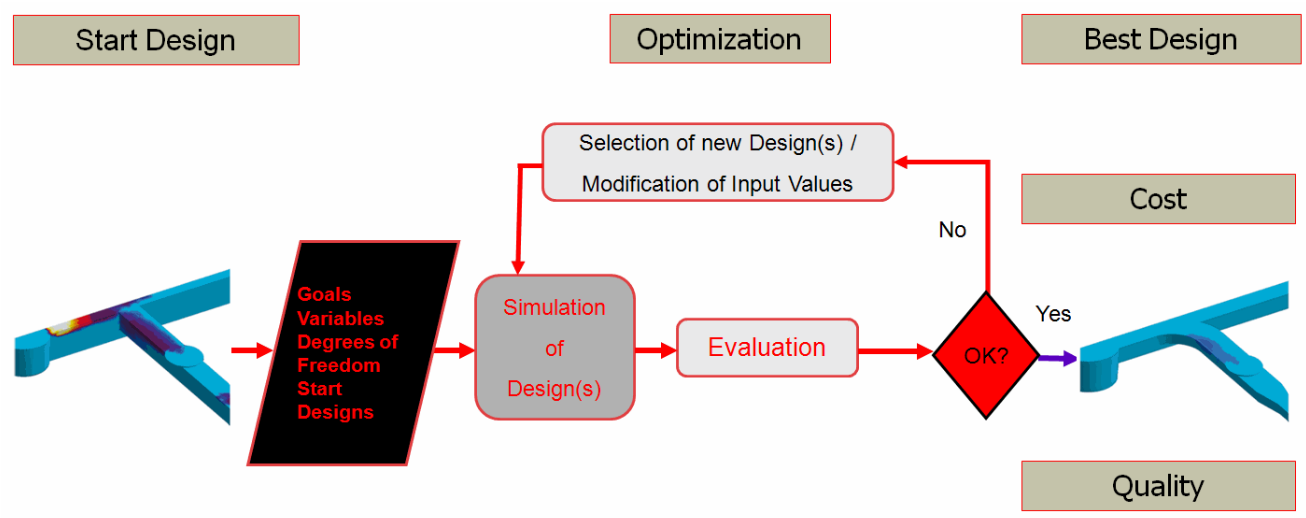


***Fig. 1. Schematic sequence of a design optimization with MAGMASOFT®.***

Autonomous numerical optimization offers new alternatives for difficult manufacturing tasks. The optimization process is running automatically, meaning “autonomously” without any human or external influence (figure 1). Here, various optimization goals (i.e. casting quality, productivity, material consumption, etc.) can be defined simultaneously. In order to achieve the desired optimization goals various manufacturing parameters (i.e. casting process conditions, materials, process timings, etc.) or geometries (i.e. gating system, risering, location and size of risers and / or chills, etc.) can be varied. For gravity sand castings various examples are available [4]. Explicitly the optimization of riser designs are to be mentioned here [5], but geometry optimizations of gating and runner systems are more and more done using this technique [6, 7, 8, 9, 10].

With autonomous optimization the user defines not only the simulation boundary conditions but also the degrees of freedom (i.e. casting temperature max. - min. or runner dimensions max. - min., etc.). The optimization goals need also be defined within the boundaries of non-variable parameters (e.g. manufacturing restrictions). The optimization software will start using statistical designs of experiments (DoE) to provide a small enough sample of designs for simulations to start the optimization process [11].

After each and every calculation, but prior to the next generation of virtual tests, the program will automatically check on the boundary conditions and the user defined degrees of freedom. In accordance with the results and matching criteria a genetic algorithm will generate a new design in the chosen casting technique. This operation follows the evolution theory of "inheritance", "combination" and "mutation". For every variant in the casting technique it will be decided whether it shall be scrapped or changed or possibly combined with previous versions. This will be repeated over and over again until no further significant improvements are achieved. Just as seen in the biosphere, the whole operation continues over various (calculation) generations until an optimal result is achieved - within this process many simulations will be carried out.

In the specific example of the simulation process, either the casting process conditions or the parametrically designed geometries will be adapted and modified automatically. In addition, the program will create a new mesh automatically and will define the new initial and boundary conditions for the then re-calculated designs - automatically. Also the evaluation of quality criteria is being carried out automatically.

After a sufficient amount of optimization rounds, results will be created providing compromised solutions based on the specific goals (figure 2) of the optimization. Practical experience has shown that parametric changes of geometries will have the biggest impact on the desired optimization goals.

As a basic principle for a goal oriented virtual optimization, clarity on the actual goal(s) need(s) to be established, i.e. all potential areas of errors must be minimized prior to starting an optimization sequence. A so-called DoE-sequence may be able to help with this step to determine the most influential factors [8]. Due to the magnitude of influencing factors (and of course the boundaries of the simulation model) it is often more advisable to optimize partial areas first to avoid loosing oversight of the actual goal of the optimization. Only at the point where no further solutions are identified, the optimization "window" would be expanded to a virtual experimentation field.

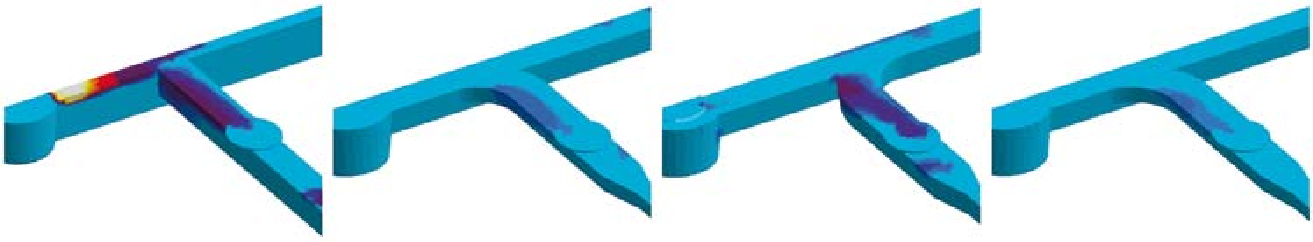

***Fig. 2. 4 design variants are depicted here, whereas about 200 simulations were carried out and utilized. The colored areas show clear signs of air inclusions and possible turbulent melt streams. The 4th variant on the right depicts minimal areas of air entrapment.***

One of the most important tasks, when defining a problem for optimization, is the successful definition of the quality criteria on one side and the optimization goal(s) on the other. Just for a gating system itself a pragmatic approach can yield many optimization options which the designer aims to achieve at once, here are examples:

- Transfer of specific filling related characteristics from one successful casting model to another while maintaining all quality requirements.
- Balancing of a filling pattern so that all cavities are filled simultaneously by modifying the gating system and the casting parameters.
- Avoidance of isolated areas of melt in the gating system and air entrapment in the casting
- Optimization of gating cross sections for optimal feeding.
- Maximization of casting yield to reduce overall material consumption.
- Avoidance of cold shuts within the casting, and many more criteria.

A distinctive advantage in working in such an environment is the availability of quantitative information that influences manufacturing quality.

Through optimization the operator is seeing beyond the current problems of the casting. This is supporting all endeavours to harmonize and standardize casting operations and parameters, which in return can be utilized for modern production methods.

## 3. The project

### 3.1 Initial situation and tasks to perform

In order to achieve an economical manufacturing process, most patterns in series production will be fitted with the maximum amount of cavities. In many cases a non-symmetrical layout is the result, especially in relation to the sprue position. As soon as more than one casting is incorporated on a pattern, the overall supply with liquid metal is no longer even. Due to different flow length and flow patterns, as well as filling times inside a gating system, the whole filling process of all cavities is inherently uneven. In addition it needs to be note that in most cases the gating system itself is not optimized for ideal flow. Inside of cross sections or along diameter changes certain low pressure phenomena and eddy currents can often be observed. Air is sucked into the runner and a lot of "free surfaces" will be generated which in return generate oxides. Most of these oxides will settle somewhere inside the cavities where they form agglomerates or surface defects. Visible oxides will classify castings as defective. They usually only become visible after shot blasting or other surface treatment.

For a principle study of using autonomous optimization on a gating system, a rather simple casting layout was utilized. A casting manufactured in a high production aluminium gravity sand casting was chosen. The molding method utilized is a state-of-the-art automated HWS molding line with impulse compacting technology. The 16-cavity mold (figure 3) is made without cores. Weight is 0.23kg and the alloy is AlSi9Cu3 (A229).

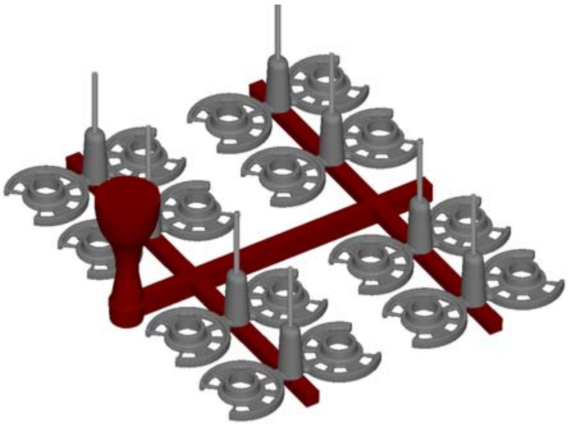

***Fig. 3. Initial situation of casting model layout.***

Initially, all cavities are in placed in a symmetrical layout and attached to the side runners, which are fed by the main runner. During production quite a number of surface defects occurred and were made visibly only after shot blasting and correctly identified as oxide inclusions (figure 4). The defects were detected in 20-30% of the parts and in all of the cavities. Some of the cavities investigated showed increased probability of the defects than others.

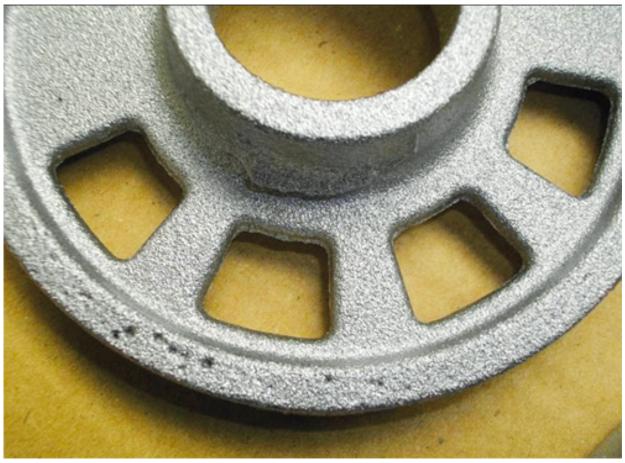

***Fig. 4. Oxide defects detected only after shot blasting.***

Main target for the autonomous optimization project was the elimination of the defects on all parts via an optimization of the runner system but under retention of the overall pattern layout.

### 3.2 Methoding

A major pre-requisite for the optimization is the clear definition of quality requirements and criteria, which can be assessed by the software. Various criteria need to be considered simultaneously. For the design of the gating system two main criteria are used in order to create a balanced layout and a cavity filling with minimal turbulences. Different fill times of the various cavities can be directly utilized as a measurement of equal cavity filling. The amount of entrapped air is directly proportional to a turbulent filling pattern. The chosen optimization goals are, therefore, the reduction in filling time differences between the cavities and the minimization of entrapped air throughout all cavities. (figures 5 and 6).

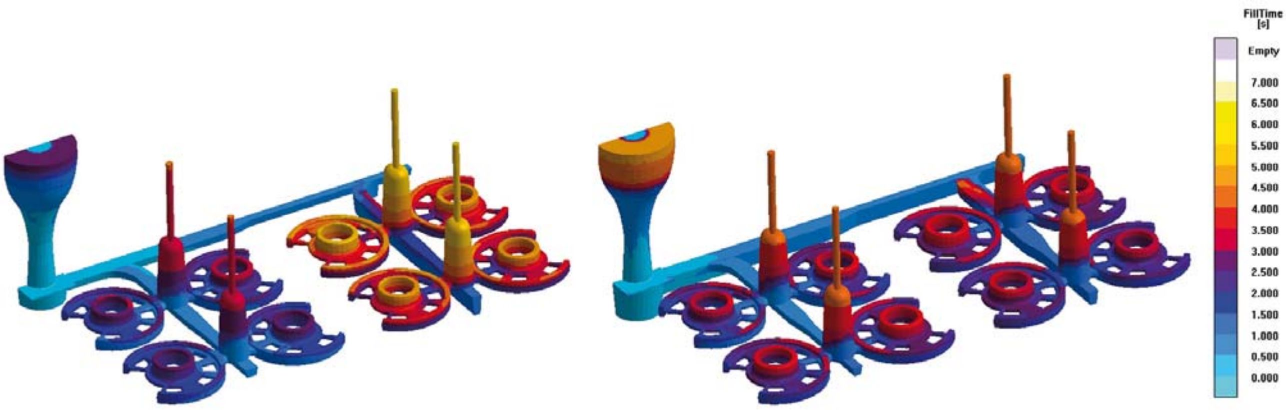


***Fig. 5. Comparison of the filling time results between a "bad" (left) and a "good" (right) runner design. Filling times in the left design are significantly different than the filling times on the right - almost optimal - design.***

***Fig. 6. Comparison of flow conditions between various gating designs. Criterion used is air pressure in [mbar] unit. All light colored areas show various levels of air entrapment inside the gating systems.***

All degrees of freedom are defined in the optimization not as fixed values but as variables or variants, which the software can change. The gating system was created as a parametric solid model in MAGMASOFT®, so the software can independently change the design and check the achieved values with the simulation results. The diameter and length values can be changed, as well as the tapering of the main side runners. In addition, radii were incorporated in the cross sections where main runner and side runners meet. Via this technique various designs were evaluated, see figure 7 and table 1.

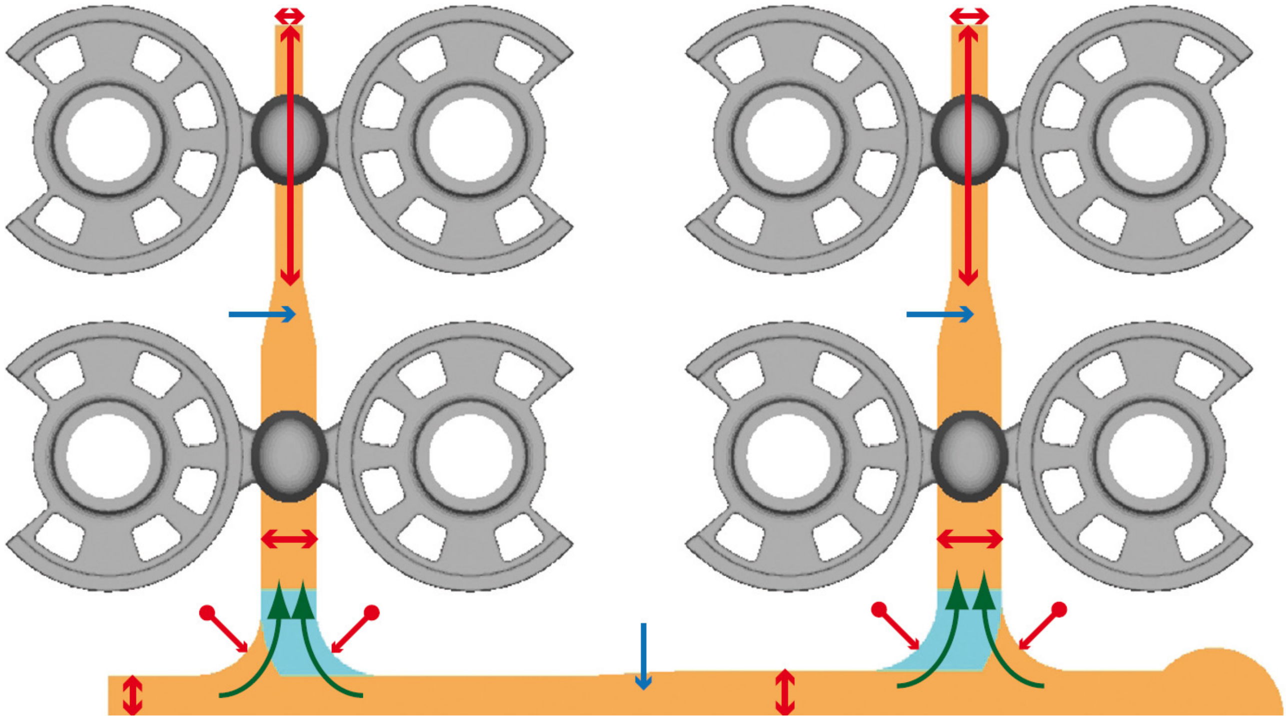

***Fig. 7. Depiction of "degrees of freedom" in the optimization run of the CAD model. The following parameters were set as variants: Flow direction in the cross section of main runner and side runner (green arrows); cross sections in 2 steps of main runner and side runner (red arrows). Fixed criteria were the length values of main runner and side runner (blue arrows).***

During the optimization process the position of all cavities was set as fixed (see table 1). While creating a "trial and error" plan on the computer a total of 196 different design and design combinations were calculated and evaluated.

In the real world, of course, such numbers of trials are not possible to run. However, depending on the complexity of the geometries and the required quality, various optimization loops could be tried on the shop floor as well, but this would cost the foundry in the range of several thousand Dollars or more.

### 3.3 Evaluation of the results

The evaluation of the calculated results can be assessed in various ways. Due to the fact that the software will create its own modifications on the selected variants of the gating system a so-called Scatter-Diagram is useful to evaluate each individual variant and its impact on the final result (figure 8). It can be see that the runner design has a significant impact on the final result. Based on the initial situation the evaluated results show a significant improvement in cavity filling time differences and potential air entrapment in the runner system.

| Variable Boundary Conditions | Size and Variants |
|---|---|
| Cross section main runner to side runner, | in flow direction, against flow direction |
| Cross sectional diameter of main and side runner | each 8 Variants |
| Length of the side runner | each 4 Variants |
| Radii at Cross section main runner to side runner | 0- 120 mm in 5 mm increments (x4) |

| Fixed Boundary Conditions | |
|---|---|
| Position of the tapering of the runners | |
| Length of the main runner | |
| Alloy | AlSi9Cu3 (A229) |
| Pouring Temperature | 750 C |
| Moulding material | Greensand, |
| Gas Permeability | 60 $cm^3$/min |

***Table 1. Design variants and fixed boundary conditions for the optimization.***

The best solution can be displayed via a "Pareto-View" projection. The marked line in the view indicates the calculated and individually evaluated variants where no better design combination is available. In the given example it can be seen that not necessarily the best gating system for reduced turbulence will provide the best overall solution. Only the consideration of the second quality criteria (fill time difference) will provide a balanced result

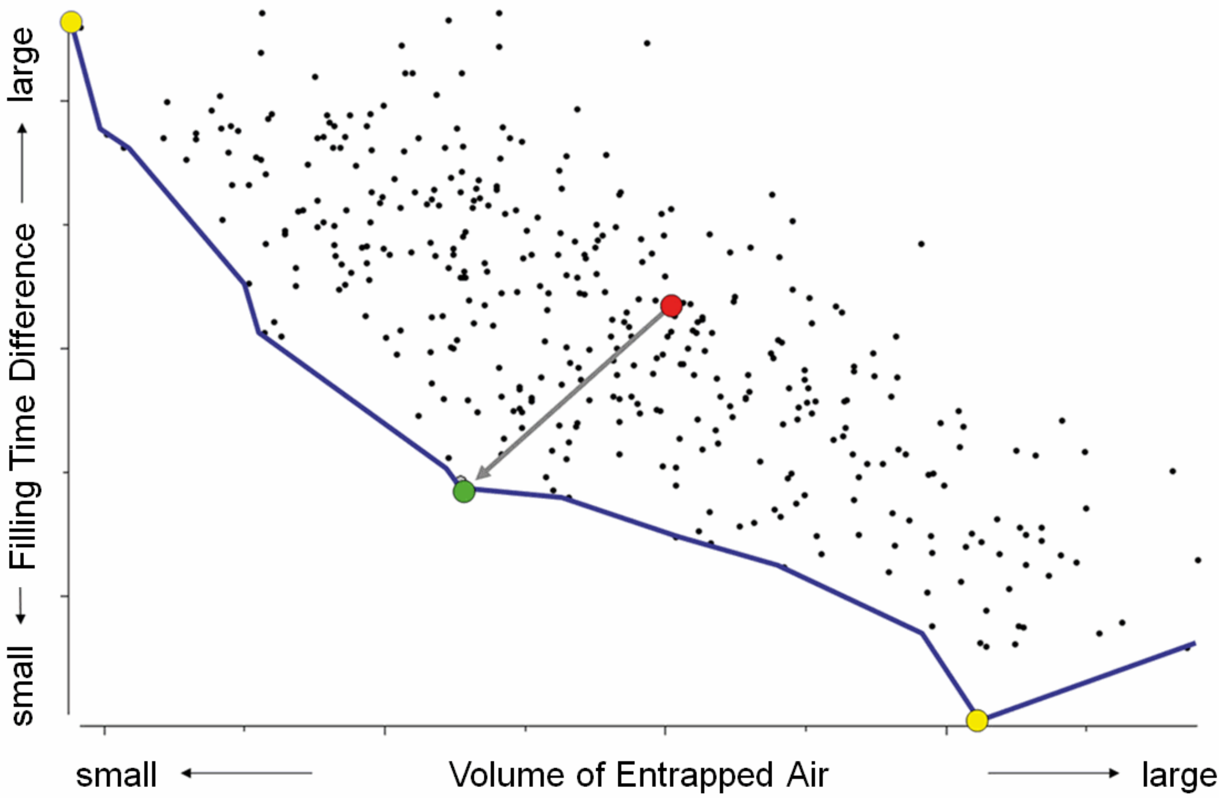


***Fig. 8: Above picture is showing a "Pareto-View" of a Scatter Diagram comparing the initial situation and the best solution. Based on the quality criteria defined and moving along the blue line it can be seen that the optimal solution either the best design (yellow dot) or the best compromise (green dot) can be chosen by the expert. Here the best design (yellow dot) is resulting in a 30% reduced filling time difference.***

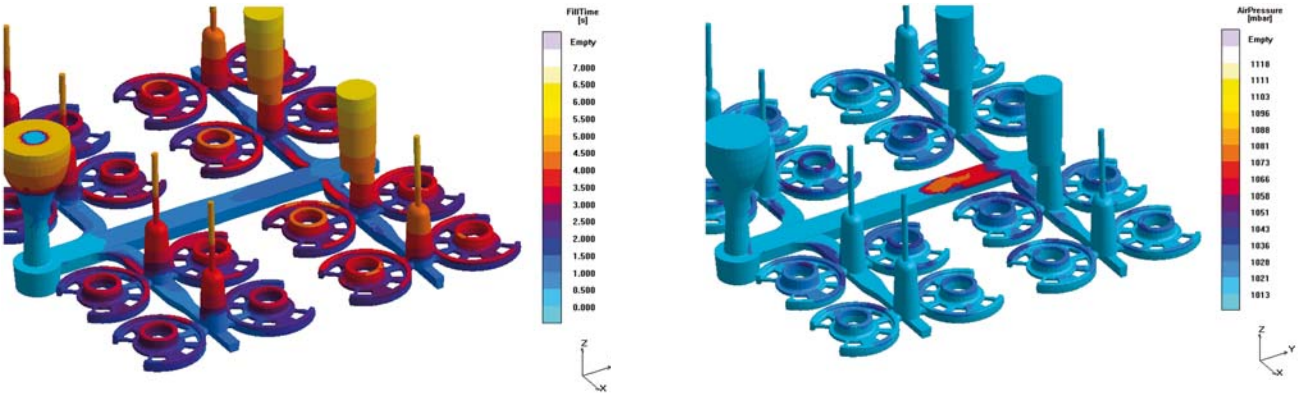


***Fig. 9. Depiction of the filling time (left) and air pressure (right) for the final design variant based on the best compromise. The filling time difference is max 1.5 sec whereas the air pressure result is showing minimal values in the casting.***

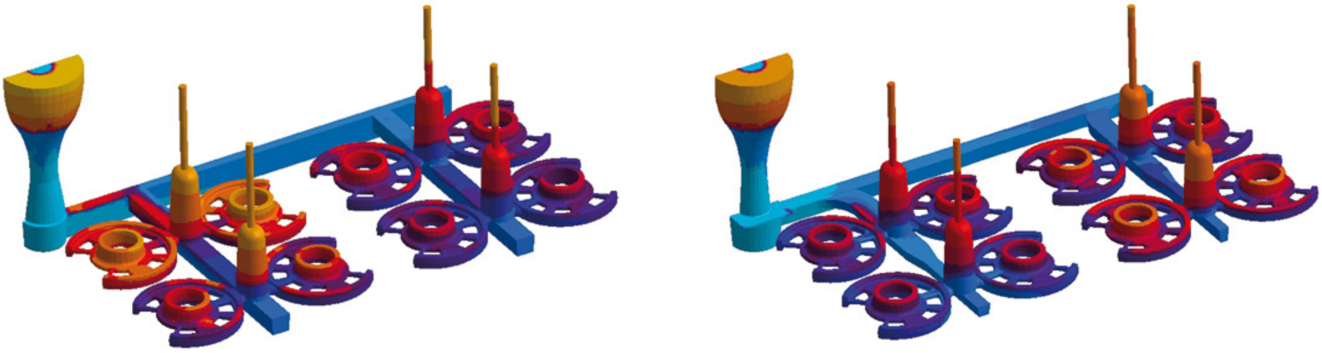

***Fig. 10. Initial situation and final optimised compromise solution is depicted. The filling time difference criterion is used. In the left picture a maximum filling time difference is more than 4 sec, whereas the right picture is showing a value of less than 1.5 sec.***

. The expert will derive a compromise for the final result to achieve a balanced gating system with the least amount of turbulent filling (figures 9 and 10). A comparison of the original layout and the optimized layout visualizes a clear improvement.

## 4. Practical Execution and Creation of Design Rules

With the finalization of the autonomous optimization and a detailed result analysis it was decided to execute and implement the proposed design. As mentioned under item 3 a "minimum in filling time difference" and the least amount of air pressure was chosen as the main quality criteria. The final design of the gating system was found through this method. The pattern modifications were transferred directly to the pattern making software through available interfaces within the software using the appropriate format.

The improved pattern went immediately into production without any further delay or additional trials (figure 11). All defects found in the previous production setup were eliminated. It is apparent that the simulation and automatic optimization has proven that the change of the gating system, the improved fill pattern and, last but not least, the drastic reduction of free surfaces lead to the avoidance of oxides and their agglomeration in the cavities.

One of the major benefits of using autonomous optimization tools is the creation of generic design rules that can be deployed on the shop floor. These design rules may or may not have applicability to all castings (different layouts/alloys/casting methods etc.) but they may contribute towards design standardization and can be used for future optimization projects. In this way the design rules can be transferred to similar situations. In the present case design rules were elaborated based mainly on geometrical changes in the runner system:

- Taper and cross section dimension in main runner and side runner
- Proportions of dimensions of main runner to side runner

- Radii in the area where main runner and side runner meet
- Orientation of radii in relation to flow direction

Based on these generic design rules, various other patterns were chosen for further autonomous optimization projects. All of these other patterns had multiple cavities, with similar casting problems. After each project these patterns went back into production showing clear improvement on the final castings.

***Fig. 11. Real casting after the autonomous optimization project was implemented. All casting defects experienced - mainly due to oxides - were eliminated in this project.***

## 5. Summary and Conclusions

Modern jobbing foundries have a strong requirement to achieve continuous cost reductions. Extensive trial and error approaches for new castings delay production, are cost intensive, and do not result in a "right the first time" approach. While engaging in an autonomous optimization project on a real aluminium sand casting in high volume production, it was shown and proven that modern casting process simulation technologies can contribute significantly towards the reduction of trial and error runs, hence, providing extensive cost savings. The achieved time and cost savings using such technology - in this case through the geometrical optimization of a runner system - were significant. In addition, an optimal and robust process window was created.

Autonomous optimization is a modern tool fully embedded in state-of-the-art simulation technology and allows the casting expert to improve casting designs and processes further by exploiting boundary conditions and manufacturing efficiency. Robust process windows and continuous process optimization can be systematically implemented in a foundry operation.

This example of an optimization of a gating system for an aluminium sand casting is showing that a foundry - through using such innovative technology - can also improve its process knowledge through virtual experiments and is able to put this knowledge into practical solutions. That way process parameters and process conditions can be understood in a better way, with the aim to improve them further. Numerical simulation in combination with autonomous optimization is, hence force, a very powerful tool for the pragmatic foundry expert and is becoming of prime importance.

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