Autodesk® Moldflow Insight 2025

Validation of the Cooling Channel Optimization

Executive Summary

With the advent of 3D printing, it is now possible to create complex conformal cooling channels that are impossible with a traditional drill and plug mold construction method. 3D printing allows more thermally efficient conformal cooling channel layouts to be generated. Determining the optimal position of these cooling channels is complex. In this report, we describe how this design process can be automated by optimally positioning the cooling channels in the mold. This will allow the plastic injection molded part to cool uniformly and quickly in a controlled manner. This technology aims to provide a cooling channel layout manufactured using modern mold-making technologies based on commercially available 3D metal printing techniques.

The optimization technique, based on the Moldflow boundary element (BEM) cool solver, provides a cooling channel layout that delivers a user-defined balance between part quality and cycle time, allowing suitable quality parts to be manufactured in the shortest time. This is achieved by concentrating the channels closer to the hotter, thicker sections of the part and by moving them away from the thinner sections and edges of the part. The technique ensures that the optimized cooling channel layouts respect minimum distances to the other cooling channels, parting planes, inserts, ejector pins, and the part itself. The cooling optimization method also maintains the symmetry of the initial design. An arbitrary initial design is used as the initial starting point and is then optimized to a design based on specific input criteria.

The design of cooling channels for injection molds using traditional methods such as drill and plug is nonintuitive and complex. As 3D printing is a relatively new process, little is known about optimal design patterns. By adopting 3D printing and this new optimization technology, an engineer with little or no mold design experience can propose cooling layout designs like an expert mold designer with many years of experience. The design automation automatically accounts for the limitations of the 3D printing process and can provide significant cooling performance gains compared to traditional drill and plug mold construction methods.

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Introduction

Plastic injection molding is best suited to mass production. Initial injection molding equipment and mold tooling costs can only be recovered through the volume of plastic products manufactured. To be competitive, the manufacture of each component must be done as efficiently as possible. The component needs to be manufactured as fast as possible to an acceptable level of quality for its intended purpose.

Heat goes into the polymer during injection molding, to be shaped into its final component form. Once the polymer is in its final component form this heat must be removed quickly in a uniform way. The quicker the heat is removed, the lower the cycle time, and the lower the production costs. In-molded residual stresses can be reduced by removing heat from the mold uniformly. As polymers cool and solidify, they contract significantly. If certain regions freeze after other regions, internal residual stresses are frozen-in at these interfaces. When the part is ejected, these frozen-in stresses cause the part to warp toward the regions that froze last. Generally, the cooling phase accounts for two-thirds of the cycle time. [1] As the cooling phase accounts for the bulk of the cycle time, it accounts for the bulk of the production costs. Hence by optimizing the cooling channel layout, cycle times can be significantly reduced, and large gains in production costs can be made. [1]

New state-of-the-art mold-making techniques, like 3D metal printing, are not as constrained as traditional drill and plug manufacturing techniques. The cylindrical cooling channels can follow the exact shape of the part where required while still maintaining a round channel like form, unlike traditional conformal cooling. With traditional conformal cooling, mold makers tended to hollow out a cavernous shape following the surface of the part, then cycled coolant through this void. The problem with this technique is that the coolant flow will always follow the path of least resistance, resulting in large areas of stagnant coolant close to the surface of the part. With stagnant coolant, heat is only removed through heat conduction instead of heat convection. Solid mold metal conducts heat better than stationary coolant. Fully turbulent flow in a cooling channel is the most efficient way of removing heat. Using 3D printing, fully turbulent flow can be guaranteed in cooling channels that follow the profile of the part very closely

Cooling layout optimization of the mold

The purpose of optimizing the cooling layout of the mold is to produce an acceptable part quality with a minimal cycle time**.** The part quality and the cycle time are directly related to the average mold-part surface contact temperature. Generally, a higher mold temperature leads to a lower cooling rate and thermal imbalances, resulting in more stress relief and less temperature difference induced warpage. Residual stresses and thermal bending are minimized through a higher mold temperature. However, a higher mold temperature results in a longer cooling time and total cycle time, resulting in higher production costs. The goal of cooling layout optimization is to reach the perfect balance between the part quality and cycle time objectives.

Simulation technologies

Traditional injection molding design aims to maintain the mold at a constant temperature for the entire injection molding cycle. To achieve this, coolant is pumped through mold cooling channels with constant set inlet temperatures. For conventional designs, this mold cooling process can be simulated sufficiently accurately by a steady-state solution of the cycle-average mold temperature. This means that an average temperature during the molding cycle is calculated for each location throughout the mold. It is assumed that during a single injection molding cycle, the mold temperatures in contact with the part only deviate slightly from the steady-state cycle averaged temperature at each location. It is the variation of the steady-state cycle averaged temperatures across the cavity surface of the mold that is the important cause of temperature difference induced part warpage.

To optimize a cooling channel layout and to ensure good numerical performance, a simulation using the boundary element solution (BEM) best meets these needs. The mold need only be represented by the outer boundaries of the mold, the surface mesh of the part and the cooling channel layout in the mold for a full steady-state 3D temperature representation inside the mold to be obtained. By using this method, the internal representation of the mold does not need to be re-meshed after each optimization, and the new cooling channel layout can be derived from the results of the previous layout. When the boundary element method is applied to the Laplace equation which describes the steady-state heat transfer equation, the internal representation of the mold is not required, [3,4]. However, with the boundary element method, every element in the domain is dependent upon every other element in the domain. This means that the resulting system matrix is a fully populated matrix and is computationally intensive. This type of system matrix cannot be banded to save memory, and basic iterative matrix solvers are used to solve it. For very large models the full system matrix cannot be stored in volatile memory and so “out of core” solvers are used.

When using such a boundary element solver to optimize the cooling channel layout, the relationships between all the elements in the model need to be re-calculated as these depend upon their spatial positions within the mold. However, the results from the previous optimization can be used as initial conditions for the new analysis, as these would not change by much between optimizations. The connectivity between all the elements remains the same, with only their positions changing. When the connectivities do not have to be re-calculated, and existing results are used as the initial solution estimate, a substantial speedup in the solution can be achieved. A literature survey showed that the boundary element method for channel optimization has been used previously [2].

Solver implementation

This optimization method runs within the existing Autodesk Moldflow Boundary Element Method (BEM) Cool solver. The solver will run the initial cooling analysis followed by the optimization method. After each optimization step, the cooling channels positions are updated. Each successive optimization step will be based on the prior channel positions.

However, since the prior model has already been run and most of the model, such as the part or outer boundaries, do not change, the connectivity matrices for these items remain unchanged, hence these do not need to be computed again. As noted previously, the boundary element method requires a full matrix, meaning that each element in the model influences every other element in the model. Hence every row and column of the system matrix will need to change as all the channel elements will have changed. Hence the boundary integrals quantifying the relationship between every element will need to be recalculated. Once recalculated, the analysis will continue to repeat until the maximum number of iterations specified by the user is met or if no further improvements are possible.

Metrics for measuring the optimization.

With the objectives of the cooling optimization being to reduce the cooling time and to minimize the temperature difference across the surface of the mold in contact with the part, two metrics are defined.

The first metric is the normalized average mold temperature in contact with the part. The average surface temperature of the mold in contact with the part is dictated by the molding resin. Certain resins such as nylons or polycarbonates require a very high mold temperature, whereas polypropylenes or polystyrenes require cooler mold temperatures. The coolant temperatures are set accordingly to achieve these desired mold temperatures. The first metric is defined as the average temperature metric. T_{m}

$$T_{m} = \frac{T_{average_{iteration}}}{T_{average_{initial}}} \qquad [1]$$

Equation [1] states that the average mold-part surface contact temperature is normalized with respect to the initial mold's average temperature result. If the average mold temperature in contact with the part decreases with subsequent analyses, the metric is a fraction smaller than 1.0, showing that the mold is colder. If the metric increases, the subsequent design is hotter than the previous one.

If there are vast improvements in this metric during optimization, the user should then recalculate the cycle time on the final design iteration to ensure that the final mold temperature meets the polymer's requirements. This analysis will raise the final mold temperature by shortening the cycle time, satisfying the first goal.

To meet the second objective to minimize the temperature difference across the surface of the mold in contact with the part, the temperature variance results will be used. The temperature variance result is defined as

$$T_{variance\ i} = T_i - T_{ave} \qquad [2]$$

Where the area-weighted average mold-part surface contact temperature is subtracted from the temperature of the mold in contact with the part. Hence, if an element is hotter than the average temperature, the metric will be positive, or if it is cooler, the metric will be negative. The goal of the optimization is to get as many elements as possible to have a low magnitude of temperature variance (close to zero). To achieve this, the standard deviation of the temperature variance will be minimized. A low standard deviation indicates that the values tend to be close to the mean of the set, while a high standard deviation indicates that the values are spread out over a broader range.

The minimization of the standard deviation of the temperature variance will be used to achieve the second objective of the cooling channel optimization. The standard deviation of the temperature variance is given by equation [3]

$$\sigma = \sqrt[2]{\frac{\int_S \left(T_{variance\ i}\right)^2 dS}{\int_S dS}} \qquad [3]$$

While one of the aims of the optimization is to minimize the standard deviation of the temperature variance in the mold, the other objective is to minimize the average mold-part surface contact temperature. To minimize average mold temperatures, the cooling channel elements may move very close to the part. This could give rise to cold spots on the surface of the part. These cold spots increase the temperature variance in these positions, which increases the standard deviation. The standard deviation metric is normalized as:

$$std_m = \frac{\sigma_{iteration}}{\sigma_{initial}} \qquad [4]$$

If this standard deviation metric decreases, it means that the individual cavity surface temperature values are closer to the average mold temperature in contact with the part.

Application of the optimization metrics

Equations [1] and [4] are used to normalize the metrics for optimizing the cooling channel locations. A weighted sum method is chosen to deal with the dual objectives of the cooling analysis. The user can set the objectives by setting the relative importance of reducing the cycle time versus reducing the temperature induced warpage. These two user inputs are normalized to a single factor α.

$$\alpha = \frac{Relative\ importance\ of\ Cycle\ Time}{(Relative\ importance\ of\ Cycle\ Time + Relative\ importance\ of\ Warpage)} \qquad [5]$$

The default relative importance of cycle time is set to 1.0 and the default relative importance of warpage is 0.0. Therefore, the default parameter values will optimize the cooling channels to achieve a reduced cycle-time without considering the part warpage. If the two user inputs have the same value, the factor of α will equal 0.5. This means that both average mold temperature (which reduces cycle time), and temperature difference (which reduces temperature induced warpage), have equal weighting during optimization. The final weighted metric is given by:

$$Metric = \alpha\, T_m + (1.0 - \alpha)\, std_m \qquad [6]$$

The aim of the cooling channel layout optimization analysis is to minimize this metric equation [6].

During optimization, the solver will update the positions of the cooling channels and do a full cooling analysis on the updated cooling layout. At each iteration, the solver recalculates the average part temperature in contact with the mold, the standard deviation of the temperature variance, equation [3], together with their respective equations [1], [4], and the metric equation [6]. Once the metric in [6] has reached its minimum, the optimal cooling channel layout has been achieved.

Results and discussion

To demonstrate the cooling channel optimization a simple box model is used, Figure 1. The initial model is a box with 4 cooling channels located far from the part in both the fixed and moving halves of the mold.

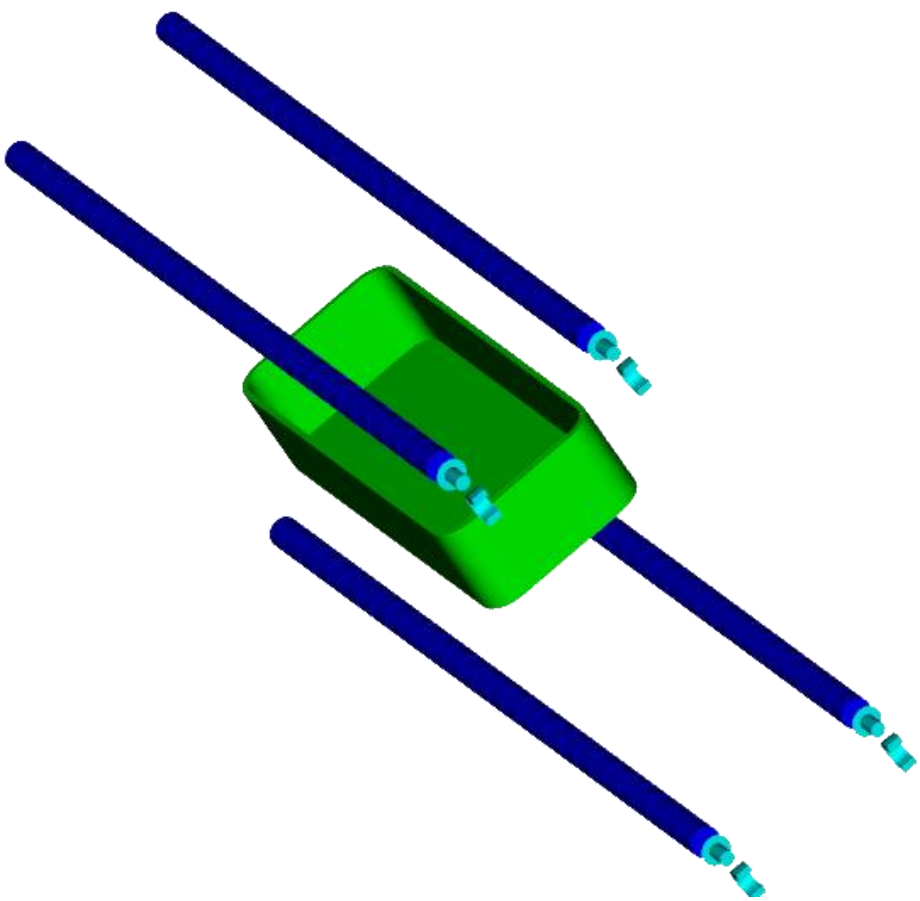

Figure 1: Box model with 4 initial cooling channel layout

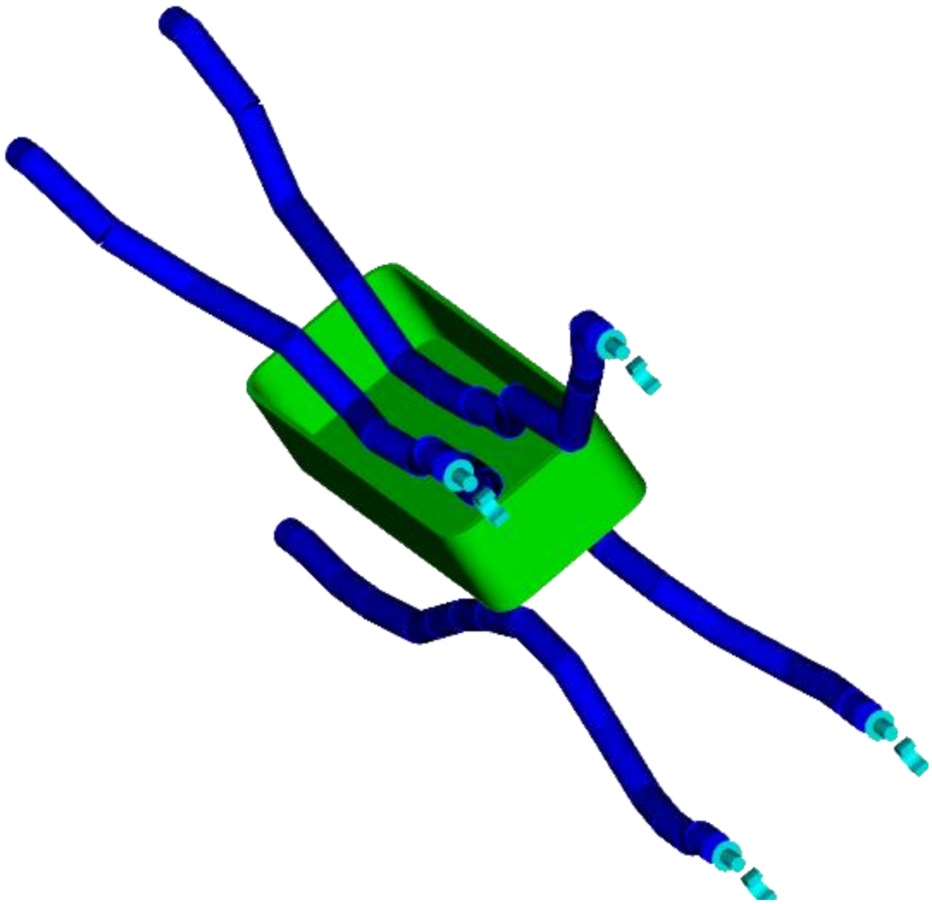

Figure 2: Optimized box model cooling channel layout

Figure 2 is the optimal cooling channel layout of Figure 1, showing the optimal cooling channel layout.

Table 1 shows the results of the optimized cooling layout, Figure 2, compared to the initial layout, Figure 1.

Model	Initial	Optimized
Overall Metric	1.0	0.58
Average mold temperature in contact with the part (Tavg) °C	53.1	39.7
Standard deviation of temperature variance (std) °C	9.6	3.9
Temperature range of mold temperature in contact with the part	26.0	18.6
Temperature metric (Tavg Mold current / Tavg Mold initial)	1.0	0.75
Standard deviation metric (Metric std current / Metric std initial)	1.0	0.41

Table 1: Initial and optimized results with $\alpha = 0.5$

Table 1 shows a:

- 42% improvement of "Metric" with the optimized cooling channel layout
- 13.4° C reduction in average mold-part surface contact temperature, T_{avg}
- 5.7° C reduction in the standard deviation of the temperature variance, σ
- 7.4° C reduction in the overall temperature range of the mold in contact with the part, T_{range}
- 25% improvement in the Average temperature metric. T_{m}
- 59% improvement in the standard deviation of the temperature variances, **s**td$_m$

Therefore, the components produced with the optimized cooling channel layout will require less cycle time because the average surface temperature is cooler and will be of higher quality because there is less temperature variation across the surface of the part.

Figure 3 shows the cooling channels maintain at least a single channel diameter from the part and other cooling channels, as seen on the inside of the box. Comparing Figures 2 and 3 shows that the cooling channels are moved closer to the part and into the hollow section of the box, as this is an enclosed area that naturally traps heat. Symmetry is maintained during optimization, left and right or top and bottom channels are drawn in toward the part by equal amounts from either side.

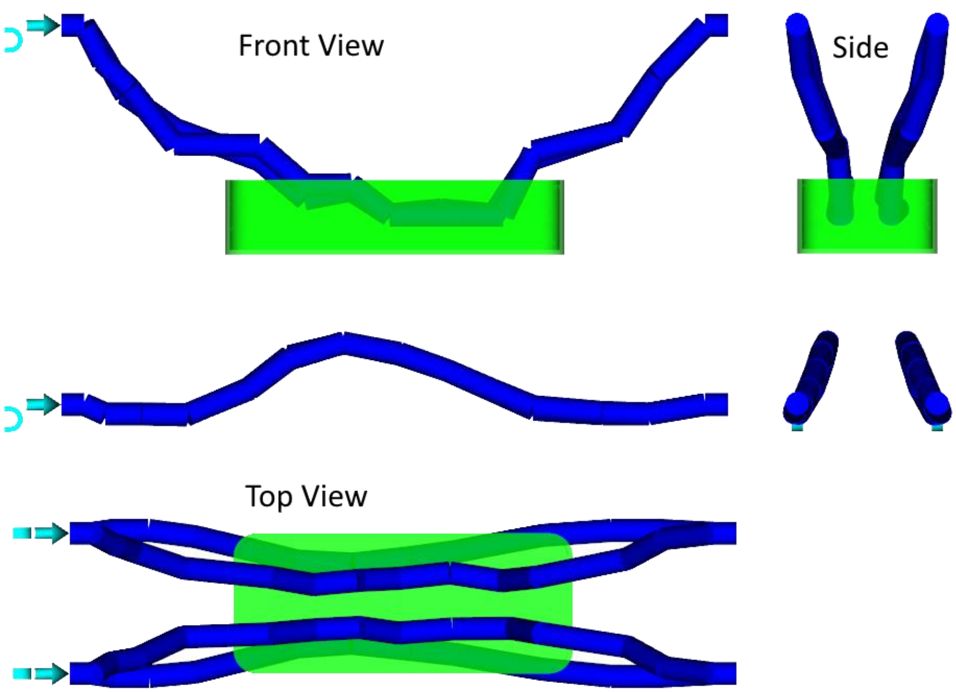

Figure 3: Front, top, and side views of the optimized layout

Figure 4 shows the temperature of the mold in contact with the part for the initial layout and for the optimized layout. It confirms that the optimized layout is much cooler than the initial layout, and the temperature differences across the part are much smaller.

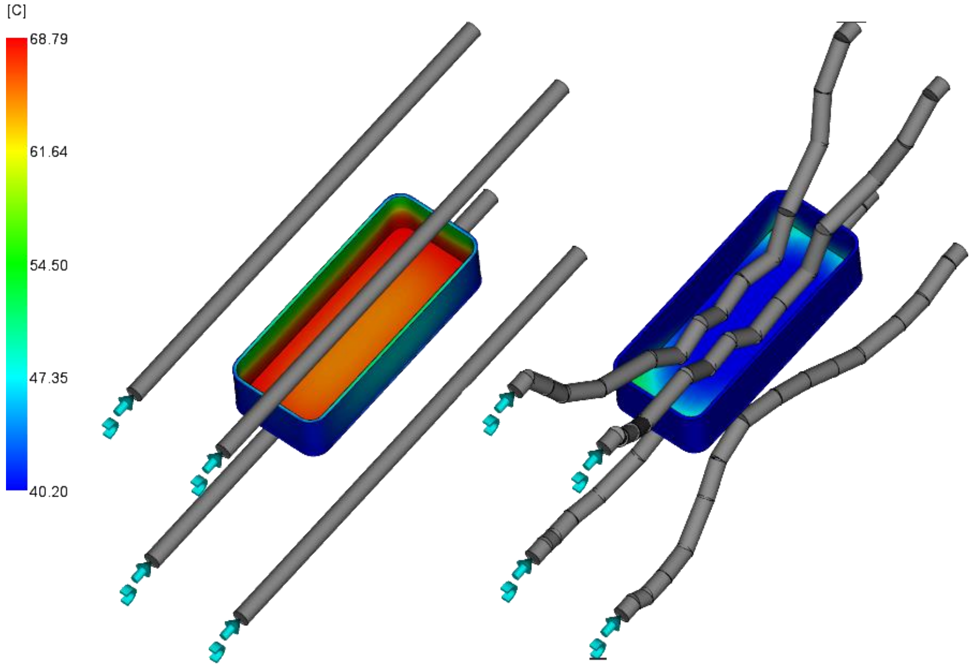

Figure 4: Mold cavity temperature for initial and optimized layouts

Figure 5 shows the optimized layout has a much lower temperature variance across the surface of the part in contact with the mold, which is one of the objectives.

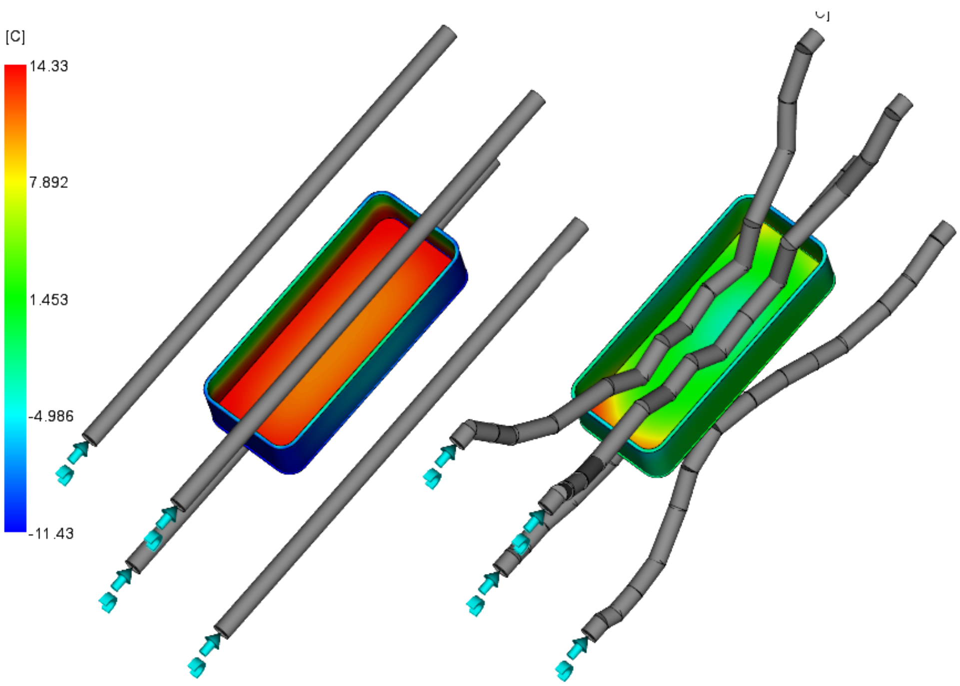

Figure 5: Temperature variance for initial and optimized layouts

The simple box model used for this demonstration shows that the channel optimization routine is working as expected. For this model, the initial channels were moved to positions that were more optimal to cool the part and maintain an even temperature distribution across the part.

The predicted final part shape is shown in Figure 6 for both the initial channel layout and the optimized channel layout. In both cases, the shape deflection has been exaggerated to allow easier comparison. The color legend shows the actual predicted deflection values. This comparison shows that the optimized channel layout, with lower temperature variance across the surface of the part, results in less bowing of the side walls of the box. Therefore, the optimized layout is expected to produce better-quality parts.

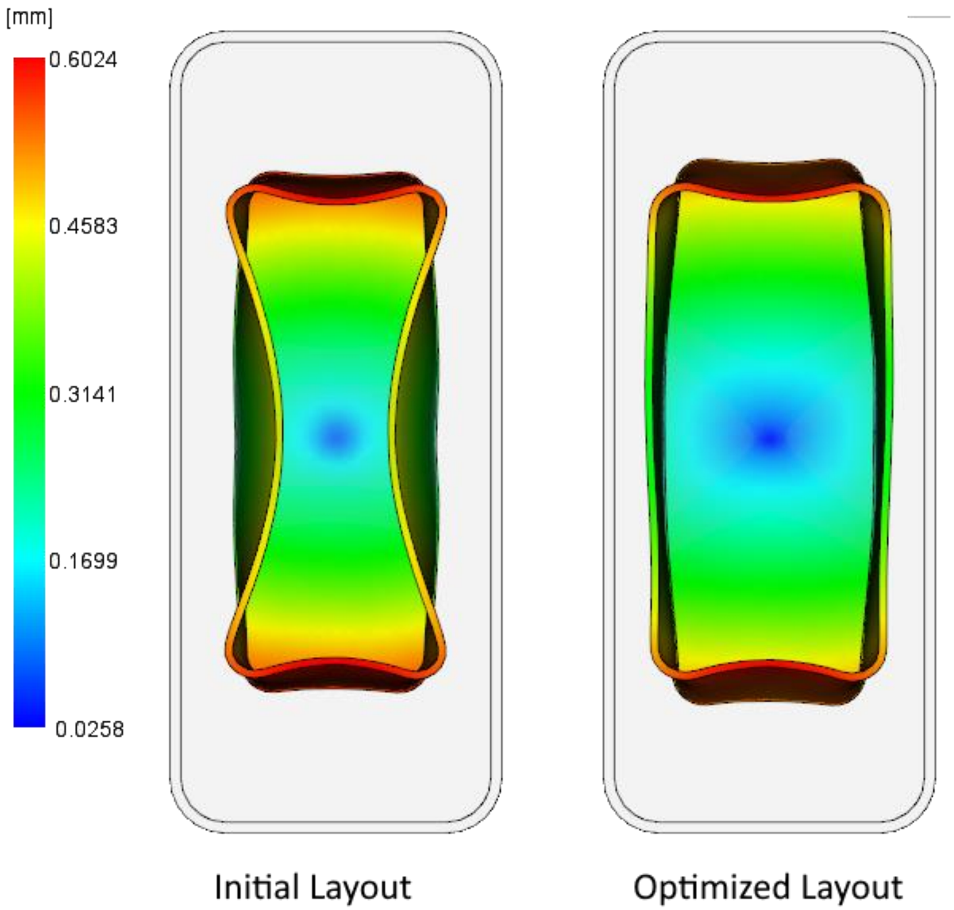

Figure 6: Warpage deflection for initial and optimized layouts

Conclusions

Cooling channel optimization delivers practical 3D printable cooling channel layouts. The characteristics of these layouts compare with designs from experienced mold designers. An example has been provided to show how this leads to optimal cooling channel locations and improved part quality.

Cooling channels are moved to maintain symmetry, where applicable, and maintain specified distances from other mold elements such as parts, parting planes, ejector pins, and other cooling channels.

The weighting of the optimization objectives are user-definable by the user.

Cooling channel layout designs from this optimization technique are tuned for 3D printing and cannot typically be produced using traditional drill and plug mold-making techniques.

References

1. Jay Shoemaker, Moldflow Design Guide, A Resource for Plastics Engineers. Moldflow Corporation 2006.
2. Nicolas Pirc, Florian Bugarin, Fabrice Schmidt, Marcel Mongeau Cooling channel optimization for injection molding. NUMIFORM 07: Materials Processing and Design: Modeling, Simulation and Applications, Jun 2007, Porto, Portugal. p.525-530, 10.1063/1.2740864. hal-01354303