# MULTIDISCIPLINARY DESIGN AND OPTIMIZATION OF A PLASTIC INJECTION MOLD USING AN INTEGRATED DESIGN AND ENGINEERING ENVIRONMENT

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## THEME

CAD-CAE Integration

## KEYWORDS

Multidisciplinary Design and Optimization, Knowledge-Based Engineering, Knowledge Management, Plastic Injection Mold Design

## SUMMARY

In order to remain competitive with respect to low-cost overseas markets, domestic moldmakers will have to increase the productivity of their engineers and maintain high quality standard, while dealing with the problem of an aging workforce. To increase the competitiveness of the European automotive industry, the concept of and Integrated Design and Engineering Environment (IDEE) has been developed within the 6th framework European project *Pegasus - Integrated engineering processing & materials technologies for the European sector*. The IDEE consists of a distributed set of software applications able to accelerate the design process of plastic injection molds by means of process automation and multidisciplinary optimization techniques.

The IDEE combines into a single user-friendly platform different technologies ranging from Knowledge Management (KM) and Knowledge-Based Engineering (KBE) to Process Integration and Automation (PI&A). Central to the IDEE framework is a KBE application, which consists of a fully parametric rule-based mold product model. On the basis of the geometry of the plastic part to be molded and other (user) inputs, the KBE application can automatically produce different mold configurations and variants. In this way, product knowledge is leveraged to automate the repetitive and therefore time-consuming CAD modelling activities typically encountered in industry.

Next to the mold geometry, the KBE application is able to generate different reports that serve as input to in-house developed or commercially-of-the-shelf

CAE applications, like Autodesk® Moldflow® Synergy. The resulting software framework enables the simulation and analysis of the injection molding process, from which important performance characteristics can be retrieved. Other disciplinary applications are used to assess the cost and the environmental impact of the molding process and tooling. All the IDEE software applications are provided as web services on remote servers according to the *Software as a Service* (SaaS) paradigm. Noesis's Optimus software has been used to link them into a seamless framework, control their execution and support all data exchange in an automated fashion over the internet.

The scope of this paper is to describe the architecture and main functionalities of the IDEE and provide the results of studies performed on representative plastic parts for the automotive industry. It is demonstrated how the IDEE can enable multidisciplinary optimization of the injection molding process and find solutions that best balance manufacturing performance and product quality. By means of the IDEE many concepts and customized variants can be quickly generated and evaluated in terms of hours or days instead of weeks or months, thereby supporting a more efficient development of innovative and complex parts. The reliability of the evaluation is enhanced by the early use of computer-based simulations in the design process, and the success rate of the overall component increased because of the more disciplines included in the evaluation (tooling design, material processing, cost, environmental impact). The IDEE can help the designer to *virtually* prototype and analyze the product and, eventually, support the "first-time-right" design principle.

## 1: Introduction

Now more than ever, European mold makers and car component designers are struggling to compete with low-wage country manufacturers. From one side the general level of complexity of products increases, while, at the same time, a higher quality level must be achieved within a shorter lead time, at a price that is competitive on the global market. Great benefits could be obtained by streamlining the overall product development process through a better integration of the supply chain. Nowadays the level of integration/collaboration between OEM and SMEs is suboptimal. A lot of repetitive activities are taking a too large portion of the engineering design process at expenses of lead time and creativity. The brains drain phenomena is taking out of the arena the most experienced engineers with the result that old errors are repeated and the use of best practices is not systematically enforced. The effective application of multidisciplinary design optimization techniques to improve product quality is not yet reality. In view of developing new technologies to increase the competitiveness of its automotive sector, the European Community has sponsored a large collaboration project called Pegasus (Integrated engineering processing & materials technologies for the European sector). One of the main Pegasus goals was the development of an new software system, called Integrated Design and Engineering Environment (IDEE), able to support collaborative and integrated development of plastic injected (automotive) components.

The IDEE is an integrated suite of software modules deployable via web connections according to the *Software as a Service* (Saas) paradigm, see figure 1. It can support and accelerate the development of plastic injection molds and perform analysis and optimization of the injection molding process of car components by means of computer simulations. The IDEE leverages three core technologies, namely Knowledge Management (KM), Knowledge-Based Engineering (KBE) and Process Integration and Automation (PI&A) to achieve a higher level of integration in the design process and effectively support Multidisciplinary Design and Optimization (MDO).

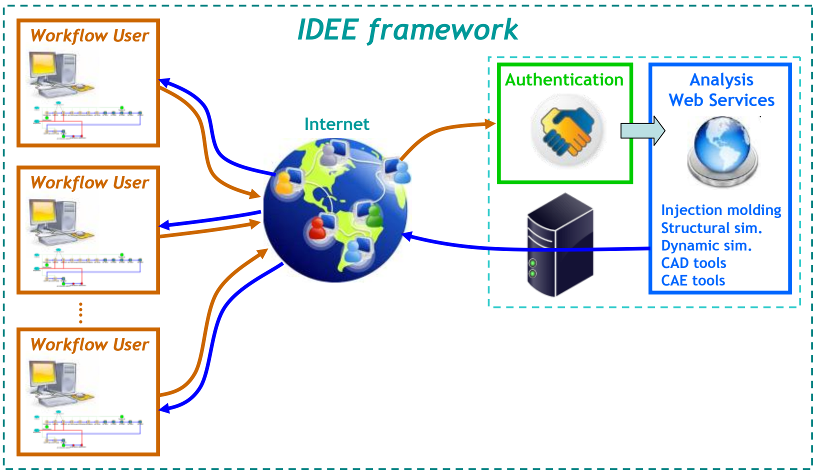



**Figure 1: IDEE Framework architecture overview**

Chapter 2 will introduce the three above-mentioned technologies and elaborate on some of the main components of the IDEE architecture. In order to demonstrate the IDEE capability, a proof of concept optimization workflow will be described in chapter 3. Although the specific IDEE implementation described here concerns a simple plastic component, the implementation of the overall framework is still representative of more complex design problems, such as the cooling system optimization process for the injection of a plastic car fender, as actually addressed in the Pegasus project (details cannot be disclosed because of confidentiality agreement). Chapter 3 will also elaborate on the hybrid optimization methodology that has been implemented within the IDEE. It will be illustrated how a given cooling system design can be improved, while keeping computational cost low and shortening the total design lead time.

## 2: Integrated Design Engineering Environment

Although the eventual IDEE concept is based on a close integration of three technologies, viz. KM, KBE and PI&A, this work will focus on all developments related towards the integration of the latter two aspects. The following sections explain how different web-services (section 2.1 and 2.2), located on a remote server at the Delft University of Technology (DUT), are integrated in a bigger software workflow architecture, which a user can manipulate and drive on his client computer (section 2.3).

## 2.1 Knowledge-Based Engineering Application

Knowledge-Based Engineering (KBE) is the ”use of advanced software techniques to capture and re-use product and process knowledge in an integrated way” [1]. A KBE application is a software application that uses Artificial Intelligence (AI) techniques to solve complex problems that would normally be performed by a person with specific expertise. However, what distinguishes KBE from a general Knowledge-Based System is the focus on engineering [2]. As a result solving problems by reasoning must be supplemented with analysis and computation. On top of that, the field of engineering comes with the challenge of geometry manipulation and product configuration. In this respect, “KBE represents an evolutionary step in Computer-Aided Engineering (CAE) and is an engineering method that represents a merging of Object-Oriented Programming (OOP), AI and Computer-Aided Design (CAD) technologies” [3]. For a thorough technology overview of KBE, see [4]. The objective of KBE is to reduce engineering time and cost of product development, which is primarily achieved through the automation of routine design tasks with retention of design knowledge. Besides automation, KBE systems enable integrated modeling, where multiple disciplinary views can be derived from a central product model.

Both automation and integrated modeling capabilities make KBE technology an enabler of Multi-Disciplinary Optimization (MDO). In what is introduced as a Design and Engineering Engine (DEE), several papers have demonstrated this [5,6]. Inside the DEE, A Multi-Model Generator (MMG) is used to describe a product family in terms of common building stones. The MMG has a generative capability to automatically instantiate geometry and an ability to create multiple perspectives on the product model. The MMG is connected to specific disciplinary analyses modules, which process information from the product model. Analysis results serve as input for the overall MDO process.

This DEE methodology has formed the inspiration for the current IDEE concept. However, where previous research has focused on aerospace applications, this research has adopted the KBE approach for the automotive industry and added particular focus on the integration and automation of software tools in the overall software workflow.

Genworks International’s General-purpose Declarative Language (GDL), a superset of the Common Lisp language, has been used as the KBE platform in this research [7]. With GDL the Delft University of Technology (TUD) has developed a KBE application, the so called Mold Multi-Model Generator (3MG), that holds a parametric description of a generic plastic injection mold system. Inside this application all rules and knowledge have been captured and programmed in order to generalize a mold design into several basic building blocks or High Level Primitives. In this way a user (human or other software application) is able to provide several inputs to generate a specific mold design from a unique product model definition

The 3MG is able to automate a significant part of the geometrically-related routine design tasks typically encountered in mold design, starting with a raw plastic part geometry file as an input (IGES, STEP or STL). Automated routine design tasks include CAD modeling activities and mesh generation. Next to these geometry-related steps, the 3MG pre-processes the product model to generate analysis models for several disciplinary analysis tools, a normally quite repetitive and time-consuming step [3]. The product model has been integrated with cost analysis, environmental impact analysis and plastic melt flow simulation software. Section 2.2 will focus on the latter coupling.

The capability of GDL to act as a web server, enabled a straightforward integration of the 3MG into the IDEE as a web service, located at the TUD.

### 2.2 Computed Aided Engineering Integration

Autodesk® Moldflow® Synergy 2010 (Moldflow) has been integrated in the IDEE as COTS software for plastic melt flow simulations [9]. Visual Basic Scripts (VBS) have been developed to automate the creation of the analysis model inside Moldflow and to set-up and drive the analyses. Several dedicated PHP scripts have been used to make the Moldflow application available on a server at the TUD and enable a modular integration of this software into the IDEE workflow as a web service. From the Moldflow analysis report, several performance and quality measures can be automatically extracted for the overall optimization process. These include cooling and warpage data, manufacturing cycle time, volumetric shrinkage, clamping force, etc. Figure 2 illustrates the resulting integration of the 3MG application and Moldflow; a branch of the overall software architecture, as discussed in the next section.

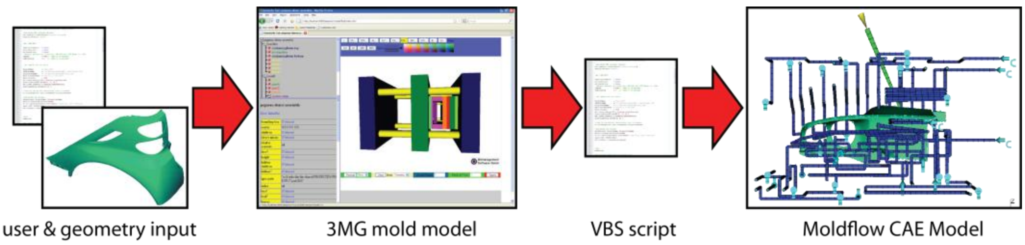



**Figure 2: CAD-CAE integration of mold product model and Autodesk Moldflow**

### 2.3 Process Integration and Automation Workflow

Both the 3MG and MoldFlow analysis tool have been integrated into one distributed, seamless design, analysis and optimization process, using NOESIS' Optimus [10]. Optimus automates the initiation of product and analysis models, drives simulations, retrieves, processes and stores simulation results and offers several optimization algorithms. Optimus graphically represents these essential operations as modular building blocks, which a user can assemble in different ways to build the workflow required for the design case at hand. The workflow that drives the optimization is given in Figure 3 and will be discussed in detail in chapter 3.

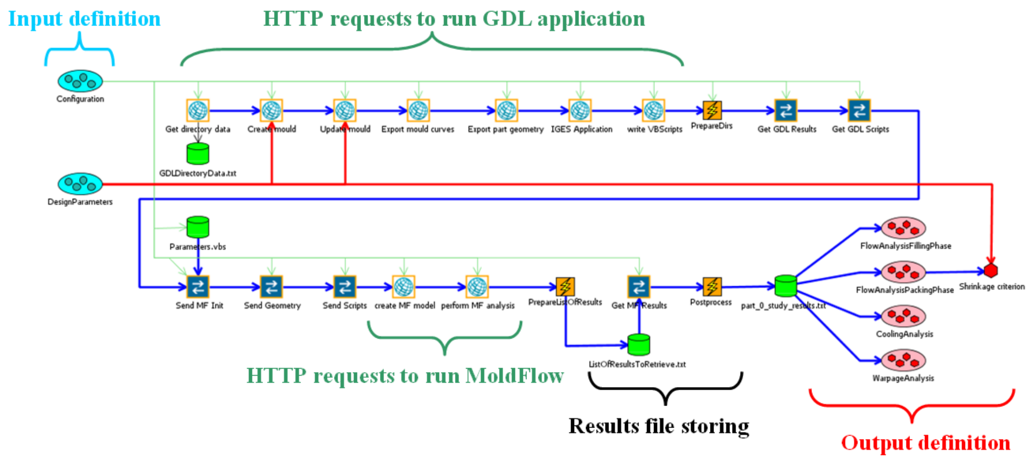



**Figure 3: Workflow developed for the cooling system optimization**

A dedicated module that has been developed for the purpose of this research is the communication capability between Optimus and the 3MG application. Communication is based on the Hypertext Transfer Protocol (HTTP). Using the ‘POST’ request method, Optimus specifies all design aspects to 3MG in the body of the request. The response to this request is then automatically handled and interpreted by Optimus. HTTP requests are for example used to create a new mold instance, or (on subsequent iterations) to update one or several mold parameters. File transactions use the (Secure) File Transfer Protocol, (S)FTP.

## 3: IDEE for cooling system design and optimization

### 3.1 Optimization problem definition

In order to demonstrate the IDEE’s capability to support MDO, a test case has been defined. This involves the optimization of a conformal cooling system design for a simple plastic part (figure 4).

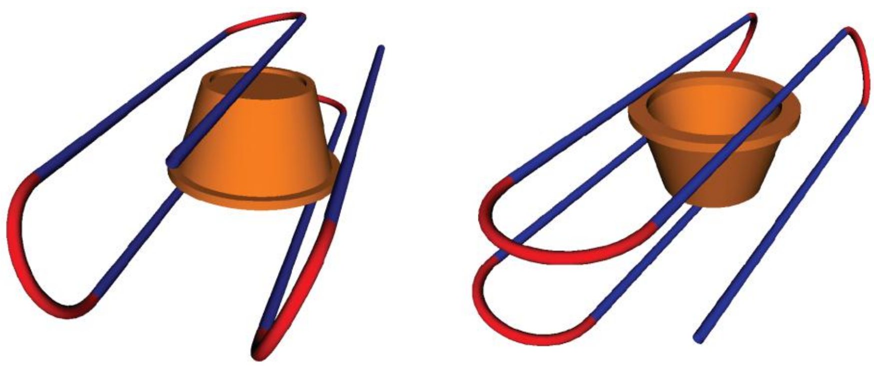


**Figure 4 – Plastic part with conformal cooling system**

Being the most time consuming step in a typical injection cycle, the first objective is to minimize cooling time. Both the number and diameter of the cooling channels are main (input) variables (Table 1).

| Name | Min | Max | Definition | Unit |
|---|---|---|---|---|
| Diameter of cooling channels | 2 | 8 | Integer with step of 2 | mm |
| Number of cooling channels | 2 | 8 | Integer with step of 1 | Adimensional |

**Table 1 – Input variable definition**

However, a fast and non-uniform cooling process can negatively affect the quality of the final product (e.g. introduce warpage). Therefore the final objective is to find the optimal balance between performance and quality, hence by minimizing both cooling time and warpage. Table 2 shows all the (output) design variables taken into account during the optimization process.

| Name | Unit | | Name | Unit |
|---|---|---|---|---|
| Cooling time | s | | Pumping power | W |
| Filling time | s | | Bulk temperature | K |
| Packing time | s | | Part surface temperature | K |
| Minimum X displacement | mm | | Cavity surface temperature | K |
| Maximum X displacement | mm | | Shear rate | 1/s |
| Minimum Y displacement | mm | | Pressure drop over cooling circuit | Pa |
| Maximum Y displacement | mm | | Peak pressure | Pa |
| Minimum Z displacement | mm | | Maximum injection pressure | Pa |
| Maximum Z displacement | mm | | Shrinkage criterion | Adimensional |
| Clamp force | N | | | |

**Table 2 – Output variable definition**

The minimum and maximum displacements along the primary axes, are the primary results used to assess the geometrical deformation of the part during the cooling process due to shrinkage and distortion. They express the difference between the dimensions of the mold cavity and the molded part, once extracted. The other results shown in Table 2 are needed to control different process parameters or are considered useful to increment the knowledge company database.

### 3.2 Software Workflow

The resulting workflow used for this optimization is schematized in figure 3. As first step all inputs are defined, consisting of “Configuration” and “DesignParameters”. The “Configuration” box contains information like project name, the addresses and ports of the different web and proxy services and the folder to store the project file. The workflow can be easily set-up to work on different user/client computers by simply editing these configuration parameters. The “DesignParameters” box holds the definition of the design variables. These variables parameterize different aspects of the analysis process and allow the designer to investigate different configurations. The configured workflow also allows to study the sensitivity of the final configuration towards parameter variations such as geometric tolerances and temperature variations.

After the input definition, a block of HTTP ‘Post’ requests follows instructing the 3MG application to create a mold instance based on the variables values defined in the input block, to update the mold instance after a change of the variables values, to export part and mold geometry and finally to write a subset of VBS scripts necessary for the Moldflow analyses. The use of individual requests over one global request give several advantages, including:

- simplicity in writing single, short requests and reduced likelihood of mistakes due to a compilation of a long and complicated global request;
- modularity/scalability, resulting in the situation where individual request can be added or removed for different, customized workflows.

Optimus automates all data exchange between web services or between service and client computer (for example geometry and scripting files) using (S)FTP connections. Intermediate results are locally copied on the user computer and form a precious knowledge base of results for the organization. For the purpose of user-friendliness, the transfer and copy of data have been captured in two elementary modules, the ‘copy’ and ‘move’ classes, that can be used as generic descriptors of specific FTP operations and are offered as a plugin to the Optimus product. The ‘move’ class of commands is used to store files in the user computer by deleting it from the remote one, thus preventing undesired access to this data by web service users, thus securing data.

The workflow in figure 3 uses five FTP operations, two to get results and scripts from the 3MG and three to send these files to the right Moldflow directories. After this, two HTTP requests take care of the simulation process. The first request creates the Moldflow model, the second starts the simulation. At the end of the simulation, all results are stored on the user computer and values of interest (table 2) are automatically extracted using elementary data management operations.

### 3.3 Optimization methodology

The plastic product used for this demonstration case is quite simple and therefore requires little computer resources. Moreover, as Table 1 points out, there are only 28 possible product configurations. For this reason, it is possible to analyze them all and select the optimal one. However, anticipating more complex industry relevant design problems, the large number of configurations and computation time would invalidate such an approach. In this case a second approach is used, based on hybrid optimization techniques to reduce computational time. The former “brute-force” approach is still used to validate the latter.

The hybrid optimization methodology used in this work consists of the combination of Design of Experiments (DOE), Response Surface Modeling (RSM) and a global optimization algorithm, discussed next.

### 3.3.1 Design of Experiments

The first methodology step is the DOE construction. The DOE is a collection of statistical techniques for planning, analyzing and interpreting sets of experiments, in order to investigate the correlation between inputs and outputs. In this work one of the most commonly-used random DOE techniques, called Latin Hypercube Designs (LHDs), has been used. Particularly a LHDs of 15 experiments (instead of 28) has been built, which needed one hour of computation time (4 minutes for each simulation). From a careful analysis of DOE warpage results it was observed that the variability of the minimum displacement along X direction and the maximum displacement along Z direction are of one order lower than the other displacements. For this reason they have been neglected in subsequent steps.

One of the main results of a DOE is a matrix with correlation coefficients between input and output quantities. A correlation coefficient of 1 indicates a perfect direct correlation; on the other hand, a correlation coefficient of -1 indicates a perfect inverse correlation; 0 indicates the absence of correlation (i.e. independence). It is important to note that the correlation coefficients are average linear correlation coefficients, meaning that they are computed as an average over the entire set of experiments used and thus express global linear trends. As a consequence, they cannot provide local information about a specific region of the design space, nor can they give information about quadratic or higher order correlations. However, this is not a limitation as in most engineering cases higher order correlations or local correlations are either very difficult to model or not useful in optimization strategies, respectively.

Figure 5a shows the correlation between different displacements. It is evident that all displacements have a strong correlation (in this case the minus sign between minimum and maximum displacement indicates a direct correlation, because the max. displacements are positive numbers while the min. displacements are negative numbers). Hence, a minimization or maximization of one displacement, also induces a minimization or maximization of the others. For this reason, and considering the fact that the variability of the maximum displacement along the X axis (*MaxDispX*) is the highest, it has been decided that the minimum warpage objective can be reduced to the minimization of *MaxDispX*.

| | MaxDispX | MinDispY | MaxDispY | MinDispZ |
|---|---|---|---|---|
| MaxDispX | 1.000 | -0.867 | 0.772 | -0.881 |
| MinDispY | -0.867 | 1.000 | -0.860 | 0.748 |
| MaxDispY | 0.772 | -0.860 | 1.000 | -0.727 |
| MinDispZ | -0.881 | 0.748 | -0.727 | 1.000 |

(a)

| | Diameter | Cooling-Nr | CoolingTime | MaxDispX |
|---|---|---|---|---|
| Diameter | 1.000 | 0.098 | -0.052 | 0.011 |
| Cooling-Nr | 0.098 | 1.000 | -0.948 | -0.798 |
| CoolingTime | -0.052 | -0.948 | 1.000 | 0.928 |
| MaxDispX | 0.011 | -0.798 | 0.928 | 1.000 |

(b)

**Figure 5 – Correlation between the displacements taken into account in the analysis (a) and correlation matrix between input and output (b)**

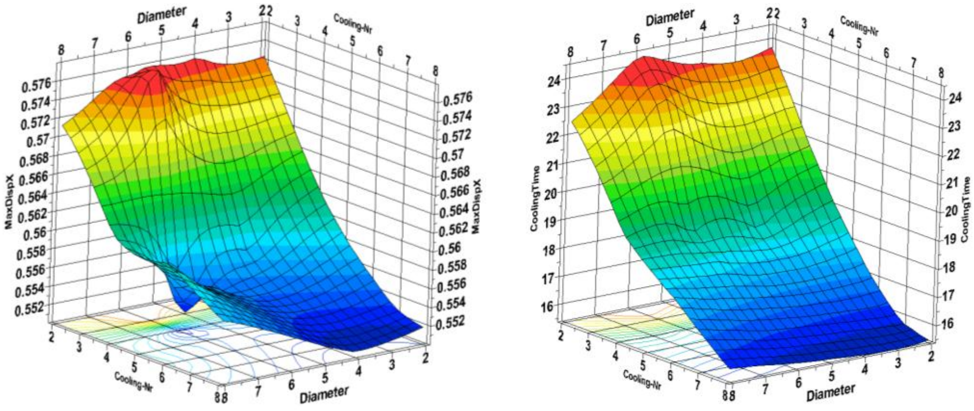
As mentioned above, the other objective is to minimize cooling time (*CoolingTime*). Figure 5b indicates correlations between the input and the output of interest. It can be noted that the diameter has a very low influence on the output values, while the number of cooling channels (*Cooling-Nr*) has a strong inverse correlation with both the two outputs. This means that the *CoolingTime* and the *MaxDispX* are cooperative objectives and that the optimal solution is the one with the highest number of cooling channels.

### 3.3.2 Response Surface Modelling

DOE have formed the basis for a first investigation of the general problem. But for a more exhaustive study, RSM is used. In general, RSM is a method to construct global approximations or interpolations of the whole system behavior just based on the results calculated for a limited number of points in the design space. For the present case, the RSM technique is based on the 15 results from the Latin Hypercube DOE. The current study uses Linear Radial Basis Functions (Linear RBF) to interpolate the RSM . This method is one of the best interpolation techniques when there are only few experiments and when inputs are discrete, as in the studied case.

Figure 6a shows the 3D response surface for *MaxDispX*, related to the diameter and number of cooling channels. It is evident that the higher the number of cooling channels, the lower the warpage along the X axis. This is in agreement with the DOE correlation results. However the response function serves two other important aspects. Firstly it does not average out correlations, hence the designer is able to evaluate the influence of varying diameters on different cooling system configurations. Secondly, the surface highlights the presence of a local minimum near the configuration composed of four channels with a diameter of 6mm. This last result, hardly predictable with other methods, could be very helpful for further company evaluation in which also cost and the environmental impacts are considered.

Figure 6b shows the cooling time response function. The surface confirms a strong influence of number of cooling channels on cooling time, while the diameter has a very low influence; moreover this low effect of the diameter decreases when the number of channels grows. Finally, a doubling of cooling channels from 4 to 8 has less influence than a similar doubling from 2 to 4. This behavior could be of a great interest in an analysis that also considers the manufacturing complexity and the cost of the cooling system.




(a) (b)

**Figure 6 – Response surfaces for the MaxDispX (a) and cooling time (b)**

### 3.3.3 Global Optimization

The last step researches the true optimum, i.e., the combination of design variables that yields the minimum cooling time and warpage. For this purpose two single objective optimizations have been performed using a Differential Evolution (DE) algorithm applied to the response function. The DE is a heuristic method for global optimization and needs more experiments (and so more computational time) with respect to the local optimization algorithm. However, because the DE algorithm is applied to the response surfaces, which are mathematically defined, it only requires a few seconds to evaluate.

| Input-Output | Optimum based on RSM | Verification experiment of RSM Optimum | Optimum based on “brute-force” method |
|---|---|---|---|
| Diameter [mm] | 4 | 4 | 2 |
| Cooling number [-] | 8 | 8 | 8 |
| Max X warpage [mm] | 0.55063 | 0.55063 | 0.54532 |
| Cooling time [s] | 15.41 | 15.41 | 15.33 |

**Table 3 – Optimization results**

The two single objective optimizations have reached the same configuration that minimizes both the cooling time and the warpage. This configuration is presented on table 3 (second column). A final simulation on the optimal configuration (8 channels of 4 mm) confirms the accuracy of the response surface method (third column). Finally this optimization methodology is compared to an optimization based on all possible configurations (at a computational cost of almost two hours, instead of one). Column 4 shows that the optimal configurations slightly differs, however with negligible differences. It is therefore safe to assume that the hybrid methodology is reliable.

## 4: Conclusions and future work

The IDEE workflow developed in this work automates modeling and simulation of an injection molding process. Software applications are connected to the IDEE using the 'Software as a Service' paradigm. Communication is performed using HTTP requests and data transfer via SFTP. In this way the workflow execution is modular, fast and secure.

The IDEE is an important platform supporting the designer during product development; it enables a thorough exploration of the design space, while reducing design time. With the developed workflow and the use of a hybrid optimization methodology, it has been possible to reliably obtain an optimal cooling system configuration that minimizes cooling time and warpage, at half the computational cost of the more basic "brute force" optimization method. Moreover some important results regarding the interaction between the input and output variables have been obtained, that prove useful for future work and decisions.

While this paper has illustrated the ability of the IDEE just for a simple case, the flexibility and scalability of the system supported by the use of smart optimization techniques allow designers to tackle the analysis of more complex objects and problems.

## 5: Acknowledgements

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