An integrated quantitative framework for supporting product design: the case of metallic mould for injection

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The design of injection moulds tools is a complex process for which market pressures demand ever-shorter development times and higher quality levels. Thus, it is considered imperative to adopt new methods and tools to support the design process, as a way to achieve faster and higher integrated mould tool design. Based on this assumption, a framework based on Design for Six Sigma methodology was developed, where a set of highly valued techniques were included, namely: the European Customer Satisfaction; the Analytical Hierarchical Process; the Axiomatic Design; and the Multidisciplinary Design Optimization. As a result, a platform was built able to support the design of any mould tool, which tackles the design of an injection mould as a non-linear optimization problem, oriented by customer preferences and its impositions. Thus, through an overseeing code system, a set of specific analysis sub-modules are responsible for the numerical simulation of the injection process. The results attained highlight the great potential of the proposed framework to achieve mould design improvements. In particularly, the value of mould solutions generated, benchmarked with an existing mould, resulted in a global improvement on mould performance of 5% leading to an increase in the quality of design of nearly 4%.

Keywords: Injection moulds design; Design for Six Sigma; Multidisciplinary Design Optimization; Non-linear optimization; Genetic algorithms.

1. Introduction

Currently, product development is assumed as the new frontier for achieving competitive advantage in today's rapidly changing business environments (Brown and Eisenhardt, 1995; Nebiyeloul-Kifle, 2005). In fact, both managers and academics increasingly realize the central role that product development plays in creating competitive advantage (Usan, 2005). This is especially true because decisions made during early stages of design have the greatest impact over total cost and quality of the system (Yang and El-Haik, 2003; Smaling, 2005). Early decisions are mainly supported by intuition, empiricism and the so-called handbook method. As a consequence, a lot of failure-trial-fix loops and development costs are dominated by failure recovery actions. As a result, typically, several iterations occur because of inherently conflicting trade-offs for which it is very difficult to find a balance. Due to these practices, the paradigm of product development is expensive, unpredictable and prone to failures, where the loss caused by selecting wrong design solutions affects the whole process and is harder to recover in later stages (Kim and Cochran, 2000). For these reasons, it is stated that only with different approaches will it be possible to mitigate these limitations (Yang and El-Haik, 2003; Smaling, 2005). Thus, more systematic and scientific methods must be explored in order to allow the exploitation of the design space and solving the system's trade-offs.

The injection mould is a high precision tool, responsible for the production of most plastic parts used everywhere. Mould's maker sector is particularly important to Portuguese Gross Domestic Product (GDP), since Portugal is one of the world's largest producers of advanced tools for injection. In 2010, exportation sales reached 318 million Euros, for a total production about 350 million. Its main customers are worldwide high-tech companies, namely the automobile (relative weight of 72% in 2010) and the electronic sectors (Cefamol, 2011). Mould design is considered critically important for the plastic part quality, as well as for its efficient processing. However, typically, no formal engineering analysis is carried out during the mould design stage. In fact, traditionally, designers rely on their skills and intuition, following a set of general guidelines. This does not ensure that the final mould design is the best option or even acceptable. At the same time, it is recognized that the majority of quality costs has its origins in errors committed in the mould design stage and in the transposition of the design to the production stage (Ferreira, 2002). As a result, a significant number of errors are only revealed after mould's manufacturing, leading to costly moulds and long manufacturing periods.

Mould makers are now highly pressured to shorten both leading times and cost, as well as to accomplish higher levels of mould performance. Therefore, it is essential to adopt new design procedures in order to design moulds right at the first time. To reach that, a new approach is proposed, based on Design for Six Sigma (DFSS) reinforced by the integration of well-known quantitative techniques, applied throughout four design stages: Identify, Design, Optimize and Validate (IDOV). To support the Identify stage, European Customer Satisfaction Index (ECSI) was adopted as a reliable and independent way of assessing customer satisfaction and its retention (Tomarken and Waller, 2005). Based on that model, a single objective function regarding customers' satisfaction levels is obtained, defined as a weighted function of specific customer attributes that are translated into Functional Requirements (FRs). The Design stage is supported by Axiomatic Design (AD) methodology (Suh, 1990; Suh, 1998; Suh, 2001). Thus, following AD guidelines, a few number of conceptual solutions are generated by mapping the FRs previously identified in the Identify stage onto the corresponding Design Parameters (DPs). Afterwards, the most ranked conceptual design solution will be detailed and optimized in the Optimize stage. This stage is supported by Multidisciplinary Design Optimization (MDO) framework, which is considered an appropriate methodology to design complex systems through an exploitation of coupling phenomena (Sobieszczanski-Sobieski and Haftka, 1997; Weck, 2004). Finally, in the last stage, Validate stage, the optimized designed entity is validated, in order to evaluate if it responds adequately to customer's requirements, as well as if it leads to reach high levels of customer satisfaction. This task is achieved by comparing the behaviour of the design solution generated by the developed platform, with the data gathered for an existing mould solution and through specific Computer-Aided Engineering (CAE) simulation codes.

2. Literature Review

Product Development (PD) is now assumed as the new frontier for achieving competitive advantage in today's rapidly changing business environments (Brown and Eisenhardt, 1995; Dahan and Hauser, 2001; Koch, Yang *et al.*, 2004; Nebiyeloul-Kifle, 2005). In fact, it is well-known the great impact of early design decisions on the overall total cost and products quality (Yang and El-Haik, 2003; Smaling, 2005). Thus, it is considered imperative to adopt well-designed and effective PD processes, allowing for faster and higher integrated product design, in order to design enhanced products *prior* to their launch on the market (Balakrishnan and Jacob, 1996; Baake, Stratil *et al.*, 1999; Tang, Liu *et al.*, 2005). For that purpose, several approaches have been proposed, mostly over the last two decades, aiming to support organization's strategies for innovation through well-designed and implemented PD processes (Ericsson, Würtemberg *et al.*, 2010; Jou, Chen *et al.*, 2010). The majority of these proposals try to make the PD process more visible and comprehensible, by carrying out the activities in a systematic way, supported on a strict theoretical background (Hasenkamp, 2010). Focusing in the product design stages, it can be observed that the PD process follows a sequential workflow on a complex set of coupled activities. For sake of clarity, and according to Krishnan and Ulrich (2001) (Krishnan and Ulrich, 2001), the design process must be broken down into four basic stages, namely, Product Definition; Conceptual Design or System-Level Design; Detail Design or Design Optimization; and, Design Validation. DFSS as an established data-driven methodology based on analytical tools is clearly connected with these four stages of design process.

DFSS has its origins in the Six Sigma methodology, which was developed by Motorola in the mid-1980s, through the form of a technical document called "Six sigma mechanical design tolerance" (Behara, Fontenot *et al.*, 1995). Although it shares the same principles, DFSS goes further upstream to recognize that decisions made during the design phase profoundly affect the quality and cost of all subsequent activities. Therefore, following a well-structured roadmap and though a systematic application of design tools, DFSS methodology can help to make the best design options early in the design process (Antony, 2002; Goh, 2002).

Currently, the rapid change in plastic industry, which is one of the world's fastest growing industries, imposes faster mould design and manufacturing in order to reduce the time-to-market of plastic parts, along with higher quality, greater efficiency and lower costs. Consequently, the conventional practices of design moulds tools are clearly inefficient, which justifies the effort to develop new approaches to support mould design (Ferreira, Cabral *et al.*, 2001; Ferreira, 2002). Thus, a large amount of scientific research has been done on mould design and its related fields over the last years, mostly on Knowledge-Based (KB) methods (Ferreira, Weck *et al.*, 2010). This approach is justified by the extensive empirical knowledge about mould component functions. Examples of works in this area are IKB-MOULD (Chan, Yan *et al.*, 2003), IKMOULD (Mok, Chin *et al.*, 2001), ESMOULD (Chin and Wong, 1996), amongst others (Lee, Li *et al.*, 1997; Lee, Chen *et al.*, 1997; Lou, Jiang *et al.*, 2004; Jong, Wu *et al.*, 2009). Also, some researchers focused their work on tuning the process parameters and part's geometry, seeking to achieve the highest possible moulding part quality under specified constraints (Deng, Zheng *et al.*, 2008). The class of process parameters more frequently analysed entails melt temperature, mould temperature, injection time, injection and packing pressure, as typical design variables (Park and Ahnb, 2004; Ozcelik and Erzurumlu, 2006; Changyu, Lixia *et al.*, 2007). Regarding the part's geometry, the typical design variable includes its geometrical dimensions and topology, and material.

According to Chan *et al.* (2003) (Chan, Yan *et al.*, 2003), one emergent area of research in the injection moulding field attempts to automatically generate the design of mould tool components. However, this approach has been considered feasible only for the automatic generation of particular mould components (Pandelidis and Zou, 1990; Lam and Jin, 2001; Lam, Britton *et al.*, 2004; Lam, Zhai *et al.*, 2004; Shen, Yu *et al.*, 2004; Lee and Lin, 2006; Qiao, 2006). Considering the existing literature, it is possible to divide this area of research in two main topics: heat-exchange system optimization (also described as cooling system optimization) (Lam, Zhai *et al.*, 2004; Mehnen, Micheltisch *et al.*, 2004; Li, Zhao *et al.*, 2009) and feeding system optimization (also described as injection system optimization) (Pandelidis and Zou, 1990; Lam, Britton *et al.*, 2004; Shen, Yu *et al.*, 2004; Lee and Lin, 2006; Zhai and Xie, 2010). These parallel approaches are based on the authors' assumptions that production efficiency (Park and Ahnb, 2004; Ozcelik and Erzurumlu, 2006; Changyu, Lixia *et al.*, 2007) and part's quality are mostly affected by the heat-exchange system design (Qiao, 2006; Li, Zhao *et al.*, 2009), or by the contrary, by the feeding system design (Lam and Jin, 2001). In both cases, the authors consider that these systems are the most important systems for controlling the production efficiency and the quality of injected plastic parts.

Although research in injection mould design optimization is underway, in general it involves only one particular aspect of the total design. However, due to the high complexity of mould systems interactions, it is not possible with this approach to exploit the synergies of interacting phenomena and adequately search the design space. Furthermore, given the different applications of plastic parts and respective customer's requirements, it is also essential to link customer satisfaction with this search for optimal solutions. For these reasons, an integrative framework, which tackles the design of an injection mould in a global and quantitative approach, aiming to guide and systematize the design process is presented (Ferreira, Cabral *et al.*, 2010; Ferreira, Cabral *et al.*, 2011).

3. An Integrated and Quantitative Framework

3.1 Developed framework

In order to achieve the previous goals, the DFSS-IDOV methodology was adopted as main framework roadmap, where a set of highly value techniques were combined (i.e. ECSI, AD and MDO), aiming to constitute an integrated and quantitative approach to support the design of injection moulds. As a result, a platform for an enhanced development was built. The platform is adequate for designing any injection mould for plastic parts without undercuts. It tackles mould's design as a non-linear optimization problem, commanded by customer preferences and impositions, in order to convert a baseline solution into an optimal mould solution. For that purpose, a set of specific analysis sub-modules were inserted in the platform, managed by an overseeing code system responsible for running the mathematical optimization schemes. Given the injection phenomena and its interaction with mould's design, they were modelled through specific high fidelity codes, namely Autodesk Moldflow® Insight 2010 code (MOLDFLOW) (Autodesk, 2011), and ABAQUS® version 6.10-1 (ABAQUS). This work also describes the customizations procedures adopted to combine this software with the overseeing code, in order to deal with injection mould design as an optimization problem. In fact, these procedures are an important basis for the developed framework, since both MOLDFLOW and ABAQUS are deterministic codes. Particular emphasis was placed on the thermal and the rheological behaviour of the injection part, as well as on the structural performance of the mould, as main engineering domains, as shown in the schematic representation presented in Figure 1. Nevertheless, the platform also encompasses a visualization sub-module to help the analysis of mould solutions (i.e. Geometry handler sub-module) and a cost model designed to allow for an economic analysis of the mould's components (i.e. Cost sub-module). Finally, a customer's satisfaction sub-module was also included in the form of a utility function.

As shown in Figure 1, all different analysis codes are connected through the integration software, which is ModeFRONTIER version 4.4.1 from ESTECO (ESTECO, 2011) (ModeFRONTIER). This overseeing software automates the iterative procedure associated to the optimization process, according to a predetermined optimization scheme. The loop of the developed framework starts with the Design stage, where a few number of conceptual mould solutions will be proposed by the mould designer, according to his know-how and the best practice guidelines. A brief description of these practical rules can be found, for instance, in the design's manual established by mould's Portuguese association (Centimfe, 2003). It is important to highlight that these initial design decisions are described as the combination of each design variable, included at the Design stage. Then, based on an established map between FRs and DPs and by assigning different values to each conceptual variable, a set of conceptual solutions will be generated and evaluated. The objective is to select the solution that has the most ranked customer satisfaction level. To assess customer satisfaction level, Ferreira *et al.* (2010) (Ferreira, Cabral *et al.*, 2010) work will be followed, where the Customer Satisfaction Index (CSI) is expressed as a weighted function of specific customer attributes, according to:

$$CSI = 0.157\ Quality\ of\ Design = 0.157\,(0.2Part + 0.19Pr \quad (1)$$

For each individual indicator of quality of design included in Equation (1) the typical Customer Attributes (CAs) were identified and translated into the specific requirements, the FRs, as shown in Table 1.

The major weakness of this approach is the largest computational time associated to the high fidelity analysis. In fact, the computational cost associated to the optimal design search in the conceptual stage is impractical, specially due to the highly discontinuous and non-convex feasible space originated mostly by the categorical and geometrical design variables. According to some authors (BreyfogleIII, Cupello *et al.*, 2001; Creveling, J.L.Slutsky *et al.*, 2003; Koch, Yang *et al.*, 2004), a good alternative is to employ Design of Experiments (DoE) methods to evaluate potential designs. In fact, since much of the platform design analysis is performed through computer simulation models, with the level of uncertainty prevalent in both these models and the injection mould problem itself, the application of optimization is not feasible for identifying optimal conceptual designs. Therefore, in the Design stage, the most ranked conceptual solution will be determined by computing each solution rank, according to Equation (1), being the design space defined by a DoE. The design matrix defined by the DoE approach can be constructed in a systematic way, specifying the values associated to the design variables of each experiment. Following this methodology, DoE becomes a good alternative to the optimization procedure, since it allows assessing the performance and quality of each studied design solution, in order to determine the most ranked.

In the Optimize stage, the geometry handler sub-module (SolidWorks® v.11) calculates the geometrical and physical dimensions of the selected conceptual solution. For each combination of design variables, the geometry handler sub-module generates a universal file (in this case, IGES[1] format) to be used in the subsequent analysis. Injection phenomena analyses are then undertaken by MOLDFLOW, responsible by the thermal and rheological behaviour analysis, and by ABAQUS, in charge of the structural analysis. Since there is no commercial software able to model the ejection phenomena, an analytical model was developed and integrated in the platform to handle this phenomenon, through Microsoft Excel® (EXCEL). Finally, cost models are also included in the platform, through EXCEL sub-modules.

[1] IGES acronym for Initial Graphics Exchange Specification.

In order to test the developed platform sub-modules and validate their integration, an existing injection mould was used as baseline. Figure 2 presents this mould that is used to produce four key holders (Figure 3) in each cycle. The existing mould is a 2-plate mould, with nine plates, where a DME standard structure made of 1.1730 steel was adopted. The cavities impressions were directly machined on the mould plates. Regarding the injection moulding machine, a EuroInj was employed, with a maximum locking force of 7.84E5N and a screw diameter of 32mm. The selected plastic part's material is Moplen HP 500N, produced by Basell Polyolefins.

3.1.1 Design stage

In order to differentiate the Design and the Optimize stages, the developed platform was structured into two levels, as previously shown in Figure 1. In the first stage, the Design one, conceptual solutions are generated and selected based on their value, as schematically shown in Figure 4.

The main objective of Design module is to conceive rough design layouts, where a set of concepts are generated through the combination of each design variable alternative. The design variables considered in this stage are summarized in Table 2. Then, by assigning different values to each conceptual variable, a number of different conceptual solutions for the mould can be accomplished through DoE. Afterwards, the most ranked conceptual solution is determined by computing each solution rank, according to Equation (1).

3.1.2 Optimize stage

In the Optimize stage, the selected conceptual solution is detailed and optimized in order to maximize customer satisfaction. Therefore, the platform for this stage is redefined in order to include all the design variables considered in the Optimize stage, which are summarized in Table 3 and schematically represented in Figure 5.

Based on that, the detailed and optimized level of mould design is performed by the Optimize module of the developed platform shown in Figure 6. Therefore, each design solution is generated by the overseeing software, according to a predetermined optimization scheme. Then, a geometrical definition of each mould component is attained through the geometry handler sub-module. The outputs of this sub-module are universal files (IGES format), which will be used in the subsequent structural analysis carried out by ABAQUS. At the same time, the rheological and thermal analyses are performed by MOLDFLOW code. Finally, the mechanical analysis of the ejection system and cost's assessment are carried out by EXCEL. Each cycle ends with the evaluation of each generated mould solution.

In order to clarify how the developed platform works, each sub-module will be detailed in the following sections.

3.1.2.1 Structural sub-module

The structural sub-module, included in the developed platform at the Optimize stage, is illustrated in detail in Figure 7. This sub-module takes into account the design variables, constraints and specific objectives regarding the structural system. The main goal of this sub-module is to determine the plate's dimensions, which minimize the mould: (i) deflection; (ii) stress distribution; and (iii) volume. These objectives are evaluated in the developed platform by ABAQUS. When using ABAQUS, the variables that can be used to access relative position between plate 2 and plate 3 (i.e. deflection) are COPEN (i.e. contact opening) and CSLIP (i.e. relative tangential motions). They are both contact output nodal data for non-kinematic scalar variables of ABAQUS. The COPEN variable reports the distance from the slave surface (plate 2) to the master surface (plate 3) along the normal direction (Z axis). Regarding COPEN, ABAQUS outputs the minimum value for contact opening, which reflects the smallest opening for each slave surface node (plate 2). In case of overclosure, COPEN corresponds to the greatest penetration value, since in this case COPEN will present a negative value. The variable CSLIP evaluates how far the slave surface (plate 2) has moved relatively to the master one (plate 3) along the contacting plane. Thus, ABAQUS outputs the two values along the principal slip directions (CSLIP1 and CSLIP2). The stress distribution minimization is controlled imposing that the von MISES stress generated by the model must be lower than the yield stress of the mould's material. In brief, nodal and element based field output variables are written to the database. The selected output responses are the maximum value of nodal variables COPEN and CSLIP, on principal directions (CSLIP1 and CSLIP2), and the maximum value of the element von MISES, defined as the mean value determined for the centroid. Finally, the mould's volume is determined through the geometry handler.

The kick-off of the structural sub-module consists on a DoE random sequence, where the design space is filled randomly with an uniform distribution, allowing to reject unfeasible and repeated designs. For each design solution, the geometry handler builds a

CAD model of each plate and determines its volume. Finally, it exports all the generated geometries through a universal file (IGES). Regarding the mould's structural components, it is important to note that several geometric relations were introduced in the geometry handler in order to respect design rules, as well as to avoid geometric interferences. For example, the geometric relations introduced for plate 3 are illustrated in Figure 8. All the universal files produced by the geometry handler sub-module are imported by ABAQUS, in order to perform the structural analysis. The interface between ModeFRONTIER and ABAQUS is controlled using a macro, which defines all the rules for the ABAQUS analysis. This macro establishes the conditions for importing the universal files, containing the geometrical information, as well as all the analysis conditions, such as material's properties, finite element type and parameters for mesh generation, interactions, boundary and constraints conditions, applied loads, and finally, numerical parameters (job conditions). This macro was written in the Python programming language[2], resulting in approximately 392 code lines.

In each ABAQUS analysis, the boundary conditions are imposed to the top surface of the injection clamping plate (plate 1), for which all displacements are constrained, as shown in Figure 9. The clamping force is applied in the bottom surface of the ejection clamping plate (plate 9). A surface-to-surface contact is defined between plate 2 bottom surface (slave surface) and plate 3 top surface (master surface). The contact with friction problem between these surfaces is treated with the penalty method and the friction coefficient was assumed to have a constant value of 0.8. Regarding the remaining structural components, tie contacts are adopted, as contact interaction between all contacting surfaces. The injection pressure is applied in the cavity and the core areas of plates 2 and 3, respectively, as shown in Figure 10. Each structural element is discretized with tetrahedral solid elements, which are known to result in efficient mesh generation algorithms for solid components. Regarding the mesh generation, the automatic algorithm recommended by default by ABAQUS was adopted, using the same average finite element size (seed) for all models. Finally, the structural sub-module finishes with the mechanical analysis of the ejection system, in order to design it, as well as a cost evaluation of the structural components of the mould. Both analyses are carried out through specific sub-modules integrated in the platform through EXCEL.

3.2 Thermal and rheological sub-module

As was previously mentioned, an important characteristic of the developed platform is the inclusion of two stages of design, namely, Design and Optimize stages. This feature is particularly important for the thermal and rheological sub-module, since the feeding and heat-exchange elements present distinct features according to the design stage where they are defined. Therefore, the developed framework aiming to determine the conceptual design variables of Design stage is represented in Figure 11, while Figure 12 shows the feeding and heat-exchange sub-module regarding the Optimize stage.

Since both feeding and heat-exchange systems are modelled by MOLDFLOW, some important

[2] Python is the standard programming language for ABAQUS.

considerations were taken into account during the construction of the thermal and rheological sub-module. First of all, since geometric features of the plastic part, as well as the number of cavities are imposed by customers, a fixed study was defined in MOLDFLOW as a baseline study. Process settings, injection, packing and cooling conditions of this study are established using MOLDFLOW algorithm recommendations. Regarding the generation of the different configurations for the feeding and heat-exchange systems, Visual Basic scripts (VBScript), corresponding to the macro shown in Figure 11 and Figure 12, were written on Application Programming Interface (API) language[3]. The API is an object linking and embedding automation interface that allow functionalities to MOLDFLOW, in order to be exposed to external applications. By creating and manipulating automation objects through the API, it is possible to invoke actions that are equivalent to Graphical User Interface (GUI) commands and actions, retrieve information regarding the model, results and plots and access advanced capabilities that are not available through the GUI, due to their programmatic nature (Autodesk, 2011). The VBScript macro was built in order to generate each feed and heat-exchange systems configurations imposed by the optimization scheme. The macro allows the generation of a dual domain mesh on the part geometry, imported from an universal file (IGES). The macro also controls the automatic mesh generation of all the other feed and heat-exchange systems configurations, involving approximately 42 lines of code. In the Design stage, the output results from MOLDFLOW are also extracted using a VBScript macro, with approximately 6 lines.

As previously mentioned, the Design stage encompasses the conceptual decisions, which involve categorical and geometrical design variables of both the feeding and heat-exchange systems. As a result, several MOLDFLOW studies are required in order to encompass, for example, different geometrical locations for the gates. To aggregate all these studies it was necessary to include several logic switch options, regarding each combination of these conceptual design variables. For example, in Figure 11, MPI_2CB corresponds to the conceptual design identified as the second position of the parts on the PP with a B position of the gates and a circular layout.

After the selection of the conceptual solution, the Optimize stage must be performed in order to detail and optimize the feeding and the heat-exchange system. This corresponds to the structure illustrated in Figure 12. The goal is to determine through optimization the most ranked solution. This rank is dependent upon each solution performance expressed as a function of FRs obtained from CAs mapping. Regarding the feeding and the heat-exchange systems, these FRs were included in the platform as objective functions, namely, Deflection (*min_deflec*), Shrinkage (*min_shrink*) Sink index (*min_sink*), In-cavity Residual stress (*min_stress*), Cycle time (*min_tcycle*), Pressure drop (*min_pres*) and Volume of material's waste (*min_waste*). These items are mostly evaluated based on MOLDFLOW results. The Deflection is evaluated based on the difference between the original and the deformed geometry, where the axis directions are determined by an anchor plane according with overlaid geometries. The Shrinkage is computed as the volumetric change for each area of the dual mesh, as a

[3] API is the standard programming language for MOLDFLOW.

percentage of the original volume. The Sink index is computed directly by MOLDFLOW, using the following relation:

$$Sink\ index = \frac{(x^{+} - x^{-})\rho_{\delta}(T_{trans}P_{atm}) - .}{2h \cdot \rho_{\delta}(T_{trans}P_{atm}} \quad (1)$$

where T_{trans} is the transition temperature of the polymer, x^{+} is the upper interfacial location where the temperature of the polymer is at the b5 value in the 2-domain Tait PVT model, x^{-} is the lower interfacial location, ρ_{δ} is the solid density of the polymer, P_{atm} is the atmospheric pressure and h is the half-gap thickness (Autodesk, 2011). This parameter indicates the likely presence and location of sink marks and voids in the part, and reflects how much material is still melted and left unpacked. Thus, the larger the volume that freezes under low pressure, the higher the sink index and the greater the likelihood of occurring sink marks. The Residual stress is also directly estimated by MOLDFLOW and corresponds to the stresses in the orientation direction before ejection. The analysis in MOLDFLOW assumes that at the beginning of the filling process the pressure is zero (or 1 atm) throughout the mould. Thus, pressure drop is obtained by the maximum injection pressure value achieved during the whole duration of the filling phase. In MOLDFLOW, the Cycle time is determined taking into account the time required for the part to fill and to freeze 80% of the part thickness. We also impose an open/release/close time. Finally, the Waste of material or scrap is computed considering the runner's volume, which defines the amount of material that will be discarded in each injection cycle. This value is computed in the platform using the calculator, in cubic millimetres.

3.3 Mechanical sub-module

Regarding the mechanical sub-module, the developed platform considers the structure presented in Figure 13. This sub-module allows determining the diameter and the length of the ejectors, in order to minimize: (i) the distortions of the plastic part mouldings (*Min_marks*), (ii) the volume of the mould (*Vmould*) and (iii) the cost of the ejectors (*Min_cost*). It also assures that the necessary ejection force is transmitted to the plastic parts, promoting the release of the plastic moulding without causing ejectors failure, by imposing the necessary constraints (i.e. *Eject_const* defined in Figure 13). In this case, the only structural elements that can have significant changes are plates 7 and 8. Thus, the mould's volume can be also evaluated through these plate's volumes. Additionally, since the ejectors pins are widely available in the market, they should be selected according to the standard dimensions. The standard dimensions used are accessible in the Hasco Catalogue (Hasco, 2010), which were included in the mechanical sub-module (indicated by *List_dEject* in Figure 13). Finally, it is important to note that the number of ejectors and their relative positions were previously established in the Design stage (see Figure 4).

3.4 Cost sub-module

As previously mentioned, the mould's structure is constituted by nine plates, typically acquired to standard suppliers. Hence, according to each plate's specification it is possible to know its cost. Based on the information available in a supplier data base (e.g. Hasco Catalogue (Hasco, 2010)), a cost model for the mould's structure was obtained through regression. This analysis was carried out using Minitab 16 (Minitab, 2011), which allowed us to obtain a model with a confidence level of 95%, validated by analysis of variance (ANOVA). As expected, the results show that the plates' costs are a function of their dimensions. These can be expressed by regression equations which are summarized in Table 4, where Z_i is the height, X_i the length and Y_i the width of plate i (with i=1,…,9).

A similar analysis was performed for ejector's cost, leading to the following cost function:

$$Cost_{Eject} = 2{,}19 - 0{,}37 d_{Ejector} + 0{,}01 \quad (2)$$

where $d_{Ejector}$ is the diameter and $l_{Ejector}$ the length of the ejector.

4. Application: the key holders mould

In order to test the developed platform modules and validate their integration, the previously described key holder mould will be used as baseline.

4.1 Identify stage of the DFSS-IDOV roadmap

According to the DFSS-IDOV approach, the first step is to detail the previous estimated CSI model for Portuguese mould makers (resumed in Ferreira *et al.* (2010)), in order to include the characteristics of this particular mould. For that purpose, the Analytical Hierarchical Process (AHP) methodology was adopted in order to refine and prioritize the identified CAs. AHP is a theory of measurement that uses pair wise comparisons along with expert judgments to deal with qualitative or intangible criteria (Figueira, Greco *et al.*, 2005). This technique is widely used for addressing multi-criteria decision-making problems, since it assures the consistency and stability of the subsequent decisions (Lu, Madu *et al.*, 1994). Thus, this mould customer was asked to compare each CA, two at a time, using a 1-9 scale with three levels (i.e. 1 - Equal importance; 3 – Moderately more important; 9 - Extremely more important). The results achieved are presented in Table 5.

After customer's preferences are completely defined, it is possible to begin the Design stage.

4.2 Design stage of the DFSS-IDOV roadmap

As mentioned before, the main objective of this stage is to conceive rough design layouts, where each concept is generated through the combination of different values for the conceptual design variables. Thus, it is necessary to build a few number of different conceptual solutions, according to practical guidelines (Centimfe, 2003). For this specific case, different alternatives were proposed, which are summarized in Table 6 and schematically illustrated in Figure 14. This figure exemplifies the two possible alternatives for the number of turns of each cooling line (A and B), the two different positions of the parts (C and D), the different positions for each gate (E and F), the different types of feeding layout (G and H), and the two possible alternatives for the number of ejector pins, respectively two and four pins per part (I and J).

The five conceptual design variables, presented in Table 6, are considered as factors of the DoE study. A full factorial design of five factors, with 2 levels each one, was carried out with the aim of determining the most ranked conceptual solution. Through the analysis of variance for each objective, it is possible to identify, with a significance level of 95%, that only the number of ejectors does not have a significant influence in the observed outputs (for more details see Ferreira, 2012). Based on the results achieved, the most ranked conceptual solution was identified, and it is compared with the baseline solution in Figure 15.

The most ranked conceptual solution has two turns of cooling channels, the position of parts on the PP is position II, the type of feeding layout is symmetrical and the gates are positioned at point B. Regarding the number of ejectors, since this design variable has a statistically negligible effect on the studied responses outputs, one can assume four ejectors per part, as defined in our baseline solution, as starting point of the Optimize stage.

The comparison between the most ranked conceptual solution and the baseline is presented in Table 7. It is possible to verify that the selected solution allows for a significant reduction on Pressure drop (11.9%) and Waste of material (9.4%). By the contrary, it leads to higher levels of Sink index (6.5%) and Shrinkage (4.7%) and a minor increase in the in-cavity Residual stress, Deflection and Cycle time. As previously mentioned, at this stage the mould's volume depends only on the number of ejectors. Thus, this objective does not present any change, when compared with the baseline.

Taking into consideration the weights of each attribute, assumed as drivers for customer's satisfaction (see Table 5), it is possible to determine the impact on quality of design improvement from adopting the new design solution instead of the baseline, as shown in Table 7. It is also possible to verify that the selected solution presents a global improvement of 1% on its performance, which can proportionate an increase of 0.05% on the CSI (assuming that in Equation (1) the remaining objectives do not change). As previously mentioned, although this seems a small value it can result in significant improvements, since the model adopted considers that the Design has a relatively small impact on the CSI (only 0.157 in Equation (1)). Nevertheless, this selected conceptual solution must be detailed in the Optimize stage of the DFSS-IDOV roadmap.

4.3 Optimize stage of the DFSS-IDOV roadmap

Given the characteristics of the injection mould design problem, in particular: (i) the number and type of design variables and constraints; (ii) the feasibility of the design space; (iii) the type of initial solution and (iv) the adequate simulation runtime, the Non-dominated Sorting Genetic Algorithm (NSGA) proposed by Srinivas and Deb (1994) (Deb, Pratap *et al.*, 2002) was adopted to carry out the optimization procedure. The main reasons for this option are: (i) it deals with both continuous and discrete variables; (ii) it allows for user defined discretization (base); (iii) it implements elitism for multi-objective search; (iv) the diversity and spread of solutions is guaranteed without use of sharing parameters; and (v) it allows concurrent evaluation of the *n* (i.e. the number of individuals per generation) independent individuals. The NSGA II optimization algorithm uses the DoE values obtained by random sequence with an initial population of *n* individuals as starting point. The parameters adopted in this study for the NSGA II algorithm are presented in Table 8 . A set of Pareto solutions were determined and are shown in Figure 16, highlighted in green. The vertical bands in the parallel coordinates plot indicate the range of feasible, unfeasible (red lines) or Pareto design variables values (green lines). The choice of the final mould design should be made from the set of Pareto optimal designs, using customer preferences. Assuming the previously established relationship between objectives (i.e. FRs), a valid utility function and ranking is generated.

Figure 17 presents the design ranking obtained, showing that the best solution found corresponds to ID 131, with a rank value of 0.824. It is also important to note that the selected conceptual solution, labelled with ID 0, has a rank value of 0.679 showing that a significant improvement was achieved through optimization. Figure 18 presents the comparison of the objectives attained with the selected solution (ID 131) and the selected conceptual solution (ID 0). It is possible to verify that the most significant differences are on Cost, Sink, Deflection, Shrinkage and Waste, where the selected solution (ID 131) presents better performance than the selected conceptual solution (ID 0). In fact, solution ID 131 is only worse than the conceptual solution on the Pressure drop.

Even though this multi-objective optimization problem does not yield a unique solution, it is possible to have an idea of the potential improvement of the most ranked solution when compared with the selected conceptual solution.

Table 9 presents this comparison in terms of the improvements achieved in each of the objectives considered. Comparing solution ID 131 with the selected conceptual solution, it is possible to verify that significant improvements were achieved in all the objectives, expect on Pressure drop. Nevertheless, according to customer's preferences this increase is clearly compensated, as expressed by the global improvement achieved by ID 131. In fact, in average, ID 131 presents an improvement on performance of about 5.7%. This enhancement can result in an increase of quality of Design of 4.4%, which represents an increase in CSI of nearly 0.7%. The selected solution (ID 131) is fully characterized and compared with the selected conceptual solution in Table 10.

Comparing the best solution achieved with the selected conceptual solution, it is possible to verify that the most important differences regarding the structural system were a significant reduction on the height of plates 3, 4 and 5. By the contrary, an increase on the height of plate 2 is proposed (Figure 19). Nevertheless, these changes are responsible for the reduction achieved on mould's cost. Regarding the changes of the feeding system, a significant reduction on runner's diameter (d_{Runner_1} and d_{Runner_2}), as well as in sprue's diameter (d_{Sprue}) was attained. By the contrary, an increase in the draft angle of the gate (*alfa_gate*) is defined. About the heat-exchange system, the distance between the cooling lines and the mould surface (Z_{Cool}) is decreased from 18 to 15mm, while the distance between the cooling lines (*pitch_cool*) increases from 76 to 91mm (Figure 20). Finally, the length of ejector ($l_{Ejector}$) decreases from 173 to 168mm due to the reduction of the plates 3, 4 and 5 heights, while the ejectors' diameters ($d_{Ejector}$) increase from 6 to 7mm.

4.4 Validate stage of the DFSS-IDOV roadmap

It is important to note that the platform was developed for the specific purpose of injection moulds design. Thus, its validity must be determined with respect to that purpose. The primary validation technique used was face validation and traces (Sargent, 2010). In fact, during this project, it was a main concern to have experts on the conceptual and simulation evaluation, to sustain the options made, as well as to help establish different admissible conceptual models. Model validation, through data validation, is usually difficult, time consuming and mostly costly. For that reason, it was not possible to obtain mould's performance data of the generated solutions. In fact, it is impractical to build, evaluate and test all the generated solutions in order to assess the platform's value. Nevertheless, the alternative was to use an existing model to compare with the data information produced by the developed platform, using it as a starting point (i.e. baseline) to be optimized by the platform. Based on the results achieved, through the comparison between the existing mould and the solutions generated at the Design and Optimize stages, it is possible to state that:

- The outputs response, evaluated by the simulation codes, which are previously validated high –fidelity codes, show that significant improvements can be attained by the developed platform, in special regarding the Optimize stage;
- The use of physical models for testing all the design solutions, generated through the platform, is time and expense prohibitive. The alternative was to initiate the design stage with an existing mould solution, and then move through the new solutions generated by the platform evaluate

improvements achieved. This procedure allowed us to verify that the existing solution can be significantly improved regarding its performance, as well as its value according to the customer's satisfaction index. In fact, a global improvement on performance of 5%, resulting in an increase in the quality of design of 3.7% with an impact on CSI of nearly 0.6%;
- Through face validation, where experts evaluate if the logic of the conceptual model is correct and if the model's input-output relationships are reasonable, the results achieved have shown theoretical consistency.

5. Conclusions

A platform was developed in order to guide and systematize the mould design process, based on the DFSS-IDOV method. For that purpose, this framework tackles the design of an injection mould in a global and quantitative approach, starting with a full understanding of critical customer requirements and its translation into FRs. Based on that, in the first stage of the DFSS-IDOV approach, Identify, an objective function expressing customer satisfaction as a weighted function of specific FRs is determined. Afterwards, in the second stage of the DFSS-IDOV approach, Design, a few number of conceptual solutions for the mould are generated. These solutions are defined as the combination of each conceptual design variable. Then, DoE methods were employed to evaluate these designs in order to determine the most ranked according to CSI. Then, this solution is detailed and optimized in the Optimize stage. This stage is mainly supported by MDO methodology, which has been considered an appropriate methodology to design complex systems. As a result, an integrated platform was developed, where the analysis of the different injection phenomena are inserted as sub-modules (e.g. structural, thermal, rheological and mechanical), managed by validated high-fidelity codes. In this sense, MOLDFLOW and ABAQUS were integrated in the platform aiming to model respectively the thermal and rheological, and the structural behaviour of the mould's functional systems. A CAD tool (SolidWorks) was also included in the platform as a geometry handler sub-module, helping to generate and visualize the design solutions. An overseeing code, ModeFRONTIER, is responsible for managing the connections between the codes, launching the simulations, accessing the outputs and changing the input data according to the pre-defined mathematical exploitation and optimization schemes. Based on the gathered results, a Pareto optimal frontier is determined. These Pareto optimal solutions, also known as non-dominated or efficient solutions, are ranked according to customer's preferences, through the previous determined CSI objective function.

To validate the developed platform, an existing mould was adopted as baseline. This mould produces four key holders, in each cycle. At the Design stage, five conceptual design variables were considered, namely, number of turns of each cooling line (*n_turns*), position of each part relatively to the PP (*position_parts*), position of each gate relatively to the PP (*position_gates*), type of feeding layout (*type_layout*) and number of ejectors per part ($n_{Ejectors}$). Thus, 32 randomized virtual solutions were generated and evaluated through the developed platform. The most ranked conceptual solution found resulted in a global improvement on the objectives of 1.03%, when compared with the baseline. In the Optimize stage, this selected conceptual solution was detailed and optimized. For that purpose, an initial population of 20 designs, obtained by a DoE with random sequence, was adopted. The optimization was carried out using the NSGA-II heuristic based method, which proved to be efficient. An improvement of 4.4% on quality of design was achieved through the optimization of the conceptual solution with an impact on CSI of nearly 0.7%. Nevertheless, due to the highly discontinuous and non-convex mould design space, the best solution found can be a local optimum. However, more important than achieving a global optimum solution is to have a platform capable of generating and testing several design solutions and to give quantitative information to aid in the design decision making. Furthermore, since mould's attributes that are important for achieving higher levels of customers' satisfaction are not intuitively obvious, starting mould design with a full understanding of customer requirements and converting them into optimal mould solutions through the developed platform proved to be an efficient way to get designers in the right directions.

In summary, it is possible to assume that the developed platform can become an essential tool for the mould maker sector, acting as a decision support system, able to convert customer needs into optimal product solutions in a systematic and quantitative way.

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Table 1: Mapping between CAs and FRs: Quality of mould design.

	Customer attributes (CAs)	**Functional Requirements (FRs)**
Part's requirements *(Part)*	Geometrical accuracy	Deflection
	Dimensional accuracy	Shrinkage
	Aesthetic aspects	Aesthetic defects (e.g. Sink marks)
	Properties	Specific property (e.g. in cavity residual stress)
Process' requirements *(Process)*	Productive capability	Cycle time
	Mouldability	Pressure drop
	Adaptability	Mould's volume
	Efficiency	Volume of material waste (i.e. scrap)
Constructive solutions *(Solutions)*	Maintainability	Mean Down Time (MDT)
	Reliability of solutions	Mean Time Between Failure (MTBF)
Accessibility *(Complexity)*	Accessibility	Information content

Table 2: Design variables considered in the Design stage.

Functional systems	**Design variable**	**Description**	**Type of variable**
Heat-Exchange	*n_turns*	Number of turns of each cooling line	Integer
Structural	*position_parts*	Position of each part relatively to the Partition Plane (PP)	Geometrical
Feeding	*position_gates*	Position of each gate relatively to the PP	Geometrical
	type_layout	Type of feeding layout	Categorical
Ejection	$n_{Ejectors}$	Number of ejectors per part	Integer

Table 3: Design variables considered in the Optimization stage.

Functional systems	**Design variables**	**Description**	**Units**

Structural	X_3	Length of plate 3 (on X axis)	mm
	Y_3	Width of plate 3 (on Y axis)	mm
	Z_3	Height of plate 3 (on Z axis)	mm
	Z_1	Height of plate 1 (on Z axis)	mm
	Z_2	Height of plate 2 (on Z axis)	mm
	Z_4	Height of plate 4 (on Z axis)	mm
	Z_5	Height of plate 5 (on Z axis)	mm
	Z_9	Height of plate 9 (on Z axis)	mm
	d_{Pillar}	Diameter of the supporting pillars	mm
Feeding	d_{Sprue}	Diameter of the sprue	mm
	l_{Sprue}	Length of the sprue	mm
	draft_sprue	Draft angle of the sprue	° (degrees)
	d_{Runner_1}	Diameter of the runner 1	mm
	d_{Runner_2}	Diameter of the runner 2	mm
	d_{Gate}	Diameter of the gates	mm
	alfa_gate	Draft angle of the gates	° (degrees)
Heat-Exchange	d_{Cool}	Diameter of the cooling lines	mm
	Z_{Cool}	Distance between the cooling line and the mould surface	mm
	pitch_cool	Distance between the cooling lines	mm
Ejection	$d_{Ejector}$	Diameter of the ejector pins	mm
	$l_{Ejector}$	Length of the ejector pins	mm

Table 4: Regression equations for plate's cost.

Cost of plates	R^2	R^2 **(adj)**
$Cost\_1\_9 = -39,3 + 3,56\, Z_1 + 0,00106\, (X_1Y_1)$	R^2= 98,6%	R^2 (adj) = 98,5%
$Cost\_2\_3 = -52,8 + 2,40\, Z_2 + 0,00157\, (X_2Y_2)$	R^2= 99,3%	R^2 (adj) = 99,2%
$Cost\_4 = -45,1 + 2,71\, Z_4 + 0,00116\, (X_4Y_4)$	R^2= 95,9%	R^2 (adj) = 95,4%
$Cost\_5\_6 = -14,3 + 0,831\, Z_5 + 0,00104\, (X_5Y_5)$	R^2= 98,2%	R^2 (adj) = 98,0%
$Cost\_7\_8 = 55,5 + 0,00175\, (X_7Y_7)$	R^2= 90,4%	R^2 (adj) = 89,6%

Table 5: Relative priority of each CA regarding the key holders mould as defined by the customer.

Customer Attributes (CAs)	Functional Requirements (FRs)	Relative weights
Geometrical accuracy	Deflection	12.2%
Dimensional accuracy	Shrinkage	12.2%
Aesthetic aspects	Sink marks	22.8%
Properties	Residual stress	2.0%
Productive capability	Cycle time	2.8%
Mouldability	Pressure	16.3%
Adaptability	Mould's volume	1.8%
Efficiency	Waste of material	5.3%
Maintainability	Mean Down Time (MDT)	5.8%
Reliability of solutions	Mean Time Between Failure (MTBF)	5.0%
Accessibility	Information content	13.7%

Table 6: Design variables considered in the Design stage: the key holders mould.

Functional systems	Design variable	Description	Type of variable
Heat-Exchange	*n_turns*	Number of turns of each cooling line	Integer (2, 4)
Structural	*position_parts*	Position of each part relatively to the PP	Geometrical (I, II)
Feeding	*position_gates*	Position of each gate relatively to the PP	Geometrical (A, B)
	type_layout	Type of feeding layout	Circular, Symmetrical
Ejection	$n_{Ejectors}$	Number of ejectors per part	Integer (2, 4)

Table 7: Comparison between the selected conceptual solution and the baseline.

	Baseline	Selected conceptual solution

$n_{Ejectors}$	4	4
n_turns	2	2
position_gates	A	B
position_parts	I	II
type_layout	S	S

	Baseline	**Selected conceptual solution**	**Relative Difference (%)**
Deflection [mm]	8.13E-4	8.21E-4	0.98%
Shrinkage [%]	12.24	12.77	4.33%
Sink [%]	1.54	1.64	6.49%
Stress [MPa]	1.28E5	1.281E5	0.11%
Cycle time [s]	34.44	34.47	0.09%
Pressure drop (MPa)	11.14	9.82	-11.85%
Volume [m^3]	1.98E-2	1.98E-2	0.00%
Waste [gr]	6.27	5.68	-9.41%
Global improvement			**1.03%**
Quality of design improvement			**0.30%**
Impact on CSI			**0.05%**

Table 8: Adopted parameters for NSGA II optimization.

Number of generations	10
Crossover probability	0.9
Probability of mutation	0.1
Mutation for real-coded vectors	0.9
Automatic scaling for mutation probability	Ok
Distribution index for real-coded crossover	20
Random generator seed	1
Evaluate repeated design	No
Evaluate unfeasible design	No

Table 9: Comparison between the best solution achieved (ID 131) and the selected conceptual solution (ID 0).

	ID 131	**Selected Conceptual**	**Comparison (%)**

		(ID 0)	
Deflection (mm)	7.20E-4	7.25E-4	-0.7%
Shrinkage (%)	12.14	13.13	-7.5%
Sink	1.14	1.67	-31.7%
Stress (MPa)	20176	20176	0.0%
tCycle (s)	36.9339	36.934	0.0%
Pressure (MPa)	14.59	10.97	33.0%
Vmould (m^3)	1.80E-2	2.04E-2	-11.8%
Waste (mm^3)	3.88E3	5.18E3	-25.1%
Cost (€)	1133.1	1225.9	-7.6%
Global improvement on performance			**5.71%**
Quality of design improvement			**4.42%**
Impact on CSI			**0.69%**

Table 10: Description of the solution achieved (ID 131) and the selected conceptual solution (ID 0).

Stage	**Design variables**	**ID 131**	**Selected conceptual solution (ID 0)**
	$n_{Ejectors}$	4	4
	n_turns	2	2
Design	*position_gates*	B	B
	position_parts	II	II
	type_layout	S	S
	X_3 *(mm)*	296.0	296.0
	Y_3 *(mm)*	246.0	246.0
	Z_1 *(mm)*	27.0	27.0
	Z_2 *(mm)*	76.0	66.0
	Z_3 *(mm)*	46.0	66.0
	Z_4 *(mm)*	36.0	46.0
	Z_5 *(mm)*	56.0	96.0
	Z_9 *(mm)*	27.0	27.0
	alfa_gate (°)	20.0	15.0
	d_{Cool} *(mm)*	10.0	10.0
	d_{Gate} *(mm)*	1.5	1.5
Optimize	d_{Pillar} *(mm)*	32.0	32.0
	d_{Runner_1} *(mm)*	5.0	6.0
	d_{Runner_2} *(mm)*	3.0	4.0
	d_{Sprue} *(mm)*	4.0	4.5
	$d_{Ejector}$ *(mm)*	7.0	6.0
	draft_sprue (°)	1.0	1.0
	dxycool (mm)	5.0	5.0
	$l_{Ejector}$ *(mm)*	168.0	173.0
	l_{Sprue} *(mm)*	85.0	85.0
	pitch_cool (mm)	91.0	76.0
	z_{Cool} *(mm)*	15.0	18.0

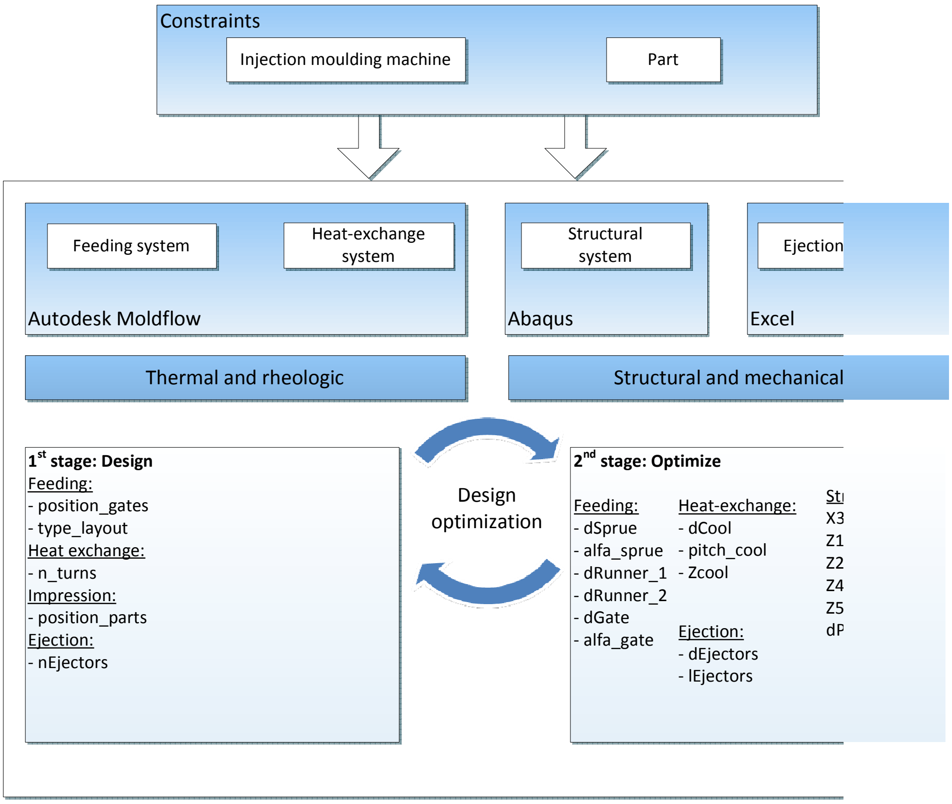

Figure 1: The two stages of the developed platform.

Figure 2: A view of the existing mould used as baseline.

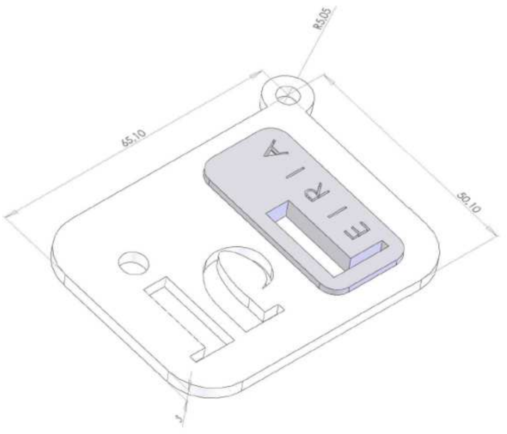

Figure 3: A schematic view of the holder part.

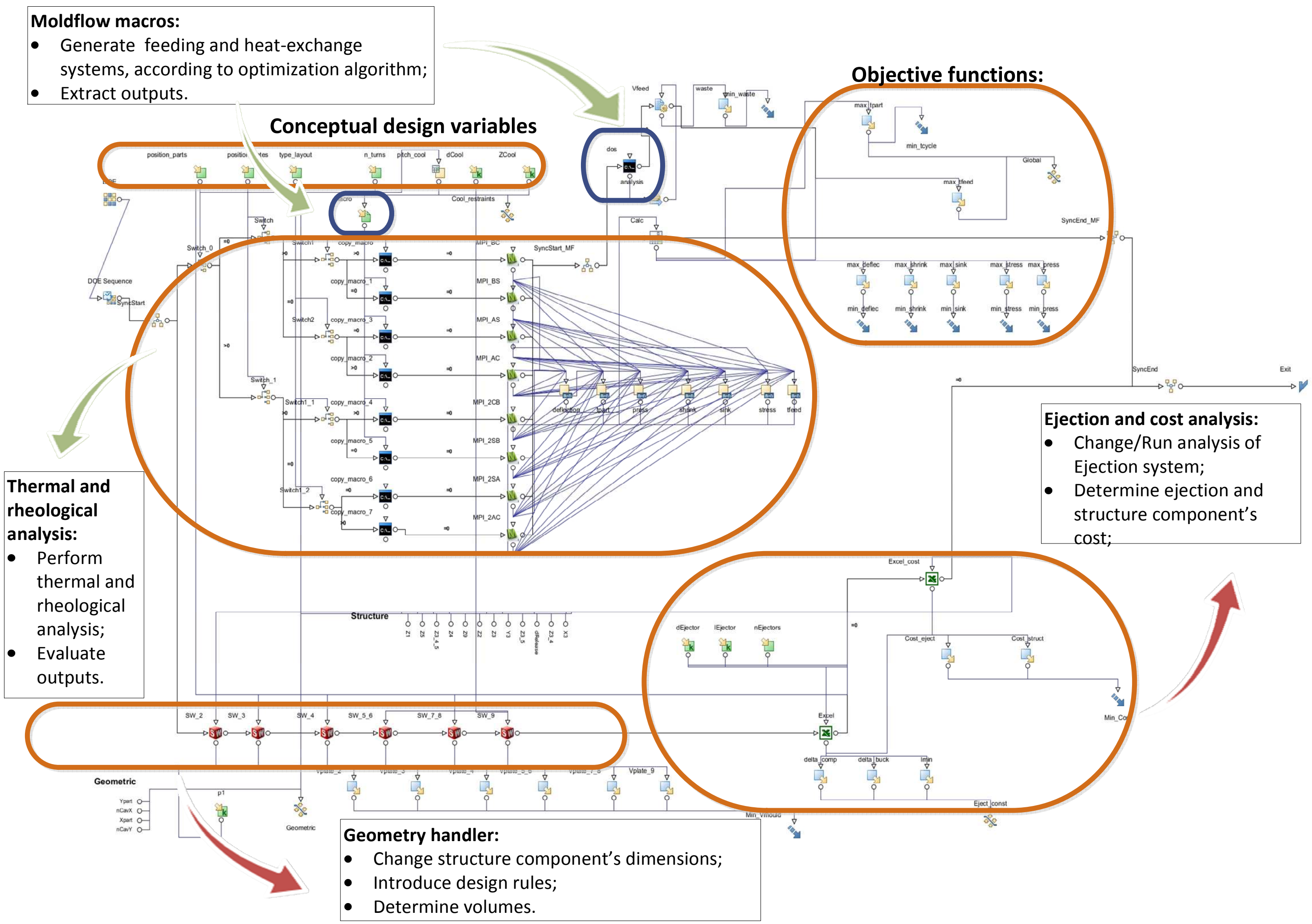

Figure 4: View of the Design module in the developed platform (ModeFRONTIER).

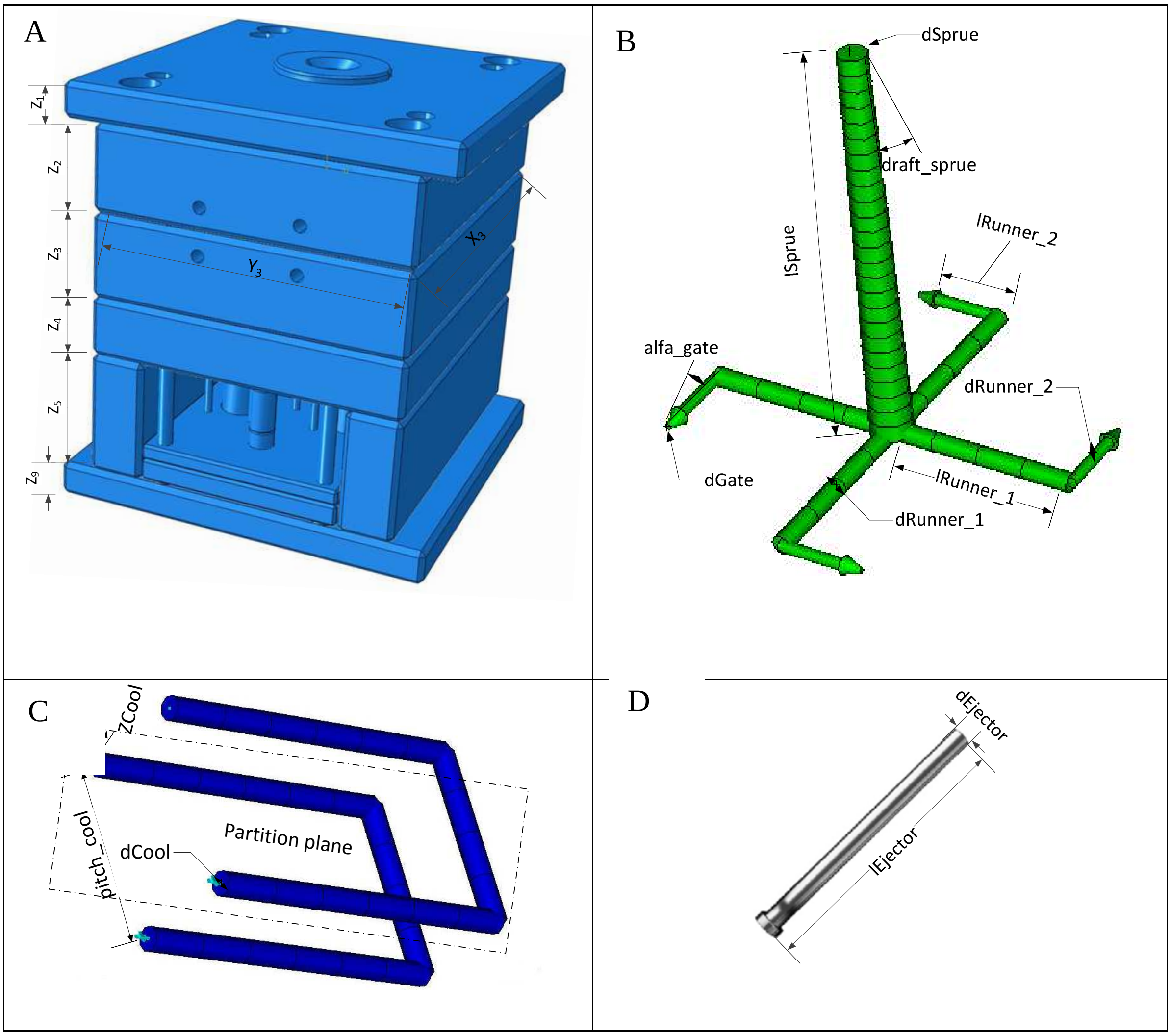

Figure 5: Design variables regarding structural (A), feeding (B), heat-exchange (C) and ejection (D) functional systems.

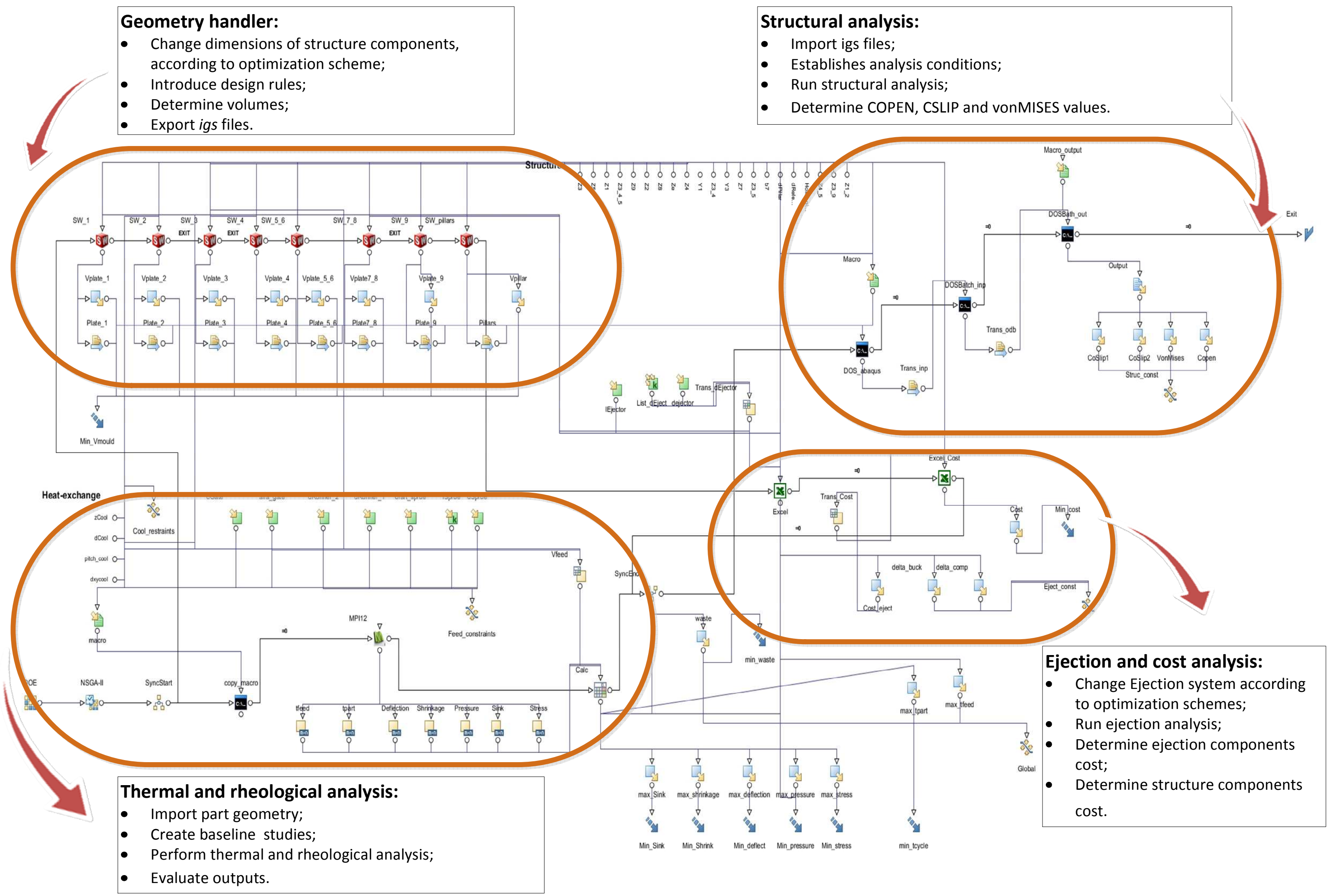

Figure 6: View of the Optimize module in the developed platform (ModeFRONTIER).

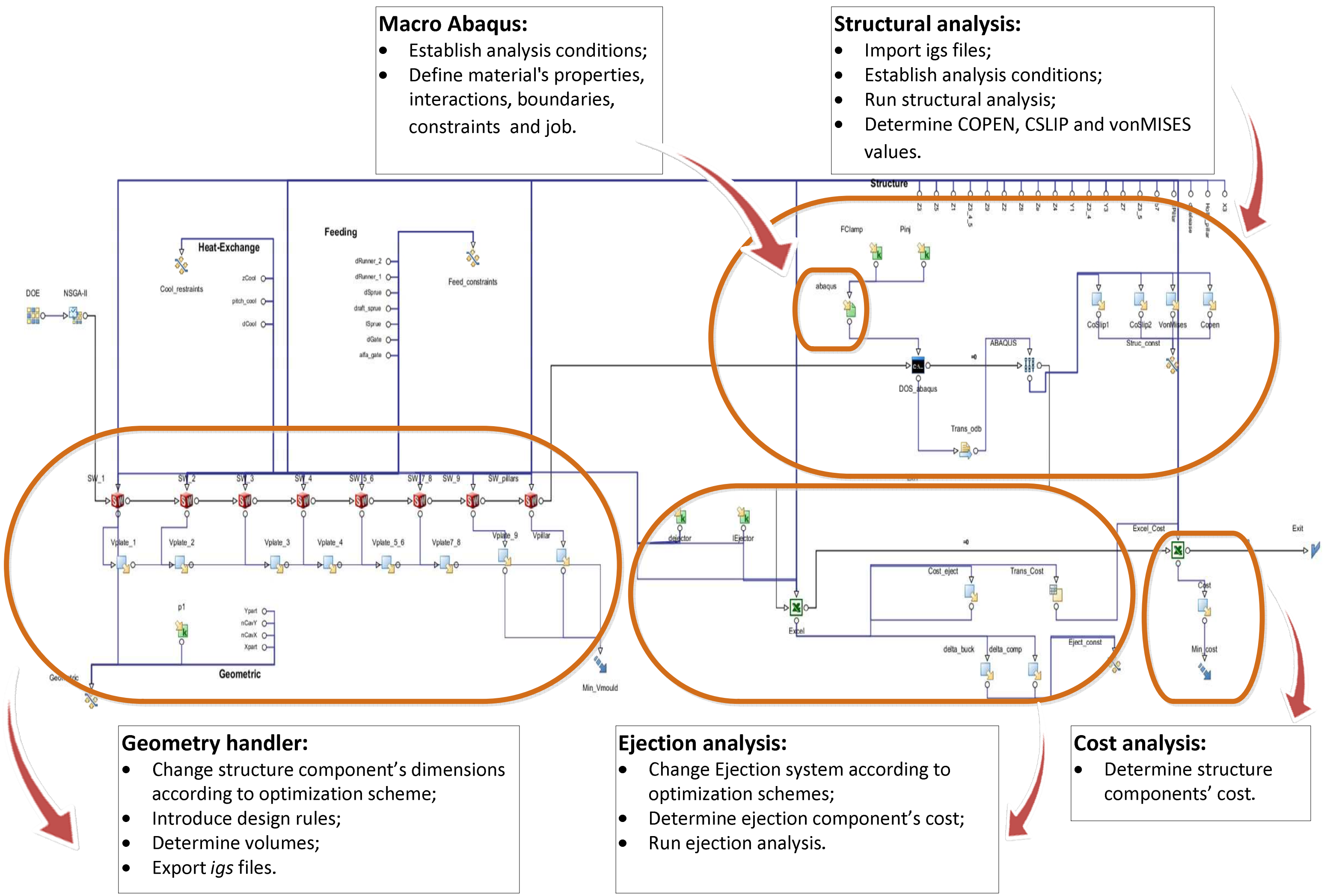

Figure 7: Main functions of the Structural sub-module included in the Optimize stage of the developed platform.

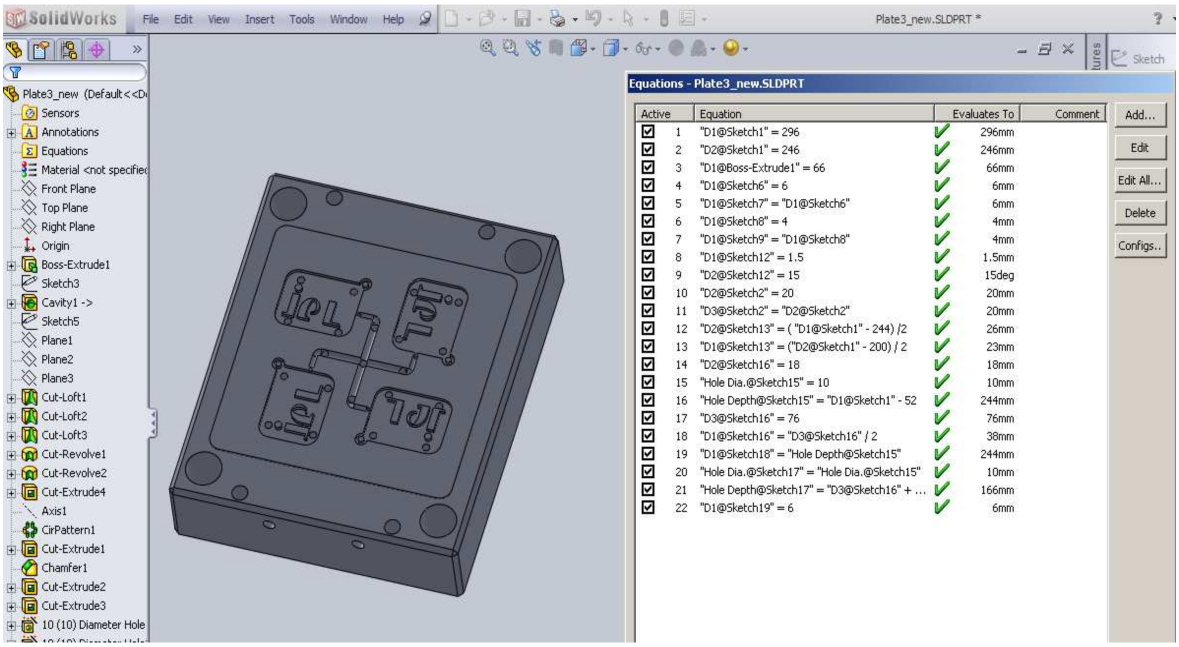

Figure 8: View of geometric relations introduced in the geometry handler regarding plate 3 (Solidworks).

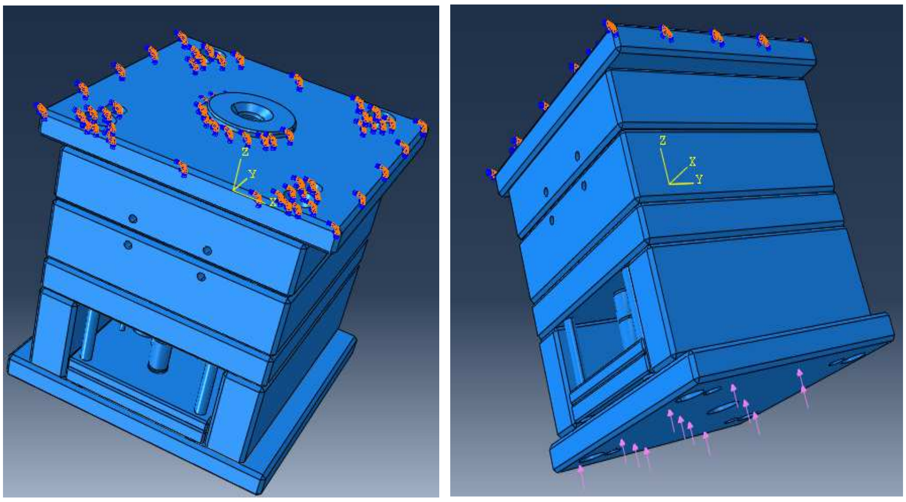

Figure 9: The boundary conditions on plate 1 and the clamping force applied on plate 9 (ABAQUS).

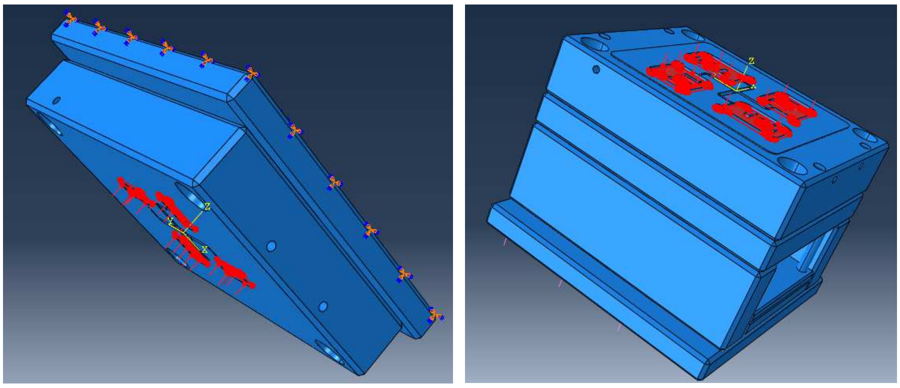

Figure 10: Application of the injection pressure in the cavity (left) and the core (right) areas of plates 2 and 3, respectively (ABAQUS).

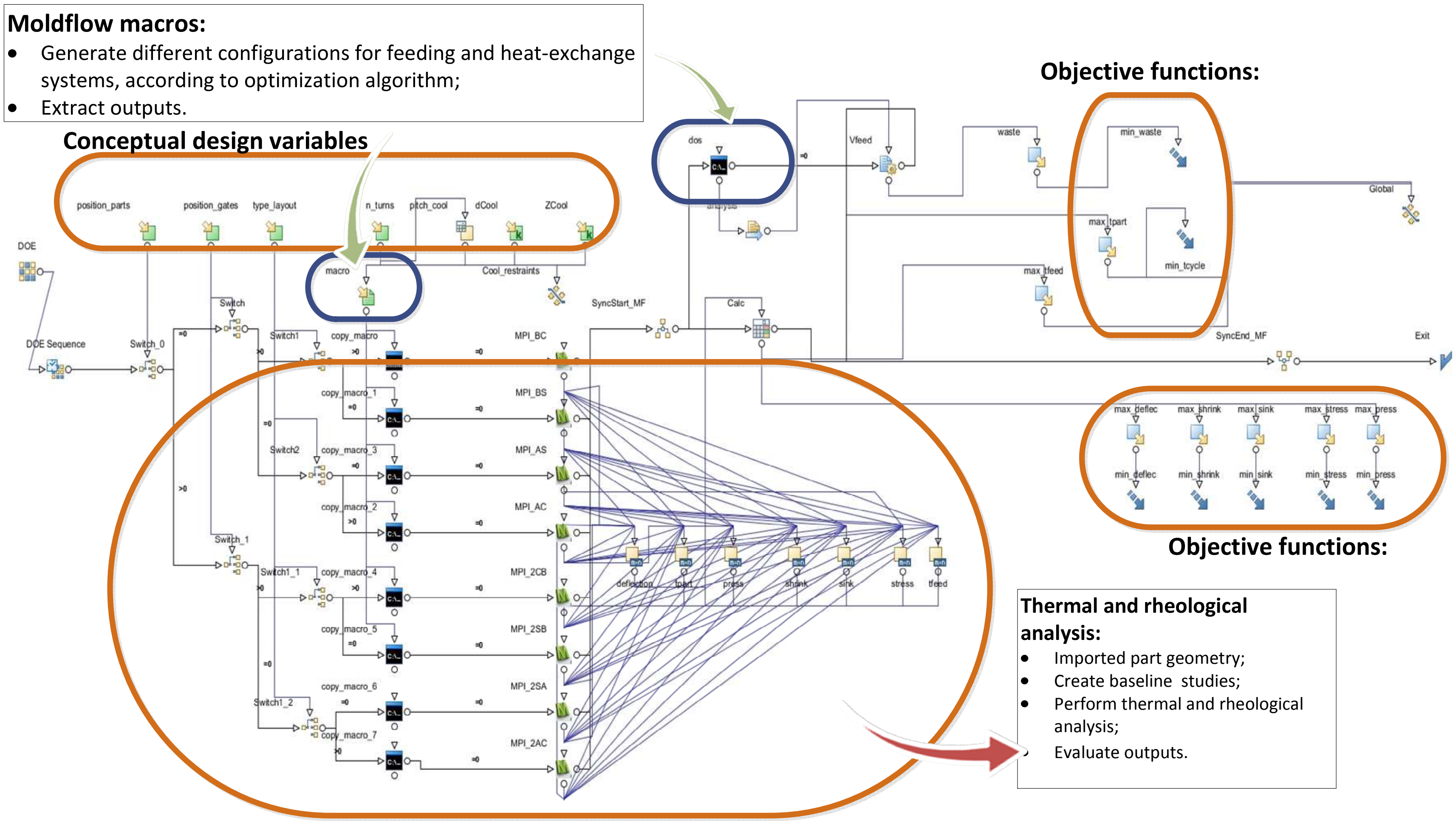

Figure 11: Feeding and heat-exchange sub-module included in the Design stage of the developed platform (ModeFRONTIER).

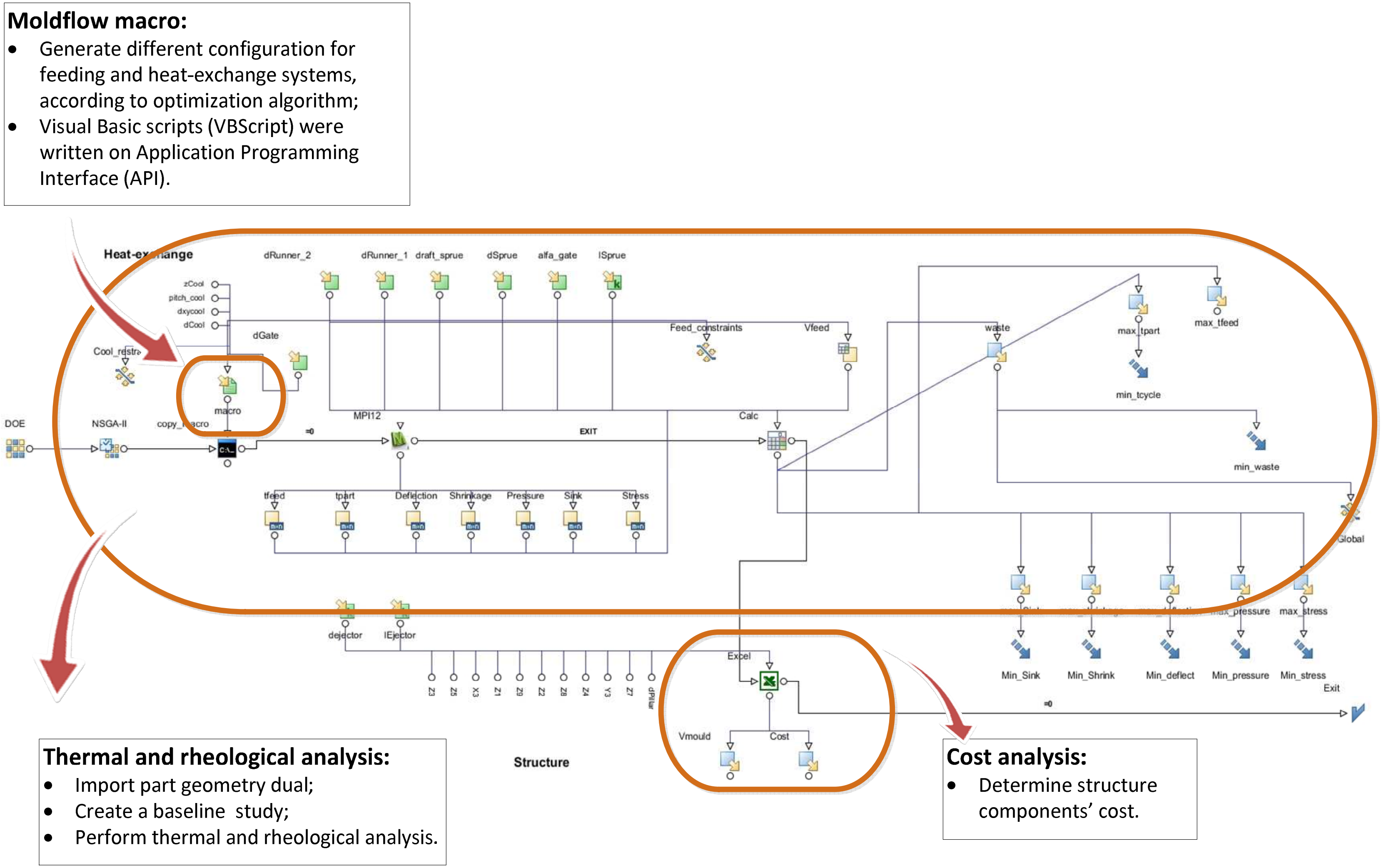

Figure 12: Feeding and heat-exchange sub-module included in the Optimize stage of the developed platform (ModeFRONTIER)..

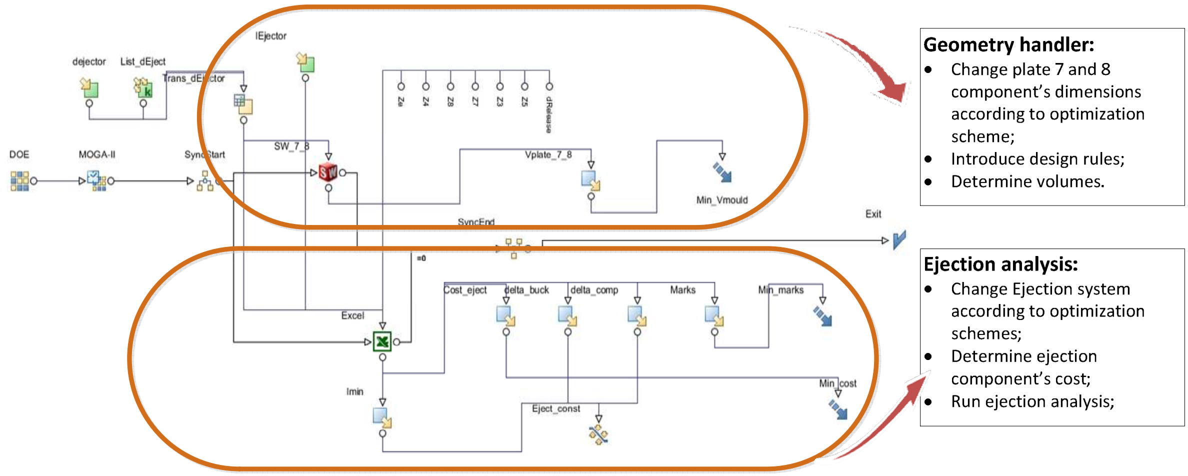

Figure 13: Mechanical sub-module included in the Optimize stage of the developed platform (ModeFRONTIER).

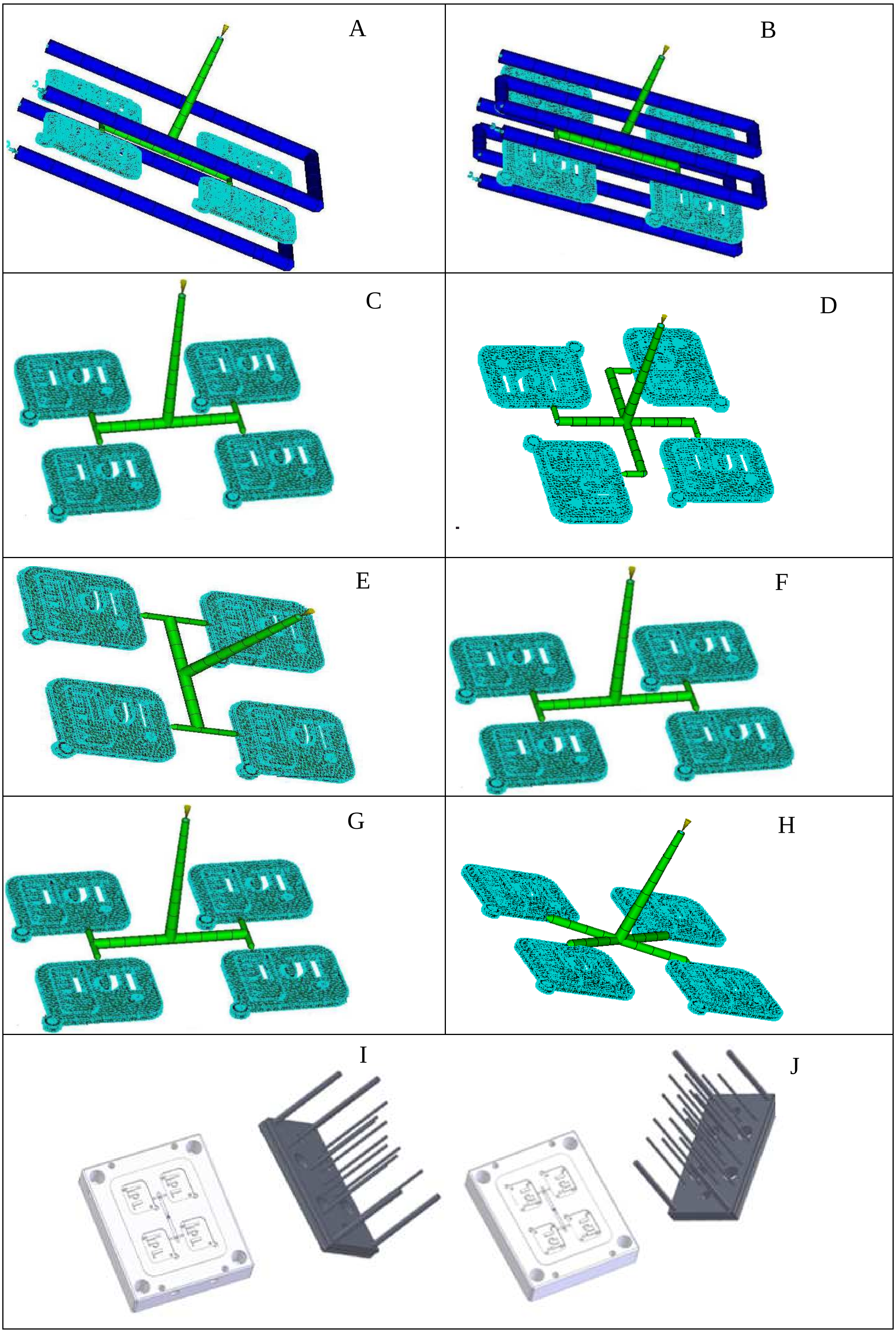

Figure 14: Conceptual design alternatives established for the injection mould case studied.

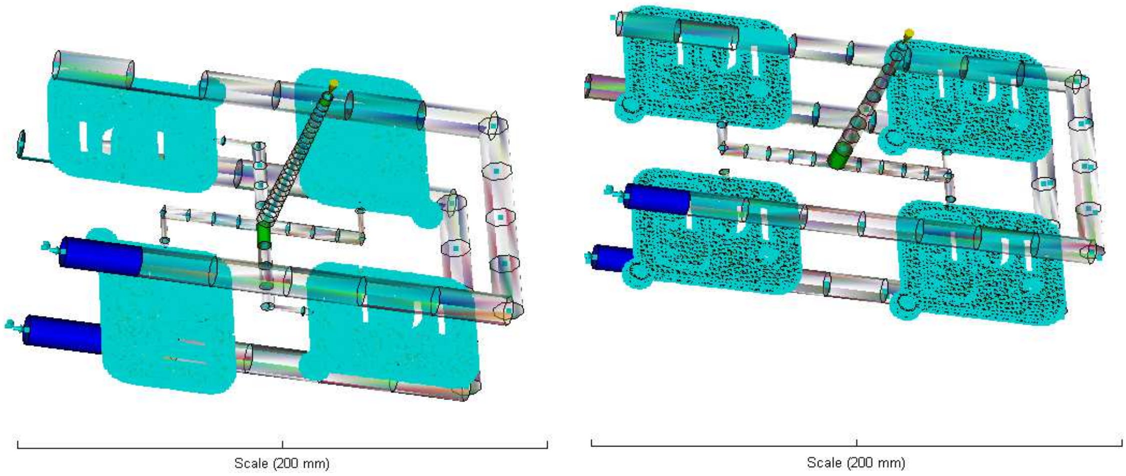

Figure 15: Most ranked conceptual solution (left) *versus* baseline solution (right).

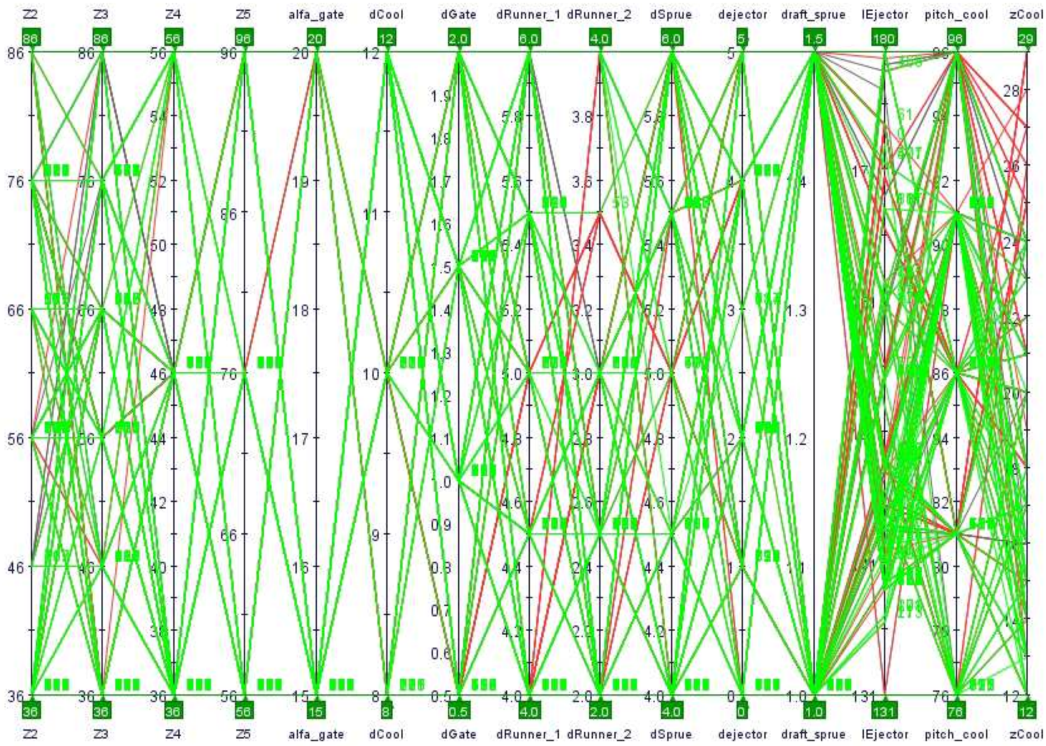

Figure 16: Pareto solutions achieved through NSGA II optimization algorithm.

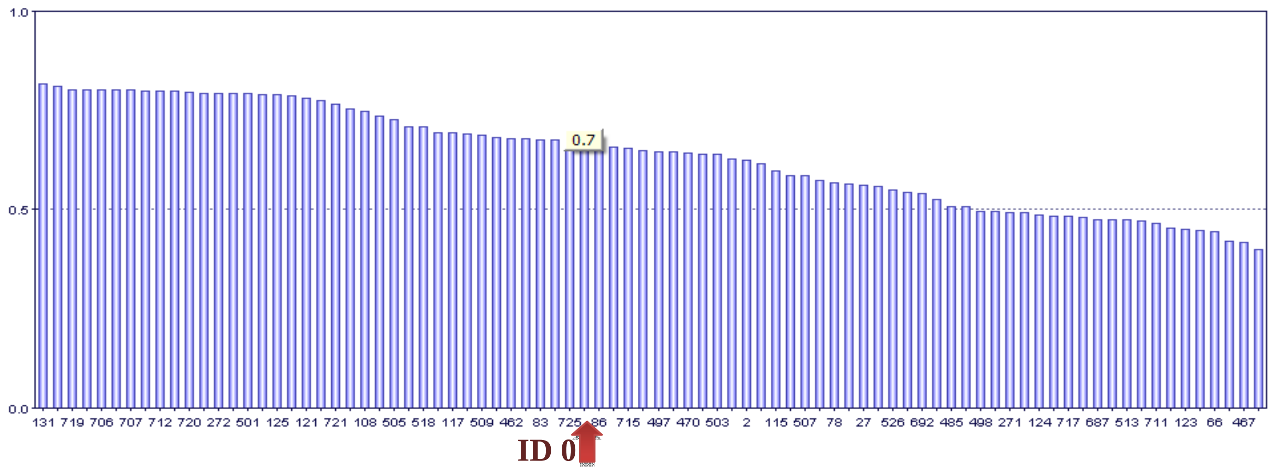

Figure 17: Ranking obtained for the design solutions where the selected conceptual solution (ID 0) is highlighted.

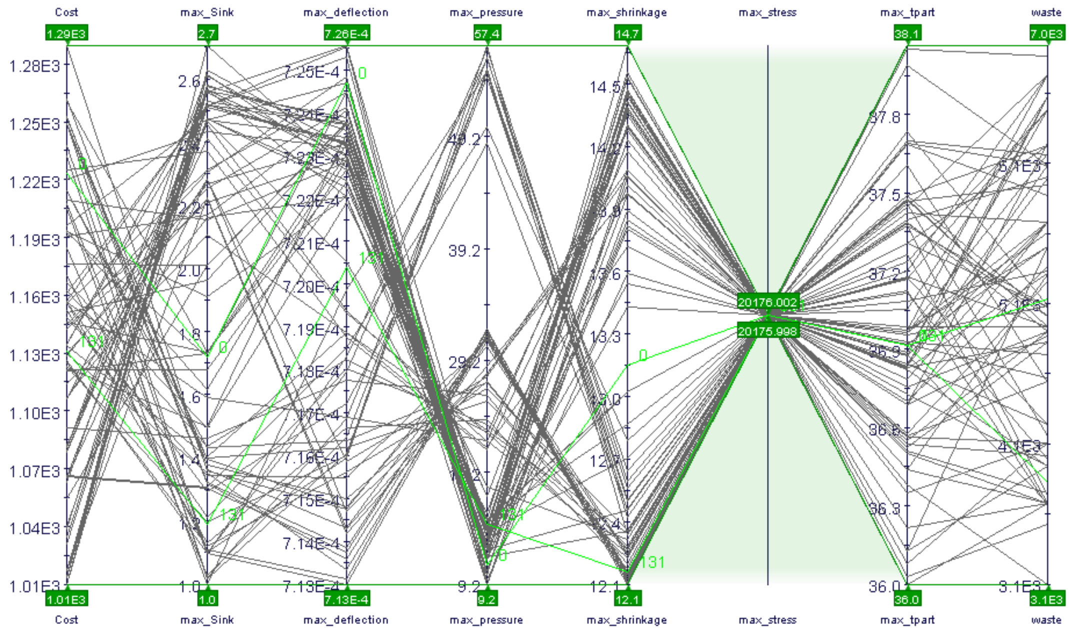

Figure 18: Parallel coordinates regarding the objectives with the selected solution (ID 131) and the selected conceptual solution (ID 0) highlighted in green.

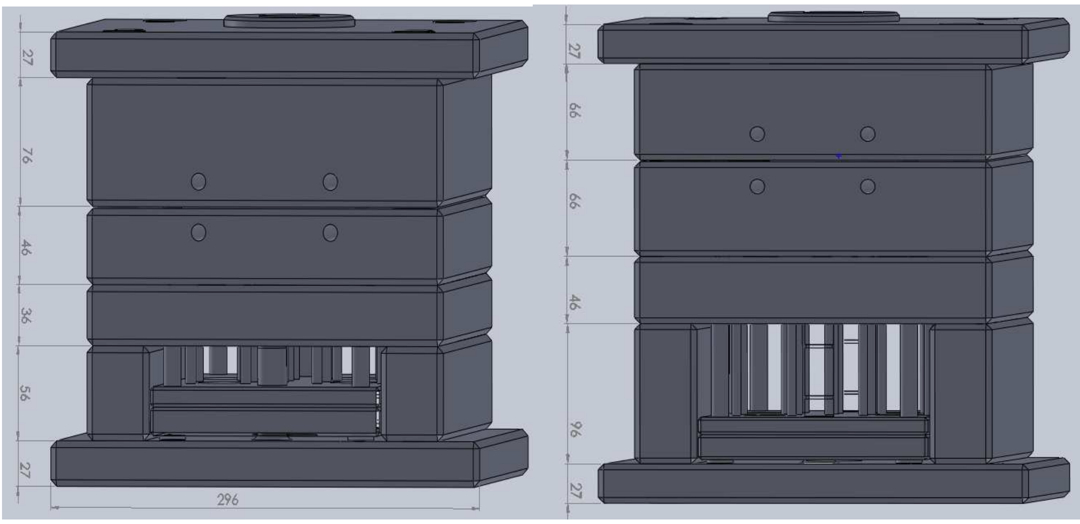

Figure 19: Structural system comparison between ID 131 (right) and conceptual solution (left).

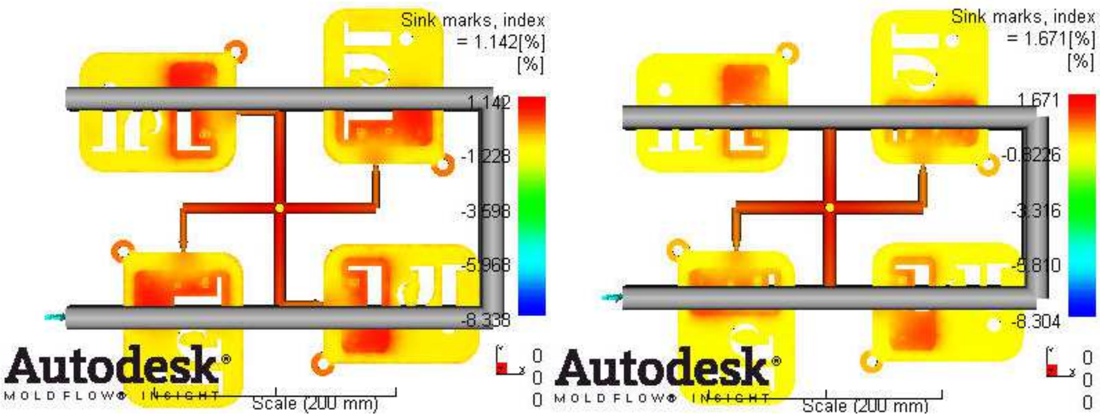

Figure 20: Feeding and heat-exchange comparison between ID 131 (right) and conceptual solution (left) through Sink index.