AN INTEGRATED QUANTITATIVE FRAMEWORK FOR SUPPORTING PRODUCT DESIGN: THE CASE OF METALLIC MOULDS FOR INJECTION.

FACULDADE DE ENGNEHARIA DA UNIVERSIDADE DO PORTO

AN INTEGRATED QUANTITATIVE FRAMEWORK FOR SUPPORTING PRODUCT DESIGN: THE CASE OF METALLIC MOULDS FOR INJECTION

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To my family.

ABSTRACT

The product development process is assumed as a crucial aspect of today companies' success. Therefore, the improvement of design process must be a strategic imperative for many companies. The design of injection moulds is one example of a complex product for which market pressures necessitate ever-shorter development times and higher quality levels.

A literature review identified that a large amount of scientific research has been done on mould design and its related fields over the last years, mostly based upon Knowledge-Based (KB) methods. However, this approach has been considered to be feasible only for the automatic generation of particular parts of mould design. In fact, due to the high complexity and mould component interactions, only with a global and integrative approach will it be possible to exploit the synergies of interacting phenomena and to adequately explore the design space in order to reach optimal mould designs.

In fact, several authors pointed that only with a more systematic, scientific and rational approach to the design process will it be possible to mitigate current poor practices of product development. For that reason, it is imperative to adopt new methods and tools for product development, allowing for faster and more integrated product design, in order to design optimal products prior to their launch.

Based on this assumption, a framework was developed aiming to support injection mould design. For that purpose, the Design for Six Sigma methodology was adopted as our main framework roadmap, where a set of highly value techniques were integrated (e.g. European Customer Satisfaction Index, Analytical Hierarchical Process, Axiomatic Design and Multidisciplinary Design Optimization), aiming to constitute an integrated and quantitative approach to support the design of injection moulds.

As a result, a platform for an enhanced development framework was built. This platform, adequate for the design of any mould regarding the injection of plastic parts without undercuts, tackles the design of an injection mould 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 end, a set of specific analysis modules were inserted in the platform, managed by an overseeing code system responsible for running the mathematical optimization schemes. Regarding the injection phenomena, and their interaction with mould tool, they were modelled through specific high fidelity codes, namely MOLDFLOW and 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 base for the developed framework, since both MOLDFLOW and ABAQUS are deterministic codes.

Particular emphasis was placed on thermal and rheological behaviour of the injection part, as well as on the structural performance of the mould, as main engineering domains. Nevertheless, the platform also encompasses a visualization module to help the analysis of mould solutions and a cost model designed to allow for an economic analysis of the mould's components. Finally, a customer's satisfaction module was also included in the form of an utility function.

A simplified version of the developed platform was initially developed in order to evaluate its potential to improve process design. Afterwards, a reinforced and more realistic version was developed, which constitutes an effective tool to support the mould design process. The results attained highlight the great potential of the proposed framework to achieve mould design improvements, with consequent reduction of rework and time savings for the entire mould design process. In particular, the value of mould solutions generated by the new framework, benchmarked with simulation codes and compared with an existing mould, present a global performance improvement of 5%, resulting in an increase of almost 4% in quality of Design. This improvement has positive impact of 0.6% on customer satisfaction than the baseline solution.

In addition, more benefits are expected due to the possibility of evaluating many different mould design configurations. This can be particularly important during the conceptual design stage, where basic, but essential, design decisions are undertaken, helping the adequacy of the generated solution to customers' needs.

In fact, it is our belief that the developed platform will constitute an important tool for increasing the design management capability of any mould makers company, since it enables the design of a mould solution with better performance regarding customer satisfaction levels in faster time cycles. The employment of specific engineering resources in the platform, such as CAE analyses, will also represent a more scientific approach to the mould design problem helping to provide knowledge about the impact of design decisions and respective trade-offs, leading the decision maker to design right at the first time.

RESUMO

Como resultado da crescente internacionalização dos mercados e do aumento das exigências dos clientes e da sociedade em geral, as empresas estão sujeitas a uma enorme pressão concorrencial, o que significa que têm que ser competitivas à escala mundial para sobreviver. Neste contexto, a Conceção e Desenvolvimento (C&D) de produtos é assumido como um fator crucial para o sucesso das empresas.

Os moldes metálicos para a injeção de plásticos são ferramentas de alta precisão geométrica e dimensional, responsáveis pela produção da maioria dos componentes plásticos utilizados no quotidiano. Dada a sua importância, quer para a qualidade das peças produzidas, quer para o total dos custos envolvidos, a C&D do molde é considerada uma etapa crucial para a eficácia do processo de injeção. Adicionalmente, as empresas são pressionadas a conceber e fabricar moldes que garantam elevados níveis de qualidade e de fiabilidade, a custos reduzidos, no menor espaço de tempo possível.

Para fazer face a estes desafios, ao longo dos últimos anos têm sido desenvolvidas novas metodologias de apoio ao processo de C&D de moldes, normalmente focadas no projeto de componentes específicos do molde. No entanto, na nossa opinião, esta abordagem é insuficiente, porque não contempla as complexas interações existentes entre os vários componentes do molde, que implicam que o ótimo individual não seja um ótimo global. Nesse sentido, no nosso entender, a C&D de moldes deve ser suportada por metodologias globais, que integrem não só todos os componentes do molde, mas principalmente que considerem as interações típicas entre estes. Só assim será possível explorar adequadamente o espaço de soluções admissíveis, de forma a identificar a melhor solução global para o molde.

Com base na revisão de literatura, foi possível identificar vários autores que afirmam que apenas com a adoção de metodologias mais sistemáticas, científicas e racionais, de suporte aos processos de C&D será possível atenuar as atuais lacunas. Por essa razão, considerou-se importante desenvolver uma metodologia global e de forte base quantitativa de suporte à C&D de moldes para injeção que, por integração de diferentes técnicas de valor reconhecido, permita tomar decisões sustentadas em dados quantitativos, reduzindo assim o número de

iterações por processos de tentativa - erro. Consequentemente, esta abordagem permitirá reduzir os prazos e os custos inerentes ao processo, que constituem igualmente objetivos a atingir.

Neste sentido, foi desenvolvida uma metodologia global, assente na metodologia Design for Six Sigma e reforçada pela integração de outras metodologias, de forte cariz científico e quantitativo, tais como a Modelação por Equações Estruturais, *Axiomatic Design* e *Multidisciplinary Design Optimization*, tendo como objetivo central guiar e sistematizar o processo de C&D.

Com base nesta metodologia, foi construída uma plataforma informática de suporte à C&D de moldes para injeção de plástico. Esta plataforma permite converter uma solução inicial, definida com base em boas práticas, em melhores soluções. Para tal, considera a C&D dos moldes como um problema de otimização não linear, gerido pelas preferências dos clientes e suas imposições. Assim, esta plataforma inclui um conjunto de módulos de análise característicos dos principais fenómenos do processo de injeção, nomeadamente, processos térmicos e reológicos, estruturais e mecânicos, orientados por um sistema responsável pela execução dos modelos de otimização matemática.

Foi desenvolvida uma primeira versão simplificada da metodologia proposta, tendo como objetivo avaliar o seu potencial para a obtenção de melhores soluções, assim como determinar a sua admissibilidade em termos de tempo de resposta. Apesar desta primeira versão adotar modelos matemáticos muito simples, permitiu demonstrar o seu potencial no alcance de melhorias significativas. De facto, os resultados obtidos destacam o potencial da abordagem proposta para alcançar melhorias no projeto do molde, nomeadamente na obtenção de melhorias nos parâmetros considerados na análise, tais como tempos de ciclo, volume de material desperdiçado e redução da pressão de enchimento, assim como no aumento do nível de satisfação do cliente.

Contudo entendeu-se que a inclusão de modelos mais rigorosos e realistas era essencial para conseguir alcançar melhorias mais expressivas, assim como permitir uma maior adequação da plataforma à realidade da indústria. Por essa razão, foi desenvolvida uma versão melhorada que integra modelos que descrevem com maior rigor os fenómenos físicos inerentes ao processo de injeção, permitindo ainda abarcar a C&D de componentes mais complexos.

No que diz respeito aos fenómenos associados ao processo de injeção, eles foram modelados com o auxílio de programas de simulação numérica já validados. O MOLDFLOW foi utilizado na simulação térmica e reológica do processo de injeção e o ABAQUS na simulação estrutural do molde. Foi ainda integrado na plataforma um módulo de visualização, de modo a permitir a análise das soluções geradas, e um modelo de custo, desenvolvido de forma a permitir uma análise económica dos componentes do molde.

Finalmente, a plataforma integra também um módulo de avaliação da satisfação do cliente, específico para a indústria nacional de moldes, que se baseia no Índice Europeu da Satisfação do Cliente. Este modelo permite construir uma função objetivo definida pela combinação linear dos pesos associados a cada requisito específico do cliente relativamente a cada molde, convertendo assim de forma consistente e sistemática, as necessidades do cliente em soluções ótimas para o molde. Assim, dos resultados do projeto desenvolvido salienta-se o reforço da informação inerente às decisões de C&D facultada pela plataforma, uma vez que mais importante que gerar melhores soluções para o molde, é o conhecimento sobre o impacto das decisões tomadas. Na verdade, considera-se que a plataforma desenvolvida constituirá uma ferramenta importante para aumentar a capacidade de gestão do processo de C&D de qualquer fabricante de moldes, uma vez que permite gerar soluções com melhor desempenho, quer em relação aos requisitos funcionais analisados, quer em relação ao nível de satisfação dos clientes. Assim, de forma sustentada, apoiada em dados quantitativos e de base científica, será possível às empresas conceber mais rapidamente, os moldes certos, para um determinado cliente.

Além disso, são expectáveis mais benefícios devido à possibilidade de avaliar várias configurações preliminares de soluções de moldes. De facto, observou-se que as decisões iniciais são críticas para a determinação do nível de desempenho do molde final. Neste sentido, a separação da etapa de C&D dos moldes em dois estágios assume-se como uma importante característica da plataforma. O recurso ao desenho de experiências permite testar várias soluções conceptuais, tendo como objetivo determinar a melhor solução preliminar, para num segundo estágio proceder à sua otimização, tendo por base os critérios do cliente.

Por forma a testar a plataforma, foram comparados os dados relativos a um molde já existente com os resultados produzidos pela plataforma. Com base nestes dados, foi possível verificar que a solução gerada na fase conceptual resultou numa melhoria de 1% no desempenho do molde. No respeitante à fase de Otimização, a solução selecionada foi ainda melhorada em 5.7%. Totalizando as duas etapas, poder-se-á afirmar que com base na plataforma foi possível melhorar uma solução já existente e validada em cerca de 0.6% ao nível da satisfação do cliente. É ainda expectável uma redução no tempo de desenvolvimento devido à redução do número de interações, bem como na redução de correções ao molde devido a erros.

RÉSUMÉ

En résultat de l'internalisation des marchés et de l'augmentation des exigences des clients et de la société en général, les entreprises sont soumises à une énorme pression concurrentielle, par conséquent, pour survivre, elles doivent être compétitives à l'échelle mondiale. Dans ce contexte, la Conception et Développement de Produits (C&D) est assumée comme un facteur crucial pour le succès des entreprises.

Les moules métalliques pour l'injection de plastiques sont des outils de haute précision géométrique et dimensionnelle, responsables de la production de la plupart des composants plastiques utilisés au quotidien. Etant donné son importance, soit pour la qualité des pièces produites, soit pour le total des coûts associés, la C&D du moule est considérée une étape fondamentale pour l'efficacité du processus d'injection. De plus, les entreprises subissent la pression de conception et de fabrication de moules qui garantissent des niveaux élevés de qualité et de fiabilité, à coûts réduits, dans les plus brefs délais.

Pour faire face à ces défis, de nouvelles méthodologies d'appui de C&D de moules qui misent sur le projet de composants spécifiques du moules, ont été développées. Cependant, nous estimons que cet abordage est insuffisant, car il n'inclut pas les interactions complexes existantes entre les différents composants du moule, qui impliquent que la meilleure solution individuelle ne soit pas la meilleure solution globale. Dans ce sens, selon notre étude, la C&D de moules doit être supportée par des méthodologies globales, qui intègrent pas seulement tous les composants du moule, mais qui considèrent principalement les interactions typiques entre eux. Celle-ci est la seule solution pour exploiter convenablement l'espace de solutions admissibles, afin d'identifier la meilleure solution globale pour le moule.

Dans la revue de littérature, plusieurs auteurs défendent que les lacunes actuelles ne sont atténuées que par l'adoption de méthodologies d'appui des processus de C&D plus systématiques, scientifiques et rationnelles.

Pour cette raison, il s'est avéré important de développer une méthodologie globale et de forte base quantitative d'appui à C&D de moules pour injection qui, par intégration de différentes techniques de valeur reconnue, permette de prendre des décisions soutenues par des données quantitatives, réduisant, ainsi, le nombre d'itérations par processus de tentative-

erreur. Conséquemment, cet abordage permettra de réduire les délais et les coûts inhérents au processus, qui constituent aussi des objectifs à atteindre.

Dans ce sens, nous avons développé une méthodologie globale, supportée par la méthodologie Design for Six Sigma et renforcée par l'intégration d'autre méthodologies, de nature fortement scientifique et quantitative, telles que la Modélisation par Équations Structurelles, l'*Axiomatic Design* et le *Multidisciplinary Design Optimization*, avec le principal objectif de guider et systématiser le processus de C&D.

Suivant cette méthodologie, nous avons construit une plate-forme informatique d'appui à C&D de moules pour injection de plastique. Cette plate-forme permet de convertir une solution initiale, définie sur la base de bonnes pratiques, en de meilleures solutions. Pour ce faire, la C&D des moules est considérée comme un problème d'optimisation non-linéaire, géré par les préférences des clientes et de leurs impositions. Ainsi, cette plate-forme inclut un ensemble de modules d'analyse caractéristiques des principaux phénomènes du processus d'injection, notamment, des processus thermiques et rhéologiques, structurels et mécaniques, orientés par un système responsable de l'exécution des modèles d'optimisation mathématique.

Nous avons développé une première version simplifiée de la méthodologie proposée, ayant comme objectif l'évaluation de son potentiel pour l'obtention de meilleures solutions et la détermination de son admissibilité en termes de temps. En effet, comme mentionné ci-dessus, de fortes restrictions sur les temps de développement et de fabrication de moules s'imposent actuellement. Malgré l'adoption de modèles mathématiques très simples dans cette première version, celle-ci a permis de montrer son potentiel en vue d'améliorations de résultats.

Les résultats obtenus mettent, effectivement, en évidence le potentiel de l'abordage proposé pour réussir des améliorations dans le projet du moule, en particulier dans l'obtention d'améliorations dans les paramètres pris en compte dans l'analyse, tels que les temps de cycle, le volume de matériel perdu, la pression de remplissage et le niveau de la satisfaction du client.

Cependant, nous avons considéré que l'inclusion de modèles plus rigoureux et réalistes était essentielle pour l'obtention d'améliorations plus expressives et pour une meilleure adéquation de la plate-forme à la réalité de l'industrie. De ce fait, nous avons développé une version qui intègre des modèles qui décrivent plus rigoureusement les phénomènes physiques inhérents au processus d'injection, permettant également la C&D de composants plus complexes.

Les phénomènes associés au processus d'injection ont été modelés à l'aide de programmes de simulation numérique déjà validés. Le MOLDFLOW a été utilisé dans la simulation thermique et rhéologique du processus d'injection et l'ABAQUS dans la simulation structurelle du moule. Sur la plate-forme, un module de visualisation et un module de coût ont été intégrés. Le premier concernant l'analyse de solutions gérées et le deuxième se rapportant à l'analyse économique des composants du moule.

La plate-forme intègre aussi un module d'évaluation de la satisfaction du client, spécifique pour l'industrie nationale de moules, qui se base sur l'Indice Européen de la Satisfaction de la Clientèle. Ce modèle permet de construire une fonction objectif définie par la combinaison linéaire des poids associés à chaque requis spécifique du client par rapport à chaque moule. Les exigences du client sont converties, de façon systématique et consistante, en solutions optimisées pour le moule.

D'après les résultats de ce projet, nous mettons en évidence le renforcement de l'information inhérente aux décisions de C&D fournie par la plate-forme. La connaissance sur l'impact de la prise de décisions est, en somme, plus importante que l'obtention de solutions optimisées pour le moule.

En vérité, nous considérons que cette plate-forme constituera un outil fondamental pour augmenter la capacité de gestion du processus de C&D pour tout fabricant de moules, une fois qu'elle permet de générer des solutions à meilleure performance, soit par rapport aux requis fonctionnels analysés, soit au niveau de la satisfaction des clients. Ainsi, les entreprises pourront concevoir, plus rapidement et de façon soutenable, les moules convenables pour un client spécifique, tenant comme base des données quantitatives et de nature scientifique. Outre ce bénéfice, d'autres sont attendus dû à la possibilité d'évaluation de plusieurs solutions préliminaires de moules.

Nous avons observé que les décisions initiales sont critiques pour la détermination du niveau de performance du moule final. Dans ce sens, la séparation de l'étape de C&D des moules en deux stages s'assume comme une caractéristique importante de la plate-forme. Le recours au dessin d'expériences, lors du premier stage, permet de tester plusieurs solutions conceptuelles, afin de déterminer la meilleure solution préliminaire. Celle-ci est optimisée au deuxième stage, ayant comme base les critères du client.

Pour tester la plate-forme, ses résultats ont été comparés aux résultats expérimentaux relatifs à un moule déjà existant. Nous avons vérifié que la solution générée lors de la phase

Conceptuelle a accru le niveau de satisfaction du client en 0.05%, sur la base d'une amélioration de 1% sur la performance du moule.

En ce qui concerne la phase d'Optimisation, la solution sélectionnée fut encore améliorée en 5.7%.

L'application de ces deux étapes sur la plate-forme a permis d'optimiser une solution préexistante déjà validée en 0.6% environ, au niveau de la satisfaction du client. De même, nous prévoyons une réduction du temps de développement grâce à la réduction du nombre d'interactions et du nombre de corrections du moule pendant la phase de fabrication.

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NOMENCLATURE

$b5$	Temperature of the polymer at the value in the 2-domain Tait PVT model
$\boldsymbol{\eta}$	Vector of endogenous latent variables
υ	Poisson ratio of plastic material
$\boldsymbol{\beta}, \boldsymbol{\gamma}$	Matrices of the coefficients of the structural model
τ_{max}	Maximum shear stress
E_{mould}	Young modulus of mould's material
$\lambda_{\xi i}$	Coefficients of the formative model associated with variable ξ_i
$\lambda_{\eta i}$	Coefficients of the formative model associated with variable η_i
η_{aeff}	Apparent effective viscosity
$\dot{Q}_{line}$	Heat transfer rate per cooling line
$\dot{V}_{coolant}$	Volumetric flow rate of the coolant
$\bar{d}_{Sprue}$	Sprue mean diameter
$\bar{v}_F$	Velocity of the flow front
$\dot{\gamma}_{max}$	Maximum shear rate
$\mathrm{d_N}$	Diameter of the connecting runner of the injection machine
$\mathrm{x^+}$	Upper interfacial location
$\mathrm{X_{cav}}$	Length of mould´s cavity (or its dimension along the X direction)
$\mathrm{Y_{cav}}$	Width of mould´s cavity (or its dimension along the Y direction)
$\mathbf{F}^*$	Utopia (ideal) solution
$A_{compression}$	Area of plates subject to compression
A_{eff}	Effective area, i.e. cross-sectional area of the plastic moulding.
A_{proj}	Projected area of moulding
$Cp_{coolant}$	Coolant specific heat
E_{pin}	Young's modulus of the ejector pin's material
F_{Clamp}	Clamping force
$F_{clampmax}$	Maximum clamping force
F_{eject}	Ejection force

$F_{ejector}$	Force applied in each ejector
F_{normal}	Normal force between the surface of the moulding and the surface of the mould
M_{int}	Minimum thickness of the moulded part
P_{atm}	Atmospheric pressure
P_{inj}	Injection pressure
T_{cool}	Cavity temperature after cooling
T_{demol}	Mean demoulding temperature
T_{eject}	Ejection temperature of plastic material
T_{melt}	Melt temperature in the cavity
T_{trans}	Transition temperature of plastic material (Tc onset ASTM 3418)
$\dot{V}$	Volumetric flow rate
V_{feed}	Volume of the feeding system (cold runner system)
V_{part}	Total volume of the moulded plastic part
X_{bars}	Distances between tie bars of injection machine on X axis
X_i	Length of plate *i*
X_{part}	Part's dimensions on X direction
Y_{bars}	Distances between tie bars of injection machine on Y axis
Y_i	Width of plate *i*
Y_{part}	Part's dimensions on Y direction
Y_{span}	Length of the span
Z_{hole}	Distance of the centre of the hole from the cavity surface
Z_{cav}	Distance in the Z direction to the cavity plate
Z_e	Height of moulding on the ejection (core plate)
Z_i	Height of moulding on the injection side (cavity plate)
Z_{mould}	Distance on Z axis for the designed mould
d_{hole}	Hole's diameters
$d_{Ejector}$	Diameter of ejector pin
d_{Gate}	Gate diameter
$d_{Release}$	Distance to release the mouldings
d_{Runner}	Runner diameter
d_{Sprue}	Sprue initial diameter
l_{Gate}	Gate length
l_{Runner}	Runner length

l_{Sprue}	Sprue lenght
l_{part}	Part's length
m_{part}	Mass of the moulding part
n_{cav_x}	Number of cavities on Partition Plane on X direction
n_{cav_y}	Number of cavities on Partition Plane on Y direction
n_{Gates}	Number of gates per each plastic part
n_{cav}	Number of cavities
$n_{downstream}$	Number of streams of each ramification
n_{ramif}	Number of ramifications of the runner
n_{safety}	Safety coefficient
p_1	Lateral distance between the impressions cavities
p_s	Design parameters
t_{feed}	Time to cool the feeding system
t_{open}	Mould opening time
t_{part}	Time to cool the moulded part
v_{open}	Mould opening velocity
w_i	Weights assigned to the objective function f_i
x^-	Lower interfacial location
$\boldsymbol{x}^{lower}$	Lower side constraint
$\boldsymbol{x}^{upper}$	Upper side constraint
$\boldsymbol{\Lambda}_{\mathbf{u}}$	Endogenous weight matrices
$\boldsymbol{\Lambda}_{\mathbf{v}}$	Exogenous weight matrices
$\delta_{\xi i}$, $\delta_{\eta i}$	Specification errors
$\delta_{bending}$	Maximum deflection through bending
δ_{mould}	Deflection across the entire mould
$\mu_{coolant}$	Coolant viscosity
μ_s	Coefficient of static friction between mould and plastic material
$\rho_{coolant}$	Coolant density
ρ_{δ}	Solid density of the polymer
$\sigma_{comp\_ejector}$	Compressive stress of ejectors
$\sigma_{fatigue\_limit}$	Fatigue limit stress of the ejectors material
$\Delta T_{coolant}$	Temperature's increase in coolant along the cooling line
ΔP	Pressure drop

alfa_gate Draft angle of gates

Area_1 Area of plate 1 (i.e. X_1Y_1)

Area_2 Area of plate 2 (i.e. X_2Y_2)

Area_4 Area of plate 4 (i.e. X_4Y_4)

Area_5 Area of plate 5 (i.e. X_5Y_5)

Area_7 Area of plate 7 (i.e. X_7Y_7)

ACRONYMS

AD	Axiomatic Design
AHP	Analytical Hierarchical Process
AIJ	Aggregating Individual Judgment
API	Application Programming Interface
ASQ	American Society for Quality
AVE	Average Variance Extracted
C&D	Concepção e Desenvolvimento
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAs	Customer Attributes
CCVA	Customer Value Chain Analysis
CDOV	Concept, Design, Optimize and Verify
CP	Compromise Programming
CSI	Customer Satisfaction Index
CTQs	Critical-To-Quality
DFSS	Design for Six Sigma
DM	Decision-Maker
DMADOV	Define, Measure, Analyse, Design, Optimize and Verify
DMADV	Define, Measure, Analyse, Design and Verify
DMAIC	Define, Measure, Analyze, Improve and Control
DoE	Design of Experiments
DPMO	Defects Per Million Opportunities
DPs	Design Parameters
EAs	Evolutionary Algorithms
ECSI	European Customer Satisfaction Index
FEM	Finite Element Method
FuR	Full-Round
FRs	Functional Requirements
GA	Genetic Algorithm
GDP	Gross Domestic Product

GLS	Generalized Least Squares
GRG	Generalized Reduced Gradient
I2DOV	Invention, Innovation, Develop, Optimize and Verify
ICOV	Identify, Characterize, Optimize and Verify
IDOV	Identify, Design, Optimize and Validate
INCOSE	International Council on Systems Engineering
KB	Knowledge-Based
MAUA	Multi-Attribute Utility Analysis
MCDM	Multi Criteria Decision Making
MDO	Multidisciplinary Design Optimization
MDT	Mean Down Time
ML	Maximum Likelihood
MOGA	Multi-Objective Genetic Algorithms
MTBF	Mean Time Between Failure
NBI	Normal Boundary Intersection
NLP	Nonlinear Programming Problem
NSGA	Non-dominated Sorting Genetic Algorithm
OLS	Ordinary Least Squares
PD	Product Development
PiP	Pin-Point
PLS	Partial Least Squares
PP	Partition Plane
QFD	Quality Function Deployment
RML	Robust Maximum Likelihood
RSM	Response Surface Models
SEM	Structural Equation Modelling
SQP	Sequential Quadratic Programming
VoC	Voice of Customer
WS	Weighted Sum

CHAPTER 1

Introduction

1.1. Purpose of the research

Currently, product development is assumed as the new frontier for achieving competitive advantage in today's rapidly changing business environments [1, 2]. In fact, both managers and scholars increasingly understand the central role that product development plays in creating competitive advantage [3]. This is especially true because decisions made during early design stages have the greatest impact over the total cost and quality of the system. Manufacturer's experience in many different industries has shown that 80% of the total time and cost of product development are committed in the early stages of product development, when only 5% of project time and cost have been expended [4, 5]. This is because in the early concept stages fundamental decisions are made regarding basic geometry, materials, system configuration, and manufacturing processes. Further along in the design cycle, it becomes harder and costly to make changes [3].

These crucial decisions are mainly supported based on intuition, empiricism and the so-called handbook method. The consequence is a lot of failure-trial-fix loops and development costs dominated by failure recovery actions. Additionally, several iterations are typically necessary because of inherently conflicting trade-offs for which it is very difficult to find a balance. Usually this iterative procedure represents a major portion of the product development lead time and cost. Due to these practices, the paradigm of product development is expensive, unpredictable and prone to failures, where the loss caused by early selection of wrong design solutions affects the whole process and is harder to recover in later stages [6].

Currently, it is assumed that only with a more systematic, scientific and rational approach to the design process will be possible to mitigate these limitations [7-9]. For that reason, it is imperative to adopt new methods and tools for product development, allowing for a better exploitation and management of the system's trade-offs in the early stages of design definition. Consequently, a faster and higher integrated product design will be achieved, in order to design optimal products [10, 11].

The injection mould is a high precision tool responsible for the production of most plastic parts used everywhere. The 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, being the total production of about 350 million Euros. Its main customers are worldwide high-tech companies, namely the automobile (relative weight of 72% in 2010) and the electronic sectors. The main markets for Portuguese moulds are Germany, Spain and France [12].

Mould design is considered of critically important for the quality of the product and efficient processing, as well as determinant for the profitability of the entire injection moulding process. 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 acceptable or the best option. At the same time, it is recognized that the majority of poor quality costs had its origins in errors committed in the mould design stage and in the transposition from the design to the production stage [13]. As a result, a significant number of errors only arise after mould's manufacturing. Solving those errors leads to costly moulds and long manufacturing periods.

Since mould makers are now highly pressured to shorten both leading times and cost, as well as to accomplish higher levels of mould performance, it is essential to adopt more scientific and structured methodologies in order to design moulds right at the first time. To reach that, a new comprehensive approach based on the integration of well-known quantitative techniques, such as Design for Six Sigma (DFSS), Structural Equation Modelling (SEM), Axiomatic Design (AD) and Multidisciplinary Design Optimization (MDO), is proposed on this research. Although some of these methods have been largely explored, individually or in combination with other methodologies, a quantitative integration of all aspects of design, in such a way that the whole process becomes logical and comprehensible, has not yet been considered.

1.2. Background

Several product development approaches were studied, aiming to help the construction of a global and strongly quantitative methodology that can work together with the intuitive non-quantitative and creative side of the mould design. In this context, a large amount of scientific research has been done on the mould's field over the last years, mostly based upon Knowledge-Based (KB) methods. This approach is justified by the extensive empirical knowledge about mould component functions. Examples of work in this area are IKB-MOULD [14], IKMOULD [15], ESMOULD [16], amongst others [17-19].

According to Chan *et al.* (2003) [14], one emergent area of research in the injection moulding field attempts to automatically generate the design of mould tool components [20-26]. However, this approach has been considered to be feasible only for the automatic generation of particular parts of mould design [14, 27], mostly due to the high complexity involved in mould design components. Nevertheless, our assumption is that automatic generation must be extended to the complete mould design. In fact, it is expected that an optimal mould solution can be quite different from the solution gathered by the integration of partially optimal mould components.

Thus, only with a global and integrative approach will it be possible to exploit the synergies of interacting phenomena and to adequately explore the design space in order to reach optimal mould designs. Furthermore, it is also essential to link the level of customer satisfaction with the search for optimal solutions. These two aspects, namely the development of a global and quantitative approach allowing for an automatic generation of a complete mould design, commanded by customer preferences, are the two innovative axes of this research, which aims to constitute an alternative to the traditional procedure of injection moulds design.

1.3. Motivation

Today's multi-national manufacturing companies recognise that they must not only offer better products than the competition: they must also bring these products to market faster and more cost effectively than their competitors. Typically, engineered products tend to have complex development processes. In addition, it is assumed that lessons learnt from studying one product development process can be applied to improve another in a similar context, which is justified from practical experience and acceptance in the existing literature.

Regarding the tooling industry, this sector has been increasingly facing the pressure to reduce the time and cost of mould development, offer better accuracy and surface finish, provide flexibility to accommodate future design changes and meet the requirements of shorter production runs [28]. Because of that, this work is mainly motivated by the need for a global and quantitative approach, aiming to support the moulds design. It is our deep conviction that this approach can become an essential tool for future quality enhancement in the moulds maker sector in order to sustain or even increase their competitive strength.

In addition, it is our belief that there should be no significant barriers in using the developed framework in other sectors that also develop products or processes. In fact, considering the systematic, quantitative and rational focus of the framework, it is our ultimate goal that this global methodology can establish a basis to support many product design activities.

Finally, as academics, it is our duty to provide well-grounded theories to support knowledge, as well as to reduce the gap between theory and practice. In this sense, by developing an integrated and systematic platform, we intend to better understand how a more scientific and quantitative approach works in supporting the design process, as well as its impact on business competitive advantage. Thus, the main challenge of this research is to build a framework acting as a decision support tool aiming to help mould makers to achieve a faster and a more efficient design, by converting, in a consistent way, customer needs into optimal product solutions. Given the importance of the design process, we think that the thesis is important not only for the academic world but also for the mould makers industry.

1.4. Research phases and methods

For sake of clarity, and according to Krishnan and Ulrich (2001) [29], the design process must be broken down into four basic stages, namely, Product Definition; Concept Design or System-Level Design; Detail Design or Design Optimization; and, Design Validation. Therefore, different tools and methods addressing each one of these stages were outlined and their contributions clarified from a DFSS point of view. Conscious of product development critical role regarding product cost and performance, as well as time to market, a product development model based on DFSS with four design stages was adopted. These stages are respectively, Identify, Design, Optimize and Validate (IDOV).

To support the Identify stage, the European Customer Satisfaction Index (ECSI) methodology was adopted as a reliable and independent way of assessing customer satisfaction and its retention [30]. Hence, an ECSI model regarding system specificities was estimated through a component-based approach, based upon Partial Least Squares (PLS). Based on that model, it was possible to build one single objective function regarding customers' satisfaction levels, defined as a weighted function of specific customer attributes translated into functional requirements.

The Design stage was supported by AD methodology [7, 31, 32]. Thus, following AD guidelines, a few number of conceptual solutions must be generated by mapping the functional requirements previously identified in the Identify stage onto the corresponding design parameters. However, even these solutions must respect the first axiom of AD theory (i.e. must guarantee functional independence) but, if some remaining coupled relations subsist, at this stage they are not considered to be prohibitive. Afterwards, this conceptual design solution will be detailed and optimized in the Optimize stage. This stage is supported by MDO framework, which is considered an appropriate methodology to design complex systems through an exploitation of coupling phenomena [33, 34]. Thus, the best conceptual solution will be detailed and optimized through a platform, developed with the aim of maximizing customer satisfaction. To that end, a single objective function defined as a weighted function of specific customer attributes, previously determined in the Identify stage, was applied as an utility function.

Finally, in the Validate stage, the optimized designed entity must be validated, in order to evaluate if it responds adequately to customer's requirements and if it leads to reach higher levels of customer satisfaction. This task was achieved by comparing the behaviour of the design solutions generated by the developed platform with the data gathered for an existing mould solution and through specific Computer-Aided Engineering (CAE) simulation codes.

1.5. Structure of Thesis

This dissertation proceeds in five chapters. In Chapter 1 the outline and the motivation for the present work are detailed. In Chapter 2, a literature review of the most used process models to support product development phases is presented, aiming to identify the most appropriate methodologies to support injection mould design. A special focus has been given to the DFSS methodology, since it has been considered, by some authors [33-35] as a powerful approach to enhance the product development process through a data-driven basis. Chapter 2 highlights that research in injection mould design optimization is underway since, due to the high complexity and mould component interactions, current approaches do not allow to exploit the synergies of interacting phenomena neither to take quantitatively customer satisfaction degrees into account, to adequately explore the design space and, consequently, reach optimal mould designs.

Taking these two main objectives into consideration, Chapter 3 presents 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. This framework was established according to the IDOV roadmap, which establishes four stages for the design process: Identify, which aims to define customers' requirements/expectations; Design, where the creation of a product concept, and its system-level design, is performed; Optimize, in which all the detailed design, through product optimization, is handled; and finally, Validate, where all product design decisions are validated, in order to verify if the new designed entity indeed meets customer and other requirements. One first attempt of mould design optimization through the developed framework was carried out, only to highlight its potential application to achieve mould design improvements.

Nevertheless, since this first attempt adopted a simplified optimization model, a new and reinforced platform must be enhanced. This reinforced platform is described in Chapter 4. Models description and main results are presented for an existing mould, which was used as comparative baseline in order to evaluate the improvements that can be achieved. At the end of the chapter, insights are summarized.

Chapter 5 summarizes all the insights gained during this research and couples them with recommendations for practical action. Finally, the research contributions are reviewed, and the opportunities for further works are highlighted and some final conclusions are also drawn.

CHAPTER 2

Literature review

2.1. Introduction

Product Development (PD) is now assumed as the new frontier for achieving competitive advantage in today's rapidly changing business environments [1, 2, 35, 36]. This statement is based on previous works that showed that 80% of the total cost of product are determined at this stage, when only 5% of time and cost have been expended [37]. In fact, the greatest impact over total cost and quality of products made by early product design decisions is well-known [4, 5]. Thus, it is considered imperative to adopt well-designed and effective PD processes, allowing for faster and more integrated product design, in order to design enhanced products *prior* to their launch on the market [10, 11, 38].

For that purpose, several approaches have been proposed, mostly over the two last decades, aiming to support organization's strategies for innovation through well-designed and implemented PD processes [39, 40]. The majority of these proposals aim to make more visible and comprehensible the PD process by carrying out the activities in a systematic way, supported on a stricter theoretical background [8]. Therefore, the activities involved in product development process, which in general begin with the perception of a market opportunity and end in the sale and delivery of a product [41], are grouped into phases based on a well-defined structure and the interrelationships between activities. Some examples of

PD process structure proposals found in the literature are: Clark (1991)[42], Wheelright (1992)[43], Ulrich and Eppinger (1995)[44], Wallace and Clarkson (1999) [45] and Pugh (1991) [46], amongst others. According to Evbuomwan *et al.* (1996) [47] classification, these proposals follow a prescriptive model based on the design process (i.e. their models are based on the procedural steps of what can be regarded as design activities or as phases/stages of design). This is clear in Ulrich *et al.* (2003) [41] proposal, where they suggested a generic model of PD with five phases, namely, concept development, system-level design, detail design, test and refinement and production and ramp-up. Instead, Pugh (1991) [46] adopted a six central core of activities, starting with user needs identification on the market, product design specification, conceptual design of product, detail design, manufacture and sales.

Focusing in strictly product design stages (i.e. product definition, conceptual and detail design of product and its test and refinement), it can be observed that the PD process follows a sequential workflow with a complex set of coupled activities. Traditionally, these PD activities are performed recursively, with decisions mainly supported by intuition, know-how and the so-called handbook method. Consequently, the PD process is commonly characterized by failure-trial-fix loops and failure recovery actions, where the loss caused by selecting wrong design solutions is costly to recover [6, 48].

In order to overcome these limitations, some authors believe that these can be mitigated by a more systematic, integrative and quantitative approach to the design process [38, 49-51]. This approach is consistent with Brown and Eisenhardt (1995) [1] findings, pointing out a disciplined problem solving sequence, characterized by a high system focus, as a vital factor to achieve successful PD process. This is also aligned with System Engineering definition, which states that all PD process activities must be integrated into a multidisciplinary effort, forming a structured development process that proceeds from product concept to its operation (Definition of the International Council on Systems Engineering (INCOSE) [52]).

The advances on knowledge of design were undergone mostly by the mechanical engineering design research community. Its focus was on a better understanding of design, as well as on the development of better design tools [53]. As a result of their efforts to make design somehow more "scientific", some design methods emerged [54]. These design methods represent any procedures, techniques, aids or tools that the designer might use and combine into an overall design process.

This subject became an academic area of study known as *Design methodology*, which according to Dixon (1995) [55], is a prescription for a process intended to solve a specified design problem type, while a design method is a procedure for implementing a step in a methodology. Consequently, a special interest in design methodologies arose in the 1980s in Europe (especially in Germany), through a series of books on engineering design research (e.g. [46] and [56]) focusing on the knowledge of how to design products. It is important to insist that *Design methodology* is different from *Design* itself. *Design* is primarily concerned with the question of what to design to satisfy some specified need, while *Design methodology*, is primarily concerned with the question of how to design. In this sense, *Design methodologies* must be assumed as a vehicle for the evolution of the design activity from an art or skill to a science [57]. Therefore, design methodology can be described as a concrete course of action for the design, which includes plans of action to link working steps and design phases according to organisation strategies, rules and principles. The aim is to achieve general and specific goals and methods to solve individual design problems [9], i.e. a scheme for organizing reasoning steps and domain knowledge to construct a solution. Therefore, it must provide both a conceptual framework for organizing design knowledge and a strategy for applying that knowledge [58].

2.2. Design for Six Sigma (DFSS)

One of the more recently methodologies proposed to support PD is DFSS, which is considered by some authors as a powerful approach to maximize positive impact during the development stage of products [59-64]. DFSS has its origins in the Six Sigma methodology, concept developed by Motorola in the mid-1980s under the form of a technical document called "Six sigma mechanical design tolerance" [65]. Based on that, the Six Sigma methodology was pioneered with the objective of dropping quality costs, through process variability reduction [66]. Thus, Six Sigma employs a well-structured continuous improvement methodology, based on the application of statistical and problem-solving tools and techniques, in a methodical and systematic manner [67].

The Six Sigma project structure is based on a problem solving model designated by DMAIC (Define, Measure, Analyse, Improve and Control)[1]. Then, by adopting a project-by-

[1] In the Define phase, the problem is carefully defined and delimited. Facts and data are collected through measurement in the Measure phase, while root causes and suitable solutions are decided through analysis in the Analyze phase. Then, the chosen solution is implemented (Improve phase) regarding a better or optimized performance and followed-up in the Control phase, to secure that the resulting gains are sustained beyond the project completion.

project cycle, continuous improvement is achieved leading to higher impacts on bottom-line results[2] [68]. Technically, Six Sigma (6σ) means 3.4 Defects Per Million Opportunities (DPMO)[3], where sigma (σ) is a statistical term (standard deviation) which represents the variation about the average of any process. The value of 3.4 DPMO assumes that the process undergo to disturbances that can cause mean to shift by as much as 1.5σ and that the process variation is normally distributed.

DFSS can be seen as a subset of Six Sigma focusing on preventing problems, instead of just fixing them. While it shares many of the principles of Six Sigma, DFSS goes further upstream to recognize that decisions made during the design phase profoundly affect the quality and cost of all subsequent activities necessary to build and deliver the product. Several definitions of DFSS can be found in the existing literature. For instance, Feo and Bar-El (2002) [69] define DFFS as "an established, data-driven methodology based on analytical tools that provide users with the ability to prevent and predict defects in the design of a product, service or process". Mader (2002) [64] describes DFSS as "an enhancement to an existing new product development process that provides more structure and better way to manage the deliverables, resources and trade-offs", while Hasenkamp (2010) [8], assumed DFSS as a systematic application of design tools that are capable of bringing the performance up to six sigma levels.

In the last years, the DFSS approach has assumed more importance, comparatively with Six Sigma, because it has become consensual that product's performance and quality is highly determined by early design decisions [35]. Six Sigma solves the problems at the event level passively, while the role of DFSS is to build quality into the design, by implementing preventing thinking and tools in the PD process. In addition, examples of DFSS success that are pointed out by several companies, such as, General Electric [70], Dow Chemical [71], W.R. Grace [72], amongst others [73], are making DFSS a phenomenon widely accepted in industry [61].

Nevertheless, academic researches consider that DFSS lacks a theoretical underpinning and a basis for other type of research rather than "best practice" studies [74, 75]. This is coherent with Berryman's statement: "DFFS is not well-documented or understood" [76]. In fact, there are many books and articles on Six Sigma and DFSS written by practitioners and consultants and only a few academic articles published in scholarly journals [77]. Additionally,

[2] Note that each Six Sigma project is result oriented and often expressed in financial terms.
[3] A defect opportunity is a process failure that is critical to the customer.

the growing of Six Sigma and DFSS literature can be generally categorized as introductory, aimed at educating people about its elementary principles and selling it as a valuable PD process management philosophy.

Recently, some studies have been carried out in order to reduce the gap between the theory and practice of DFSS. By reviewing the existing literature, Hasenkamp (2010) [8] clarifies the contribution of DFSS to the different stages of a systematic engineering design process, while Chung *et al.* (2008) [78] studied the impact of DFSS activities implementation on business competitive advantages. Brady and Allen (2006) [79] proposed an agenda for future research.

Examples of research on the basic theory and techniques of DFSS are: He *et al.* (2010) [80] that studied the Critical-To-Quality (CTQs) decomposition in the context of product design; Raharjo *et al.* (2010) [81] that provided a quantitative approach which links Kano's model with Quality Function Deployment (QFD) in a dynamic way; Erlandson (2006) [82] that developed two candidate meta-models to enable prediction of automatic transmission torque output as a transfer function of customer-correlated engineering metric; and Gerhost *et al.* (2006) [83] that proposed a parametric model for exhaust manifolds through computational fluid dynamics and experimental design techniques.

In order to provide additional insights regarding DFSS implementation, Franza and Chakravorty (2007) [75] described an electric "tie-down" prototype design through DFSS, while Kalamdani and Khalaf (2006) [84] described DI FSS application to FORD manufacturing process, namely, assembly, heat treatment, grinding and casting. Al-Aomar (2006) [85] presented a simulation-based approach for applying a Lean DFSS methodology on a service system and Johnson *et al.* (2006) [86] provided a DFSS project to design a new dormitory at the University of Miami. These examples highlight the broad application of the DFSS methodology.

However, according to Berryman (2002) [76] and Yang and El-Haik (2003) [4] perceptions, most of the thinking about DFSS is driven toward different packaging of the Six Sigma methodology (i.e. DMAIC approach) plus "voice of the customer" tools. Thus, the majority of DFSS deployment examples are concentrated around phasing DMAIC methods in the development process boosted, commonly proposing high doses of tool complexity. Yet, most of recommended Six Sigma statistical tools are useless in the DFSS approach, mostly due to the unavailability of data in the early design phase. In fact, while in the early design phases the potential defects are more difficult to identify and measure, because they require predictive ability, later in manufacturing they are easily recognized but expensive to correct.

Some additional misconceptions regarding the DFSS methodology are summarized on Table 2.1.

Table 2.1: Common DFSS misconceptions [76].

DFSS misconceptions	Actual DFSS methodology
DFSS is a replacement for current design process.	DFSS is an enhancement to current design processes. It must be integrated with the existing design procedures and tools already implemented.
DFSS is just Six Sigma application to process design.	DFSS is a complex system engineering analysis methodology enhanced with mostly conceptual methods (instead of only statistical tools, due to the absence of data).
DFSS is a collection of tools.	Tools alone, without knowledge of application to specific engineering design opportunities, will not ensure DFSS success.
DFSS means extensive statistical analysis and modelling of all requirements.	Each engineering requirement must be dealt within its optimal scope. Some are statistically analysed and some are handled with traditional engineering methods.
DFSS allows too much design margin that will result in costly designs.	DFSS always balances cost, schedule and quality. Six Sigma margins are not always the optimal margins, sometimes less or more margin is best.
DFSS will increase development cycle times and result in missing market opportunities.	In the long run DFSS will reduce development cycle times through better product understanding. This is achieved by using modelling and simulation approaches in order to acquire knowledge in the early stages of product design.
DFSS applies only to specific engineering disciplines.	Since DFSS is not discipline specific, it applies to all engineering disciplines. DFSS states a multidisciplinary and a system level architectural view of product in order to attain an optimal system.
DFSS can be coordinated out of the quality organization.	DFSS must be owned by the company, with strong expectations of application by company management and engineering leadership. This is justified by the necessary integration of current process design.
DFSS is applied on CTQs by a CTQ basis.	DFSS is a systems engineering methodology that optimizes all CTQs for best system performance. A basic principle of DFSS is a strong customer linkage to product requirements.

DFSS follows a project structure similar to the Six Sigma approach. However, contrarily to the DMAIC approach in Six Sigma, DFSS roadmap is not universally recognized or defined. In fact, in the last years, several proposals have been recommended, such as the DMADV - Define, Measure, Analyse, Design and Verify ([87] and [88]), the CDOV - Concept, Design, Optimize and Verify [89], and the ICOV - Identify, Characterize, Optimize and Verify [4], the I^2DOV – Invent, Innovate, Develop, Optimize and Verify [89] and the DMADOV - Define, Measure, Analyse, Design, Optimize and Verify [90], amongst others less known. One popular roadmap recommended by the American Society for Quality (ASQ) [90] is DMADV[4], which retains the same number of phases and a similar framework to DMAIC applied in Six Sigma.

[4] The DMADV methodology steps are: Define (D) – define the goals of the project along with internal/external customer demands; Measure (M) – Measure and determine Customer Needs (CNs) and specifications requirements; Analyse (A) – Analyse the options for the process of meeting CNs; Design (D) – Design the details needed to meet the CNs; Verify (V) – Verify design performance and its ability to meet the CNs.

Although each proposal differs in the name of each phase and in the number of phases (and, of course, in the acronym), the approaches are based on the same principles [89]:

– Identify or define customer requirements, in which the definition of the customer can include internal and external customers and other stakeholders;
– Design or develop design concepts that are stable and capable of fulfilling customer's requirements;
– Optimize design performance so that measured performance is robust in the presence of real sources of variation;
– Verify or validate the conceived design in order to ensure that it meets the set of requirements.

Based on that, it is possible to observe that the DFSS principles are clearly connected with the different stages of a systematic engineering design process (i.e. product definition, conceptual and detail design of product and its test and refinement). Then, an important issue regarding these phases is which methods or techniques are recommended to use in each one. For that purpose, DFSS offers an advanced toolbox containing a large collection of well-tried best practice tools and techniques from different areas. Nevertheless, the huge amount of DFSS tools makes it harder to find which tool or technique is optimal to use [40].

In fact, detailed discussions on which DFSS tools should be used, and when, are scarcely available [79]. Spite of that, it is assumed that the power lies in the organization in order to apply the tools in a coherent strategy, which allows for a much higher rate of success when compared to traditional design approaches [91]. Thus, assuming that each PD stage is supported by a DFSS principle, then, four basic stages (i.e. Product Definition; Concept Design or System-Level Design; Detail Design or Design Optimization; and, Design Validation) must be considered, and different tools addressing each one of these stages must be outlined and their contributions clarified from a DFSS point of view.

2.2.1. Product definition

Bearing in mind that product design must be strongly linked to what satisfies the customer (see Gruner and Homburg (2000) [92], who verified that customer interaction has a positive impact on new product success), DFSS provides a customer oriented perspective. Obviously, it is assumed that without a strong definition of the product requirements, product development becomes risky and it is typically characterized by evolving and changing requirements making the design of product more difficult [76]. Because of that, most experts agree [93, 94] that the most common causes of project failure are the lack of full understanding of customer requirements. In fact, customers tend to give imprecise and ambiguous information about their needs, because they lack experience in identifying and expressing their desires. As a result, they state these desires in terms that could be misunderstood by the design team.

Secondly, since customers are not often aware of the underlying coupling and interrelationships amongst various requirements regarding product performance, the interrelationships between their needs and product requirements are often not available. Thirdly, the customer has only a superficial understanding of many of the functions that the product may support: frequently, product life-cycle, manufacturability, reliability and maintainability are out of his concerns. Fourthly, and the last reason for lack of understanding, is the absence of a defined structure requirement information, which promotes an implicit inference [95].

Accordingly, in order to design or redesign a product, firstly it is necessary to accurately capture Customer Attributes (CAs). After that, these needs must be translated into specific product requirements: the Functional Requirements (FRs). This approach is consistent with AD theory [7], which states that the world of design is made up of four domains: the customer domain, the functional domain, the physical domain and the process domain. Thus, after determining CAs accurately, it is necessary to translate these CAs into specific requirements, the FRs, which are formalized in the functional domain [96].

AD methodology does not comprise special references to on how this task should be carried out. Therefore, different approaches have been proposed aiming to establish the link between customer and functional domain. In general, these approaches are conducted by market research and involve different ways to capture, analyse, understand and anticipate customer requirements, i.e. the Voice of Customer (VoC)[5]. Notice that one of the most widely accepted tool in DFSS for linking customer requirements to detailed technical system is QFD[6] [81, 97]. Nevertheless, according to He *et al.* (2010) [80], some issues have not been adequately addressed by this DFSS approach, including product design quality and its implications in design, as well as the use of historical data to realize quality improvement in design.

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[5] VoC is a disciplined, cyclical approach to obtaining, understanding, and prioritizing customer wants and needs.

[6] For a more complete description of the QFD approach see ReVelle, J.B., J.W. Moran, and C.A. Cox, The QFD Handbook. Vol. 1. 1998: Jonh Wiley &Sons.

Regarding the ability to capture customer's requirements, there are two common ways to gather them: through indirect information (collected from consumer labs, trade journals, competitive benchmarking and forecasts, etc.), and through direct customer engagement (obtained from interviews, focus groups, customer councils, field observations, etc.). About direct customer information gathering techniques, and according to Griffin *et al.* (1993) [98], the one-on-one interviews are more costly effective than focus group. Further, Mazur (1993) [99, 100] suggested the Gemba[7] method, because it is not necessary to rely on customer's memories to report problems and needs, neither to remove these inquiries to an artificial site. Nevertheless, considering the actual context of rapidly changing environment, due to the influx of new technology and innovation, some additional considerations must be taken into account, such as the absence of dynamics overlook in these customer's needs auscultation methods. In fact, it is well-known that customers of tomorrow will have needs and expectations different from those of today. Therefore, it is important to develop frameworks that allow keeping up, in a systematic way, the customer satisfaction level and its drivers.

Currently, a reliable and independent way of assessing customer satisfaction is the ECSI model [101]. This model is a framework adapted from the Swedish Customer Satisfaction Barometer and the American Customer Satisfaction Index [102], which aims to harmonise the Customer Satisfaction Indexes (CSI) in Europe [103]. This model, which is supported in SEM theory, aims to measure and explain customer satisfaction and customer loyalty as latent constructs, according to well-established customer behaviour theories.

SEM has become a very popular data-analytic technique [104], which is particularly well suited to research needs [30], in order to quantify and test theoretical models [105]. These techniques are based upon sets of linear equations used to specify phenomena in terms of their presumed cause-and-effect variables [106], where these hypothesised relationships are translated into mathematical models that are tested against empirical data. In general, these models are established for variables, latent variables or constructs, which cannot be measured directly and, thus, must be inferred through observing or measuring specific features that operationally define them, the manifest variables or indicators. It is important to highlight that customer satisfaction is a typical example of a latent variable.

[7] This method encompasses, after introducing the observer, a customer walk through his business process and observe him at work (or daily life for the product) dealing with his problems or his customer's problems.

Given the ECSI model accepted by Portugal, a structural model with seven latent variables is adopted, linking customer satisfaction to its main drivers (namely, Company Image, Customer Expectations, Perceived Quality and Perceived Value) and its main consequences (Loyalty and Complaints) in terms of casual relationships [107]. Through empirical data it is possible to test the model and to determine the impact of each model latent variable on customer satisfaction (i.e. the main drivers of customer satisfaction). Therefore, in order to achieve high levels of customer satisfaction, the Critical-to-Quality requirements (i.e. CTQs) must be identified, especially regarding perceived quality of products and services.

Nevertheless, according to Pugh (1991) [46], the work of gathering customer needs is hardly worthwhile unless they are properly translated into product functional characteristics (i.e. FRs). In fact, deriving FRs is assumed as a crucial part of any PD process, because they constitute the objectives and boundaries for all subsequent design phases.

To support this critical task, an evolution model and decomposition method of CTQs requirements for products must be established [80]. Therefore, according to Hitchins (2007) [108], after all CTQs are clearly identified within a system engineering perspective, a system oriented DFSS process must also include requirements traceability and modelling ability to flow down, optimize and development internal subsystem and, eventually, component level requirements. This CTQ flow-down tree, combined with the system architecture, is also promoted by AD theory, which states that the design process must progress from a system level down to a more detailed level (i.e. until the design is completely parametrically described), in a top-down hierarchical manner called the zigzagging approach [7, 48].

Finally, a prioritisation must be achieved through decision-maker judgements about the dominance of each FR over other FR, to determine the relative priority of all decomposed FR according to its importance to customers. Then, a measurement of every FR importance must be identified as a way to determine an utility function. The best design is the one that maximizes this utility function.

Assuming that FRs are utility independent, product utility function can be constructed as the weighted sum of FRs. There are alternatives by which the weights are applied to the respective importance levels of each FR. A possible approach to determine these weights can be the Analytical Hierarchical Process (AHP)[109], through pairwise comparison [110]. This technique is widely used for addressing multi-criteria decision-making problems, since it assures the consistency and stability of the subsequent decisions [111] and it is considered the most accurate way for humans to perfectly compare many criteria, two at a time [112].

2.2.2. Concept Design or System-Level Design

According to Ulrich and Eppinger (1995) [44], the Concept design stage must be divided into two consecutive parts: Concept Generation and Concept Screening. At the Concept Generation stage the objective is to generate as many as possible product concepts involving different design solutions. All solutions will be then evaluated and screened at the Concept Screening stage. The product concepts must be conceptually defined (i.e. high level system definition), which means that a roughly product design must be achieved through some technical decisions.

The DFSS mechanism for developing system level requirements consists of linking the previous identified FRs with Design Parameters (DPs) through engineering models, sometimes called transfer functions. The way these models are created, analysed and optimized is an important part of the DFSS methodology. In this sense, Suh (1990) [7] defines *Design* as "the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs in the functional domain and the DPs of the physical domain, through the proper selection of DPs that satisfy FRs". This is true for all designs. Therefore, after customer attributes identification and its translation to specific requirements (i.e. the FRs), a physical embodiment, characterized in terms of DPs, must be created with the objective of satisfying the FRs and Constraints.

For that end, basic physical configurations of the product must be achieved, where a useful representation can be made by a vector of specific functional requirements (e.g. reliability, price, cycle time, etc.) linked with customer satisfaction levels. Then, the design process must progress conceiving different physical embodiments, through mapping previously identified FRs into the corresponding DPs. This process evolves from a system level down to a more detailed level, i.e., the output of each domain progresses from the abstract concepts to the detailed information, in a top-down hierarchical manner (Figure 2.1).

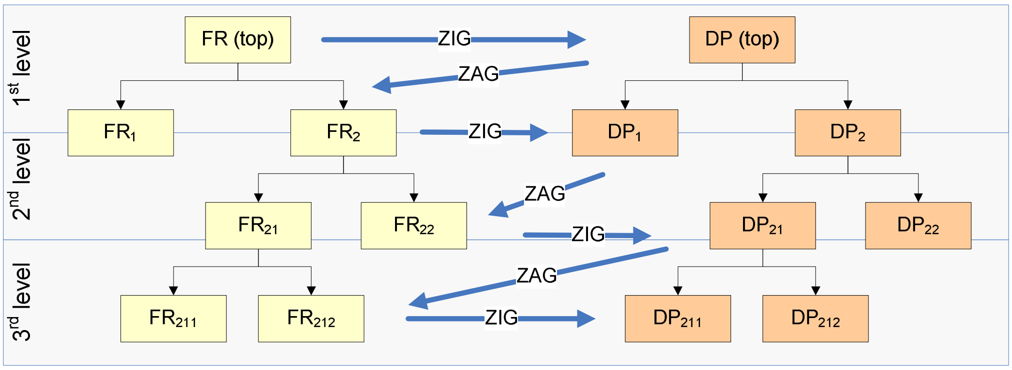


***Figure 2.1:** Top-down hierarchical design following a zigzagging approach.*

This process may be represented in terms of a design hierarchy and these hierarchies exist for both the functional and the physical domains. Thus, the decisions made at higher levels affect the statement of the problem at lower levels, such that the hierarchical decomposition in one domain cannot be performed independently of the evolving hierarchies in the other domain. This decomposition is considered helpful to facilitate the physical structure generation [4], as well as to lead to an in-depth analysis for the potential system interactions (coupling) [113].

As a result, several architectural concepts can be developed to fulfil the previously identified FRs. In theory, for any given set of requirements, the number of plausible solutions, is unlimited, depending only upon designers. With the final goal of determining the best design solution, a basic postulate of the AD approach is that there are two fundamental axioms that must govern the design process. These two axioms were identified by Suh (1990) [7], by examining the common elements that are always present in good designs. Axiom 1, the Independence Axiom, states that the independence of FRs must always be maintained, and Axiom 2, the Information Axiom, stating that the best design amongst designed solutions that satisfy the independence axiom is the one that has the smallest information content.

Based on that, there are three types of design solutions, namely: uncoupled, decoupled and coupled [114]. The uncoupled design is the preferred one because it guarantees axiom 1. Decoupled design is normally the second choice, because the FRs can be answered systematically, from FR_1 to FR_n, by only considering the first *n* DPs. Finally, the coupled design is undesirable because in this design solution a change in a DP may influence all FRs simultaneously.

Although coupled design is not promoted by AD because it does not guarantee the first axiom, some authors (e.g. [115, 116]) believe that there are some cases where uncoupled/decoupled solutions may not be viable, especially when performance, efficiency and packaging constraints dominate the PD. Therefore, according to these authors, if some remaining coupled relations subsist, they can be considered at this stage.

Afterwards, all generated concepts must be evaluated in a screening process for which a large number of methods can be used. Inherent to the majority of the existing methods is the notion that customers should play a significant role in design selection [117]. For example, customer's preferences determined through customer's survey is adopted by QFD [97], while the Pugh method establishes a matrix format to subjectively compare each concept against the important technical criteria and customer concerns from a total perspective [46]. The Pugh's method is the most used technique for concept selection in DFSS methodology, mostly due to its simplicity [4]. Nevertheless, once Pugh method can lead to an optimum product that is not necessarily the product comprised of the optimal attributes (when each one is taken separately), other methods must be studied.

In this sense, and according to Hazelrigg (2003) [117], the choice screening must be supported on a set of properties that the selection process must have, namely, be self-consistent and logical (i.e. it should not contradict itself), and should make maximum use of the available information in order to allow for a rank ordering of candidate designs. However, none of the existing screening methods have all the desired properties. Still, certain methods might show advantages under specific circumstances.

Decision theory and optimization are closely linked in this kind of decision making, where all decisions involve some amount of optimization. The idea is that the optimal choice is the alternative whose outcome is the most preferred. However, because optimization tries to find the optimal combination of the decision factors, it usually requires a large number of potentially expensive simulations. Unfortunately, the recent advances in computational hardware and algorithm have not resolved completely this issue. For that reason, according to several authors, the enormous computational costs of complex engineering simulation makes impractical to rely exclusively on simulation for the purpose of design optimization [118, 119]. Moreover, this mode may never uncover the relationship between factors and outputs responses, and therefore may never allow for the identification of the best setting of input values [119].

This is particularly important at the conceptual Design stage, where simulation-based analysis tools are used during preliminary design in order to explore design alternatives. However, the enormous computational cost of running complex high-fidelity engineering simulations calculations makes impractical to exclusively use simulation codes for the purpose of design optimization [120, 121]. Consequently, approximation methods such as Design of Experiments (DoE) and Response Surface Models (RSM) are commonly used in engineering design to minimize the computational expense of running such analyses and simulations.

DoE has been considered as one of the most powerful statistical tools developed in the 20^{th} century [122], because it establishes an efficient procedure for planning experiments, in a way that the data obtained can be analysed to yield valid and objective conclusions about the factors interaction. Over the time, experiments have been used to study the effects of factors as they are set at various levels. Thus, in an experiment, one or more process variables (or factors) are deliberately changed in order to observe the effect of these changes into one or more response variables. Then, through a strong statistical basis, DoE fits the response data to mathematical equations. Collectively, these equations serve as models to predict what will happen for any given combination of values. With these models, it is possible to optimize critical responses and find the best combination of factors levels. Taking into account that, screening is related to “sparse” effects, the “parsimony” or Pareto principle (i.e. 20-80 rule), DoE can be used for screening experiments allowing to identify critical factors and to reduce the problem dimension.

At the same time, aiming to reduce computational cost, surrogate models, also known as meta-models[8], are often used in place of high-fidelity simulation models. The basic approach is to construct a simplified mathematical approximation of the computationally expensive simulation and analysis code, which is then used in place of the original code to facilitate the exploitation of the design space [123]. A variety of approximation models exist (e.g. polynomial response surfaces, kriging models, radial basis functions, neural networks, multivariate adaptive regression splines). The common idea is to identify the locations in the design space that are most promising to conduct simulations. To gain a better understanding of how approximation methods are currently viewed and being used by industry and government agencies, a panel discussion on Approximation Methods was held at the 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis & Optimization (1998) [124]. More recent reviews and comparisons of many of these approximation models can be found in Barton (1998) [125], Jin *et al.* (2001) [118] and Simpson *et al*. (2001) [119].

[8] Since the approximation model acts as a surrogate for the original code (i.e., a “model of a model”), it is often referred to as a surrogate model, approximation model or meta-model.

The existing approaches, which use response surfaces for global optimization, can be classified according to the type of response surface and the method used to select search points. The type of response surface is either non-interpolating (i.e. minimizes sum of squared errors from some predetermined functional form) or interpolating (passes through all points) [126]. Considering the characteristics of a mould design problem, particularly regarding the type of design variables, the non-interpolating surfaces may not sufficiently capture the shape of the function, as well as can include not feasible solutions. Therefore, interpolating surfaces are recommended. It is important to note that in this approach the data is interpolated with a linear combination of basic functions, where the basic functions can be fixed (e.g. thin-plate splines, hardy multiquadrics, etc.) and can have parameters that are tuned (e.g. kriging) [127].

Regarding the search point methods, two different types can be adopted: a two-stage approach or a one-stage approach. In the two-stage approach, firstly a response surface is fitted and its parameters are estimated. Then, at the second stage, the parameters are used to compute new search points. In the one-stage approach, the initial step of fitting a surface to the observed data is skipped and the response surface is used instead to evaluate hypotheses about the location of the optimum. For example, the hypothesis that the optimum occurs at a point $\mathbf{x}^*$ with function value $f^*(\mathbf{x})$ may be determined by examining the properties of the best-fitting response surface that passes through the observed data and the point $\left(\mathbf{x}^*, f^*(\mathbf{x})\right)$. Thus, in this approach the credibility of the hypothesis is based not only on parameters obtained by fitting a surface to the observed data [126].

Traditionally, the construction of response surfaces (or model-building) relies on the theory of experiments [128], where a typical application begins with the postulation of the approximate model function. By running the simulations at the set of points (experimental designs) and fitting response surfaces to the resulting input-output data, one obtains fast surrogates for the objective and constraint functions, which can be used for optimization. In addition, and because this approach starts with an experimental design, statistical analyses can be performed in order to identify the most important design variables (i.e. variables that contribute the most for the variance of responses). Finally, it is also possible to use the surfaces as fast surrogates to quickly compute trade-off curves between competing objectives. Nevertheless, the injection moulding phenomena are modelled by simulation codes, where several computer experiments are obtained by running the code for different values of design variables. Thus, the gathered output is deterministic (i.e. rerunning the code with same inputs will give identical observations), which differs substantially from the physical experiments. According to Sacks *et al.* (1989) [129], the classical notions of experimental blocking, replication and randomization are irrelevant when it comes to deterministic computer experiments.

The typical procedure of meta-modelling (or replacement of actual computer analysis by statistical approximations designed by meta-models) involves, firstly, the selection of an experimental design for generating data, then, choosing a model to represent the data and, in the last step, fitting the model to the observed data. Due to RSM maturity, simplicity and readily accessible software tools, most meta-modelling applications are built around creating low order polynomials using central composite designs and least squares regression. However, according to Simpson *et al.* (2001) [118], its application in deterministic applications can cause problems.

In this sense, the introduction of a suitable approximation of the objective function and constraints in a certain part of design space, and afterwards, determining the optimum solutions for this approximate problem, can be a good alternative [128]. This approach is a popular way within the engineering community of developing fast surrogates to overcome time-consuming computer simulations [127]. It is also adopted to compute unknown "transfer functions" between design variables or design parameters and functional requirements, to be used directly in the optimization procedure. Several experimental design types can be used. The most common are Full or Reduced factorial, Central Composite design, Box-Benhken, Latin Square and Plackett Burman [130].

2.2.3. Detailed design or design optimization

As mentioned before, the process design starts with an idea that can answer to customers' needs, which takes successively firmer shapes and finishes with a set of manufacturing instructions and necessary documentation. This evolution is depicted as phases from conceptual to a detailed design. The majority of engineering systems design involves a large number of design decisions. All of these decisions are restrained by several constraints regarding different areas, such as technological, legal, economic, amongst other, as well as dependent of the assessment of customer requirements.

After an initial conceptual solution is achieved through high level design decisions, subsequent decisions must be undertaken regarding the definitions of the detailed design into its several subsystems and components. This task is sometimes designated as *Embodiment design*, where "Embodiment design is the part of design process in which, starting from the principle solution or concept of a technical product, the design is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production" ([9] page 227).

This task is considered particularly complex because it involves a higher level of information regarding different areas of knowledge where any change in one area has repercussions in the remaining areas. It is also common that this stage of design process includes corrective cycles in which analysis, synthesis, simulation and evaluation constantly alternate and complement each other [131].

Considering the diversity of areas of knowledge (sometimes known as disciplines) that are involved in this stage, which have different requirements and constraints to satisfy, as well as different objectives (often contradictory), the need for an integrative approach is been increasingly recognized [36]. In fact, this integrative approach, entitled multidisciplinary design, has a set of characteristics that can contribute for producing better designs.

The first characteristic is the inclusion of different points-of-view regarding multiple disciplines. These disciplines conceptualize distinct knowledge about classic areas of engineering, such as mechanics, kinematic, aerodynamics, control, amongst others. However, as a result of a highly focused expertise in each field, each area developed its own terminology and methods, and tends to define goals that are often in conflict with the global design goals. Secondly, considering the iterative nature of design, it is costly and time consuming to repeat disciplinary designs. As a consequence, an integrated design methodology, through multidisciplinary approach, allows combining a broad range of expertise needs.

Another important characteristic is related with the complex interactions between the different disciplines involved in product design, which means that multiple disciplines might be interested in one parameter at the same time. Therefore, the integration in multidisciplinary design makes possible for different disciplines to participate simultaneously in the process of assigning values to these shared parameters. As a result, any possible conflict on the assigned value is discovered and solved immediately. Furthermore, with simultaneous participation of disciplines, there will not be any “lead discipline” dominating the design process [57]. Of course, this cannot be done based on intuitive approaches, and comprehensive studies are required in order to develop solutions for problem integration. It is also important to highlight that, given the detailed design scope, this stage usually represents the major portion of the product design lead time and cost.

Since MDO allows better exploitation and resolution of the system’s trade-offs, its application in the detailed design stage is considered beneficial [3]. In fact, it is recognized that while conceiving different design concepts, its detailed analysis and optimization must be supported by quantitative mathematical models, of course using computers as indispensable tools.

A large amount of research focused on MDO has been developed in the last years [33], with its kicking mark on the first Multidisciplinary Analysis and Optimization symposium, that was held in April

1984 at NASA Langley Research Center [3]. After that, MDO has been assumed as a new discipline that exploits the synergism of the interdisciplinary couplings, through the combination between analyses and optimizations in the individual disciplines with those of the entire system [132]. Thus, MDO involves the systematic approach to optimization of complex coupled engineering systems, supported in a mathematically-based manner, where "multidisciplinary" refers to the different aspects that must be included in a design problem [133]. Since this mathematical model cannot be available until the conceptual design is completed, MDO can be only undertaken at the detailed design stage. Its goal is to decide values of DPs while satisfying and/or optimizing some desired performance characteristics [29]. Thus, MDO of engineering design problems can be viewed as a search of a multidimensional space of possible designs, where each point in this multi-dimensional space is a possible design that satisfies the constraints. The dimensions of such space are the parameters that describe the product.

Based on that, it is possible to state that MDO's goal is to find the optimal design of engineering systems through analysis that accounts for interactions amongst the disciplines (or parts of the system). This procedure enables designers to make decisions on a rational basis that gives equal consideration to all the influences that different disciplines exert on the system, directly or indirectly, through their complex interactions. Based on that, "the MDO enhanced design process has the clear potential for radically improved product quality achieved by systematic exploration of the alternatives created by human creativity and bringing each of these alternatives to the optimal state among which a fair choice can be made by engineer's judgement" [132].

For that purpose, MDO provides a body of methods and techniques to assist designers in moving engineering system design closer to an optimum level. In this sense, several approaches for solving MDO problems have been proposed, which considers different ways of dealing with the objectives and the physical constraints that engineering problems are faced with [133]. These techniques encompass two major elements: Formulation, which aims to express the problem as a set of mathematical statements; and Algorithm, which involves the definition of a procedure for solving the problem.

MDO Formulations

In general, an optimization problem consists of one objective function (or more), constraints, parameters and design variables. The objective function is the goal of the optimization, for example, to minimize the cycle time of an injection moulding process. The objective function $f(\mathbf{x})$ can be considered as a vector **J** of $f_k(\mathbf{x})$, *k* being the number of *s*ystem responses or characteristics that one wants to maximize or minimize. The design space is characterized by a design vector $\mathbf{x}$, which contains *n* variables. During design space exploration or optimization the entries of $\mathbf{x}$ can be changed.

Parameters p_s are quantities that affect the objective, **J**, but are considered fixed (i.e. cannot be changed by the designers). Constraints act as boundaries of the design space $\mathbf{x}$, imposed, usually, by technological or market limitations. There are four different types of constraints: equality constraints ($h_i(\mathbf{x}) = 0$), inequality constraints $\left(g_j(\mathbf{x}) \leq 0\right)$, and side constraints $\left(\boldsymbol{x}_q^{lower} \leq \boldsymbol{x}_q \leq \boldsymbol{x}_q^{upper}\right)$. Therefore, the standard optimization problem can be summarized in the following equations:

$$
\begin{aligned}
&\text{Minimize } f(\mathbf{x}) = f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_k(\mathbf{x}) \\
&\text{subject to} \\
&h_i(\mathbf{x}) = 0, \qquad i = 1 \text{ to } p \\
&g_j(\mathbf{x}) \leq 0, \qquad j = 1 \text{ to } r \\
&\boldsymbol{x}_q^{lower} \leq \boldsymbol{x}_q \leq \boldsymbol{x}_q^{upper} \text{with } q = 1 \text{ to } n \\
&\text{with}
\end{aligned}
\qquad \textit{Eq. 1}
$$

$\mathbf{x} = [x_1, x_2, \dots, x_n \quad , \quad p_1, p_2, \dots, p_s]$ Design vector

With $x_1, x_2, \dots, x_n$ design variables and $p_1, p_2, \dots, p_s$ design parameters

$\mathbf{J} = [J_1, J_2, \dots, J_k]$ Solution vector

With $J_1, J_2, \dots, J_k = f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_k(\mathbf{x})$

Algorithms: Solving MDO problems

Regarding real world engineering design problems, usually, they are characterized by the presence of many conflicting objectives [134]. Therefore, it is natural to look at the engineering design problem as a multi-criteria or multi-objective optimization problem, which can be mathematically expressed as in Eq. 1 or in simplified form as:

$$
Minimize\ \boldsymbol{F}(\mathbf{x}) = \begin{bmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \\ \vdots \\ f_k(\mathbf{x}) \end{bmatrix} \qquad \textit{Eq. 2}
$$

$$subject\ to\ \mathbf{x} \in S$$

$$\mathbf{x} = (x_1, x_2, \dots, x_n)^{\mathrm{T}}$$

Where $f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_k(\mathbf{x})$ are the k objectives functions, $(x_1, x_2, \dots, x_n)$ are the *n* optimization variables and $S \in R^n$ is the solution or variable space. Obtainable objective vectors, $\{\mathbf{F}(\mathbf{x}) | x \in S\}$ are denoted by **J**, so $\mathbf{F}$: S ⟼ **J**, S is mapped by ***F*** onto **J**. For a general engineering design problem, **F** is non-linear and multi-modal, and *S* might be defined by non-linear constraints containing both continuous and discrete member variables.

Given that the objective functions are in conflict over the design space, where $f_1^*,\ f_2^*, \dots, f_k^*$, denote the individual minimum of each objective function, then it is impossible to find a point at which they would assume their minimum values simultaneously and, consequently, the classical concept of a common optimal solution does not apply. Instead, this multi-objective optimization problem tends to be characterized by a family of alternatives, which must be considered equivalent in the absence of information concerning the relevance of each objective relative to the others. In this situation, the concept of Pareto solutions is applied, where the Pareto set consists of solutions that are not dominated by any other solutions (i.e. a solution $\mathbf{x}$ is said to dominate $\mathbf{x}'$ if $\mathbf{x}$ is better or equal to $\mathbf{x}'$ in all attributes, and strictly better in at least one attribute). Thus, considering a minimization problem and two solution vectors $\mathbf{x}$, $\mathbf{x}' \in S$, $\mathbf{x}$ is said to dominate $\mathbf{x}'$, denoted by $\mathbf{x} \succ \mathbf{x}'$, if:

$$\forall i \in \{1,2,\dots,m\}: f_i(\mathbf{x}) \leq f_i(\mathbf{x}')\ and\ \exists j \in \{1,2,\dots,m\}: f_j(\mathbf{x}) < f_j(\mathbf{x}') \quad \textit{Eq. 3}$$

The space in R^m formed by the objective vectors of Pareto optimal solutions is known as the Pareto optimal frontier, $\mathcal{P}$. Pareto optimal solutions are also known as non-dominated or efficient solutions. Minimizing each objective function individually over the design space one obtains $\mathbf{F}^* = (f_1^*, f_2^*, \dots, f_k^*)^{\mathrm{T}}$, which yields an utopia (ideal) solution. Due to the conflict between the objective functions, the utopia point is never in **J**.

Based on that, there is general consensus that multi-objective optimization methods can be broadly decomposed into two categories: scalarization approaches and Pareto approaches [34]. The scalarization approach is based on a preliminary identification of the relative importance of each objective function, in order to build an aggregate objective function which contains contributions from each objective in vector **J**. The Pareto methods, on the other hand, do not needs to know previously the preferences regarding each objective, since they use the concept of dominance to distinguish between inferior and non-inferior (i.e. non-dominated) solutions. In this sense, a set of non-dominated points keeps the elements of the objective vector **J** separate throughout the optimization process.

Nevertheless, the most common approach to deal with multi-objective optimization problems has been through scalarization methods, where an aggregate objective function is formed through contributions of each objective function, and, then it is used to find the optimum [34]. This procedure is only possible when the decision-maker preferences are previously known, allowing to combine all objectives in an utility function, *U*. This function expresses the goodness of a particular design solution in a dimensionless scalar quantity.

The most widely used scalarization method is the Weighted Sum (WS) approach, where the aggregate objective *U* always forms a strictly convex combination of objectives by ensuring that all weights, w_i, add to unity and are themselves positive scalars. Based on that, the set of optimal solutions is obtained by changing gradually the weight from one objective to another. Nevertheless, many interesting points are missed and the resulting optima are unevenly distributed [135].

According to Andersson (2000) [134], the multi-objective optimization problem can be handled in four different ways, depending on when the Decision-Maker (DM) articulates his preference on the different objectives. Based on that, the first way has *No articulation of preference information*; the second way includes *Priori aggregation of preference information*, the third way involves a *Progressive articulation of preference information* and, finally, the last way encompasses the *Posterior articulation of preference information*. Regarding the first type*, No preference articulation*, which does not use any preference information, an example of this kind of approach is the *Min-Max* formulation and the global criterion method that is based on the minimization of the relative distance from a candidate solution to the utopian solution $\mathbf{F}^*$. It is important to note that in this approach, the output is just one point on the Pareto front, which the DM has to accept as the final solution. Different points on the Pareto front could be found only by changing the way of calculating the distance.

The second type and the most common way of conducting multi-objective optimization is by *Priori articulation of the DM preferences*. The most frequent way to aggregate the different objectives is through a single figure of merit, by using a WS approach. This method performs the minimization of a linear combination of the objective functions for finding Pareto solutions. The corresponding WS problem is:

$$Minimize \sum_{i=1}^{m} w_i\, f_i(\mathbf{x}) \qquad \textit{Eq. 4}$$

$$subject\ to\ \mathbf{x} \in S$$

Where $w_i \geq 0, \mathrm{i} = 1, \ldots, \mathrm{s}$, and $\sum_{\mathrm{i}=1}^{\mathrm{s}} w_i = 1$. Scalars w_i are referred to as the weights assigned to the objective f_i, $i = 1, .., k$, and determine the importance of each objective. By choosing different weightings, w_i for the different objectives, the preference of DM is accounted for. Others examples of *priori* articulation of preference information methods are non-linear combination, utility theory, fuzzy logic, goal programming, amongst others (a brief description of these approaches can be found in [134]).

Based on that, and by *Priori articulation* of the DM preferences, an objective function must be formulated yielding a scalar value that expresses the value of a candidate solution. It is important to highlight that the results of solving an optimization model using Eq. 4 can vary significantly as the weighting coefficients change. Although the WS approach is the most used method, very little information is known about how to determine these coefficients. In fact, the main weakness of the WS approach is related with the difficulty in determining the appropriate weights [136].

Additionally, there are other drawbacks regarding the WS method in multi-criteria optimization. These drawbacks encompasses the minimization of the weighted non-convex combinations [137, 138] (i.e. if the Pareto curve is non-convex, there does not exist any **w** for which the solution of the problem lies in the non-convex part) and, even if the Pareto curve is convex, an even spread of points on the Pareto curve is not produced though a spread of weights **w** is used. To overcome these limitations some alternatives approach have been proposed (e.g. Adaptive Weighted Sum [135]).

Regarding the *Progressive articulation of preference information* methods, which are also referred to as interactive methods, they rely on progressive information about the DM preferences simultaneously with the search through the solution space. These methods are very common within the field of operations research [134]. Nevertheless, this approach requires a high effort from the DM during the whole search process and is highly dependent on how well the DM can articulate his preferences. Furthermore, since these methods are built on linearity and differentiability assumptions of the objective and constraint functions, they are unsuitable for the majority of engineering design problems.

Finally, the *Posteriori articulation of preference information* techniques enable performing an initial search on the solution space for a set of Pareto optimal solutions and, subsequent presentation to the DM. The major advantage of this method is that the solution is independent of the DM preferences. Therefore, the analysis has only to be performed once, as the Pareto set would not change as long as the problem description is unchanged. However, a large computational effort and many solutions to choose are appointed as limitations regarding this approach. Moreover, if the optimal solution cannot be accepted, because the function used excludes aspects of the problem which were unknown prior to optimization, new runs of the optimizer may be required until a suitable solution is found.

Among the Pareto approaches, two in particular have gained increased acceptance in recent years: Normal Boundary Intersection (NBI) and Evolutionary Algorithms (EAs). While NBI [139] relies on equality constraints normal to a line connecting the anchor points in the objective space, EAs evolve populations of designs gradually so that they approximate a Pareto frontier as closely as possible. Therefore, multiple individuals can search for multiple solutions in parallel, eventually taking advantage of any similarities available in the family of possible solutions to the problem [140]. As a result, EAs have been recognized to be possible well-suited to multi-objective optimization since early in their development.

The most popular type of EAs methods is a Genetic Algorithm (GA), which is based on mechanics of natural selection. In GA, each optimization parameter (y_n) is coded into a gene where all corresponding genes for all parameters, $y_1,..,y_n$, form a chromosome describing an individual. Thus, each individual represents a possible solution and a set of individuals form a population. In a population, the fittest are selected for mating. Mating is performed by combining genes from different parents to produce a child, in an operation called crossover. Finally the children are inserted into the population and the procedure starts over again. The optimization continues until the population has converged or the maximum number of generations has been reached. Despite the fact that there is not an optimization method that is the best for any given problem, GA seems to be the most suitable to handle multi modal function landscapes and to identify multiple optima of real and discrete parameters in a robust manner [134]. However, high computational cost and difficulty to implement are usually recognized as GA's limitations. Nevertheless, the high number of GA software available, in almost any programming language, as well as different types of GA evolutions regarding specific type of problems compensated these limitations.

Given its recognized advantages over other methods, especially GA manipulation of a population of individuals, which allows capturing the whole Pareto front in one single optimization run, lately, there has been a large development of different types of Multi-Objective Genetic Algorithms (MOGA). In the literature, two different approaches in MOGA can be found: Non Pareto-based and Pareto-based approaches.

The Non Pareto-based approach uses the selection mechanism of the GA to produce non-dominated individuals, where each individual objective is designated as the selection metric for a portion of the population. Therefore, the rank of a certain individual corresponds to the number of chromosomes in the current population by which it is dominated. Thus, the main strengths of this approach are its efficiency and relatively easiness to implement. On the contrary, its main weakness is that it works sharing the objective value space, which implies that two different vectors with the same objective function values cannot exist simultaneously in the population.

The Pareto-based approach introduces a non-dominated sorting to rank a search population according to Pareto optimality. Therefore, a procedure for identifying non-dominated sets of individuals and to remove them from the population is repeated until the whole population has been ranked. An example of this approach is the Non-Dominated Sorting Genetic Algorithm (NSGA) proposed by Srinivas and Deb (1994) [141], where the non-dominated individuals in the population are identified given a high initial individual score and then removed from the population. This procedure allows searching for non-dominated regions and results in fast convergence of the population toward such regions. Based on that, its main strengths are the handling of any number of objectives and the sharing of the parameter value space instead of the objective value space, which ensures a better distribution of individuals and allows multiple equivalent solutions [136]. However, its main weakness are the higher computationally inefficiency and the less quality of the Pareto fronts produced.

Since engineering design problems often consist of a mixture of numerical simulations, analytical calculations and catalogue selections, one additional issue exploited in MDO is decomposing a large system into smaller subsystems, connected by information flows from outputs of one subsystem to be used as inputs of another. These information flows between subsystems analyses are termed couplings [142]. These sub-problems are generally defined by disciplinary area or by components and each one can be then solved using different analysis tools.

Based on that, MDO assumes that an overall superior design will be only achieved if the design problem is solved considering the existing interactions [33]. However, only with the latest advances in computing performance has it been possible to develop more powerful numerical optimization methods, capable of solving the complex multidisciplinary optimization problem. Thus, parallel to the development of MDO, a number of software packages have been created to facilitate integration of codes, data and user interfaces, leading to its emergence as a tool for mainstream application in product and process development (e.g. iSIGHT-FD [143], ModeFRONTIER [144], Phoenix Integration ModelCenterTM [145]).

2.2.4. Design Validation

Taking into consideration that the main goal of this project is to develop a tool capable of supporting the design of injection moulds in a global and quantitative way, an important issue of the Validate stage is deciding if the simulation model developed is valid. To that end, two main tasks must be performed, namely the Conceptual and Computerized model validation and the Operational model validation [146, 147]. Conceptual and Computerized model validation is defined as determining if the theories and assumptions underlying the conceptual model are correct and if the model representation of the problem is reasonable for the intended purpose. Operational model validation is defined as determining if the model's output behaviour has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability.

Several validation techniques can be found in the literature. Some are used subjectively and others objectively (i.e. some techniques adopt some type of mathematical or statistical procedure, such as hypothesis tests). A brief description of these techniques can be found in Sargent (2010) [147]. Based on each technique scope, and considering platform specificities, five different techniques can be used, namely: Face Validity; Comparison with other models; Historical data validation, Parameter variability-Sensitivity analysis; and Predictive validation.

Face Validity involves some individuals knowledgeable about the modelled system, who are asked about the reasonability of the conceived model and/or its behaviour. Therefore, this technique is considered the most adequate to analyse the validity of the Conceptual and Computerized model. Regarding the analysis of the Operational model validity, *Comparison with other models*, *Historical data validation*, *Parameter variability-Sensitivity analysis*, and *Predictive validation* can be used at different stages with different purposes. Note that, *Comparison with other models* encompasses the comparison of the results of the simulation model with the results of other, already validated, models. This approach also includes the comparisons of the results obtained with the model applied to simple cases with the ones obtained with analytic models.

Historical Data Validation can be used when some historical data is available. A part of the data is used to build the model and the remaining is used to determine (test) whether the model behaves in the same way as the system. The data can be obtained by conducting experiments on the developed system. For that purpose, a data model that relates the inputs to outputs from the systems in the detailed to the aggregate inputs and outputs of the system can be used. At each level of integration the appropriate models of each subsystem must be adopted. These models are simulated by defined sets of inputs and tested to determine if the appropriate outputs are obtained.

Parameter variability-Sensitivity analysis consists of changing the values of the input and internal parameters of the model to determine the effect upon the model's behaviour or output. An optimal sensitivity analysis can take many forms, each providing a different level of information concerning changes in the optimal solution. The simplest form of post-optimality analysis requires only an accurate prediction of the Lagrange multipliers of the solution [148]. In general, sensitivity analysis can be regarded as a standard method of post-optimality analysis. One objective of post-optimality analysis methods is to determine the range of parameters, such as the right-hand-side values or cost coefficients that can be perturbed without causing a significant change in the optimal solution [149]. Thus, sensitivity analysis is the study of local perturbation of solutions with respect to changes in the optimization problem, while post-optimality analysis is the evaluation and interpretation of the results obtained for any optimization problem [149]. In this sense, sensitivity analysis may be used to characterize the design space about the present solution and infer changes in this solution, as a result of constraint or parameter variations.

Finally, *Predictive Validation* is used to predict (forecast) the system's behaviour. Comparisons are made between the system's behaviour and the model's forecast to determine if they are the same.

Assuming that through the IDOV approach, several conceptual solutions will be generated and the most promising solution is selected (in the Design stage), and after that detailed and optimized (in the Optimize stage), then two levels of validation must be undertaken: Conceptual validity and Optimization validity. Conceptual validity attempts to demonstrate if the design, from a high-level statement, was evolving properly in order to evaluate the degree of matching between designed concept capabilities and customer's requirements. Regarding Optimization validity, and since it addresses if the system has been correctly developed, it is necessary to quantify how well the designed system responds adequately to the functional requirements, as well as if it is being solved appropriately. It is important to keep in mind that the developed platform has the main objective to conceive and optimize products or systems. Thus, the designed systems must be also verified and validated, as schematically represented in Figure 2.2. Therefore, the designed system must be evaluated in order to verify if it indeed meets requirements (Verification), as well as it is necessary to evaluate if the designed system satisfies costumer's needs (Validation).

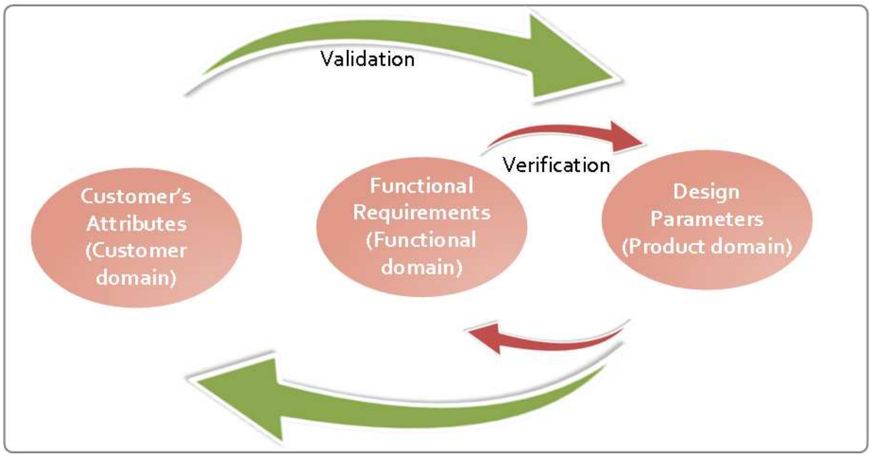


Figure 2.2: Main tasks of validation stage: Validation and Verification.

Since there are several methods for qualifying the system through verification and validation[9], the selection of the most adequate must be made judiciously. According to Buede (2009) [150], there are four categories of methods regarding validation and verification tasks, namely: 1) inspection; 2) analysis and simulation; 3) instrumented test; and 4) demonstration or field tests. Inspection is used for physical or human verification of specific requirements aiming the comparison between system attributes and requirements. Analysis and simulation involves the use of models to test key aspects of the system. Typically, these models are used where physical models are not available or are expense prohibitive. Instrumented test uses calibrated instruments to measure system's outputs, while demonstration or field tests check of the system in its appropriate environment.

2.3. The design of an injection mould tool

The injection mould is a high precision tool, responsible for the production of mostly plastic parts used everywhere. Its design is considered critically important to product quality and efficient processing [14, 27], as well as determinant for the economics of the entire injection moulding process [151]. The moulds for the production of plastics parts must be custom designed and built. Usually, no formal structural analysis is performed on the mould designs. Usually, the designer relies on his skill [152] and intuition, and follows a set of general guidelines for designing plastic injection moulds, which does not ensure that the mould design is acceptable and the best option [153]. This is particularly problematic for low-volume products or rapidly changing high volume products [154, 155].

Traditionally, the design practice involving mould design tends to quickly converge to a solution (corresponding to a point in the solution space), which is then modified until it meets customer's impositions. This procedure can be very time consuming and tends to provide suboptimal design solution. In addition, subsequent iterations to refine the solution will generally occur after mould manufacturing and trial, where most of the design gaps will come up. As a result, the conventional method for making moulds typically involves a great amount of errors that are translated as wastes of time and money, resulting in very expensive products and long manufacturing periods [13, 14, 27, 151, 156].

[9] Buede (2009) defines qualification as the process of verifying and validating the system design, where verification is the determination of how well the system was built right while validation determines that the right system was built.

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 are clearly inefficient, thus justifying the effort to develop new approaches to support mould design. In fact, previous research work in the injection moulding field pointed out the need for new approaches to support the mould design process [13, 157].

Thus, a large amount of scientific research has been done on mould design and its related fields over the last years, mostly based upon Knowledge-Based (KB) methods [151]. This approach is justified by the extensive empirical knowledge about mould component functions [17-19, 158]. At the same time, past work in injection moulding is also focused on tuning the process parameters and part's geometry, seeking to achieve the highest possible moulding part quality under specified constraints [159]. The class of process parameters entails melt temperature, mould temperature, injection time, injection and packing pressure, as typical design variables [160-162]. In relation to part's geometry, this class generally includes its geometric dimensions, topology and material.

According to Chan *et al.* (2003) [14], 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 to be feasible only for the automatic generation of particular parts of mould design [14, 27]. 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) and feeding system optimization. These parallel approaches are explained by authors' assumptions [159, 163] that production efficiency and part's quality are mostly affected by the heat-exchange design or, on the other hand, by the feeding or injection system.

As examples of heat-exchange research, Mehnen *et al.* (2004) [164] studied the automation of heat-exchange subsystem design, while Lam *et al.* (2004) [25] pursued a multi-objective approach with integration of GA and CAE. Li *et al.* (2009) [165] determined the optimal design for heat-exchange system, considering as design variables the distances between the neighbour channels. For that purpose, design experiments were applied, using Latin Hypercube design method, where a quadratic response surface equation was established for calculating temperature distribution uniformity and used as objective function.

Concerning optimal feeding systems, the kick-off was done by Pandelidis and Zhou (1990) [24]. In this work, they presented an optimization of gate location through a combined scheme of a simulated annealing and hill-climbing method. Lee and Lin (2006) [21] combined the Finite Element Method (FEM) with Taguchi's method and an abductive network to select the best parameters. Lam *et al.* (2004) [23] proposed an automated gate optimization routine and Shen *et al.* (2004) [22] developed a modified hill-climbing algorithm in order to determine the best gate location. Lee and Kim (2007) [166] adopted a traditional WS method, in the context of multi-objective optimization, aiming to minimize both maximum injection pressure (at the injection port) and maximum pressure difference among all the gates. More recently, Zhai and Xie (2010) [163] proposed a combination between numerical simulation of injection mould filling process and design optimization to find the optimum gate location, in order to achieve balanced flow. For that purpose, they adopted as objective function the difference between the maximum and minimum times of boundary filing and as design variables the coordinates of the gate location.

These examples highlight the fact that research in injection mould design optimization is underway, but generally involves only one particular aspect of the total design. However, due to the high complexity and mould component interactions, it is not possible with this approach to exploit the synergies between interacting phenomena and adequately explore the design space, in order to reach optimal mould designs. Furthermore, given the different applications of plastic part's and respective customer's requirements, it is also essential to link customer satisfaction with the search for the optimal solutions. Based on that, an integrative framework, which tackles the design of an injection mould in a global and quantitative approach, aiming to guide and systematize its design process [101, 167] is presented in the following chapters. It is important to underline that, although the proposed methods have been largely explored individually, or in combination with other methodologies, a quantitative integration of all aspects of design, in such a way that the whole process becomes logical and comprehensible through the integration of scientific basis tools, has not been considered yet. This will be the main focus of the following chapters.

CHAPTER 3

Development of a framework to support mould design

3.1 Introduction

Conscious of PD critical role regarding product cost and performance, as well as time to market, this chapter aims to provide a further contribution to the development of global methodologies to support PD activities. The majority of the existing proposals attain to make more visible and comprehensible the PD process by carrying out its activities in a systematic way, based on a strict theoretical background [8, 47][10]. In fact, given the current degree of innovation and the increasing number of new products in the market, currently, an effective PD model is considered as a strategic issue for the design of enhanced products *prior* to their launch [10, 11, 38]. To reach that goal, a PD model with four design stages, *Product Definition*, *Concept Design* or *System-Level Design*, *Detail Design* or *Design Optimization*, and *Design*

[10] This procedure is described as a prescriptive model based for the design process, which tends to look at the design process from a global perspective, covering the procedural steps and suggesting the best way to do something.

Validation, will be proposed in this chapter. This model will be supported by a global framework reinforced by the use of quantitative tools and methods.

For that purpose, DFSS will be adopted as a systematic data-driven methodology, and complemented by the most appropriate tools regarding the problem's characteristics, in order to generate a product solution that maximizes customer satisfaction [66, 67]. This option is based on the fact that DFSS tends to predict and improve quality before products and processes are launched (i.e. based on the proactive up-front nature of DFSS). In fact, although product defects are easy to come out in the manufacturing stage, they are costly to correct. Thus, it is recognized that the later in the product life cycle problems are discovered, the higher the cost to correct these problems. Furthermore, it is clear for some authors that it is not possible to achieve six sigma levels of performance without addressing the design of the product [76]. Then, DFSS bet is that early investments of time and effort are grandly compensated by getting the product right the first time. As a result, future problems at the manufacturing and service stages are reduced, and processes and products effectiveness, not just efficiency, are enhanced [168].

It is our conviction that DFSS implementation will enable to predict and prevent problems and to choose the best options, since all design activities are systematically planned and organized with a high degree of predictability end results. Assuming that each PD stage is supported by a DFSS principle, then four DFSS phases must be considered. Based on the existing proposals [4, 87, 89, 90, 169], the IDOV roadmap will be followed to support the design process. This roadmap establishes four stages: ***Identify***, which aims to define customers' requirements/expectations; ***Design***, where the creation of a product concept, and its system-level design, is performed; **Optimize**, in which all the detailed design, through product optimization, is handled; and finally, **Validate**, where all product design decisions are validated, in order to verify if the new designed entity indeed meets customer and other requirements. However, DFSS offers an advanced toolbox containing a large collection of well-known tools and techniques, where different tools can be address to each stage. Therefore, an exhaustive study of tools and techniques adequacy will be undertaken in order to develop the most adequate framework to support the design of injection moulds.

3.2 The design of injection moulds tools

Currently, the search and generation of alternative methodologies for design of moulds arises as an answer for the plastic industry to cope and compete with new market threats. The potential improvements on mould design only can be reached if the design process begins by broadly considering sets of possible mould solutions and, then, gradually narrowing the set of possibilities to converge to a final solution. This procedure, which helps to find more easily the best solution [41], can be achieved by a better exploration of the design space and by the resolution of system's trade-offs, early in the design. Moreover, since the design of an injection mould is a highly interactive process (i.e. involves substantial knowledge of multiple areas, such as mould design features, mould making processes, moulding equipment and part design, all of which highly coupled to each other), a multidisciplinary view of injection mould must also be adopted [151].

Thus, the main challenge of mould design is to conceive and produce a mould that is straightforward to manufacture, while providing uniform filling and cooling of the plastic parts. At the same time, the mould must be strong enough to withstand millions of cyclic internal loads, from injection pressures and external clamp pressures, in order to assure the target part's reproducibility. Based on that, an injection mould must be seen as a complex multidisciplinary system with some functional subsystems, such as the structural, impression, feeding, heat-transfer and ejection systems. Therefore, its design must encompass the multidisciplinary design of these five main highly-coupled systems, in a global way, assuring part and operational process constraints, in order to maximize customer satisfaction.

Given the current challenges and in order to achieve high levels of product quality in less time, new methods to address mould design projects must be studied. To that end, a framework aiming to help designers to achieve more efficient design of moulds must be developed, acting as a decision support system, by converting, in a consistent way, customer needs into better mould solutions.

3.3 A new PD framework to support injection mould design

In order to achieve the previously mentioned goals, a new approach for PD support is proposed [96, 170, 171]. The enhanced framework is based on DFSS methodology [4, 89] and established according to the IDOV roadmap. According to the proposal of Yang and El-Haik

(2003) [4], the IDOV roadmap, which is based on the ICOV phases (Identify, Conceive, Optimize and Verify) establishes four stages for design process: Identify, Design, Optimize and Validate. To support the Identify stage, ECSI was adopted as a reliable and independent way of assessing customer satisfaction and its retention [30]. Hence, an ECSI model regarding system specificities must be designed and validated. Afterwards, a CSI model must be estimated through a component-based approach, constructed upon PLS techniques. Based on this model, it will be possible to build one single objective function regarding customers' satisfaction levels, defined as a weighted function of specific customer attributes.

The next stage, Design stage, was supported by AD [7, 31, 32]. Its main objective is to generate physical solutions, characterized by DPs, by mapping the FRs of products onto the corresponding DPs. Following AD guidelines, this mapping must be accomplished in order to get an uncoupled design (i.e. the functional independence of FRs must be guarantee in order to accomplish the AD first axiom). Nevertheless, there are some authors that consider the practical application of this approach infeasible, especially for complex engineering systems. Thus, the main purpose of AD at this stage is to conceive a conceptual solution for products, regarding instead the minimization of coupling relationships. Afterwards, this conceptual design solution will be detailed and optimized in the Optimize stage. This stage is supported by MDO, which is considered an appropriate methodology to design complex systems through an exploitation of coupling phenomena [33, 34].

Finally, in the last stage, Validate stage, the new designed entity, generated by our MDO framework, is evaluated in order to verify if it responds adequately to customer's requirements, as well as if it allows reaching higher levels of customer satisfaction. This task is achieved by comparing the behaviour of the design solutions generated by the developed framework with the behaviour predicted by numerical simulation codes (exiting models) and, when possible, based on some data gathered for an existing mould.

In brief, the proposed framework integrates as main supporting methodologies the ECSI [172, 173], the AD [7] and the MDO [132]. Although these methods have been largely explored, individually or in combination with other methodologies, they have never been used as a quantitative integration of all aspects of design. In this sense, the developed framework tackles the design in a global and quantitative approach, as a way to guide and systematize the injection mould design process. All the stages of the framework (and its steps) are described in the next sections. They are illustrated with real examples from the Portuguese injection moulds industry.

3.3.1 Identify stage

This stage is an essential step to achieve successful products. If it is not done correctly, the design process will be initiated without fully understanding the customer requirements, probably leading to less satisfactory products [93]. In fact, customer needs are generally defined in an imprecise language, which can be easily misunderstood by the designer team. Furthermore, typically, customers have only a superficial understanding of the functions supported by a product and they lack experience in identifying and expressing their desirable requirements. Thus, it is considered very difficult to acquire entirely and accurately the CAs and, consequently, to convert them into a successful design. Assuming that this first phase is essential for a successful design, a special effort has been put in this stage. Therefore, the proposed framework encompasses firstly an exploratory analysis, qualitative research, with the aim of obtaining and understanding customer wants and needs. To that end, two sequential activities must be conducted: initially it is identified who are the customers that need to be listened to (i.e. “keystone” customers), and, then, it is necessary, through direct customer engagement, to identify their needs and expectations.

Finally, four steps were established: Identification of “keystone” customers (Step 1); Identification of main factors that might contribute towards customer satisfaction and loyalty (Step 2); Validation and quantification of the relative importance of each factor previously identified into customer satisfaction and loyalty (Step 3); and, at last, in order to link product definition with product design stage, the CAs are converted into FRs (Step 4). A summary of the objectives and supporting methods involved in the Identify stage are illustrated in Table 3.1.

Table 3.1: The proposed research approach for the Identify stage.

Steps	Description	Methods
1	Identify "keystone" customers	Customer Value Chain Analysis (CVCA)
2	Identify factors that contribute for customer satisfaction and loyalty	Semi-structured interviews, KJ
3	Validate and quantify the relative importance for factors	Estimation of ECSI model: PLS
4	Linking product definition and product design	AHP

Step 1, an innovator method, designated by Customer Value Chain Analysis (CCVA) [174], was adopted because it extends the functionality and utility of the Customer Chain by a value of the relationships between the several customers in the whole chain. Afterwards, in Step 2, an illustrative sample, representative of “keystone” customers of Portuguese injection mould makers, was studied through semi-structured customer interviews and visits. This exploratory stage allowed to identify the factors that might contribute to the perceived quality of moulds and to inherent services, and to elicit a comprehensive set of questions regarding the construction of a survey [96]. Additionally, since CAs are usually a mixture of demanded quality, quality characteristics, functions, methods, reliability and other issues [175], these needs cannot be used directly as the requirements for product or process design. Thus, the KJ method[11] was applied to translate them. KJ method is considered to be a powerful tool to map the assumptions and viewpoints of a team of individuals [176].

Afterwards, Step 3 starts with the quantitative analysis. A survey was developed in order to validate and generalize the previous findings, i.e., to confirm the customer needs identified by qualitative research. Furthermore, this task also intends to quantify the relative importance of needs, and, finally, to evaluate the factors that contribute towards the global satisfaction of customers. The survey was supported on the ECSI methodology, but complemented by new latent variables aiming to include mould makers specificities. As a result, a set of specific attributes were ranked according to its relative importance to mould's customers, in order to address the critical items (i.e. Critical-To-Quality (CTQs) items).

Finally, Step 4 aims to link customer's critical items into functional requirements, which are the minimum set of product requirements that completely characterize the design objectives for a specific need. For that purpose, the AHP methodology was adopted, because it is considered as an easy way of setting priorities through pairwise comparison amongst a range of different criteria [112].

Step 1: Identify "keystone" customers

In this step, the main objective is to identify the key customers as an instrumental way to identify wants and needs. According to Donaldson and Ishii (2006) [174], the pertinent customers and stakeholders who are involved with the effective delivery of the product to the end user and their support throughout its life cycle, can be identified by CVCA. Firstly, the strategic objectives for the design process, the boundary conditions and the target market must be established. Secondly, the pertinent parties involved with the product must be delineated (e.g. all the product end-user, important customer who may include business

[11] KJ method, also called Affinity Diagram, was created in the 1960s by Jiro Kawakita. It allows organizing a large number of ideas into their natural relationships, through a team's creativity and intuition work.

partners, regulatory bodies, specific departments and regulatory agency), as well as the links between them, in order to map the value relationships or flows between the several parts. Then, through analysis of input and output flows, previously established, critical customers (i.e. "keystone" customers) will be identified.

Four CVCA maps representing the main scenarios for Portuguese mould makers sector were established. The first difference amongst these scenarios is linked with the relation between who orders the mould (i.e. mould's customers) and the respective mould maker. It is important to note that the majority of the Portuguese mould maker's customers are international leading companies. Consequently, a mould order can be placed by a leading company with its core business on the plastic part design that will be injected. In this case, the mould is ordered by customers regarding a specific plastic part design. The CVCA map corresponding to this scenario is presented Figure 3.1.

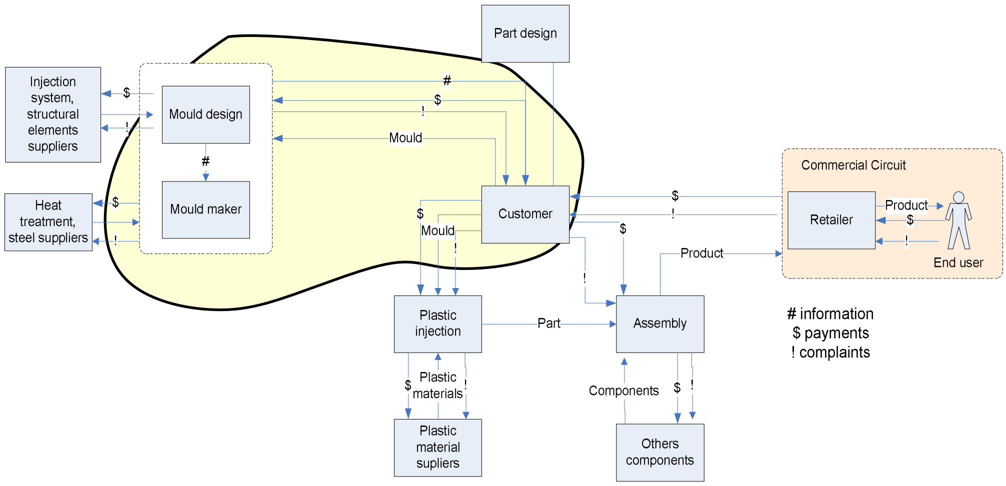


Figure 3.1: CVCA for mould makers assuming a single mould order.

The second scenario comprises leading companies who order not only the mould, but also complementary manufacturing operations, such as part's injection, superficial finishing operations for plastic parts (e.g. painting, pan, etc.), and part's elements assembly. These operations are all included as a complete purchase "package" in the CVCA map, as shown in Figure 3.2. Although these "packages" are sometimes controlled by mould makers (who, when needed, request an injection company as internal supplier), this role is majority assumed by the injection companies who request the mould makers service. This situation is typical for electronic device parts industry.

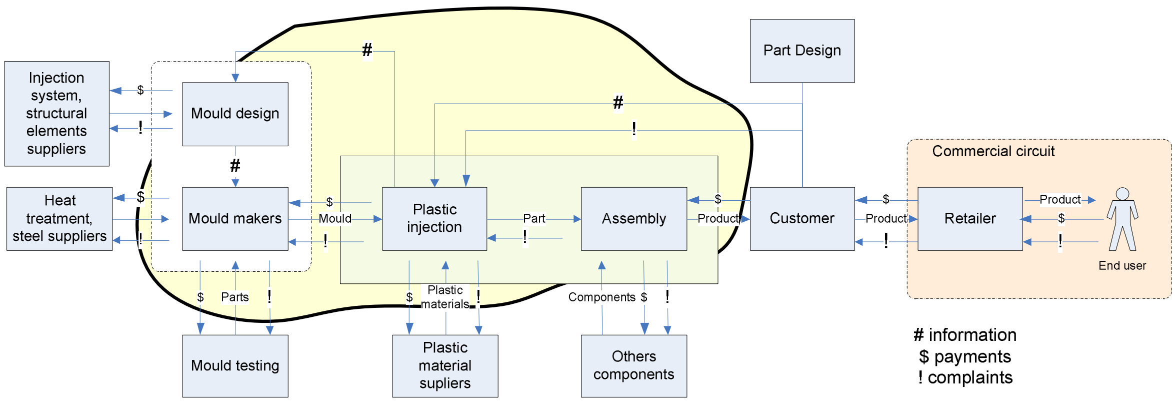


Figure 3.2: CVCA for mould makers assuming a "package" order.

Note that, in this scenario, the responsibility of the whole process belongs to the injection companies, except part's design that is the customers' core business. If part's design is also included in the "package" some differences emerge in the CVCA map, as illustrated in Figure 3.3.

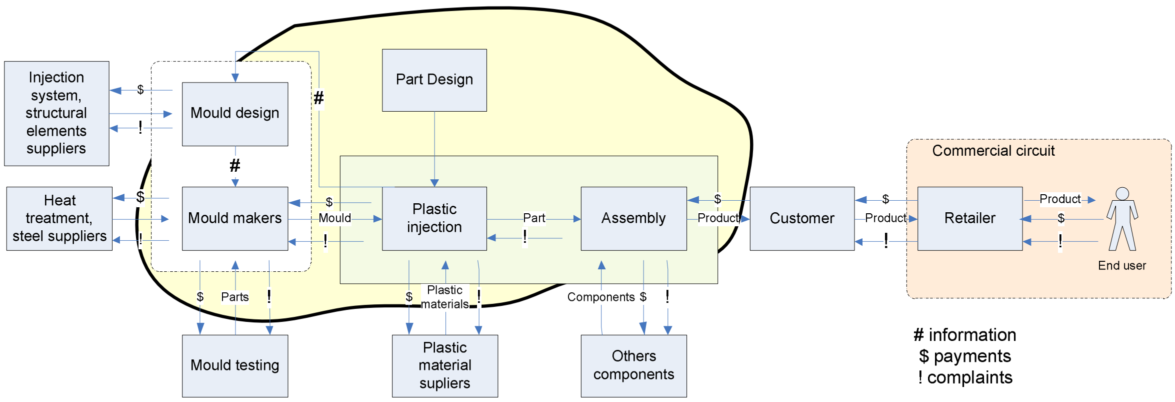


Figure 3.3: CVCA for mould makers assuming a complete "package" including part's design.

Finally, due to the existence of economic agents (i.e. intermediate agents) with the main function of establishing the connection between leading companies and mould makers, a four CVCA scenario was identified, which is presented in Figure 3.4. Usually, these agents sub contract the design and the manufacture of the moulds ordered by the final client to mould makers (i.e. mould makers do not know who are the real end customers).

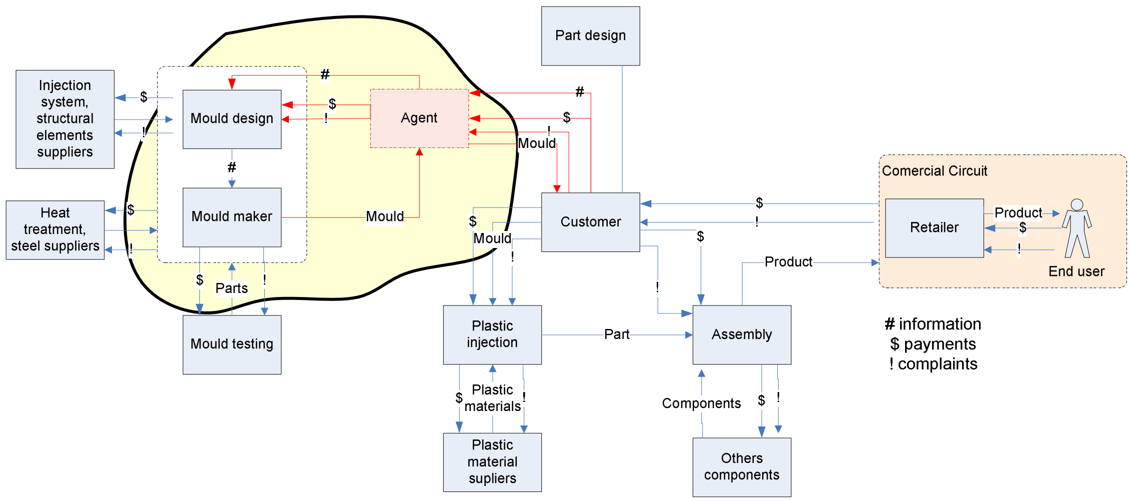


Figure 3.4: CVCA for mould makers assuming intermediate agents.

Based on these four CVCA maps, it is possible to observe that, in the majority of the cases critical customers are the plastic injection companies, since they are, directly or indirectly, responsible for specifying mould's requirements. In addition, because these companies are moulds end-users, they are the most important entities to listen in order to understand when, where, why and how they are using the mould for, as well as what are the typical mould's problems. Nevertheless, regarding the differences amongst the identified CVCA maps, an adequate illustrative sample of Portuguese injection companies to interview was selected. Table 3.2 presents a summary of the selected companies' main characteristics.

Table 3.2: Illustrative sample of mould´s customers.

Company	Number of workers	Main clients industries	CVCA scenario
1	250-499	Automotive	2, 3
2	100-249	Automotive	2, 3
3	50-99	Household electrics	2, 4
4	50-99	Electronic communications	1, 2
5	20-49	Others	1
6	20-49	Packing, home appliances	1
7	50-99	Household electrics	2, 3
8	100-249	Automotive	2, 4

Step 2: Identify factors that contribute for customer satisfaction and loyalty

For the previous "keystone" customers, a semi-structured customer interview plus visits where conducted, aiming to identify the specific factors that contribute to customer's satisfaction and loyalty. This interview was made of three parts (see Appendix I). The first one concerns the identification of main customers' requirements regarding product quality. In addition, it includes an evaluation of the importance of the moulds' quality for their own manufacturing processes. The second part of the interview aims to perceive the customer needs and expectations regarding services provided. The last part of the interview intends to know their perspectives of future evolution for the sector, with the main objective of evaluating their real satisfaction and loyalty levels.

Is it important to highlight that the structure of this interview is coherent with the ECSI model [103]. Thus, customer satisfaction and retention are considered as key issues for organizations in today's competitive market place, a vital concern to achieve customer loyalty [177, 178]. For that reason, it is important to develop reliable and independent ways of assessing customer satisfaction, allowing the comparison between companies within the same sector or at a macroeconomic level.

As a SEM, ECSI is based upon sets of linear equations used to specify customer satisfaction in terms of their presumed cause-and-effect variables [106, 179]. These variables, the latent variables or constructs, cannot be measured directly (e.g. customer satisfaction). Thus, they must be inferred through observing or measuring specific features that operationally define them, the so-called manifest variables or indicators. Consequently, the ECSI model is composed of two models: the Structural Model, or Inner Model, and the Measurement model, or Outer Model. The first one specifies the relations between the constructs, while the Measurement model includes the potential interrelationships between constructs and their indicators. Technically, the SEM can be described through the following expression:

$$\boldsymbol{\eta} = \boldsymbol{\beta}\boldsymbol{\eta} + \gamma\xi + \boldsymbol{\vartheta} \qquad \textit{Eq. 5}$$

Where $\boldsymbol{\eta}$ is the vector of endogenous latent variables, and $\boldsymbol{\xi}$ is a vector of exogenous latent variables. The exogenous variables are exclusively influenced by factors lying outside the model, while variables that are hypothesized to be influenced from inside the model are endogenous variables. The coefficients of the structural model are organized in the matrices, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$, which measure the direct impact on a latent variable when there is a unit change in an antecedent latent variable. If the antecedent variable is an exogenous variable, the direct impact is represented by $\boldsymbol{\gamma}$, while $\boldsymbol{\beta}$ represents the direct impact over endogenous variables derived by a unit variation of another endogenous variable. The vector of specification residuals for the endogenous latent variables $\boldsymbol{\eta}$ is represent by $\boldsymbol{\vartheta}$. On the Measurement Model side, there are three possible types of relations between latent variables and its indicators. When the observed variables are assumed to be the reflex of the latent variables, the model is reflective:

$$\mathbf{v} = \mathbf{\Lambda_v}\boldsymbol{\xi} + \boldsymbol{\delta} \qquad \textit{Eq. 6}$$

$$\mathbf{u} = \mathbf{\Lambda_u}\boldsymbol{\eta} + \boldsymbol{\varepsilon} \qquad \textit{Eq. 7}$$

Where $\mathbf{v}$ and $\mathbf{u}$ are the exogenous and endogenous manifest vectors, respectively, $\mathbf{\Lambda_v}$ and $\mathbf{\Lambda_u}$ are the correspondent weight matrices (loadings), and, finally, $\boldsymbol{\delta}$ and $\boldsymbol{\varepsilon}$ are measurement error vectors. The formative model is used when the observed variables are assumed to cause or form the latent variables:

$$\xi_i = \sum_{l=1}^{G} \lambda_{\xi i_l} v_l + \delta_{\xi i} \qquad \textit{Eq. 8}$$

$$\eta_i = \sum_{l=1}^{H} \lambda_{\eta i_l} u_l + \delta_{\eta i} \qquad \textit{Eq. 9}$$

Where $\lambda_{\xi i}$and $\lambda_{\eta i}$ are coefficients of the formative model associated with variables ξ_i and η_i, respectively, and G and H are the number of manifest variables. Finally, $\delta_{\xi i}$ and $\delta_{\eta i}$ are the specification errors. The mixed model combines both models. Thus, the hypothesized relationships amongst variables are then translated into mathematical models, which are tested against empirical data.

As it is illustrated in Figure 3.5, the ECSI model adopted by Portugal encompasses seven latent variables, where customer satisfaction is linked to four drivers (Image, Expectations, Perceived Quality and Perceived Value). The antecedents of customer satisfaction are Image (which embraces the global idea that customers have of the product or company), Expectations (which includes the information that customers have acquired in the past regarding products and services offered by the company), Perceived Quality (which integrates product quality and service quality and corresponds to the evaluation of recent consumption experiences of products and associated services, respectively) and Perceived Value (which is the perceived level of product quality and the price paid for it). The consequences of customer satisfaction are Complaints, which evaluate the frequency and management of complaints, and Loyalty, which measures a long term customer’s commitment and his/her re-purchasing intention [107].

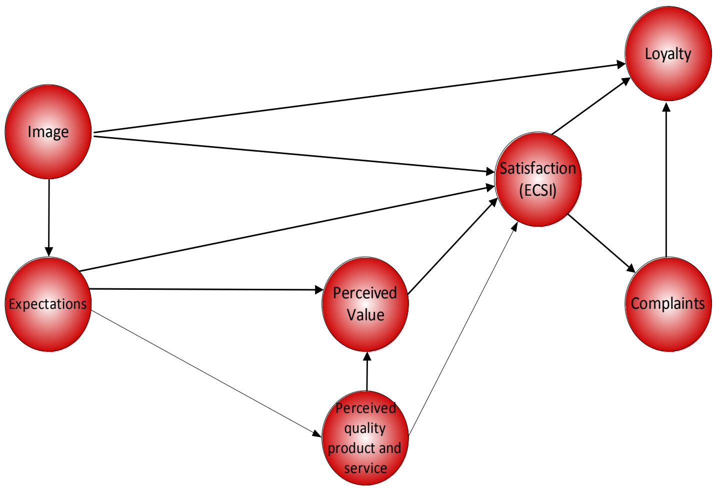


Figure 3.5: ECSI structural model adopted by Portugal.

Therefore, in order to build an ECSI model, able to assess the particularities of the sector in analysis, it was important to identify the concepts to be measured regarding Perceived Quality of Product and Service, as well as to elicit a comprehensive set of questions that are potentially relevant in measuring these concepts. In this sense, following the developed research approach, Step 2 was carried out through the conduction of eight semi-structured interviews. The information gathered from these interviews, which was complemented by a KJ study [176], using the illustrative sample of "keystone" customers identified through CVCA, allowed the identification of the factors that might contribute towards Perceived Quality of that particular product and service. These factors are Quality of mould's design, Quality of the moulds' construction, Cooperation, Resources, Response Capacity and Contracts [96]. Then, the ECSI model adopted by Portugal was reinforced with more six latent variables in order to include the specificities of the mould maker's sector, as schematically shown in Figure 3.6.

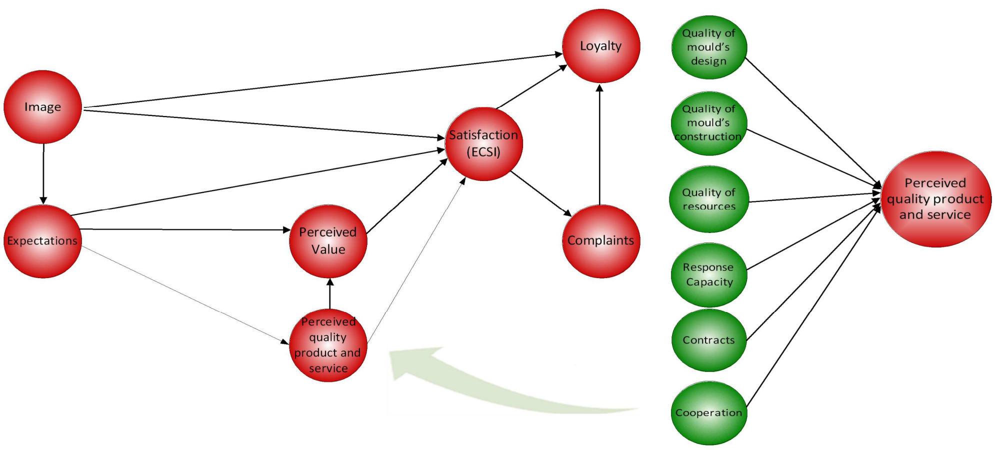


Figure 3.6: ECSI model designed for moulds makers sector.

Step 3: Validate and quantify the relative importance of factors

According to the underlying structure, in the step 3 generic questions regarding multiple indicators potentially relevant to measure each latent variable were defined, in order to construct a standardised closed questionnaire (see Appendix II). For each latent variable, at least two per latent variable generic questions were defined as multiple indicators, as shown in Table 3.3. In agreement with the majority of national ECSI indexes, and assuming that the collected data must have enough variation in order to support a statistical analysis, as well as equidistance between measurement values [180], the scale adopted for ECSI indicators is based on a 10-point scale (1-completely disagree to 10-completely agree). Afterwards, the CSI and all other latent variables are transferred to an index ordinary scale of 0 to 100, where 100 denote the highest possible value.

Usually, the data for model estimation is obtained from data collected through telephone interviews, out of a national representative sample of customers who have recently acquired specific products or services. In this project, data was collected by sending a questionnaire directly to Portuguese injection companies (CAE Rev 3[12] 25240) who are/or were in the last three years customers of Portuguese mould makers.

[12] CAE Rev 3 is the code of economic activity established, according to Portuguese Classification of Economic Activities.

Table 3.3: Questions used as indicators in ECSI model for mould makers sector.

Latent variables	Observed variables	Code
Image	This mould maker is a reliable and trustworthy company	*IMAGE_1*
	This company is innovative and always looks ahead	*IMAGE_2*
	This company is a customer-oriented company	*IMAGE_3*
	This company has lots of experience in moulds production	*IMAGE_4*
	This company is stable and well established	*IMAGE_5*
Expectations	Overall quality of this company	*EXP_1*
	Company's capacity in offering moulds that answer to customer needs	*EXP_2*
	Moulds makers' reliability and provided service	*EXP_3*
Quality of the mould's design	The capacity of the mould's design meeting customer's product requirements	*PROJ_1*
	The mould's design capacity according to the customer's specific injection process	*PROJ_2*
	Adequacy of constructive solutions	*PROJ_3*
	The company's accessibility in discussing the mould's design	*PROJ_4*
	The overall quality of the mould's design	*PROJ_5*
Quality of the mould's manufacturing	Quality of the structural elements	*MANUF_1*
	Reliability of the adopted constructive solutions	*MANUF_2*
	The adequacy of manufacturing processes (type, parameters and tools) to customer requirements	*MANUF_3*
	The overall quality of the mould's construction	*MANUF_4*
	Quality of the structural elements	*MANUF_5*
Cooperation	The company's accessibility in sharing responsibilities for the part's quality	*COOP_1*
	The following up of the mould performance during its life cycle	*COOP_2*
	Company's pro-activity in collaborating in solving problems during the mould's life cycle	*COOP_3*
	Capacity for integrating complementary services	*COOP_4*
Resources	The technical staff's know-how	*RESOUR_1*
	Level of its high-tech equipment	*RESOUR_2*
	Quality of the installations	*RESOUR_3*
Contracts	The company's flexibility	*CONTR_1*
	The fulfilment of the conditions previously agreed	*CONTR_2*
Response Capacity	Response capacity to the customer's requirements	*CAPAC_1*
	Capacity in answering quickly to the customer's needs and problems	*CAPAC_2*
Perceived value	Quality of product/service given the price paid	*VALUE_1*
	Prices of product/service given the mould's quality	*VALUE_2*
Customer Satisfaction	Overall satisfaction with the company's products and service	*ECSI_1*
	Considering customer expectations, to what extent have the company fulfilled them	*ECSI_2*
	How close is the company to customer ideal provider	*ECSI_3*
Complaints	How many times have things gone wrong	*COMPLA_1*
	Identify who has complained	*COMPLA_2*
	How well was the last complaint handled	*COMPLA_3*
Loyalty	How likely will you order from this company a new mould	*LOYALT_1*
	How likely will you recommend this company to others	*LOYALT_2*
	Sensibility to price changes	*LOYALT_3*

This questionnaire was sent during the spring and summer of 2007. A total of 108 surveys were replied, out of a total number of 489 mould companies which operated in Portugal at that time [170]. The collected data set contains a number of incomplete observations, 2.35% in average, which were assumed to be missing at random. All variables are treated as continuous (except COMPLA_2, which is a nominal variable), since the type of scale used enables a good approximation to interval scales [181] (note that the data was obtained using an ordinal 1-10 scale). Through statistical tests, it is possible to verify that the majority of the variables showed evidence of moderate non-normality (see Table 3.4 for multivariate normality).

Table 3.4: Test of Multivariate Normality for Continuous Variables (Missing Data estimated by means) given by Minitab 16.

Skewness			Kurtosis			Skewness and Kurtosis[13]	
Value	Z-Score	p-Value	Value	Z-Score	P-Value	Chi-Square	P-Value
618.69	8.59	0.000	1558.9	4.842	0.000	97.207	0.000

One brief characterization of the studied companies is illustrated through the following figures. Figure 3.7 presents the main industries that are mould companies customers, showing a wide spread among different core businesses. Figure 3.8 shows that most companies are small since they ordered, on average, less than 20 moulds per year. It is also evident that most companies are manufactures, although some integrate the area of product development and design (Figure 3.9). Regarding the certification of quality systems, 66% of the companies have its quality system audited and certified, as shown in Figure 3.9.

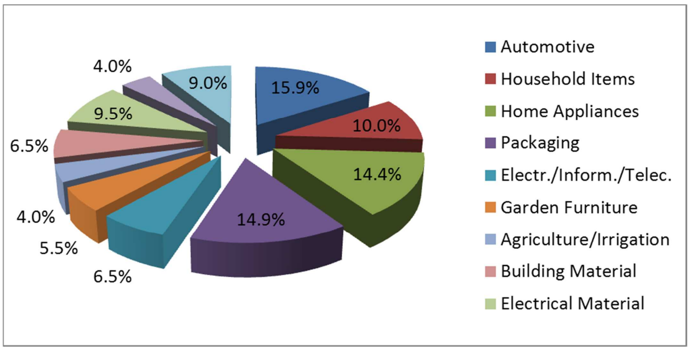


***Figure 3.7:** The main customers industries for the observed companies.*

[13] Skewness is a measure of the asymmetry, while kurtosis is a descriptor of the shape of a probability distribution.

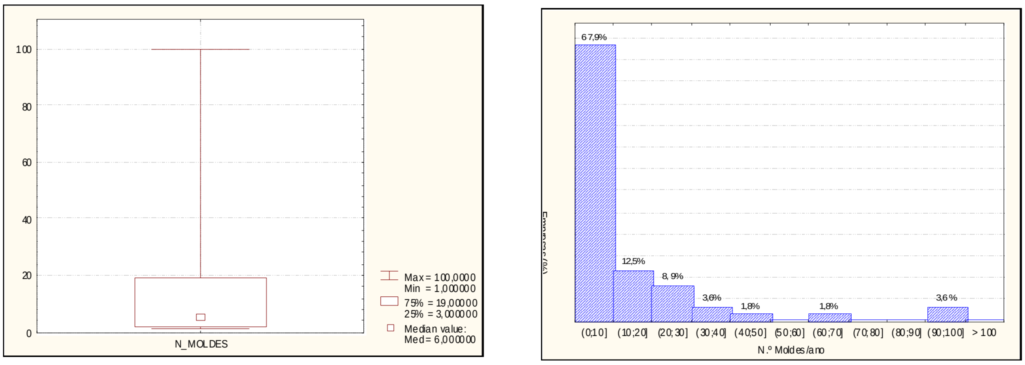


***Figure 3.8:** Number of moulds, in average, ordered per year for the observed companies.*

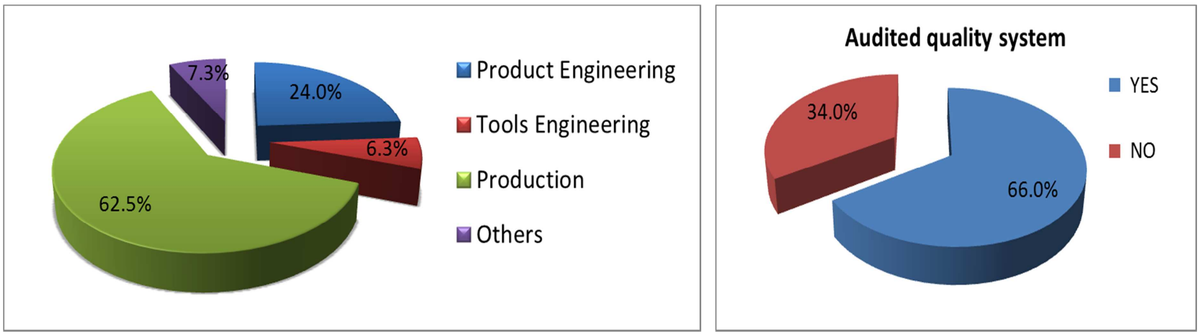


***Figure 3.9:** The main departments and the existence of an audited quality system (sample).*

The estimation of direct, indirect, and total structural effects amongst latent variables in a structural equation model can be accomplished using two main types of methods: covariance-based and component-based methods [172, 173, 182-185]. Covariance-based techniques estimate path coefficients and loadings by minimizing the difference between observed (obtained by the gathered data) and the predicted variance-covariance (defined by the hypothesized model) matrices. To that end, some different estimation procedures can be adopted, where the most widely used is Maximum Likelihood (ML) [186]. This method produces consistent and efficient parameter estimates, as well as model test statistics for assessing the adequacy of a hypothesized model [187, 188].

The component-based approach is an iterative procedure that generates estimates of the observations of the latent variables, the so-called case-values or scores, so that they fit into both the structure of the latent variables and the measurement system [177]. This technique is also known as PLS, because it studies a system of linear relationships between latent variables, by solving blocks (combinations of theoretical constructs and measurements) one at a time (partial), through the use of interdependent Ordinary Least Squares (OLS) regressions. The detailed description of a PLS algorithm can be found in Cassel *et al.* (2000)

[177], Chatelin *et al.* (2002) [189], Chin (1997) [190], Tenenhaus *et al.* (2002) [191] and Vilares *et al.* (2005) [103], amongst other authors.

Since the instigation of the ECSI, PLS has been used to estimate CSI models, rather than using covariance-based methods. The more important reasons pointed out for such a choice are the following: PLS is best suited for predictive purposes [190]; PLS does not rely on strict assumptions about the data [192]; PLS estimates can be obtained with relatively small sample sizes and it is free from the independence and multivariate normal distribution assumptions; PLS avoids the indeterminacy problem [193] and provides an exact definition of component scores [190, 194]; finally, PLS can estimate SEM for both formative and reflective models.

However, some authors believe that the PLS option, especially for ECSI studies, is based upon some misconceptions about the use of covariance-based methods [195, 196]. These authors consider that the recent advances in covariance-based methods, in particular those leading to estimation methods that are robust to non-normality and missing data, must be taken into account. In this context, although PLS is considered a powerful method of analysis and it is recommended by the ECSI framework, it is pertinent to compare both approaches, using robust covariance-based methods instead of the traditional approaches regarding the gathered data. In this work, due to the strict assumptions about the data demanded by covariance-based methods, i.e. multivariate normality and large-sample needs, the fully covariance-based approach estimation was not feasible for addressing the complete ECSI model estimation. Therefore, the alternative approach proposed by Fornel *et al.* (1992) [197], the reduced ECSI model obtained by Image and Complaints removal, was used instead [170].

Reduced model estimation through covariance-based approach

Since the number of surveys answers is small when compared with typical ECSI studies, some rules of thumb can be used in order to perform the covariance-based approach (regarding its strong data assumptions). Nevertheless, according to the three rules established by Chin *et al.* (1997) [198], the sample size is sufficient. However, it is important to highlight that the optimal ratio of cases to free parameters is unclear and depends upon other factors, such as whether the data are multivariate normal, the strength of the relation between the measured and latent variables, and the number of indicators per factor [199].

Accordingly, mostly due to the small sample size (number of companies equal to 108) and the non-normality of the gathered data, the basic assumptions for a fully covariance-based approach estimation are not accomplished. The alternative approach [197] obtained by removing the Image and Complaints latent variables from the complete model is illustrated in Figure 3.10.

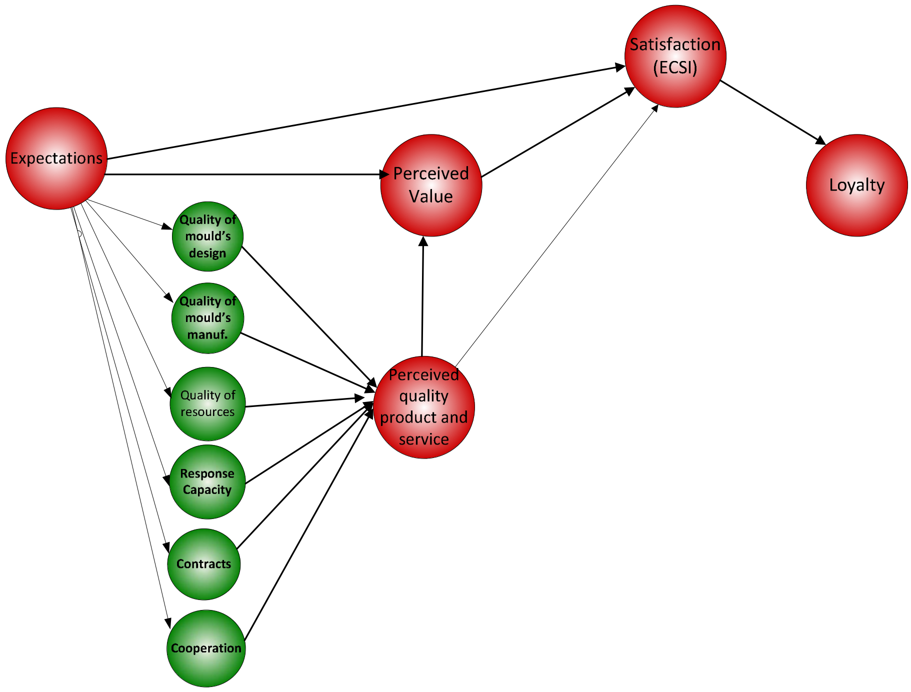


Figure 3.10: The reduced ECSI model specific for mould's makers sector.

Due to the non-normality of the data the Robust Maximum Likelihood (RML) method was used. This method is considered to be robust when applied to non-normal data and adequate for small sample sizes [195]. RML estimation was carried out by LISREL 8.8, over the complete data set obtained by mean substitution [170]. Additionally, we imposed that the Variance of Expectations (exogenous variable for the reduced model) to be equal to 1.00 and the Error Variance to be equal to 0.005 (in order to correct for improper solutions, such as the negative variance for error). Based on that, the estimated standardized values obtained for the moulds maker sector can be observed in Figure 3.11. The variable Loyalty_2 was dropped out in order to ensure individual item reliability (since its estimated loading was lower than 0.5 [193]).

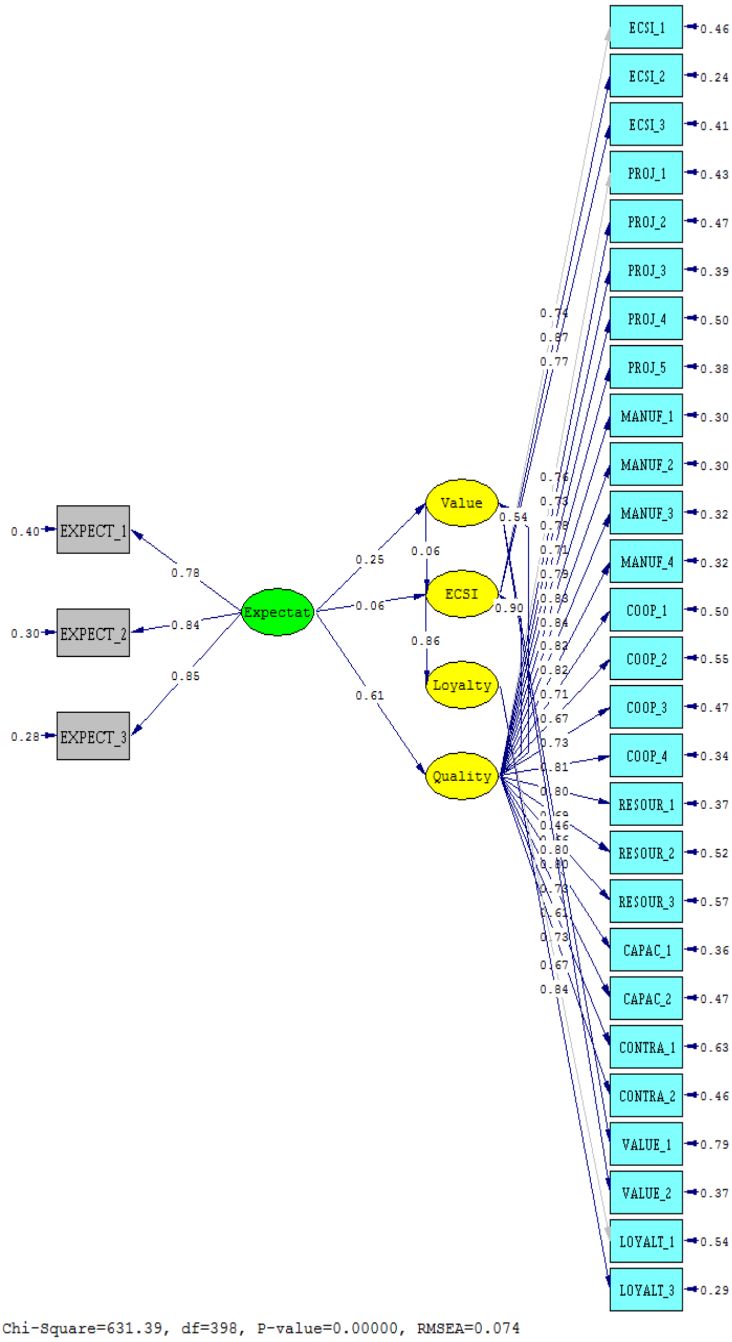


Figure 3.11: ***The reduced ECSI model specific for mould's makers sector: standardized estimates.***

The overall model fit can be assessed statistically by the $\chi 2$ test, and heuristically by using the adequate fit indexes proposed by Hu and Bentler (1999) [200]. Regarding some additional issues, like the small sample size [201], the non-normality of data [202, 203], and the existence of missing data [204], the more appropriate indexes, and respective cut-off values, are described in Table 3.5. It is thus possible to verify that the tested model can be accepted.

Table 3.5: Goodness-of-Fit values obtained by covariance-based approach.

Index	Cut-off criteria	Model
SB $\chi 2$	-	631.39
df	-	398
RMSEA	≤0.08	0.074
TLI or NNFI	>0.95	0.98
CFI	>0.95	0.98
SRMR	≤0.08	0.057

SB $\chi 2$ goodness-of-fit statistic; *df* corresponds to the degrees of freedom; RMSEA is the Root Mean Squared Error of Approximation; TLI is the Tucker-Lewis Index; NNFI that is similar to TLI is the Non normed Fit Index; CFI is the Comparative Fit Index; and SRMR is the standardized root mean squared residual (for more details see Hu and Bentler (1999) [200]).

Then, the analysis proceeds with the evaluation and interpretation of the estimated model parameters. The *t-test* was used in order to assess the significance of individual parameters: *t-values* values lower than 2 are considered to be non-significant and can be removed from the model without causing a significant decrease in fit. These parameters are illustrated in Figure 3.12 (red highlighted). Regarding the parameters that are removed from the model, they are mostly related with the construct Value. In fact, it seems that customers are not very concerned with the final cost of moulds. This aspect can be also observed by the smaller value of the impact through the variable Value into ECSI.

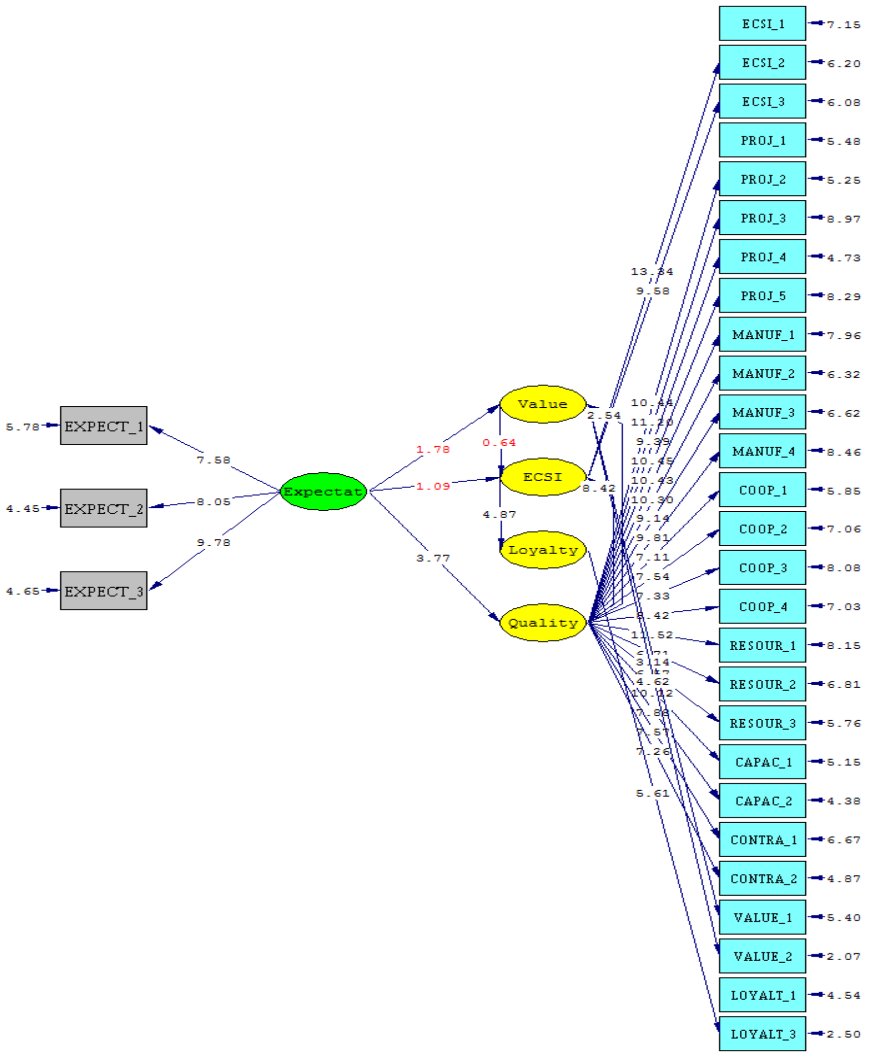


Figure 3.12: The t-values statistics for the estimated parameters for the ECSI reduced model.

Reduced model estimation through component-based approach

In the component-based approach, each latent variable is determined by both the structural and measurement model, so that in each iteration both equations are used to find an approximation of the latent variable. The estimated case-values will optimally fit into both equations.

After an initial rather arbitrary guess of the latent variables, the procedure iteratively switches between the inside and outside approximation until convergence is achieved. Therefore, in each step a minimization of residual variance is undertaken with respect to a subset of parameters, given a fixed-point constraint of the other parameters [205]. To proceed with the component-based approach, missing data were replaced by the mean of the correspondent variable on the available data. Notice that the manifest variables, with values of matrix $\mathbf{V}$, are scaled from 1 to 10 and normalized according to the following expression:

$$\mathbf{x} = (\mathbf{V} - 1) \times \left(\frac{100}{9}\right) \qquad \textit{Eq. 10}$$

In the inside approximation, the sum of squared inner residuals from Eq. 10 is minimized; in the outside approximation the minimization concerns the errors of the measurement models (Eq. 6 to Eq. 9) [177]. Afterwards, a PLS algorithm was applied to the raw manifest variables, meaning that manifest variables are not centred nor standardized (i.e. standardization parameter used METRIC 4). The reasons for that is the equality of variables scales adopted in the ECSI model, as well as the interpretability of its means and also because variance is related to variance importance.

Regarding the normalization of the latent variables, Wold (1985) [206] recommends that these variables shall have a standard deviation equal to one and mean equal to zero. Furthermore, the latent variables standardized must be estimated by External or Internal estimation. In External estimation, the latent variables are derived as weight values of the associated indicators. This task is done separately for each block of manifest variables, $\mathbf{x}$ and $\mathbf{y}$, and the related latent variable, which can be exogenous, $\boldsymbol{\xi}$, or endogenous, $\boldsymbol{\eta}$, according to:

$$\hat{\xi} = \mathbf{w}_{\xi}\mathbf{x} \qquad \textit{Eq. 11}$$

$$\hat{\eta} = \mathbf{w}_{\eta}\mathbf{y} \qquad \textit{Eq. 12}$$

According to the type of measurement model, formative or reflective, these weights are determined in two different ways. If the relation is outwards directed or reflective, the latent variables are similar to principal components of the indicators in the corresponding block, so the weights are the loadings from the latent variable to its indicators (the case-values represent the best predictors). In terms of an inwards directed or formative model, the regression coefficients between the latent variable and indicators are used as weights. These weights are estimated using the Mode A (or Outward Mode), where $\mathbf{w}$ are the covariances between the manifest variable $\mathbf{x}$ and the internal estimation $\mathbf{Z}$ (Eq. 13).

$$\mathbf{w} = cov(\mathbf{x}, \mathbf{Z}) \qquad \textit{Eq. 13}$$

This option only makes sense when all weights are positive. In case of negative signs, the related manifest variables must be removed from the model [207]. The PLS algorithm begins with an arbitrary choice of weights $\mathbf{w}$, which were assumed all equal to 1. About the Internal estimation, there are three schemes that can be followed: Centroid, Factor weighting and Path weighting. Nevertheless, according to Esposito *et al*. (2002) [207], in practice the results of the different weighting schemes do not show significant differences. Therefore, the Centroid Scheme was chosen (the centroid scheme considers only the signal of the correlation between the latent variables, with each one being replaced by +1 or -1, according to this latent variable being positively or negatively correlated). The previous options are coherent with the Fornell choices (see Bayol *et al.* (2000) [208]) and are summarized in Table 3.6.

Table 3.6: ***The selected options regarding PLS algorithm: reduced model.***

Data Metric	METRIC 4 (original data)
External Estimation	Mode A
Internal Estimation	Centroid scheme
Weights (starting vector)	All equal to 1
Missing Value	Mean replacement

The software used to undertake PLS estimation was the SmartPLS Beta version 2.0 [209]. The estimated parameters are illustrated in Figure 3.13.

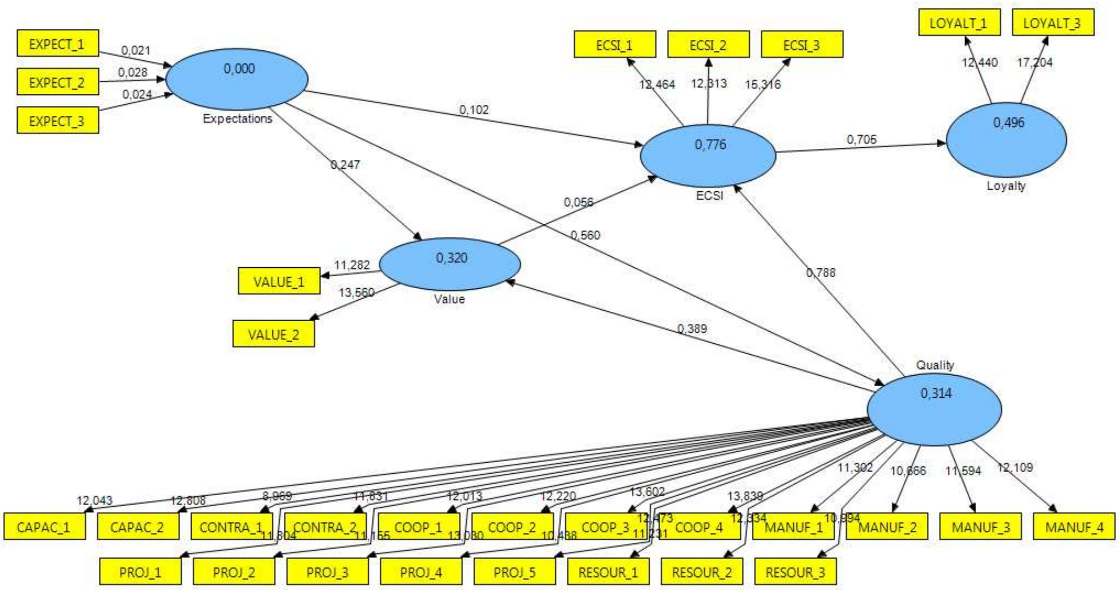


Figure 3.13: ***The model's parameters estimated by the component-based approach, i.e. PLS for the ECSI reduced model.***

The PLS approach does not have overall goodness-of-fit measures, and it does not require any kind of assumption regarding indicators and standard error distributions. Thus, there are two main groups of techniques that are usually used in PLS to validate the model (both being no parametric). The first one aims to determine the quality of fit and to quantify the explaining capacity of the model, using the determination coefficients (R^2) and the Average Variance Extracted (*AVE*). The second group intends to test the parameters estimates through Jackknife or Bootstrap techniques [189]. Following Tenenhaus *et al.* (2002) [191] recommendations, the resampling procedures used to validate the model were Bootstrap with Individual Change[14] and Construct Level Changes[15], which pointed out that Expectations→ECSI and Value→ECSI are non-significant paths (i.e. *t-values* lower than 2.0) as shown in Table 3.7 and Figure 3.14.

***Table 3.7:* The t-values statistics obtained by Construct Level Change and Individual Sign Change for path coefficients, regarding the ECSI reduced model.**

t- values	**Constructs Level**	**Individual Sign**
ECSI -> Loyalty	13.464	12.082
Expectations -> ECSI	**1.393**	**1.434**
Expectations -> Quality	5.256	4.932
Expectations -> Value	2.301	2.256
Quality -> ECSI	12.246	11.259
Quality -> Value	3.190	3.407
Value -> ECSI	**0.933**	**1.156**

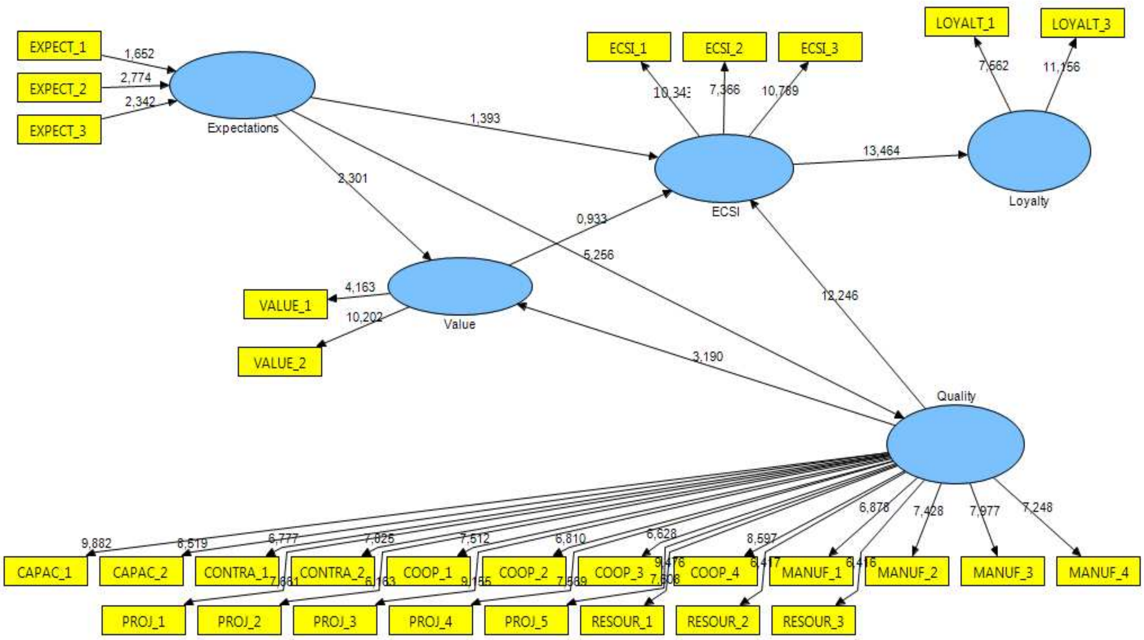


***Figure 3.14:* The t-values statistics obtained by Bootstrapping procedure: Construct level changes (ECSI reduced model).**

[14] When estimating the PLS outer weights from the resamples, arbitrary sign changes may occur. This implies that also the loadings and the path coefficients estimated from the resamples may show arbitrary differences with respect to the signs of their estimates obtained on the original sample. In the Individual change method, the resampling statistics are computed where the sign of each individual outer weight in the resample is made equal to the sign of the corresponding weight. This procedure seems to be a good procedure in the case where all signs in the same block are equal.

[15] In the Construct Level Changes procedure the vector of loadings for each latent variable in each resample is compared to the corresponding vector of loadings in the original sample.

Reduced model estimation: comparison between both approaches

Theoretically, the main differences between PLS and covariance methods estimations are related with the order used to calculate model parameters and latent variables, and with the imposed constraints. Using PLS, latent variable estimates are first computed subject to the constraint that they must comply to their manifest variable space. Model parameters are then computed using OLS multiple regression. With covariance-based methods, model parameters are computed by ML (or by Generalized Least Squares - GLS), and few constraints are imposed on the latent variables. Based on this, it may be expected that the structural equations are more significant with covariance-based methods than with PLS (coefficients of determination are larger) and the correlations between the manifest variables and their latent variables are stronger with PLS [189].

Regarding the results obtained for moulds makers' ECSI reduced model, the comparison between both approaches was based on the quality of estimated parameters (measured by coefficients of determination) and on the model loadings for measurement indicators. It is possible to verify that the differences between the results of the two approaches are the following: covariance-based methods increase the R^2 for the structural model (Figure 3.15) and PLS increases the loadings for the measurement model (Figure 3.16). This occurs because, as was already mentioned, PLS procedures estimate the latent variable as a linear combination of its manifest variables, so that the measurement model is favoured. In covariance-based methods, because each latent variable is estimated by regression of the "theoretical" latent variable on the whole set of own manifest variables, the structural model is favoured.

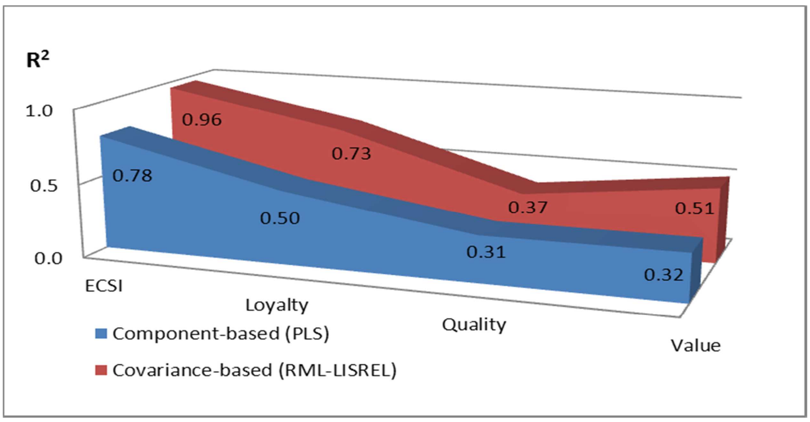


***Figure 3.15:** Quality of estimated models parameters measured by R^2: comparison between covariance-based and component-based approaches.*

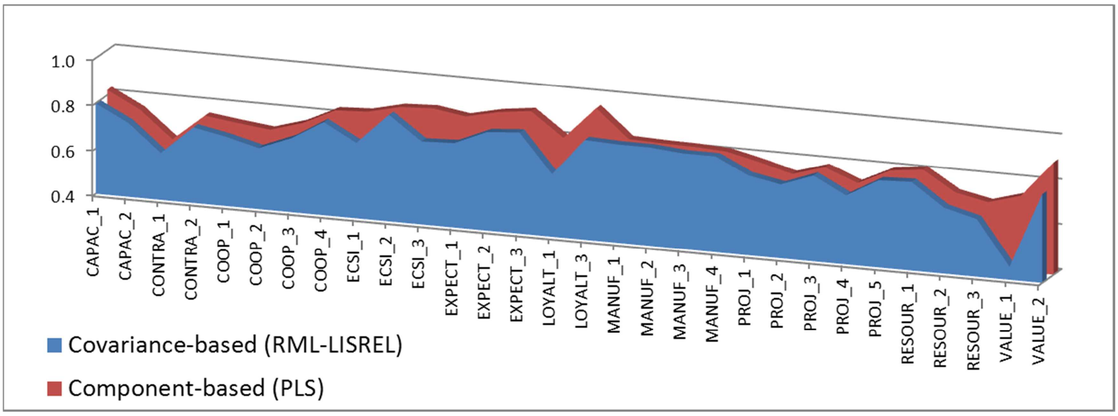


Figure 3.16: ***Measurement model loadings: comparison between covariance-based and component-based approaches.***

Nevertheless, it is possible to conclude that both methods give similar estimates, and it is possible to verify that the minimum R^2 value for customer satisfaction is 0.78 (PLS approach), which is quite satisfactory, particularly taking into account the model complexity. The comparison shows that the structural equations are more significant with covariance-based than with component-based approach (assessed by R^2), and that the correlations between the manifest variables and their latent variables are, in the majority of cases, stronger with component-based than with covariance-based approach. These results are theoretically consistent [173]. In addition, as shown in Figure 3.17, the correlation between the relative weight estimated by both approaches is quite high (R^2 = 0.998), indicating that both approaches produce similar estimates in this particular situation.

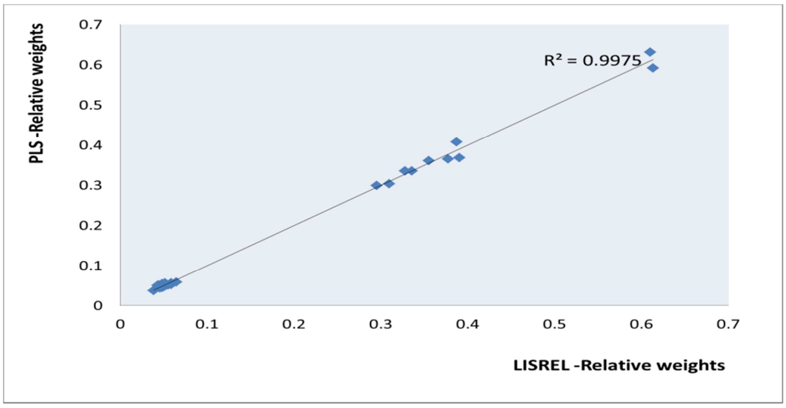


Figure 3.17: ***Comparison between component-based (PLS) and covariance-based (RML-LISREL) relative weights.***

Based on the previous conclusions, namely that similar results are obtained by the two approaches, and considering covariance-based limitations (which clearly limits its scope), the PLS approach will be used to determine the complete ECSI model parameters estimation.

Complete model estimation through component-based approach

At this stage, the PLS algorithm is used for the estimation of the complete ECSI model, designed for the Portuguese mould's maker sector and previously presented in Figure 3.6. Due to the high complexity of the model, and considering that the goal is to identify which design characteristics would meet customer's satisfaction and retention, the *Perceived Quality* construct is now decomposed into three constructs instead of the initial six. To that end, the latent variables concerning complementary attributes for moulds, namely, Cooperation, Contracts, Quality of Resources and Capacity of Response, are grouped in a single construct entitled *Service.* Therefore, the *Perceived Quality of Product and Service* is now described by *Quality of mould's design* (Design), *Quality of mould's construction* (Manufacturing) and *Service*, as schematically illustrated in Figure 3.18.

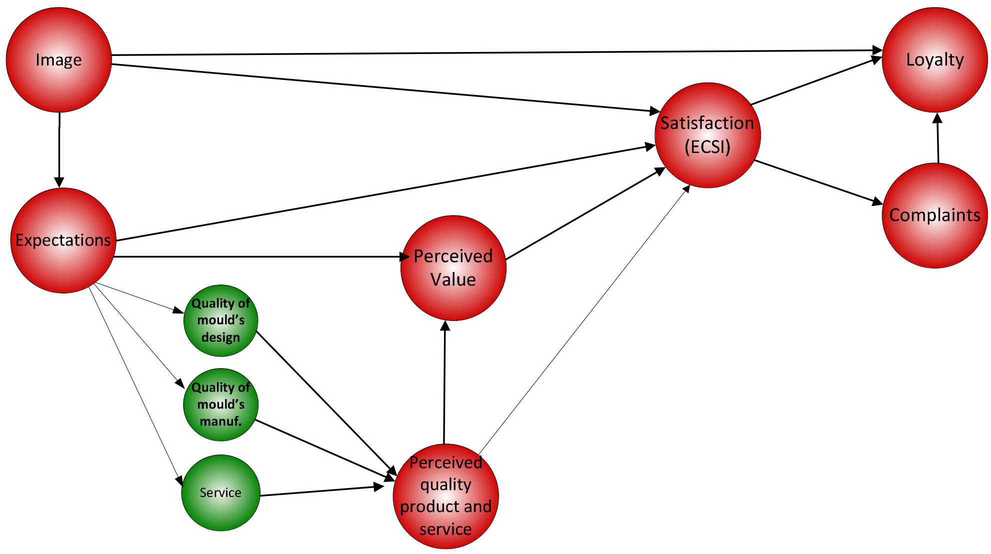


Figure 3.18: Final ECSI model for mould´s makers sector.

Then, using the same options described in Table 3.6, the parameters for the complete ECSI for moulds makers were estimated. The results are presented in Figure 3.19. Note that PLS assumptions regarding the existence of correlation between manifest variables and the respective latent variable imply that the outer weights associated to a latent variable have a positive sign or, at least, have the same sign. Therefore, the model was estimated by removing *Image_2* (i.e. this variable has an opposite sign, regarding the remaining manifest variables of the Image block). *Loyalty_2* was also dropped out because its estimated loading was lower than 0.5. This low value means that there is less shared variance between the construct and its measure than error variance (i.e. this item has no individual reliability) [193].

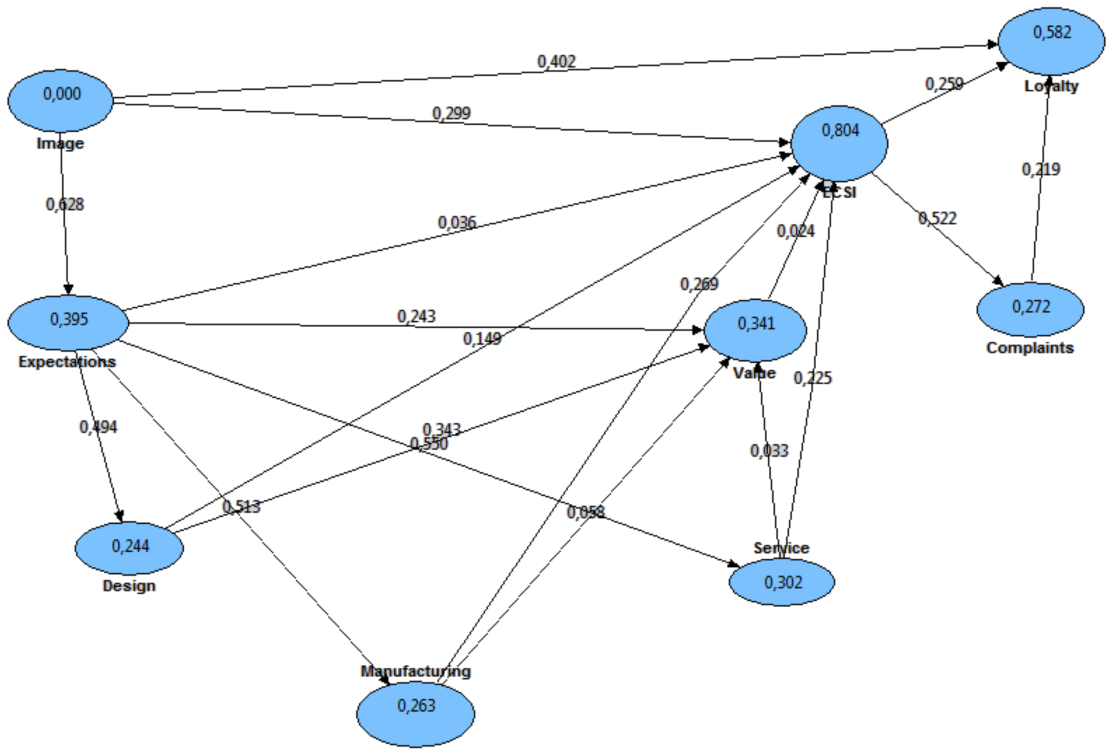


Figure 3.19: Path model for final ECSI model regarding Portuguese mould´s makers sector.

The R^2 value for ECSI is 0.804 (see Figure 3.19). Considering that the minimum required R^2 value for accuracy, established by the ECSI Technical Committee, is 0.65, it can concluded that the model presents a very good capacity of CSI explanation, especially considering its complexity. Regarding the model validation, first of all, it is necessary to check if all the manifest variables of a single latent variable/block are positively correlated. This condition emerges because PLS Path modelling assumes that blocks of the reflective measurement model are unidimensional. There are three tools to check block's dimensionality (internal consistency): *Cronbach's* α, Principal component analysis and *Dillon-Goldstein's* ρ. The Dillon-Goldstein's value is considered to be a better indicator (Chin (1998) cited by [191]). The results obtained for this indicator can be observed in Table 3.8. Considering that unidimensionality holds if the value of *Dillon-Goldstein's* ρ is at least 0.7, it is concluded that all blocks have unidimensionality.

Table 3.8: Verification of block's unidimensionality.

	Dillon-Goldstein's ρ
Complaints	0.858
ECSI	0.899
Expectations	0.903
Image	0.886
Loyalty	0.878
Manufacturing	0.950
Design	0.920
Service	0.940
Value	0.793

The results of PLS modelling may be validated by assessing the model as a whole and by testing the significance of model parameters. Hence, following Tenenhaus *et al.* (2002) [191] recommendations, the assessment of the significance of model parameters can be performed by Bootstrapping analysis with Construct Level Changes. The results obtained are presented in Table 3.9 and Table 3.10 for latent and observable variables, respectively. Based on these results, there are four most likely non-significant paths (identified in bold in Table 3.9). Each path was removed from the model, one by one, and the new model was re-evaluated. This procedure indicates that three paths must be removed from the model, namely: Expectations→ECSI, Manufacturing→Value and Service→Value. Value→ECSI must be kept in the model, since its removal reduces the R^2 of ECSI.

Table 3.9: t-values obtained by Bootstraping procedure regarding latent variables (N=200): ECSI model.

	t – values
Complaints -> Loyalty	2.858
ECSI -> Complaints	5.851
ECSI -> Loyalty	2.119
Expectations -> ECSI	**0.760**
Expectations -> Manufacturing	3.996
Expectations -> Design	4.072
Expectations -> Service	4.499
Expectations -> Value	2.087
Image -> ECSI	2.938
Image -> Expectations	6.964
Image -> Loyalty	3.090
Manufacturing -> ECSI	2.964
Manufacturing -> Value	**0.507**
Design -> ECSI	1.966
Design -> Value	1.943
Service -> ECSI	2.523
Service -> Value	**0.225**
Value -> ECSI	**0.553**

Table 3.10: t-values obtained by Bootstraping procedure regarding observable variables (N=200): ECSI model.

	t – values		*t – values*
CAPAC_1 <- Service	9.273	IMAGE_4 -> Image	9.659
CAPAC_2 <- Service	6.841	IMAGE_5 -> Image	8.361
COMPLA_1 <- Complaints	10.497	LOYALT_1 <- Loyalty	8.280
COMPLA_3 <- Complaints	5.910	LOYALT_3 <- Loyalty	11.206
CONTRA_1 <- Service	7.229	MANUF_1 <- Manufacturing	9.204
CONTRA_2 <- Service	6.940	MANUF_2 <- Manufacturing	9.919
COOP_1 <- Service	8.510	MANUF_3 <- Manufacturing	10.007
COOP_2 <- Service	7.339	MANUF_4 <- Manufacturing	10.432
COOP_3 <- Service	6.354	PROJ_1 <- Design	9.033
COOP_4 <- Service	9.758	PROJ_2 <- Design	8.715
ECSI_1 <- ECSI	11.323	PROJ_3 <- Design	11.189
ECSI_2 <- ECSI	8.587	PROJ_4 <- Design	7.869
ECSI_3 <- ECSI	9.903	PROJ_5 <- Design	9.344
EXPECT_1 <- Expectations	8.269	RESOUR_1 <- Service	10.112
EXPECT_2 <- Expectations	9.344	RESOUR_2 <- Service	8.302
EXPECT_3 <- Expectations	12.131	RESOUR_3 <- Service	7.453
IMAGE_1 -> Image	10.407	VALUE_1 <- Value	3.517
IMAGE_3 -> Image	9.655	VALUE_2 <- Value	10.35

Once the significance of the model parameters was established, the final estimation of our complete ECSI model is reached. Figure 3.20 presents the estimated model. To conclude, a final validation must be performed considering an assessment of the overall model. This final step includes convergent and discriminant validity, as well as prediction relevance assessment.

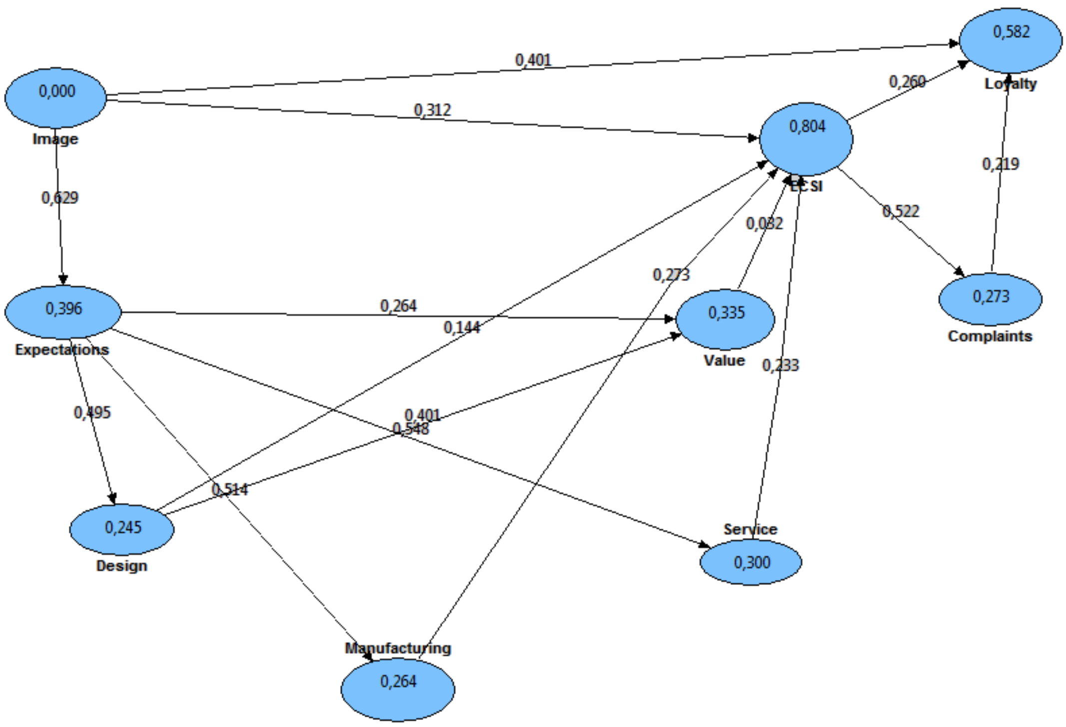


Figure 3.20: Estimated model regarding the complete ECSI for mould´s makers sector.

Convergent validity assessment

This validity aims to measure the goodness of the measurement model in terms of how much of the total validity of the manifest variables is explained by the respective latent variable. This can be evaluated by the amount of variance that each latent variable captures from its indicators with respect to the amount due to the measurement error. The index reflecting this amount is given by the Fornell-Larcker's *AVE*. If the latent variables have *AVE* scores greater than 0.5, this means that the construct has convergent validity. The present model has convergent validity because all the *AVE* values are greater than 0.5 (see Table 3.11).

Table 3.11: ***AVE for the model's constructs.***

	AVE
Complaints	0.743
ECSI	0.743
Expectations	0.781
Loyalty	0.774
Manufacturing	0.828
Design	0.701
Service	0.594
Value	0.674

Discriminant validity assessment

The discriminant validity measures the extent to which the indicators of a given construct differ from the indicators of other constructs [193]. In fact, although the latent variables can be correlated, they must measure different concepts. Thus, it must be possible to discriminate between them [207]. There are different ways to evaluate the discrimination validity. The most well-known consists of comparing the *AVE* values for all latent variables with the squared correlation between the respective constructs [210]. If the variance explained by the construct is greater than the variance shared between the construct and other constructs in the model, this means that it has discriminant validity. This evaluation can be described mathematically by the following equation:

$$AVE_j > cor^2\left(\hat{\xi}_j, \hat{\xi}_{j'}\right) \forall j' \neq j \qquad \textbf{Eq. 14}$$

where AVE_j is the portion of variance of each block *j* explained by its own latent variable ξ_j that must be larger than the portion of variance of each other latent variable $\xi_{j'}$ explained by ξ_j. From the operational point of view, this comparison can be performed replacing the diagonal elements in the correlation matrix of the latent variables by the corresponding

$\sqrt{AVE_j}$. If the diagonal value is larger, in absolute value, than all the elements in the y[th] column of the matrix, the discriminant validity is verified. Table 3.12 presents the results obtained to evaluate discriminant validity regarding the proposed model.

Table 3.12: ***Correlation matrix with diagonal elements substituted by*** $\sqrt{AVE_j}$.

	Comp	*ECSI*	*Exp*	*Loy*	*Man*	*Des*	*Serv*	*Value*
Complaints	*0.862*	0.522	0.196	0.528	0.499	0.510	0.543	0.304
ECSI	0.522	*0.862*	0.570	0.702	0.811	0.801	**0.842**	0.521
Expectations	0.196	0.570	*0.884*	0.442	0.514	0.495	0.548	0.463
Loyalty	0.528	0.702	0.442	*0.880*	0.624	0.641	**0.730**	0.336
Manufacturing	0.499	0.811	0.514	0.624	*0.910*	0.805	**0.808**	0.482
Design	0.510	0.801	0.495	0.641	0.805	*0.837*	**0.818**	0.532
Service	0.543	0.842	0.548	0.730	0.808	0.818	*0.771*	0.486
Value	0.304	0.521	0.463	0.336	0.482	0.532	0.486	*0.821*

From Table 3.12, it is possible to conclude that there is a discriminant validity problem regarding Service (in bold). This fact can be explained by a possible customers misunderstanding about what are service activities and what is mould's design or mould's manufacturing. These items are, typically, highly correlated and important for customer satisfaction.

Prediction relevance assessment

Since PLS does not require any kind of assumption regarding indicators and standard error distributions, the typical goodness-of-fit indices used in covariance-based approaches cannot be applied here. The structural prediction of the model can be achieved by R^2, whose values are presented in Table 3.13. The R^2 for customer satisfaction is 0.804 and for Loyalty is 0.582 (i.e. the model is able to explain 80.4% of customer satisfaction and 58.2% of Loyalty variabilities), which can be considered very satisfactory values.

Table 3.13: ***Prediction power of structural model: complete ECSI model.***

	R^2
Complaints	0.273
ECSI	0.804
Expectations	0.396
Loyalty	0.582
Manufacturing	0.264
Design	0.245
Service	0.300
Value	0.335

In summary, it is possible to conclude that, although the model is not perfect, there is a good reason to be satisfied with its estimation. In fact, it has internal consistency, convergent validity (*AVE*>0.5) and a very good capacity of prediction (more than 65% of ECSI variation is explained by its drivers).

Model interpretation

The estimated indexes for each of the latent variables are presented in Table 3.14. Considering the total effect (direct plus indirect) over the ECSI, it is possible to observe that the most important variable over customer satisfaction is *Image* (0.53). On the other hand, *Value* has no significant impact on customer satisfaction (0.032), which is not a very typical situation in ECSI studies, and may indicate that the mould's value is not a main preoccupation for customers. This evidence may be justified by the critical importance of moulds for the injection process performance [14]. Hence within certain limits, mould's price can be regarded by customers as a minor factor. On the other hand, *Loyalty* mainly depends upon *Image* (0.601), followed by *ECSI* (0.374) and *Complaints* (0.219). It is also possible to observe that the highest index value obtained is for customer's *Loyalty* (76.0), which reveals a positive customer's commitment and retention [185], whereas *Perceived Value* presents the lowest score (61.1). Furthermore, it is also possible to define ECSI and Loyalty structural equations as follows:

$$ECSI = \boldsymbol{\beta} + 0.354\text{Expectations} + 0.535\text{Image} + 0.157\text{Design} + 0.273\text{Manufacturing} + 0.233\text{Service} + 0.233\text{Value} + \zeta \qquad \textit{Eq. 15}$$

$$Loyalty = \boldsymbol{\beta} + 0.6\ \text{Image} + 0.132\text{Expectations} + 0.06\text{Design} + 0.102\text{Manufacturing} + 0.087\text{Service} + 0.012\text{Value} + 0.374\text{ECS} + 0.219\text{Complaints} + \zeta \qquad \textit{Eq. 16}$$

Table 3.14: ***Direct, total effect and index values.***

	ECSI		*Loyalty*		*Index*
	Direct	**Total**	**Direct**	**Total**	***values***
Complaints	-	-	0.219	0.219	67.9
ECSI	-	-	0.260	0.374	70.6
Expectations	-	0.354	0.000	0.132	70.7
Image	0.312	0.535	0.401	0.601	74.8
Loyalty	-	-	-	-	76.0
Manufacturing	0.273	0.273	-	0.102	74.5
Design	0.144	0.157	-	0.059	75.0
Service	0.233	0.233	-	0.087	67.4
Value	0.032	0.032	-	0.012	61.1

Based on the values presented in Table 3.14, it is possible to build a map that points out the priorities that should be taken into account in order to achieve higher levels of customer satisfaction. Following Hsu *et al.* (2006) strategy, a company must actuate on the most critical items (i.e. items with more impact on ECSI and with smaller index values). This strategy indicates that it is necessary to improve the items that do fall under the "do better" quadrant. According to the proposed model, for the industry under analysis these items are: Service, Expectations and Manufacturing, as shown in Figure 3.21. However, it is important to mention that the values used to define each quadrant's size should be determined strategically by the company's managers. The values assumed here correspond to the ones recommended by Hsu *et al.* (2006) [211].

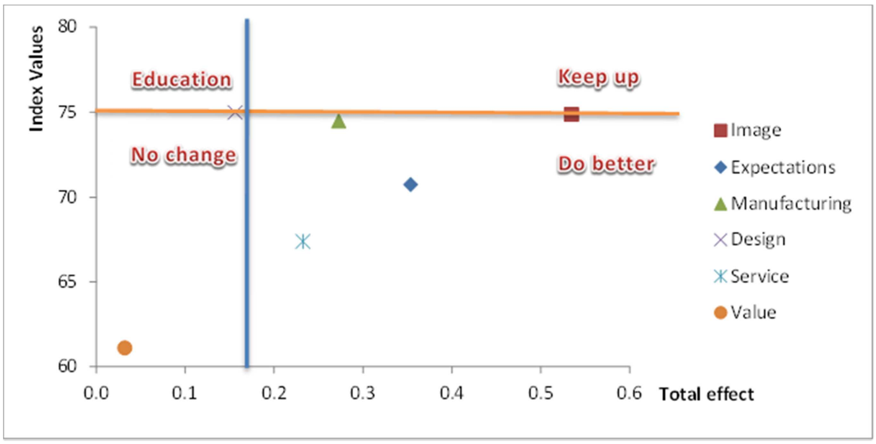


Figure 3.21: The indexes values versus total impact effect regarding model's latent variables.

Finally, an important goal of the product definition stage is to identify the critical items for achieving high levels of customers' satisfaction and loyalty. Therefore, one special focus must be put on the design quality construct (i.e. Quality of mould design). To that end, it is necessary to determine the relative weights of each one of the five indicators of Quality of mould design construct in order to identify the critical items to achieve high scores on quality of the design. Table 3.15 presents the relative outer weight values gathered through PLS estimation for each one of the five indicators. It is possible to observe that all indicators present similar importance, where the highest weight is 0.23, for "The use of adequate constructive solutions", while "The companies' accessibility in discussing the mould's design" presents the smallest weight value of 0.18. This evidence points out that all these items are important for customers and for that reason none can be disregarded.

Table 3.15: Relative outer weights for the indicators of quality of design.

Indicators of Quality of moulds design	Relative weights
The capacity of the mould's design meeting your product requirements	0.20
The mould's design capacity according to your specific injection process	0.19
The use of adequate constructive solutions	0.23
The companies' accessibility in discussing the mould's design	0.18
The overall quality of mould's design	0.19

Afterwards, since the importance (weight) of each individual indicator regarding the quality of mould design is known, it is necessary to deploy each indicator into the respective attributes requested by customers. A team of seven mould experts identified the typically CAs required by the injection mould customers when they order the mould. Figure 3.22 summarizes the CAs identified and its links to the individual indicators.

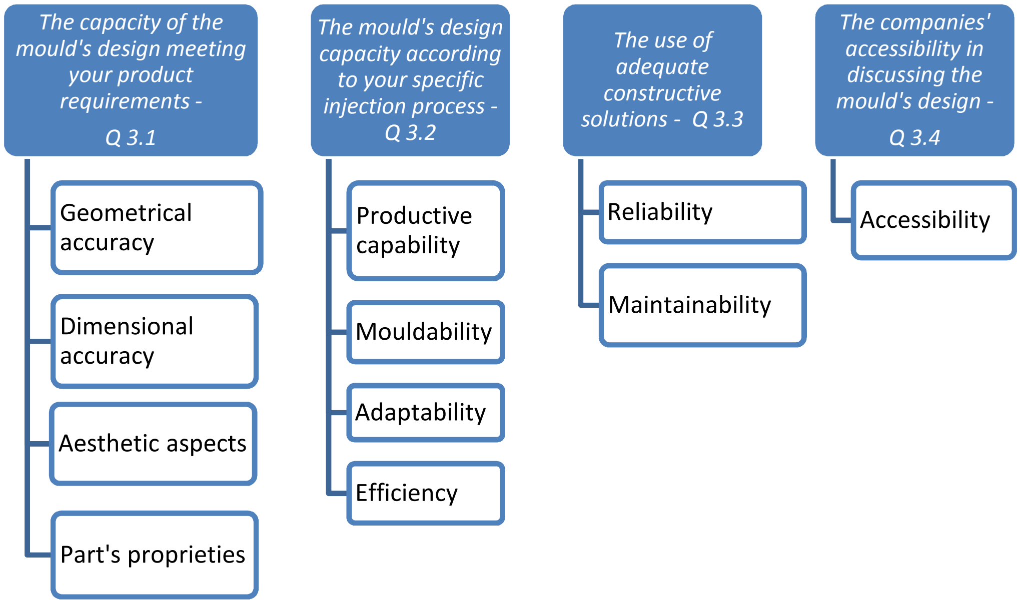


Figure 3.22: Typical CAs regarding injection mould design.

The AHP methodology was adopted in order to refine and prioritize the identified CAs. AHP is a theory of measurement that uses pairwise comparisons along with expert judgments to deal with qualitative or intangible criteria [212]. This technique is widely used for addressing multi-criteria decision-making problems, since it assures the consistency and stability of the subsequent decisions [111]. Therefore, the team of seven mould experts was also requested to compare each CAs previously identified, two at a time. They used in this comparison a 1-9 scale [110], with three levels: 1 - Equal importance; 3 – Moderately more important; 9 - Extremely more important. In order to get a meaningful group preference, and assuming that each decision-maker is of equal importance, the Aggregating Individual Judgment (AIJ) approach was used [112]. Hence, each attribute was ranked according to its relative importance to customers in order to build a weighted objective function. The results can be observed in Table 3.16. It is important to note that at this stage the rank is done globally, even though it must be defined for each particular mould order in order to encompass its specificities.

Table 3.16: Relative priority of each CAs: Quality of mould design.

Customer Attributes		Relative weights per indicator
Part's requirements (Q3.1)	Geometrical accuracy	0.436
	Dimensional accuracy	0.234
	Aesthetic aspects	0.198
	Properties	0.132
Process' requirements (Q3.2)	Productive capability	0.422
	Mouldability	0.289
	Adaptability	0.235
	Efficiency	0.054
Constructive solutions (Q3.3.)	Maintainability	0.568
	Reliability of solutions	0.432
Accessibility (Q.3.4)	Accessibility	1.000

Based on these values, it is possible to mathematically express customer satisfaction in order to take into account the quality of design improvements, as a function of the previous CAs:

$$\begin{aligned} CSI &= 0.157Design = 0.157(0.2\text{Part} + 0.19\text{Process} + 0.23\text{Solutions} + 0.18\text{Accessibility}) \\ &= 0.157(0.08\text{Geometrical} + 0.05\text{Dimensional} + 0.04\text{Aesthetic} \\ &+ 0.03\text{Properties} + 0.09\text{Capability} + 0.05\text{Mouldability} + 0.04\text{Adaptability} \\ &+ 0.01\text{Efficiency} + 0.13\text{Maintainability} + 0.10\text{Reliability} \\ &+ 0.18\text{Accessibility}) \end{aligned} \qquad \textit{Eq. 17}$$

It is important to highlight that Eq. 17 was obtained through the ECSI equation previously determined (Eq. 15). However, since customer satisfaction must be expressed mathematically as a specific function of CAs, at this stage the objective is to determine CSI instead of ECSI.

Step 4: Linking product definition and design

According to AD theory, the world of design is made up of four domains: the customer, the functional, the physical and the process [7] (see Figure 3.23). Thus, the starting point of the process design must be the identification of CAs, in the customer domain. These must be translated into specific requirements, designated as FRs, which are formalized in the functional domain. This analysis will help the designer to better identify the critical aspects of the design and thereby making the design process simpler and more effective [213].

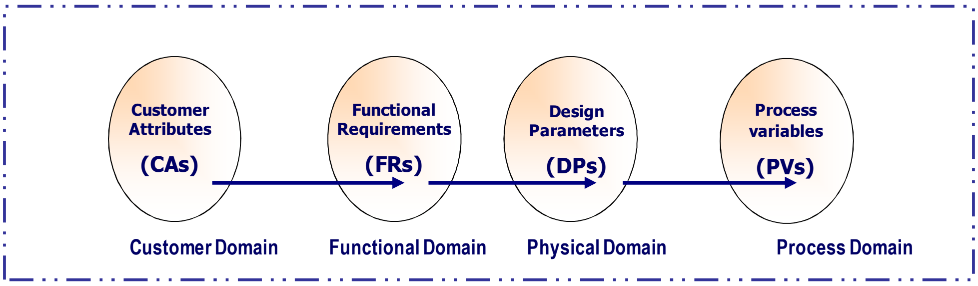


Figure 3.23: World of AD design: domains.

Based on that, the previously established CAs were translated into specific requirements, the FRs, as shown in Table 3.17. This corresponds to the minimum set of FRs in the functional domain.

Table 3.17: Mapping between CAs and FRs: Quality of mould design.

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

Given the previous mapping, it is possible to reformulate Eq. 17 as a function of FRs instead of CAs as expressed by:

$$\begin{aligned} CSI = 0.157Design &= 0.157(0.2\text{Part} + 0.19\text{Process} + 0.23\text{Solutions} + 0.18\text{Accessibility}) \\ &= 0.157(0.08\text{Deflection} + 0.05\text{Shrinkage} + 0.04\text{Sink} + 0.03\text{Stress} \\ &+ 0.09\text{tCycle} + 0.05\text{Pressure} + 0.04\text{Vmould} + 0.01\text{Waste} + 0.13\text{MDT} \\ &+ 0.10\text{MTBF} + 0.18\text{Information}) \end{aligned} \qquad \textit{Eq. 18}$$

Regarding the construction of the previous table, some important theoretical considerations were taken into consideration that must be explained. In the following list a brief clarification of the translation of the identified CAs into the FRs is presented.

1. *Geometrical Accuracy* was translated into *Deflection*. Deflection or Warpage is one of the most important factors affecting the geometric form of injected plastic parts [160]. Warpage, which can be described as a distortion of the shape of the final injection moulded item, is mainly caused by differential cooling [214]. Thus, the non-uniform cooling leads to differential shrinkage through the thickness of the part where the hotter surfaces tend to shrink more that the cooler surfaces. This differential shrinkage causes internal stress that is likely to warp the part;

2. *Dimensional accuracy* was translated into *Shrinkage*. The injection moulding process is generally used to produce parts that have fairly tight dimensional tolerance requirements. However, many plastic materials exhibit relatively large mould shrinkage values and, unfortunately, mould shrinkage is not always isotropic in nature [214]. Then, because plastic parts shrink, it is essential to accurately account for this shrinkage in the design of the mould so that critical dimensional tolerances can be met;

3. *Aesthetics* was translated into *Sink Marks*. The formation of sink marks on the moulded parts is one of the flaws that limits the overall success of the injection moulding technology. It occurs when the hot melt contacts with the cold mould wall, cooling too quickly, which causes a thin skin below the surface around the hot melt [215]. Then, the subsequent thermal contraction of the core hot melt can result in the surface skin sinking. If there is not enough melt to compensate it, then a sink mark is formed [216]. These depressions are typically small, but quite visible and significantly impair the surface quality of the plastic parts. Although sink index does not affect part strength or function, these are perceived to be severe quality defects [217];

4. Part's *Properties* was translated into *Residual Stress*. Despite the injection moulding being one of the most important polymer processing methods for producing plastic parts, with high retirements regarding part's quality, there are still several unresolved problems that confound the overall success of this process. One of these problems is residual stress caused by inappropriate mould design and can be the cause of premature part failure in service [218]. Residual stresses in the part result from stresses generated during mould filling and packing (i.e. flow-induced stresses) and from thermal-induced stress, caused by differing rates of cooling due to variations in the part surface temperatures. Several theories were developed for calculating residual stress distributions. A brief detail of some works can be found in [219, 220]. It is also important to note that in Autodesk Moldflow® Insight 2010 code (MOLDFLOW) [221], the in-cavity residual stress represents

the stresses in the part before it is ejected [222]. Thus, the value of residual stress in the orientation direction is determined by MOLDFLOW as In-cavity residual stress in the first principal direction;

5. *Productive capability* was translated into *Cycle time*. Injection moulding is recognized as one of the most efficient manufacturing techniques for economic production of precision plastic parts with complex shapes [223]. Thus, the time of each injection moulding stage is an important issue, because it significantly affects the process productivity. The sequence of events that are repeated in each injection process cycle begins with the heating of the plastic material in the plasticator, i.e. in the *Plasticizing* stage. Then, in the *Injection* stage, a controlled volume shot of melt is injected under pressure into the closed mould. Once the cavity is filled, a holding pressure is maintained to compensate for material shrinkage and to prevent back flow of the melt. This stage is designated *After-Filling* or *Packing* stage. At the same time, in the *Cooling* stage, the thermoplastic is cooled, or the thermoset is heated, until it is sufficiently rigid to be ejected. Once the part is sufficiently rigid to be demoulded, the mould opens, the part is ejected and the mould is closed so that it is ready to start the next cycle. This final stage is known as *Release* stage. Based on this sequence of events, cycle time can be computed as the overall sum of each stage's time, namely, injection stage plus packing stage plus cooling stage plus plasticising stage, and finally, plus the release mould stage. A more complete description of the followed approach regarding cycle time computation, can be found in Ferreira *et al.* (2010) [151];

6. *Mouldability* was translated into *Pressure*. Injection mouldability quantifies the capability of a plastic part to be moulded [224], which mainly depends of plastic behaviour at its melting point. In fact, there are materials that show sharp decreases in viscosity at their melting point, which allows them to flow in the mould cavity more readily. Given the fact that material is typically imposed by mould's customers, it is important to determine the minimum filling pressure to overcome the resistance to flow of that specific material. Ideally, filling pressure variation should be gradual and not abrupt. Thus, a good mouldability occurs when pressure gradient, i.e. pressure drop per unit length, is constant along the flow path. In this sense, Cheng *et al.* (2008) [225] highlighted that it is important to integrate mouldability evaluation with mould design for the purpose of achieving low product costs, as well as short cycle times. In fact, it is important to design a mould that can lead to an arrangement that will save on power, as well as wear and tear on machines, by using lower injection pressures;

7. *Adaptability* was translated into mould's *Volume*. In terms of mould's adaptability, the goal of the customers is to acquire moulds that are compact, easy to install and easy to operate. About its size, it is critical that it obeys to some characteristics of the available injection machines [226] (a brief description of the critical injection machine characteristics can be found in Rosato *et al*. (2001) ([227] page 131). For instance, the mould designer should verify that the mould physically fits in the injection machine. Moreover, even if the mould fits the moulding machine it may still not be operable with the mould. This is the case when the injection unit does not have enough shot volume, or does not provide enough melt pressure to fill the cavity, or does not exert sufficient clamp tonnage to hold the halves of the mould together when pressurizing the plastic melt. Finally, since injection machine features also contribute to mould's life and to an efficient operation, it is important to correctly specify mould's dimensions in order to take full advantage of the available injection machines;

8. *Efficiency* of injection process was translated into volume of material *Waste* through the feeding system. For cold runner moulds[16], mould's efficiency is mostly dependent of the feeding system because in each cycle its components are discarded (i.e. they are scrap of the process). Additionally, since the thickest wall section is often found in the cold runner, it is necessary to assure that the runner is solid enough to be ejected, which strangles the cooling time of the injection cycle. At the same time, the reduction of feeding system dimensions reduces the amount of plasticizing required by the injection unit, as well as the pressure needed to fill the mould, which in turn reduces the energy consumption per part;

9. Mould making sector covers a broad range of activities beyond its design. That is the case of prototype manufacturing, the production of new moulds and fixtures, its maintenance and modifications and technical assistance. According to Altan *et al.* (2001) [228] die maintenance is especially important because they tie up expensive production equipment and affect lead times. In fact, injection moulds allow the production of rather complex parts with undercuts or hollow geometries. Thus, these tools usually have multiple motion slides and punches, as well as cooling channels that complicate its operation. Based on that, maintenance and process robustness are two main issues to take into consideration during mould design:

[16] The moulds can be classified as either "cold runner" or "hot runner" moulds. For thermoplastics, a cold runner refers to a mould in which the sprue, the runner and gates are cooled, solidified and ejected with the moulded parts during each moulding cycle.

9.1. *Maintainability* was translated into *Mean Down Time (MDT)*. The repair and maintenance of moulds must be performed rapidly in order to maintain the production and keeping the injection process always running (i.e. getting a mould solution the most possible available to operate). The MDT is the average time that a system is non-operational due to repair, corrective and preventive maintenance. Based on that, maintainability concerns will be integrated with mould design regarding the use of inserts, standard components and multiple motion slides and punches, which can be decisive for achieving a short MDT;

9.2. *Reliability* was translated into *Mean Time Between Failure (MTBF)*. The mould solution focuses must be robust mould, i.e. should correspond to a solution that is the less sensitive to various variations caused by inherent functional interactions, or user conditions, or by adjusting the process parameters for obtaining a robust process [89]. This aspect has consequences on mould's reliability due to several reasons. First, there is a reduction in the number of breakdowns, as well as consequent production of irrecoverable plastic parts. Second, it becomes possible to use injection process running for a greater number of hours. Third, since mould design was adjusted to process parameters, it can be less sensitive to the effects of uncontrolled variations, which results in breakdowns and losses in process speed, as well as in the quality of injected plastic parts. MTBF quantifies the predicted elapsed time between inherent failures of a system during its operation;

10. *Accessibility* of mould design solution was translated into the *Information content*. Any designed solution must be described by a block of information that will be used in subsequent product manufacturing and operation. This information can be in the form of drawings, equations, material specifications, operational instructions, software, etc. Thus, to be able to produce and operate the product, this kind of information is required. According to AD theory [7], the amount of the required information, which is different for the several proposal solutions, must be measured in order to select the best solution. For that purpose, AD provides a selection metric based on design information content and states that, among those designs that satisfy the independence axiom (axiom 1), the design that has the smallest information content is the best design. This information measure is based on the second axiom of AD theory, called the Information Axiom. Regarding the design of injection moulds, customers are mostly focused with mould's install and operation. In this sense, their goal is that the moulding machine operator will be able to install and operate the injection mould with minimal information. Thus, the

Accessibility of mould design solution was translated into the Information content needed to install and operate the mould.

The objective of design is to conceive physical solutions that meets FRs. The solutions are characterized in terms of DPs. Therefore, the design must progress by interlinking these two domains (functional and physical) through a zigzag approach. For that purpose, in the next stage of the IDOV framework (i.e. the Design stage), a few number of solutions will be created by mapping the previous FRs into a set of DPs, in order to design some conceptual alternatives that maximize the level of customer satisfaction.

3.3.2 Design stage

The *Design* stage is mainly supported by the AD theory [7]. The main objective of this stage is to generate a few number of alternative moulds solutions, characterized by different values of DPs. To that end, different physical embodiments must be created, through mapping between the previously identified FRs and the respective DPs. Following AD guidelines, this mapping must be undertaken through a zigzagging approach. This approach states that design must progress from a system level down to a more detailed level (see Figure 2.1). As previously mentioned, this process may be stated in terms of a design hierarchy, in both functional and physical domains. The hierarchy implies that the decisions made at higher levels affect the statement of the problem at lower levels. This AD decomposition can help the physical structure generation [4] and to identify the potential system interactions (coupling) [113].

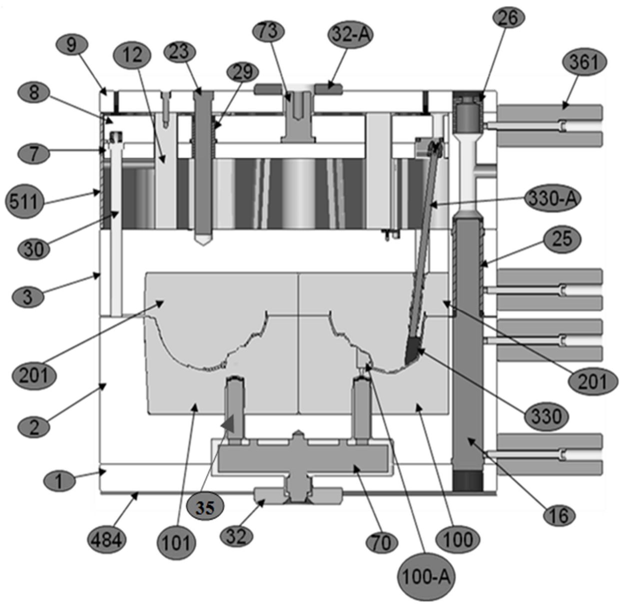
First of all, a top level set of FRs must be developed. The FRs are both collectively exhaustive and mutually exclusive, meaning that they define the entire scope of requirements for the entire system, and there is not any overlapping in the requirements which they describe. Once the top level FRs is defined, it is mapped, or zigged, to DPs at the same level of detail. Then, the top level FRs and DPs are both decomposed, or zagged, through a series of levels of various details, such as system, sub-system, component and function. For each level of decomposition, a design matrix **A** must be developed relating the FRs to their associated DPs, at that level. When working at the top-level design matrices, they can be initially populated with an X or 0, indicating either a mapping relationship or a lack of mapping relationship, respectively. Additionally, the basic postulate of the axiomatic approach to design, established by AD theory, is that there are two fundamental axioms that govern the design process. As previously mentioned, three types of design solutions emerge based on the relations between FRs and DPs. In the Uncoupled design, most preferred because it guarantees axiom 1, the **A** matrix is a diagonal indicating the independence between FR-DP pairs. In the Decoupled design, the FRs can be answered systematically, FR_1 to FR_n, by considering only the first *n* DPs. Thus, the corresponding **A** matrix is triangular. Finally, the more undesirable solution is the coupled design, where a change in a DP may influence all FRs, simultaneously. Therefore, the **A** matrix has no special structure and consists of mostly non zeros elements.

Although the AD theory promotes that an uncoupled design solution must be achieved, some authors (e.g. [115, 116]) believe that there are some situations where uncoupled/decoupled solutions might not be feasible. This is the case of metallic moulds for plastic parts injection [229], for which, by technological and time reasons, mould designs are generally a coupled solution, or at least have some coupled areas. For that reason, if some remaining coupled relations subsist, they are not considered prohibitive.

In order to proceed with FRs-DPs mapping regarding an injection mould, it is important to define its main function. Although there is not much research being done on this initial stage of design (conceptual stage) [158], it is assumed that the replication of the geometry and of the finish requirements of the plastic parts are the main functions of an injection mould. Thus, from the technical point of view, the challenge is to design and produce a mould with machinable components, which provides an uniform filling and cooling, and, at the same time, must often be strong enough to withstand millions of cyclic internal loads, from injection pressures higher than 200 MPa and external clamp pressures that can reach over 7 000 tons [230]. Accordingly, an injection mould must satisfy the following main sub functions:

– Define the volumes which will form the parts that are to be produced, ensuring the reproducibility: *Impression system*;
– Allow the complete volume to be fulfilled by the plastic (provide means for molten plastic to be delivered from the injection moulding machine to the part forming cavities): *Feeding system*;
– Act as a heat-exchanger (cool the part rapidly and uniformly): *Heat-exchange system*;
– Promote the ejection of the parts from the mould: *Ejection system*;
– Have a structure that will resist internal melt pressures and compressive forces from the moulding machines clamp: *Structural system*.

Therefore, an injection mould can be seen as a structure with some typical functional systems, such as the impression system (cavity and core parts), the injection or feeding system (which includes the venting system), the ejection system and the heat-exchange system. Usually, its structure is composed of two halves, where the top half of the mould is commonly referred as to the cavity half, the fixed half of the mould or plate 2. The bottom half is known as the core, the movable half or plate 3. Both halves can be identified in the cross-sectorial view of a common mould assembly presented in Figure 3.24. In some cases, the cavity and core halves can be switched. The path for the melt (liquid plastic) to travel from the injection machine to the parting line is defined by a sprue bushing, which may feed directly a cavity (at a single gate point), a runner in a multi-cavity (more than one part injected for each injection cycle), or a multi-gates point part (more than one gate point per part). For cold runner systems, the plastic sprue and the runners are pulled from the sprue bushing by the ejection system during mould opening. For hot runner systems, the runners stay molten and are ejected during the moulding cycle.



Item	Designation	Item	Designation
1	Injection clamping plate	32-A	Locating ring
2	Cavity retainer plate	35	Sprue bushing
3	Core retainer plate	70	Mainfold
7	Ejector pin plate	73	K.O.
8	Ejector pin retainer plate	100	Cavity insert
9	Ejection clamping plate	100-A	Sub-insert
12	Support pillar	101	Cavity insert
16	Leader pin	201	Core insert
23	Ejector plate pin	330	Jinggle pin
25	Guide bushing	330-A	Jinggle pin rod
26	Centering sleeve	361	Mold floor support
29	Ejector plate bushing	484	Insulator plate
30	Return pin	511	Ejector protection plate
32	Locating ring		

Figure 3.24: Cross-sectional view of a common mould assembly (with authors' permission [231]).

Typically, the bottom half of the mould contains the core and the ejection system. The core usually refers to the portion of the two mould halves where there are protrusions, onto which the forming plastic part will shrink and to which it will adhere during mould opening. The part is then usually pushed off the core by a mechanical ejection system. In order to release the part after cooling, some space is normally provided to allow the movement (ejector stroke) of the ejector plates to which ejector pins are attached. This back and forth movement is assured by a hydraulic cylinder to which the ejector plate is attached. Based on this cycle, the main components of a typical injection mould, and respective functions, are as follows [151]:

(a) **Feeding System** (including the venting system). Its main function is to channel the molten plastic material coming from the injection nozzle of the moulding machine and distribute it into each cavity, through the runners and respective gate points. Generally, injection moulds can be classified as either “cold runner” or “hot runner” moulds. A cold runner refers to a mould in which the feeding system is cooled, solidified and ejected with the moulded part in each moulding cycle. In the case of a hot runner mould, the runner is kept in a molten state, avoiding a runner that must be refilled and discarded in each cycle. The hot runner system is typically composed of two components: the manifold and the drop(s). The venting subsystem must allow for gas release, because when the melt enters into the cavity the displaced air must have a means to escape. The design of this subsystem depends mostly on the part’s geometry, the injection moulding machine characteristics, parts position in the mould and its gating;

(b) **Heat-transfer System**. It supplies the mould with a system of cooling channels, through which a coolant is pumped. Usually, its main function is to remove heat from the mould, so that - once filled - the part is sufficiently rigid to be demoulded. Note that, given the fast cycle time of most machines, the coolant flow is continuous and, thus, some amount of heat evacuation is always ongoing;

(c) **Ejection System**. Its main function is to knock out the injection moulded parts, in order to release them from the mould. Typically, after the mould is opened, the hydraulic cylinder of the injection machine will actuate the ejection system to move forward, pushing the moulded parts out. It is critical that the ejection system does not cause damage (marks) of completed parts;

(d) **Structural System**. It must allow the mould (tool) to be coupled into the injection machine and assure the overall assembly of its components. It is also necessary to guarantee the alignment and guiding of the mould. According to the type of mould, it involves several metal plates to form a rigid body where some components are assembled together (e.g. locating ring, guide pins and guide bushings, amongst others);

(e) **Impression system**. The main function of the impression system is to give the required shape to the part. To do so, it is composed by the cavity, which is generally responsible for the external impression of the part, and by the core, which produces the internal impression. Typically, both cavity and core are machined in insert blocks of material, which are then tied to the cavity and core plates, as shown in Figure 3.25. Nevertheless, there are situations where both the cavity and core are machined directly on plates 2 and 3, respectively, as presented in Figure 3.26.

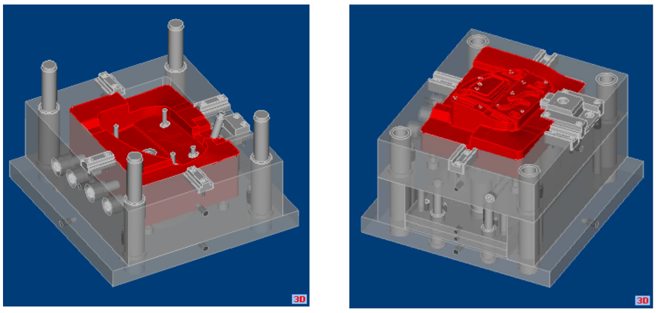


Figure 3.25: Cavity (left) and core (right) machined as cavity and core inserts.

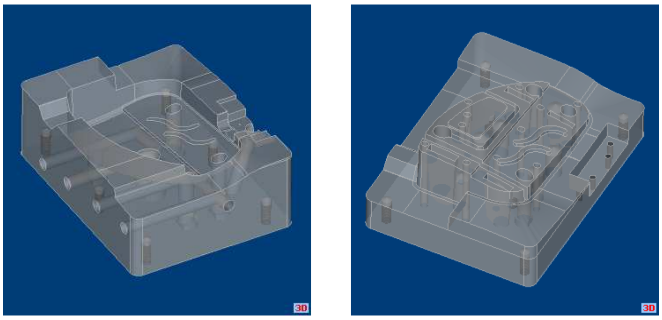


Figure 3.26: Cavity (left) and core (right) machined directly on plates 2 and 3.

(f) **Others components**: for complex plastic parts, some other mechanisms, such as slides, lifters, unscrewing devices, amongst others, might also be necessary.

Associated to each of these systems there are different DPs, which can dictate different requirements. Following these guidelines, and through zigzagging approach, the FRs-DPs mapping regarding injection mould's design was undertaken for the upper levels. Figure 3.27 presents the top design levels structure defined for the FRs and Figure 3.28 for the DPs.

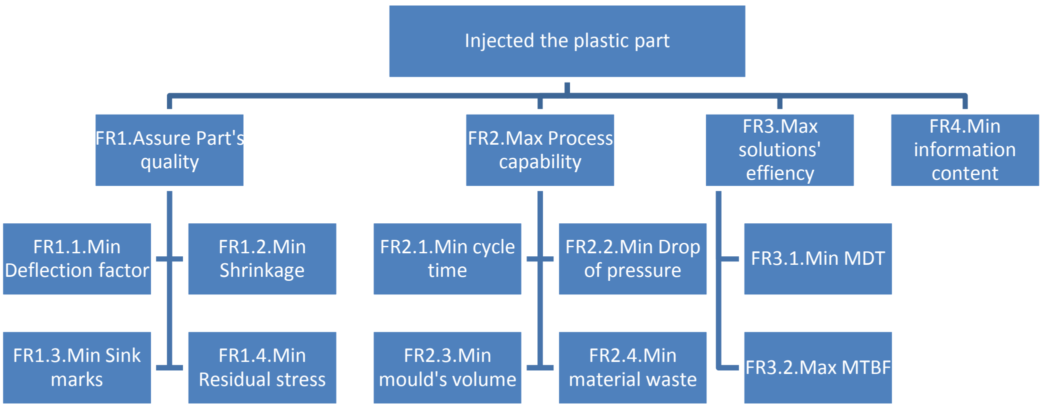


Figure 3.27: FRs defined for top design levels.

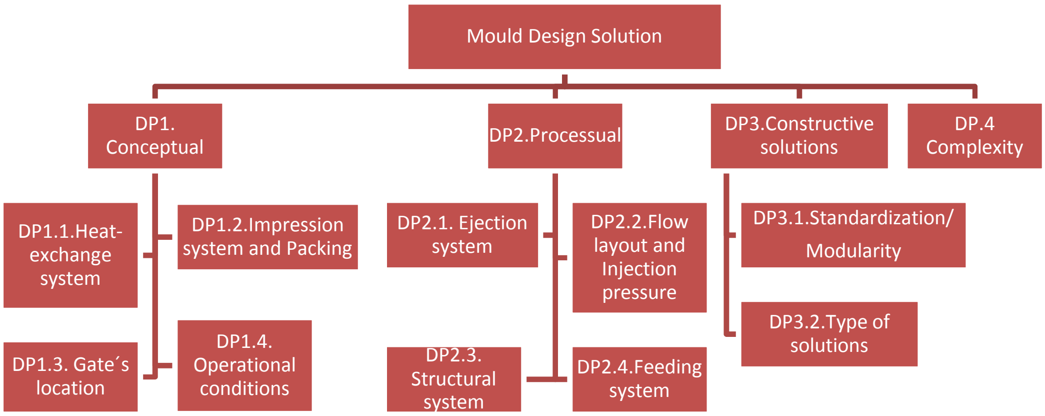


Figure 3.28: DPs defined for top design levels.

Based on the previous figures, it is possible to observe that, regarding the first two levels, the map between FRs and DPs has no special issues. However, this is not true for the third level, where some theoretical considerations were taken into account in its definition. A brief description of these considerations can be found in the following subsections.

Nevertheless, it is also important to highlight that some important decisions regarding the mould design are imposed by the mould customer. Because of that, they are assumed as fixed parameters for the mould design problem. Example of fixed design parameters are: part's geometry, part's material, number of cavities and injection machine characteristics (e.g. maximum clamping force, maximum allowable dimensions for moulds, etc.).

FR 1.1.: Deflection or Warpage – DP 1.1.: Heat-exchange system design

The Deflection or warpage of an injected plastic part is typically assigned to the following effects: differential cooling, orientation effects and corner effects [227]. The differential cooling reflects the warpage due to the internal stress caused by a non-uniform cooling, while orientation effect depends of melt's flow (i.e. flow-induced residual stress). Corner effect depends mainly of part's geometry but it is also influenced by cooling lines position. Variation in the cooling rate from the mould wall to its centre can cause thermal-induced residual stress. Furthermore, asymmetrical thermal-induced residual stress can occur if the cooling rate of the two surfaces is unbalanced. Such unbalanced cooling will result in an asymmetric tension-compression pattern across the part, causing a bending moment that tends to cause part warpage. In addition, non-uniform cooling in the part and asymmetric cooling across the part thickness from the mould cavity and core can also induce warpage after ejection.

Part warpage is a dimensional distortion that causes structural unfitness and aesthetic problems. This warpage is one of the critical quality issues for injection moulded parts, because when the moulded part does not satisfy a dimensional tolerance it is useless as final product [232]. For that reason, several studies on the effective factors of warpage have been reported [160, 218, 233, 234]. According to Liu (1996) [218], the warpage can be largely the result of thermally induced effects that arise during the mould cooling stage of the injection process. The magnitude of these effects is coupled to the geometry of the mould cavity and the viscoelastic behaviour of the plastic material. In his research, he verified that geometric presentation of the cooling process in terms of cooling channels should not be neglected. Similarly, through a numerical simulation model, Shen and Li (2003) [232] concluded that mould cooling has a significant effect on part warpage. Therefore, mould cooling parameters (e.g. cooling channels layout) must be carefully set. In addition, it is possible to verify that the flow induced stresses are generally lower, by one to two orders of magnitude, than those induced by thermal stresses [234, 235]. Thus, thermal stress caused by a non-uniform cooling is assumed as the major cause of part warpage. Since deflection and warpage depend mostly upon the heat-exchange system design (see DP 1.1. in Figure 3.28), this system must be detailed in the design variables presented in Table 3.18.

Table 3.18: Design variables regarding the heat-exchange design (DP 1.1.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	*n_turns*	Number of turns of the cooling line in cavities	Integer
Optimize	d_{Cool}	Diameter of the cooling lines	Continuous
	Z_{Cool}	Distance between the cooling line and the mould surface	Continuous
	pitch_cool	Distance between the cooling lines	Continuous
	dxycool	Distance on Y axis between cooling line and impression cavity	Continuous

Note that it is assumed that cooling lines are placed symmetrically regarding the position of parts' cavities on the Partition Plane (PP), and parallel to the Z axis. Regarding the type of coolant, for simplicity reasons it is always assumed that water is used.

FR 1.2.: Shrinkage – DP 1.2: Impression system and packing conditions

In general, three types of shrinkage occur in the injection moulding process: in-mould shrinkage (shrinkage during processing), as-moulded shrinkage (the shrinkage just after mould opening and sometimes referred to as-mould shrinkage), and post-shrinkage (time effects during storage as physical aging, recrystallization, etc.) [236]. The as-moulded shrinkage is of particular interest to the injection moulding industries and it is also the type of shrinkage included in the model. It can be computed as the difference in dimensions between the cavity and core dimensions, and the part [237]. Controlling the part shrinkage is of paramount importance in mould design, particularly in applications requiring tight tolerances. The impression system design (i.e. cavity and core design) should take shrinkage into account, in order to conform to the part dimension.

On the other hand, recent experimental studies showed that as-moulded shrinkage of injection moulded products is also affected by processing parameters [238, 239]. All studies conclude that the packing pressure is by far the most important parameter affecting shrinkage. For example, Jansen *et al.* (1998) [236] showed that the shrinkage of injection moulded products is strongly influenced by the packing pressure and melt temperature[17], while Kwon *et al.* (2006) [238, 239] found that the packing time and packing pressure are the most important parameters affecting volumetric shrinkage. Therefore, since shrinkage mainly depends of the impression system and packing conditions, these parameters were considered to be DP 1.2. The detailed design variables associated to this system and to the packing conditions are detailed in Table 3.19.

Finally, part's geometry may affect shrinkage due, for instance, to the existence of geometrical constraints (e.g. ribs, bosses, etc.) that affect the shrinkage boundary conditions. However, as mentioned before, since part's geometry is imposed by mould's customer this effect is included in the model as a fixed parameter.

Table 3.19: Design variables regarding impression system design and packing conditions (DP 1.2.)

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	*position_parts*	Position of each part relatively to the PP	Geometrical
	partition_plane	Position of the PP	Geometrical
	type_mould	Type of mould	Categorical (e.g. 2-plate, 3-plate)
Optimize	*cavity_dimensions*	Cavity dimensions (on X,Y and Z axis)	Continuous
	core_dimensions	Core dimensions (on X,Y and Z axis)	Continuous
	P_{pack}	Packing pressure	Continuous
	t_{pack}	Time of packing	Continuous

[17] It is important to note that melt temperature will be further included in the model as operational condition.

FR 1.3.: Sink Marks – DP 1.3.: Gate's location

In general, the aesthetic quality of a moulded part requires the absence of defects such as sink marks, bubbles, weld lines, flashing, etc. The injection moulded part quality is normally ensured by setting up the closed-loop controls of some important process/machine variables such as barrel heater temperatures, injection velocity profile and packing pressure profile [240]. In this sense, according to Ozcelik and Etzurumlu (2006) [160], the process parameter settings for plastic injection moulding greatly affect the quality of the plastic injection moulded product. The correlation between process conditions and final part quality has been widely studied both experimentally and theoretically [241].

As mentioned and regarding aesthetics defects, one of the major problems limiting the overall success of injection moulding is the presence of sink marks [215, 216]. Shen *et al.* (2007) [215] investigated the influence of the process conditions on sink marks formation. They concluded that the packing pressure, the melt temperature and the mould temperature are the principal factors affecting sink marks on an injection moulded part. On the other hand, several authors impute the quality of injected parts to the gate's location [24, 242], because it influences the manner in which the plastic flows into the mould cavity. For example, Pandelidis and Zou (1990) [24] considered that quality surface defects, such as sink marks, weld lines and over packing, can be only effectively controlled by the gate location. Therefore, the product quality can be greatly improved by determining the optimum gate location, as well as by some operational variables such as the packing pressure, melt and mould temperatures.

Since packing conditions were already included in the model due to the shrinkage (see Table 3.19), they were not related with sink marks. Regarding melt temperature and mould's temperature, they will be included in the model as main factors of part's proprieties, for reasons that will be presented later. Therefore, sink marks were assumed to be mainly related with the gate's location. Accordingly, the design variables included in the model as determinant for the aesthetics defects formation are the number of gates and its position, as shown in Table 3.20.

Table 3.20: Design variables regarding gate's location design (DP 1.3.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	n_{Gates}	Number of gates per part	Integer
	position_gates	Position of each gate relatively to the PP	Geometrical
	type_gate	Type of gate's geometry	Categorical

Regarding the design of gates, one important assumption was adopted. Since there are several types of gates, such as Edge (E), Submarine (SB), Pin-Point (PiP), Tab (T), Fan (F), Film (FI) and Diaphragm (a detailed description of each type, as well as its advantages and disadvantages, can be found in [226, 230, 243-245]), the developed platform assumed the PiP type as gate's geometry for any mould[18]. The main reasons for this option are the easily degating and the minimal vestige on the plastic part provided by the PiP type.

FR 1.4.: Residual stress – DP 1.4.: Operational conditions

According to Yang and Gao (2006) [246], the quality characteristics of the plastic injection moulded products can be roughly divided into three kinds of properties: (1) the dimensional properties, (2) the surface properties and (3) the mechanical properties. Since the first two groups were already included in the model, it remains to do the analysis of the mechanical properties. These properties involve, typically, the tensile strength and the impact strength of the plastic part.

As previously mentioned, during injection moulding the plastic material is injected in the molten state until attaining the desired shape. Then, this shape is rapidly frozen-in under pressure while stress builds-up. For these reasons, injection moulded products have always these stresses (the so-called residual stresses) that may adversely affect a proper product performance [247]. In fact, these processing stresses are important since they add up to the mechanical stresses that a product may experience during use, acting on the part with effects similar to the ones of the externally applied stresses [219]. If these residual stresses are high enough to overcome the structural integrity of the part, the part will warp upon ejection from the mould or crack with external service load [163].

Therefore, several theories were developed for estimating the residual stress distributions associated to the injection process. A summary of these theories can be found in Jansen and Titomanlio (1996) or Kabanemi *et al.* (1998) [219, 220]. For example, Zoetelief *et al.* (1996) [248] state that there are mainly two sources of residual stresses that influence the properties of injection moulded products. First of all, the viscoelastic flow of the melt during the filling and post-filling stage of the process causes frozen-inflow-induced stresses. Secondly, the differential shrinkage that occurs during cooling, both inside the mould and after demoulding, causes residual thermal stresses. Comparing the flow-induced and thermal

[18] At the reinforced platform (chapter 4), this assumption is not a limitation since the developed framework allow to generate different gate's geometry, as well as additional runner's configurations.

stresses magnitudes it is possible to observe that, typically, flow-induced is smaller. However, they induce anisotropy of several properties, because of the different orientations in the direction parallel and perpendicular to the flow direction. On the other hand, the thermal residual stresses cause warpage and may induce environmental stress-cracking. Additionally, since the injection process is characterized by high pressures, some authors found that considerable tensile stress arises at the surface of injection moulded parts during the packing stage [219, 248].

Nevertheless, both theories relate residual stresses with operational conditions, and, consequently were assumed as DP 1.4. These operational condition (see Table 3.21) encompass injection speed and temperature settings (e.g. melt temperature and mould temperature), as well as pressure conditions. Since packing conditions were already included in the model, they are not considered here.

Table 3.21: Design variables regarding operational conditions (DP 1.4.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Optimize	T_{melt}	Temperature of the melt	Continuous
	T_{mould}	Temperature of the mould	Continuous
	t_{inj}	Time of injection	Continuous

FR 2.1.: Cycle time – DP 2.1.: Ejection system design

Cycle time, FR2.1., can be defined as the sum of each stage time, considering that the injection moulding process has five main stages [227]. The first one, designated as Plasticizing (1), involves the heating and melting of the plastic in the plasticator. The second stage, named Injection (2), encompasses a shot of melt into the closed mould. The third stage, called After-Filling or Packing (3), aims to prevent back flow and tries to compensate the decrease in volume of the melt during the solidification. The fourth, named the Cooling (4), involves the cooling of the moulded part, in the mould, until it becomes sufficiently rigid to be ejected. Finally, the last stage corresponds to the Release (5), in which the part is removed through ejection pins driven by hydraulically opening of the mould. Afterwards, the mould is also hydraulically closed and the next cycle starts. In order to minimize the cycle time, the plasticizing stage (1) normally occurs simultaneously with the packing one (3), as shown in Figure 3.29. Therefore, it is not considered in the cycle time computation. Regarding the cooling stage, in fact, it begins with mould filling and finishes when enough heat has been removed from the part, in order to eject it without distortion. For this reason, the real cooling time results from the summation of the packing (3) and the so-called cooling stage (4).

Nevertheless, for cycle time computation the cooling time (4) is not the total time of cooling (i.e. real cooling), but only the excess cooling time required for the part to freeze [151].

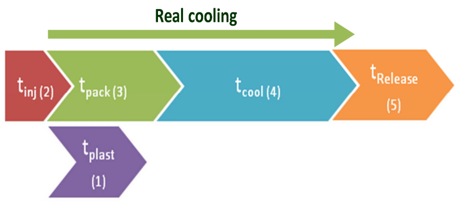


Figure 3.29: Timeline of injection moulding stages.

Injection (2) and packing (3) time are mostly dependent of the feeding system design, as well as of the operational conditions (e.g. injection pressure and injection time). Regarding the cooling time (4), it mainly depends on the heat-exchange system and some operational conditions, like for instance, the melt and the mould temperatures. Finally, the release time (5), which includes mould opening, part ejection and closing mould time, it is mainly function of the ejection system [221]. At this stage, only the ejection system design is not included in the model. Thus, based on the previous analysis it is assumed that the cycle time requirement is a function of the ejection system design. Therefore, FR2.1. (Cycle time) is mapped with DP2.1. (Ejection system design), which can be detailed according to Table 3.22.

Table 3.22: Design variables regarding the ejection system design (DP 2.1.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	$n_{Ejectors}$	Number of ejectors per part	Integer
	position_ejectors	Position of ejectors in relation to the PP	Geometrical
Optimize	$d_{Ejectors}$	Diameter of the ejectors pins	Continuous (standard)
	$l_{Ejectors}$	Length of the ejectors pins	Continuous (standard)

Furthermore, the ejection system design shall also consider the position of the plastic parts on the PP, since the ejectors must not cause damage (marks) on the completed parts. Thus, this system is dependent of the PP location included at the structural system design. It is also important to note that, at this stage, the design of complex elements of the ejection system, such as sliders or lifters, is not included. These elements are normally necessary to guarantee undercuts in plastic parts.

FR 2.2.: Pressure – DP 2.2.: Flow path and injection pressure

As mentioned before, a good mouldability occurs when the pressure drop per unit length is constant along the flow path. In fact, the pressure drop is caused by the viscous flow in the feeding channels, which generates shear stresses against the side walls. This pressure drop must be minimized since it reduces the injection pressure needed to inject the melt. Moreover, it is important to note that by using lower injection pressure, power is saved and the wear and tear on machines is minimized, consequently enlarging the mould's life. Based on that, FR2.2. (Pressure) is mapped with DP.2.2. (Flow path and injection pressure). They can be detailed on the design variables presented in Table 3.23.

Table 3.23: Design variables regarding the flow path and injection pressure (DP 2.2.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	*type_layout*	Type of feeding layout	Categorical (C, S)*
Optimize	P_{inj}	Injection pressure	Continuous

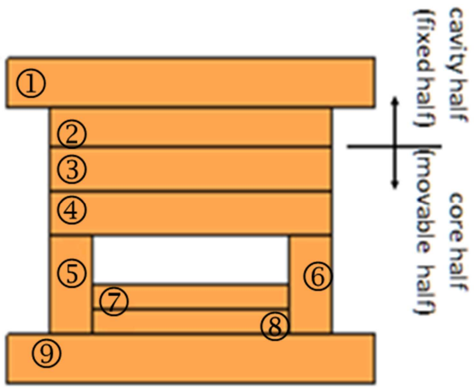
*C: Circular, S: Symmetrical

Regarding the design variable *type_layout*, some issues must be taken into consideration. First of all, there are three possible feeding configurations or layouts for cold runners, namely, Symmetrical (or in series configuration), Circular and Hybrid (i.e. that combines both circular and symmetrical layouts). A symmetrical layout can mostly compactly deliver the melt to many in-line cavities through a single primary runner, with many subsequent secondary runners leading to individual cavities. Since the secondary runners branch off at different locations down the length of the primary runner, the flow rate will be different for each cavity (lower for the cavities located further away from the sprue). This disadvantage can be overcome by assuming different diameters for each cavity, which can be difficult to do in practice. An alternative solution can be the branching of the feed system in multiple locations (multiple branching).

Regarding circular layouts, they naturally assure a balanced flow rate and melt pressure, with a moderate amount of runner volume. However, this balance is somewhat limited to the base of the sprue. Nevertheless, this can also be overcome by multiple branching. Note that multiple branching has limits, since a branched layout consumes significantly more material while it also imposes a higher pressure drop between the sprue and the cavities.

FR 2.3.: Mould's size – DP 2.3.: Structural system design

Regarding the FR2.3. (Mould's size), since the structural system design is the one that contributes the most for the size of the mould, it was defined as DP2.3. Note that this study considers a 2-plate mould type, which, in fact, includes nine plates, as shown in Figure 3.30.



1	Injection clamping plate or top clamping plate
2	Cavity retainer plate or plate A
3	Core plate or plate B
4	Core retainer plate
5, 6	Spacer Block
7	Ejector pin plate
8	Ejector pin retainer plate
9	Ejection clamping plate or bottom clamping plate

***Figure 3.30**: Typical structure for a 2-plates mould type.*

Based on that, a set of variables regarding the design of the structural system is defined and summarized in Table 3.24. A schematic representation of the design variables regarding structural system is illustrated in Figure 3.31.

Table 3.24: Design variables regarding the structural system design (DP 2.3.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	***mould_material***	Mould's material	Categorical (e.g. 1.1730, 1.1191)[19]
	cavity_material	Material for cavity's inserts	Categorical (e.g. 1.2767, 1.2743)
Optimize	X_3	Length of plate 3 (on X axis)	Continuous (standard)
	Y_3	Width of plate 3 (on Y axis)	Continuous (standard)
	Z_3	Height of plate 3 (on Z axis)	Continuous (standard)
	Z_1	Height of plate 1 (on Z axis)	Continuous (standard)
	Z_2	Height of plate 2 (on Z axis)	Continuous (standard)
	Z_4	Height of plate 4 (on Z axis)	Continuous (standard)
	Z_5	Height of plate 5 (on Z axis)	Continuous (standard)
	Z_9	Height of plate 9 (on Z axis)	Continuous (standard)

[19] Defined according to EN 10027-2, where a numerical identification of steel composition, but not product form, is provided. It is based on the German "Werkstoff" numbering system. These materials are recommended for general applications where simple and low toughness mould can be adopted [230].

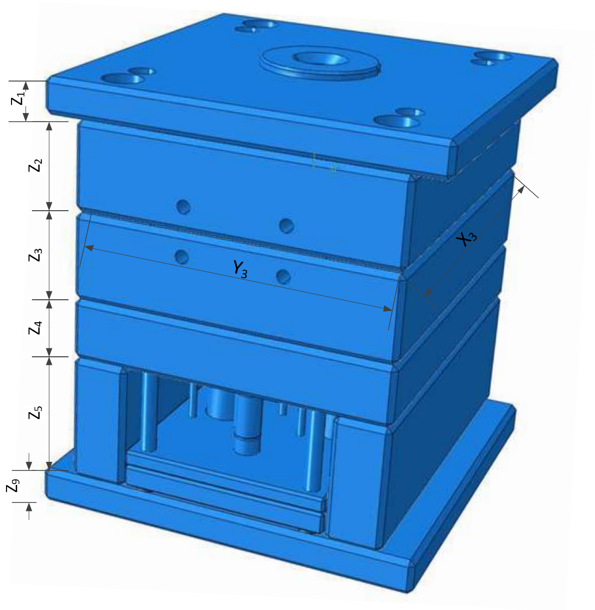


Figure 3.31: Design variables regarding structural system.

FR 2.4.: Volume of scrap – DP 2.4.: Feeding system design

Finally, about FR2.4. (Volume of scrap), considering only cold runner moulds, it is possible to verify that this FR depends upon the volume of the feeding system. Thus, the correspondent DP is the feeding system design. The outcome of the deploying of this system into the design variables that must be considered at the design stage is presented in Table 3.25.

Table 3.25: Design variables regarding feeding system design (DP 2.4.).

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	***type_runner***	Type of runners cross-section	Categorical (e.g.FuR, T, R, HR)*
Optimize	d_{Gate}	Diameter of gates	Continuous
	l_{Gate}	Length of gates	Continuous
	alfa_gate	Draft angle of gates	Continuous
	d_{Runner_1}	Diameter of main runner	Continuous
	d_{Runner_2}	Diameter of secondary runner	Continuous
	d_{Sprue}	Diameter of sprue	Continuous
	l_{Sprue}	Length of sprue	Continuous
	draft_sprue	Draft angle of sprue	Continuous

*Full-Round (FuR), Trapezoidal (T), Rectangular (R) and Half-Round (HR)

The main function of the runners is to distribute the melt in such a way that it arrives, ideally, under the same pressure at all cavities at the same time. Thus, it is important to note that, independently of the type of layout adopted for the feeding system (i.e. symmetrical, circular or hybrid), the secondary levels of the runners diameters must be reduced in relation to the primary runners, in order to get a uniform flow. However, because this artificial balancing does not assure a consistent part quality, a maximum number of two possible branch ramifications is imposed for the feeding layout. For that reason, Table 3.25 only includes d_{Runner_1} and d_{Runner_2}, the first being the diameter of the main runner and the second the diameter of the secondary runner. Nevertheless, the extension to other types of cross-sectional involves only the redefinition of the design variables that characterize their geometry.

Regarding the type of possible geometries for the runners' cross-section, there are the Full-Round (FuR), Trapezoidal (T), Rectangular (R) and Half-Round (HR). A detailed description of the advantages and disadvantages of each type can be found in [226, 230, 243-245]. Based on their characteristics, the FuR circular runners were adopted, which is extremely common in mould designs, because they render uniform shear rates and shear stresses around the perimeter of the cross-section.

FR3.1.: Minimize Mean Down Time (MDT), FR3.2.: Maximize Mean Time Between Failure (MTBF) and FR4.: Maximize information

For the remaining FRs, namely FR3.1. (Minimize MDT) and FR3.2. (Maximize MTBF), they are mapped with DP3.1. (Standardization/Modularity) and with DP3.2. (Type of constructive solutions), respectively. In relation to the FR4. (Maximize information content of mould), it is mapped to DP4 (Minimize mould's complexity), since the objective is to design the simplest mould solution.

Since these requirements are not a direct function of the mould design variables, at this stage they are not included in the model. The main reason for this option is that they were not previously explored in the literature as design parameters of injection moulds. Therefore, their inclusion would require a high effort in order to analyse their relation with mould design variables.

Design matrix

For each level of the previously described decomposition, a design matrix $\mathbf{A}$ must be developed, relating the FRs to their associated DPs, at that level. When working with the conceptual stage of Design, design matrices can be populated with an X or 0. Those symbols indicate a mapping relationship or lack of mapping relationship, respectively. However, mathematically, the relationship between the FRs and DPs is expressed as:

$$\mathbf{FR} = \mathbf{A}\,\mathbf{DP} \qquad \textit{Eq. 19}$$

Where, **FR** is the functional requirement vector, **DP** is the design parameter vector and **A** is the design matrix that characterizes the design. In general, each entry A_{ij} of **A** relates the ith **FR** to the jth **DP**. Nevertheless, in detailed analysis it is possible to determine the element A_{ij} using the following relation:

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \qquad \textit{Eq. 20}$$

Each element A_{ij} must be evaluated at the specific design point in the physical space. The matrix **A** structure defines the type of design being considered, known as [114]:

– *Uncoupled* Design (most preferred). Matrix **A** is diagonal indicating the independence of FR-DP pairs. Thus, each FR can be satisfied by simply considering the corresponding DP;

$$\begin{aligned} &A_{kk} \neq 0 \\ &A_{ij} = 0,\ when\ i \neq j \end{aligned} \qquad \textit{Eq. 21}$$

– *Decoupled* Design (second choice). Matrix **A** is triangular. Therefore, the FRs can be answered systematically, from FR_1 to FR_n, by only considering the first n DPs. This design appears most frequently in real life;

– *Coupled* Design (undesirable). Matrix **A** has no special structure (the design matrix consists of mostly non-zeros elements). Therefore, a change in any element of vector **DP** may influence all elements of the **FR** vector simultaneously.

Considering the **FR** and **DP** vectors defined for each level of decomposition, as shown in Figure 3.32, the respective design matrixes **A** were developed using X and 0 to express the relationships between FRs and their associated DPs. Figure 3.33 presents the design matrix **A** obtained. It is easy to verify that the injection mould design is a highly coupled solution, as expected.

No.		FR		DP
0	FR	Injected the plastic part	DP	Mould solution
1	FR	Max part's quality	DP	Conceptual
1.1	FR	Deflection	DP	Heat-exchange system
1.2	FR	Shrinkage	DP	Impression system and packing
1.3	FR	Sink marks	DP	Gate's location
1.4	FR	Residual stress	DP	Operational conditions
2	FR	Max process capability	DP	Processual
2.1	FR	Cycle time	DP	Ejection system
2.2	FR	Drop of pressure	DP	Flow layout and Injection pressure
2.3	FR	Mould's volume	DP	Structural system
2.4	FR	Material waste	DP	Feeding system
3	FR	Max solution's efficiency	DP	Construtive solutions
3.1	FR	Mean Down Time (MDT)	DP	Standardization/Modularity
3.2	FR	Mean Time Between Failure (MTBF)	DP	Type of solutions
4	FR	Min information content	DP	Complexity of solution

Figure 3.32: Mapping of FRs-DPs for an injection mould design.

	0: Mould solution	DP1: Conceptual	DP1.1: Heat-exchange system	DP1.2: Impression system and pack.	DP1.3: Gate's location	DP1.4: Operational conditions	DP2: Processual	DP2.1: Ejection system	DP2.2: Flow layout and pressure	DP2.3: Structural system	DP2.4: Feeding system	DP3: Construtive solutions	DP3.1: Standardization/Modularity	DP3.2: Type of solutions	DP4: Complexity of solution
FR0: Injected the plastic part	X														
FR1: Max part's quality		X					X	O	O	O	O	X	O	O	X
FR1.1: Deflection			X	X	X	X	X	O	X	X	X	X	O	X	X
FR1.2: Shrinkage			X	X	X	X	X	O	X	O	X	X	O	X	O
FR1.3: Sink marks			X	X	X	X	X	O	X	O	X	O	O	O	O
FR1.4: Residual stress			X	X	X	X	X	X	X	O	X	X	O	X	O
FR2: Max process capability		X	X	X	O	X	X					X	O	O	X
FR2.1: Cycle time		X	X	X	X	X		X	X	X	X	O	X	X	X
FR2.2: Drop of pressure		X	O	O	X	X		O	X	O	X	O	O	X	O
FR2.3: Mould's volume		X	O	X	O	O		X	O	X	X	O	O	X	X
FR2.4: Material waste		X	O	O	X	X		O	X	O	X	O	O	X	O
FR3: Max solution's efficiency		X	X	O	O	X	X	X	X	X	X	X			X
FR3.1: Mean Down Time		X	X	O	O	X	X	X	O	X	X		X	O	X
FR3.2: Mean Time Betwe		X	X	O	O	X	X	X	O	X	X		O	X	X
FR4: Min information content		X	X	O	O	X	O	X	O	X	O	X	X	X	X

Figure 3.33: Design matrix for an injection mould design.

Based on the design matrix, it is possible to conceive rough design layouts, where each concept will be generated through the combination of each design variable alternative. Then, based on the previous FRs-DPs map, and by assigning different values to each design variable, a number of different conceptual solutions for the moulds can be produced. Thus, the starting point for stage 3 of the IDOV approach (Optimize) will be an initial mould solution selected from the generated conceptual solutions. For that purpose, a platform based on MDO was built aiming to optimize the mould design as an integration of mould's subsystems (including the heat-exchange, feeding, ejection, structural and impression systems).

The system level of this platform involves both conceptual and optimization design decisions, as well as the integration of the functional modules as interlinked subsystems. The conceptual level includes, for instance, the type of layout of the feeding system, the number of cooling lines and the number of ejectors, amongst others. The optimization design level requires decisions such as the diameter and pitch of the cooling lines and the heights of plates. The respective inputs and outputs of each mould's subsystems were defined and a block diagram was built in order to identify the feed forward and feedback paths between them. Figure 3.34 presents the block diagram highlighting the conceptual and the optimize design levels, their specific modules and design variables.

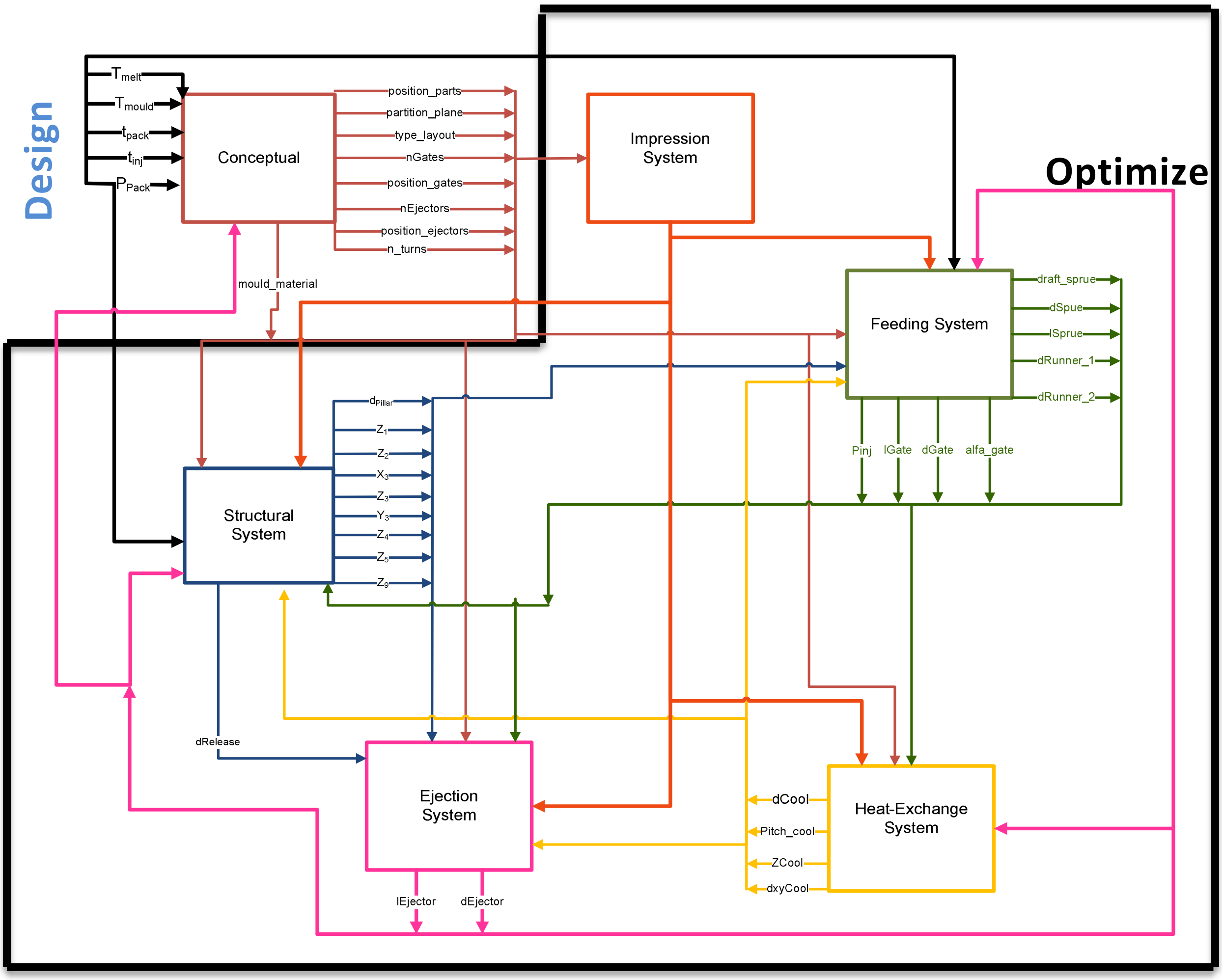


Figure 3.34: Interactions between the conceptual and optimize design decisions levels, with the identification of their specific modules and variables.

It is important to note that this block diagram is totally generic. In fact, it was established independently of both specific plastic part and injection machine characteristics (i.e. these modules and their relations are present in every mould design problem). This approach allows the mathematical formulation of the injection mould design as a multidisciplinary system design problem. The multidisciplinary processes considered were: (i) rheological, which seeks to model and evaluate the mould filling process; (ii) thermal, encompassing heat transfer; and, (iii) structural, aiming to minimize the mould's deformation induced by compressive and bending stresses. As previously mentioned, some assumptions have been made to simplify this MDO approach, which is applicable to the injection mould design of any plastic part without undercuts. The developed platform will be described in detail in the following section.

3.3.3 Optimize stage

In many world large-scale engineering systems, as is the case of an injection mould, the FRs–DPs relationships are highly non-linear and impossible to be represented in a straightforward, closed, analytical form. In order to populate the design matrices with numerical values, a model or series of models must be developed which relate the various DPs to each FR. A number of different types of models can be used including, for instance a sequential DoE and surrogate modelling process, to build differentiable functions for the underlying relationships between the FRs and DPs[20] [249].

MDO is a powerful approach that exploits the synergies of the interdisciplinary couplings through a systematic and mathematically-based manner [132]. Its goal is to find the optimal design of complex systems, achievable by the systematic exploration of the alternatives generated at the conceptual stage, which are lead to the optimal state in the detailed stage. In order to pursue this goal, MDO adopts formal optimization methods to achieve design improvements, where some algorithms facilitate the exploitation of large design spaces, including those that may be characterized by discrete variables or discontinuous functions [250]. This procedure enables product designers to deal with complex interactions, due to the existence of several constraints (e.g. technology, time, resources), using quantitative mathematical models. Furthermore, another approach exploited in MDO is decomposing of large system into smaller subsystems, connected by information flows from outputs of one

[20] Where each element of design matrix [A] can be found by looking at the change in a FR caused by a change in a DP

subsystem to the inputs of another. These information flows between subsystems are termed couplings [142].

The main objective is to develop a framework that tackles the design of an injection moulding system in a global way, through the integration of the structural, thermal and rheological domains. Following this purpose, a first attempt will be carried out in order to evaluate if the proposed approach will lead to design moulds with higher levels of customer satisfaction, as well as if it is computationally viable. In this context, a preliminary platform was built where process integration is achieved by a building approach through modules, where all different analysis codes are connected through an integration software (e.g. iSIGHT-FD [251]), in order to automate the iterative procedure of the optimization process. Since this first attempt aims to study if a multidisciplinary approach can help designers to improve mould performance during design, only simplified mathematical models were used.

To better illustrate how the platform works when applied to the design of a particular mould, a first optimization procedure concerning one single objective function will be considered. The aim of in this first analysis is cycle time minimization. The cycle time is commonly assumed as a good indicator of a mould technical performance. Afterwards, a multi-objective optimization will be undertaken aiming to globally optimize the mould design as a system, adopting the cycle time, the injection pressure drop and the feeding system volume as objectives [151]. As previously mentioned, the pressure drop must be minimized in order to reduce the injection pressure needed to inject the melt. The minimization of this variable also contributes to the mould's life time. The feeding system volume is an indirect measure for scrap. The overall framework is schematically represented in Figure 3.35, highlighting the considered subsystems.

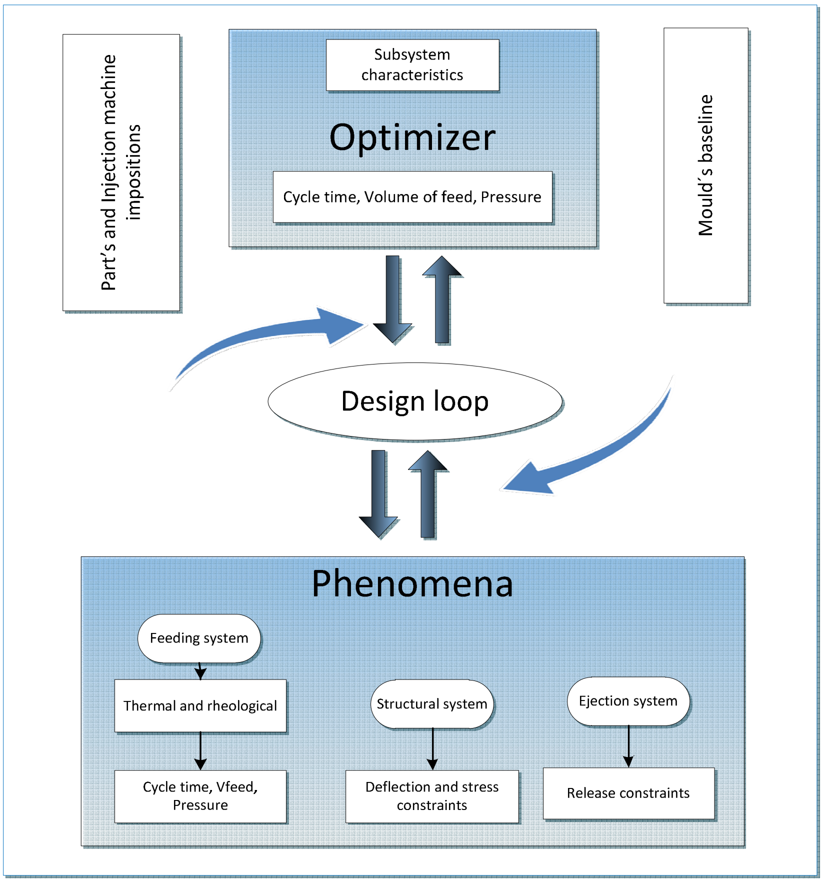


Figure 3.35: Framework process integration: simplified version.

The remaining individual objectives for each one of the systems considered are presented in Table 3.26. They were included in the model as objectives or as constraints.

Table 3.26: Individual objective functions of mould's systems.

System	Objective Functions
Feeding	Min Pressure drop
	Min Volume of waste
Heat-Exchange	Max Heat-exchange rate
Ejection	Min Marks
Structural	Min Mould's bending
	Min Mould's deflection
	Min Mould´s volume

To carry out the cycle time optimization as a single objective function a gradient-based approach will be adopted. In order to select the most adequate gradient-based algorithm, some important characteristics of injection mould design were considered, namely the number and type of design variables and constraints, the feasibility of the design space, the type of initial solution and the adequate simulation runtime. Based on these factors, and following iSIGHT criteria [251], a brief characterization of this mould design problem was obtained. The main characteristics of mould design expressed in a mathematical formulation are summarized in Table 3.27.

Table 3.27: Mathematical problem formulation for the main characteristics of mould design: simplified version.

Design variables (Factors)	
Number of design variables	High (>20)
Number of constraints	Low (<1000)
Type of design variables	Real; Integer and Categorical
Objective/ Constraints functions	Non-linear
Constraints type	Inequality/Equality
Feasible space	Non-convex and discontinuous
Initial point	Feasible
Simulation run time	Short

It is known that certain optimization techniques do not perform adequately in the presence of equality constraints (e.g. Method of Feasible Directions - CONMIN). Additionally, other techniques are better adapted to handle problems with unfeasible initial designs (e.g. penalty-based optimization techniques). Therefore, based on the characteristics presented in Table 3.27, some gradient based methods can be excluded. Moreover, the mould design problem is a large-scale Nonlinear Programming Problem (NLP), with mostly smooth non-convex nonlinear functions. In fact, there are some constraints and at least one objective that is a non-smooth nonlinear function of the decision variables. Thus, the choice of the optimizer shall be made judiciously, since the most widely used and effective methods applied to this type of problems are the Generalized Reduced Gradient (GRG) and Sequential Quadratic Programming (SQP). One special advantage of the GRG method is that the extension for determining the solution of large sparse problems is conceptually simple. The availability and user-friendly nature of the GRG2 method [252] justified its adoption to undertake this task.

The multi-objective optimization will be carried out through a MOGA. The reason for this choice is that this multi-objective exploratory technique is well-suited for discontinuous design spaces. This option is coherent with some optimization characteristics, namely the population-based search technique with no unfeasible population members, which provides multiple designs (rather than only one solution) with good performance [134, 136]. In addition, it has been shown that GA is able to solve complex design problems, characterized by nonlinear and non-smooth functions with both discrete and continuous variables, by exploring the space design and exponentially exploiting promising areas through different GA operators. As a result of these advantages, GA has already been proposed to address the problem of multi-optimization [162, 165, 166, 216, 253].

In order to carry out the MOGA optimization, the NSGA proposed by Srinivas and Deb (1994) [141] will be adopted. In particular, the NSGA II will be applied since it is a non-dominated sorting based multi-objective algorithm, where the selection process is based on two main mechanisms: the "non-dominated sorting" and the "crowding distance sorting". Thus, the Pareto set is constructed where each design has the "best" combination of the objective values and were improving one objective is impossible without sacrificing one or more of the other objectives [136]. Based on that procedure, NSGA II alleviates the three limitations attributed to multi-objective evolutionary algorithms, namely, the computational complexity, the non-elitism approach and the need for a sharing parameter [254]. In addition, it can handle any number of objectives and ensures a better distribution of individuals and multiple equivalent solutions than MOGA [136].

Optimization model

The main design loop of the developed platform starts with a geometrical configuration of the initial mould solution, designed according to the best practice guidelines [245] (the mould's baseline, as presented in Figure 3.35). Then, an auxiliary module calculates the geometrical and physical dimensions that will be used in the following steps and subsequent analysis (e.g. surface area and volume of the plastic part). At this stage, phenomena analyses are carried out by specifically built analytical models, which use a simplified mathematical formulation. The cycle time is computed considering the sum of each of stage times involved in the injection moulding process [227].

As previously mentioned, since plasticizing time occurs simultaneously with the packing stage, it was not considered in cycle time computation. Regarding filling time, which depends mostly on process conditions, it was assumed to have a reasonable imposed value (user selected), similarly to the modelling procedure adopted in MOLDFLOW. This is a realistic assumption and allows comparing the solutions modelled by the proposed framework and the MOLDFLOW simulations. The cooling stage is the most important stage, since it absorbs about 80% of the cycle time [26]. In fact, this stage begins with mould filling and finishes when enough heat has been removed from the part, in order to eject it without distortion. The heat exchange between plastic and coolant, which occurs at this stage through thermal conduction, can be described by Fourier's differential equation [243]. Since heat is mainly removed in one direction (thickness direction), heat-transfer is usually described using a one dimensional description [226, 243]. Following this approach, Fourier's differential equation can be reduced to:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$ ***Eq. 22***

Where α is the thermal diffusivity, T is the temperature, t is time and z is the thickness direction coordinate. Assuming that immediately after injection the melt temperature in the cavity has an uniform constant value of T_{melt} and that the temperature of the cavity walls jumps abruptly to the constant value T_{cool}, which remains constant, the cooling time for a strip plane geometry can be estimated using the previous equation, leading to the following expression [226]:

$$t_{cool} = \frac{s^2}{\pi^2 \alpha} ln\left(\frac{8}{\pi^2}\frac{(T_{melt} - T_{cool})}{(T_{demol} - T_{cool})}\right)$$ ***Eq. 23***

Where s is the wall thickness, assuming the plastic part is a strip plate, and T_{demol} is the mean demoulding temperature (the temperature at which the material is rigid enough to be ejected). It is also important to consider that the time required for cooling the feeding system is longer than the time needed to cool the part itself. This constraint avoids the premature freezing inside the part, which could lead to incomplete filling. Therefore, the bottleneck of the cooling process will be the feeding system, or more precisely the sprue, which corresponds to the biggest component of this subsystem, since it must supply the entire feeding system with enough melt. Due to the conical shape of this component [243], the generic equation (Eq. 22) must be replaced by:

$$t_{cool} = \frac{\bar{d}_{Sprue}{}^2}{23.1\alpha} ln\left(0.692\frac{(T_{melt} - T_{cool})}{(T_{demol} - T_{cool})}\right)$$ ***Eq. 24***

Where $\bar{d}_{Sprue}$ is the sprue mean diameter. Note that both Eq. 23 and Eq. 24 are solutions of Eq. 22, but Eq. 23 is valid only for strip plates, while Eq. 24 assumes a cylindrical geometry. Note that $\bar{d}_{Sprue}$ can be determined based on the geometrical characteristics of the sprue as:

$$\bar{d}_{Sprue} = d_{Sprue} + tan\left(\frac{draft\_sprue.\pi}{180}\right) l_{Sprue}$$ ***Eq. 25***

Where d_{Sprue} is the initial diameter, l_{Sprue} is the length and $draft\_sprue$ is the draft angle of sprue.

The post-filling time, generally known as packing time, is determined based on the gate dimensions [226]. The packing stage main function is to force additional melt into the cavity, after the filling stage, in order to compensate for volumetric shrinkage of the part and to avoid any back flow of melt. Therefore, if the gate is too small the melt will prematurely solidify and no additional material will enter into the cavity (packing does not occur). If it is too large the gate will take more time than necessary to solidify, which results in a longer pack time. Thus, the packing stage time must end with the gate freeze-off. The necessary cooling time for gates (i.e. gate freeze-off) is determined using Eq. 26 but considering the gate diameter d_{Gate}, which results in the following expression:

$$t_{pack} = \frac{{d_{Gate}}^2}{23.1\alpha} ln\left(0.692\frac{(T_{melt} - T_{cool})}{(T_{demol-}T_{cool})}\right) \qquad \textit{Eq. 27}$$

The mould opening time is calculated as the ratio of the mould opening distance $(d_{Release})$ and the mould opening velocity, v_{open}. This velocity was determined based on Kazmer's regression ([226] page 129), which states that the velocity is a logarithmic function of the ratio between the clamping force and a unit reference force, such that:

$$v_{open} = 184 + 13log\left(\frac{F_{Clamp}}{F_{ref}}\right) \qquad \textit{Eq. 28}$$

Where v_{open} is expressed in millimetres per second. Since the clamping force can be computed as the injection pressure (P_{inj}) times the projected area of moulding (A_{proj}), the mould opening time can be calculated using the following relation:

$$t_{open} = \frac{d_{Release}}{v_{open}} = \frac{d_{Release}}{184 + 13log\left(\frac{P_{inj}A_{proj}1 \times 10^{-3}}{9.8F_{ref}}\right)} \qquad \textit{Eq. 29}$$

In this work, it is assumed that the time to open is equal to the time to close the mould (i.e. the time to release the part is equal to two times the opening time, as schematically shown in Figure 3.29). In summary, the theoretical cycle time involves the summation of cooling time (expressed by the necessary time to cool the sprue), plus the packing time (which is limited by gate's freezing), and, finally, the time to open and to close the mould. The cycle time is considered as the single objective function in our first approach and it is determined by the following expression:

$$Cycle\ time = \frac{\left[d_{sprue} + tan\left(\frac{draft\_sprue.\pi}{180}\right)\right]}{23.1\alpha} ln\left(0.692\frac{(T_{melt} - T_{cool})}{(T_{demol-}T_{cool})}\right) + \frac{{d_{Gate}}^2}{23.1\alpha} ln\left(0.692\frac{(T_{melt} - T_{cool})}{(T_{demol-}T_{cool})}\right) + 2 \times \frac{d_{Release} 1 \times 10^3}{184 + 13log\left(\frac{P_{inj}A_{proj} 1 \times 10^{-3}}{9.8F_{ref}}\right)} \quad \textbf{Eq. 30}$$

Note that the plasticizing time is neglected since it occurs in parallel with the other injection events. Also the injection time is very small compared with the other and it is assumed to have a constant value (1.5 seconds for this case study). Finally, the cooling time is not the total time during which cooling occurs, but only the excess cooling time required for the sprue to freeze.

In order to optimize the cycle time it is also necessary to take into account the following constraints:

$-P_{inj} + \frac{32(l_{Sprue} + l_{Runner} + l_{Gate} + l_{part})\varphi\bar{v}_F \eta_{aeff}}{\left(\frac{2MaxYM_{int}}{MaxY+M_{int}}\right)} \leq 0$	*The pressure demand to counter the resistance to flow in the plate (flow length/wall thickness ratio derived from Hagen-Pouseuille's law [15]).*	**Eq. 31**
$P_{inj} - \frac{F_{clampmax}}{A_{proj}} \leq 0$	*The melt pressure acting in the projected area of mould cavities must not surpass the maximum clamp force (required to hold the mould closed during operation).*	**Eq. 32**
$l_{sprue} - Z_2 - Z_1 + Z_{cav} = 0$	*The sprue length must be equal to plate's distance starting in injection nozzle, until PP, to assure geometric feasibility.*	**Eq. 33**
$d_{Gate} + 2\left[\frac{(3+\frac{1}{n})\dot{V}}{\pi\dot{\gamma}_{max}}\right]^{1/n} \leq 0$	*The shear rate for the flow in the gates must not surpass the maximum allowable shear (Power law is assumed, which is a conservative approach).*	**Eq. 34**
$-d_{Release} + MaxOpen - Z_{mould} \leq 0$	*Distance of part's release must not surpass the maximum free open distance of mould.*	**Eq. 35**
$d_{Release} - 2.5MaxZ \leq 0$	*The mould opening distance must assure the part's release.*	**Eq. 36**
$-d_{Sprue} + d_{Runner}\sqrt{n_{downstream}} \leq 0$	*The sprue must have enough capacity to fulfil all the downstream runners.*	**Eq. 37**

where l_{Runner} is the runner length, l_{Gate} is the gates length and l_{part} is the part length; φ represents a constant ratio between the width and the thickness of the part, which is assumed to be equal to 1.5, when the width is much bigger than thickness; $\bar{v}_F$ is the velocity of the flow front and η_{aeff} is the apparent effective viscosity; $MaxY$ and $MaxZ$ are the part maximum distances along the Y and Z directions, respectively; $F_{clampmax}$ is the maximum clamping force; the variables Z_{cav}, Z_1, Z_2 and Z_{mould} correspond to the distance in the Z direction for the cavity plate, plate one and two, and for the complete mould, respectively; n is the power index of the Power Law model; $\dot{V}$ is the volumetric flow rate and $\dot{\gamma}_{max}$ is the maximum shear rate for the plastic; $MaxOpen$ is the maximum distance for the mould in the Z direction; the runner diameter is defined by d_{Runner} and, finally, $n_{downstream}$ is the number of streams of each ramification.

The design variable bounds are defined based on practical guidelines, as follows (the dimensions are in millimetres):

$$d_{Sprue} \leq 10$$ ***Eq. 38***

$$1 \leq draft\_sprue \leq 2$$ ***Eq. 39***

$$0.5 \leq d_{Gate} \leq 3$$ ***Eq. 40***

$$0.5 \leq l_{Gate} \leq 1$$ ***Eq. 41***

If cycle time minimization is the only objective (single objective optimization), it is also necessary to take into account the following additional constraints:

Volume of feeding system: $V_{feed} \leq 0.3V_{part}$ ***Eq. 42***

Pressure drop: $\Delta P \leq 0.5P_{inj}$ ***Eq. 43***

Where V_{part} is the total volume of the moulded plastic part.

The minimization of wasted material is defined based on the volume of the feeding system (cold runner system), V_{feed}, computed by:

$$V_{feed} = \frac{\pi}{4}\left(\bar{d}_{Sprue}^2 l_{Sprue} + n_{downstream} n_{ramif} d_{Runner}^2 l_{Runner} + d_{Gate}^2 l_{Gate} n_{Gates}\right)$$ ***Eq. 44***

Where n_{ramif} and n_{Gates} are the number of ramifications of the runner and number of gates per each plastic part, respectively.

The minimization of the pressure drop is determined using the equation of motion, which states that the force due to the pressure drop along the flow (caused by the viscous flow in the channel) must be equal to the force resulting from shear stresses. Both occur along the length of the melt flow. The Power Law Model will be used since it has been shown to provide accurate results [226]. Using this model, which states that viscosity is an exponential function of the shear rate, it is possible to estimate the pressure drop as a function of the volumetric flow rate. For a channel with a circular shape, the pressure drop estimate ΔP is given by:

$$\Delta P = \frac{4kL}{D}\left[\frac{\left(3+\frac{1}{n}\right)}{\pi\left(\frac{D}{2}\right)^3}\right]^n \quad \textit{Eq. 45}$$

Where k is the viscosity evaluated at a shear rate of one reciprocal second, D is the diameter and L is the channel length. Based on this expression, the total pressure drop caused by the feeding system is established as:

$$\Delta P = \frac{4kl_{Sprue}}{\bar{d}_{Sprue}}\left[\frac{\left(3+\frac{1}{n}\right)\dot{V}}{\pi\left(\frac{\bar{d}_{Sprue}}{2}\right)^3}\right]^n + \frac{4kl_{runner}}{d_{Runner}}\left[\frac{\left(3+\frac{1}{n}\right)\dot{V}}{\pi\left(\frac{d_{Runner}}{2}\right)^3}\right]^n + \frac{4kl_{Gate}}{d_{Gate}}\left[\frac{\left(3+\frac{1}{n}\right)\dot{V}}{\pi\left(\frac{d_{Gate}}{2}\right)^3}\right]^n \quad \textit{Eq. 46}$$

Case study

In the previous section, the simplified mathematical formulation associated to the design of an injection mould was defined. However, since the mould design is highly dependent on the plastic part geometry, it was necessary to use a specific plastic part to test the MDO framework. The benchmark plastic part studied can be observed in Figure 3.36, where the dimensional measures are also presented. A simple geometry was selected since the objective was only to evaluate the potential of the developed platform, at this stage of research. Since it is a well characterized material, the ABS Cycolac MG47 produced by GE Plastics - USA was adopted. All necessary information regarding its physical, mechanical and rheological proprieties are included in most material industrial databases. An initial solution was established according to the practical guidelines summarized on mould designer manuals [245].

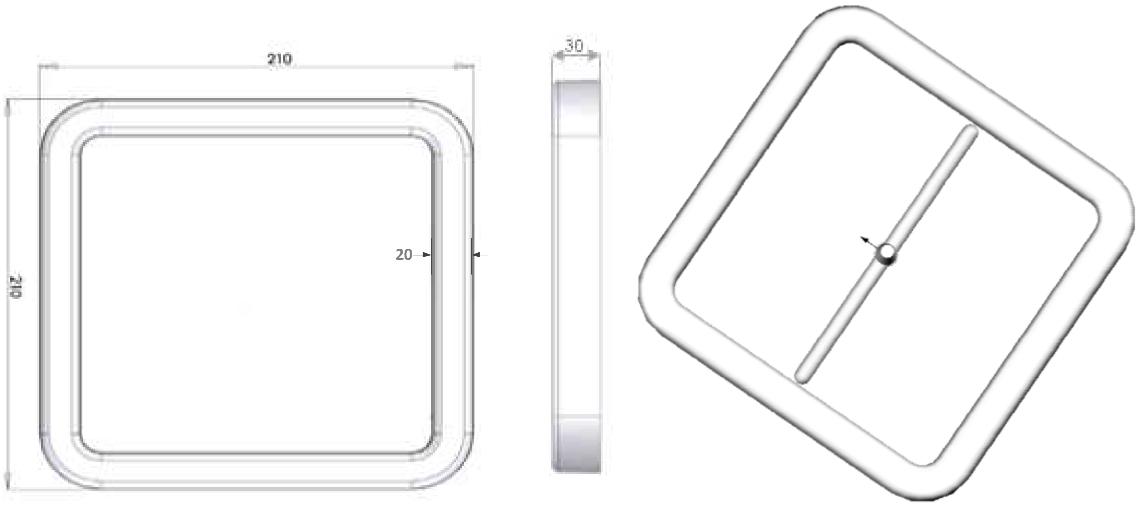


Figure 3.36: The designed part: a) Front and b) Lateral views and c) with feeding elements.

Optimize stage: single optimization

In a first optimization procedure, cycle time minimization was considered as the single objective function. As already mentioned, the remaining objective functions, concerning the Structural, Feeding, Heat-Exchange and Ejection systems, were included in the optimization model as constraints. Given the characteristics of the optimization problem, in particular the number and type of design variables and constraints, the feasibility of design space, the type of initial solution and the adequate simulation runtime, the GRG method was adopted. The application of GRG2 [252] resulted in an optimized solution, which allows a cycle time reduction of 41.7%, when compared with the initially (feasible) solution (Table 3.28).

Table 3.28: Optimal design solution obtained by the GRG2 algorithm: single optimization.

Design Variables		Baseline	Optimal
P_{inj}	MPa	180	211
$d_{Release}$	mm	75	75.0
l_{Sprue}	mm	90	102
d_{Sprue}	mm	12.0	8.49
draft_Sprue		1.0	1.0
d_{Gate}	mm	0.5	1.44
	Cycle time (s)	**112.7**	**65.7**
		Ratio	**-41.7%**

Based on these results, it is possible to observe that cycle time reduction is mostly due to the diameter of sprue reduction. In fact, since the cooling time is the longest part of the cycle time, which is limited by the sprue dimensions, a reduction on the sprue diameter results in a reduction of the cycle time. However, this decrease is accompanied by a significant increase of the injection pressure in order to overcome the increase of pressure drop (for more details see [151]). In fact, a pressure drop of 40.90MPa was reached for the optimal solution. If the single objective was instead to minimize the pressure drop, this value will be reduced to 26.58MPa. Thus, it is very important to consider a multi-objective analysis instead of a single optimization, as we will show in the following section.

Optimize stage: multi-objective optimization

In order to globally optimize the mould design as a system, cycle time, pressure drop and feeding system volume were adopted as objective functions. To undertake this optimization, the NSGA II was used, since it alleviates the three limitations attributed to multi-objective evolutionary algorithms, namely, computational complexity, non-elitism approach and the need for a sharing parameter. In this method, each objective is treated separately and a Pareto front is constructed by selecting feasible non-dominated designs. The tuning parameters and their respective values used on the optimization procedure are summarized in Table 3.29.

Table 3.29: Tuning parameters used in NSGA-II: multi-objective optimization.

	Values
Population size	20
Number of generations	20
Crossover probability	0.9
Crossover distribution index	50
Mutation distribution index	100

A generated optimal design solution can be seen in Table 3.30, where it is compared with the mould's baseline. The Pareto points are illustrated in Figure 3.39, where also the original baseline solution is plotted (highlighted point). Even though multi-objective optimization does not yield a unique solution, it was considered important to evaluate the potential improvement when compared with the previous single-objective optimization solution presented. In this sense, the baseline solution was compared with the optimal solution described in Table 3.30. The results are shown in Figure 3.37, where it is possible to verify that an improvement was achieved for all the three objectives. These improvements mean significant impact for the entire injection moulding process. Notice that 2 seconds less (almost 2% reduction) for each cycle corresponds to 80 more parts produced per week, with approximately the same amount of material scrap and much less energy consumption (due to the 10% reduction achieved for injection pressure). Nevertheless, it is important to mention that the baseline solution was obtained following some empirical guidelines, which rendered an initial good solution. Finally, it is possible to determine the impact of the new optimal solution on customer satisfaction index when compared with baseline solution, through Eq. 18. Assuming that all the other requirements remain constant, the increase on quality of Design is 0.62% with a positive impact on CSI of 0.1%.

Table 3.30: One Pareto solution obtained by NSGA-II: simplified version.

	Baseline	Optimal	Comparison
d_{Gate} (mm)	0.5	2	-
draft_Sprue (°)	1.0	1.0	-
$d_{Release}$ (mm)	75.0	132.0	-
d_{Runner} (mm)	9.0	9.0	-
d_{Sprue} (mm)	12.0	12.8	-
l_{Gate} (mm)	0.500	0.502	-
l_{Runner} (mm)	84.5	84.0	-
$n_{downstream}$	2	2	-
n_{Gate}	2	2	-
n_{Ramif}	1	1	-
P_{inj} (MPa)	180	131	-
Cycle time (s)	**134.18**	**131.84**	**-1.7%**
Pressure drop (MPa)	**98.80**	**89.70**	**-9.2%**
V_{feed} (m^3)	**2.82E-5**	**2.80E-5**	**-0.7%**
Performance improvement	**-**	**-**	**3.87%**
Quality of Design impact	**-**	**-**	**0.62%**
Impact on CSI	**-**	**-**	**0.10%**

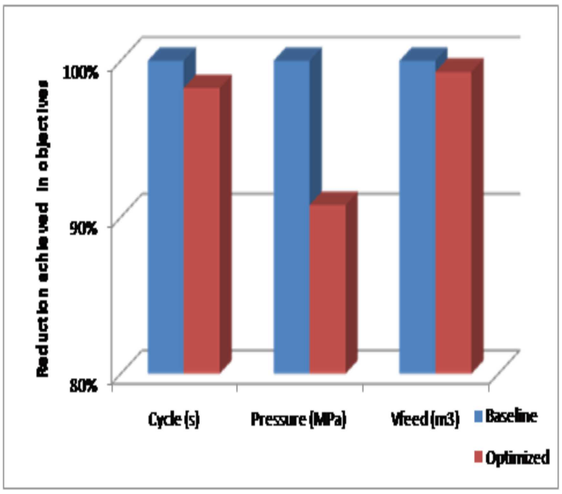


Figure 3.37: Comparison in objectives using baseline as a reference: simplified version.

The pairwise Pareto fronts in Figure 3.39 show that there is no significant trade-off between the feeding volume and the cycle time. As volume increases so does cycle time. However, there is a significant trade-off between the injection pressure required and the cycle time. As injection pressure is increased above 100 [MPa], cycle time can be reduced to below 100 [s]. However, this will come at the cost of tool life time and more energy consumption. There also appears to be a strong trade-off between the feeding volume and the injection pressure: if the injection pressure is higher than 100 [MPa] the feeding volume is reduced to below 2.75E-5 [m^3].

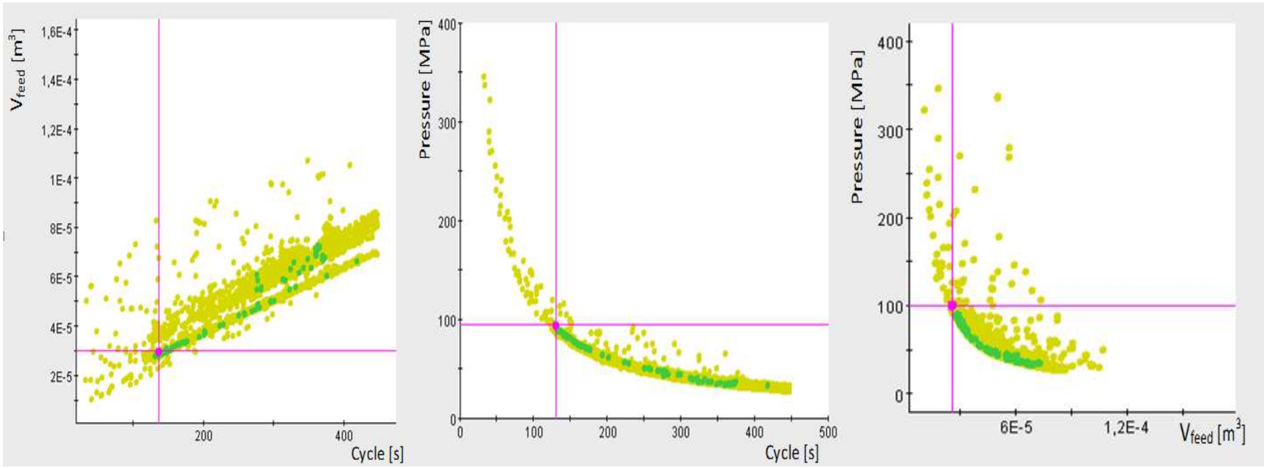


Figure 3.38: Pareto solutions identified: simplified version.

The choice of the final injection mould design should be made from the set of Pareto optimal designs, using additional customer preferences and criteria that may not be explicitly represented in the model. For example, the expected total production volume for the specific injection moulded parts will be an important decision criterion to select designs along the Pareto front. The vertical bands in the parallel coordinates plot presented in Figure 3.39 indicate the range for feasible design variables.

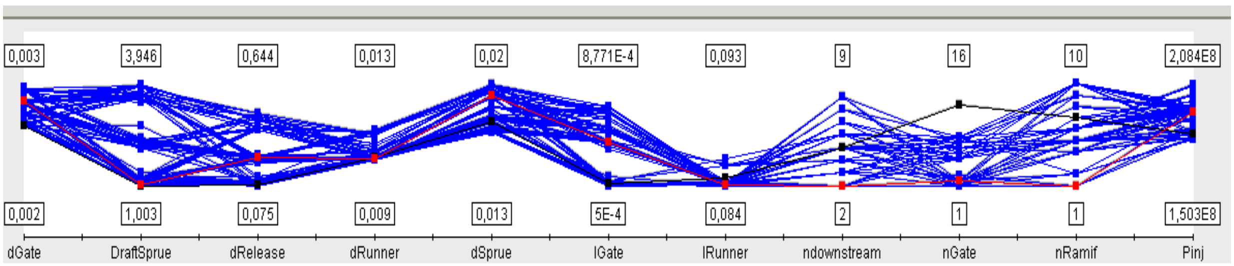


Figure 3.39: Design variables parallel coordinates with the optimal solution red highlighted (simplified version.)

It is interesting to note that runner length and diameter appear to be tightly clustered for all designs, while the number of gates, number of ramifications and sprue dimensions can vary more significantly. This shows that the design details of the feeding system have a very large impact on the ultimate mould performance. Among these, Figure 3.39 shows that the sprue design appears to have the largest impact on the overall mould´s performance. This is a reasonable conclusion, since productivity, waste of material and energy consumption are dependent on sprue geometrical dimensions. In fact, the sprue is the element that needs the longer time to cool, the sprue is the largest component of the feeding system and the flow resistance of the feeding system dictates the injection pressure needed.

3.3.4 Validate stage

In order to assess the real improvement of the optimized designs obtained by the framework, both baseline and optimal single objective solutions were tested using high-fidelity MOLDFLOW code (MPI 6.1 rev 3 build 012567), under the same processing conditions. The comparison between the baseline solution and the one obtained by using GRG2 is presented in Table 3.31. It is also possible to determine the impact of the new optimal solution on CSI when compared with baseline solution, through Eq. 18. Assuming that all the other requirements remain constant, the increase on quality of Design resultant of cycle time reduction is 3.8% with a positive impact on CSI of 0.6% (i.e. $\Delta CSI = 0.157 \times 0.09 \times 41.7\%$).

Table 3.31: Comparison between results obtained by proposed framework and MOLDFLOW numerical simulations.

Design variables	Baseline	Optimal
P_{inj} (MPa)	1.80E+08	2.11E+08
$d_{Release}$ (mm)	75.0	75.0
l_{Sprue} (mm)	90.0	102.0
d_{Sprue} (mm)	12.0	8.49
draft_sprue (°)	1.0	1.0
d_{Gate} (mm)	0.5	1.44
	Cycle time (s)	
Framework	**112.70**	**65.70**
MOLDFLOW	**119.80**	**66.72**
Reduction on cycle time	-	**41.7%**
Quality of Design improvement	-	**3.8%**
Impact on CSI	-	**0.6%**

Figure 3.40 ilustrates the time to freeze, in seconds, obtained by MOLDFLOW for both models. This is not the total cycle time, since it is also necessary to take into account the other stages of the injection cycle. It is possible to observe that the results produced by the proposed framework are consistent with MOLDFLOW simulations results. Based on these results, the optimal solution determined corresponds to a cycle time reduction of 41.7%, as compared with the baseline solution.

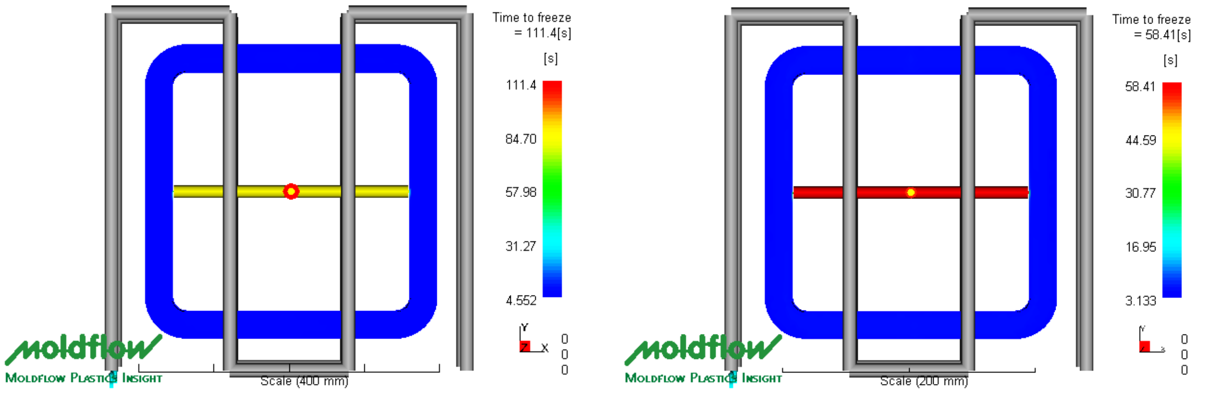
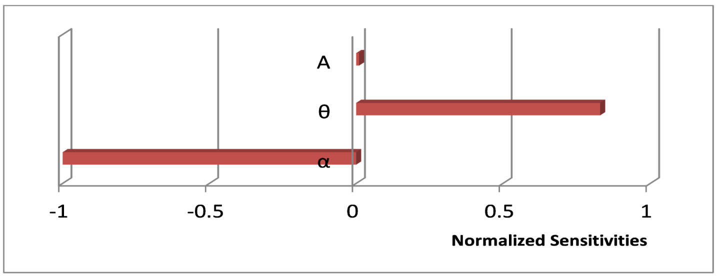


Figure 3.40: Time to freeze in seconds obtained by MOLDFLOW numerical simulations: Baseline (left – 111.4s) and Optimal (right – 58.41s).

Afterwards, sensitivity analysis at the optimum point was performed. First, the unnormalized sensitivity was computed evaluating the partial derivates at the optimal point. Then, these values were normalized in order to estimate the normalized sensitivity values through:

$$\frac{\Delta \mathbf{J}/\mathbf{J}}{\Delta x_i/x_i} \approx \frac{x_i^*}{\mathbf{J}(\mathbf{x}^*)}\bigg|_{x^*} \qquad \textit{Eq. 47}$$

The computed values, which physically correspond to the % change in the objective function per % change in the design variable/parameters, can be compared in Figure 3.41 for the fixed parameters and in Figure 3.42 for the design variables.



A - Projected area of molded part

$\theta = \left(T_{melt} - T_{cool}\right) / \left(T_{demol} - T_{cool}\right)$

α - *Thermal diffusitivity*

Figure 3.41: Parameter normalized sensitivity values.

Regarding the fixed parameters, the most sensitive are the thermal diffusivity and the ratio between the difference of the melt and coolant and the demoulded and coolant temperatures. This is also physically consistent, since the larger the thermal diffusivity the more heat is transferred between the melt and the coolant and, consequently, the faster the part's cooling. Conversely, higher differences between the melt and the coolant temperature impose a higher quantity of heat to be removed from the part, which requires a longer cycle time.

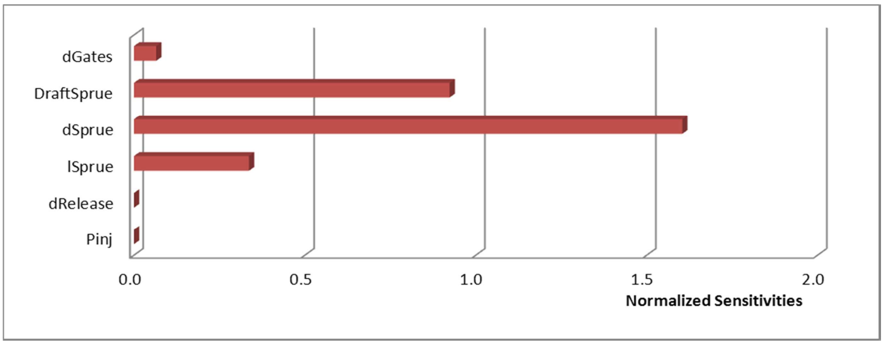


Figure 3.42: Normalized sensitivity values for design variables.

Based on the normalized sensitivity values for design variables values, one can verify that the most sensitive are the sprue diameter (d_{Sprue}) and the sprue cone angle (*draft_sprue)*. This result is also physically consistent, since the cycle time is primarily determined by mould temperature control, i.e. cooling time [227]. Since the sprue must be large enough to feed several runners and gates, this component will be the largest of the feeding system, and requires the longest time to cool. Additionally, in order to avoid premature melt freezing in feeding channels, a constraint was imposed that guarantees that the time required to cool the feeding system is longer than the time needed to cool the part itself. This constraint reinforces the importance of the sprue dimensions for the cycle time. Regarding the *draft_sprue*, there is a correlation with its diameter, d_{Sprue}, as shown in Figure 3.43. Therefore, the previous explanations are also true for this variable, since the higher the draft sprue, the higher the final volume of the sprue.

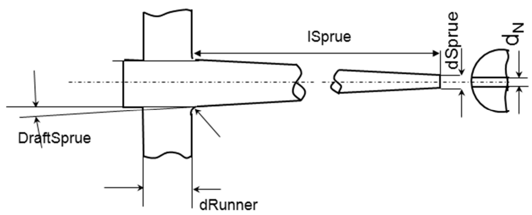


Figure 3.43: Schematic design of the sprue.

3.4 Conclusions

A conceptual framework, based mainly on DFSS, ECSI, AD and MDO methodologies, was developed in order to guide and systematize the mould design process [167]. This framework tackles the design of an injection mould in a global and quantitative approach, starting with the full understanding of the critical customer requirements and its translation into functional requirements. Based on that mapping, an objective function, expressing customer satisfaction as a weighted function of specific functional requirements, was determined. Afterwards, the conceptual design of the mould was supported by AD, aiming to map the functional requirements with the corresponding design parameters. In this stage, the initial mould design decisions were established according to FR-DP mappings, developed for the upper levels of mould design. In spite of seeking for the independence of functional requirements, some remaining coupled relations may subsist. However, they were not considered to be prohibitive. Consequently, through an adequate exploitation of interacting phenomena MDO supported the detailed design stage. As a result, an integrated platform was developed, where all different analysis modules (e.g. structural, thermal and rheological) were inserted and optimized through an overseeing code system, regarding the maximization of customer satisfaction levels.

However, due to the high complexity and mould component interactions, a first attempt was undertaken through simplified modelling of mould phenomena. In order to validate it, two optimization cases were carried out. First, using the GRG2 algorithm, the developed model was optimized regarding cycle time, which allowed for a 42% reduction of this variable, when compared with a baseline solution. Secondly, multiple objective optimization was carried out through the simultaneous minimization of cycle time, pressure drop and feeding volume. The results showed that cycle times below 100 seconds are possible, but they require larger injection pressures. In addition, it appears that the feeding system volume and cycle time are linearly correlated. This task was carried out using the iSIGHT-FD 2.5 NSGA-II heuristic based method. Both approaches point out the great potential for mould design improvement over current heuristic guidelines.

Table 3.32 presents the computational time associated with both optimization procedures. It was found that the gradient search with GRG2 was computationally more efficient. However, this method could not deal successfully with non-smooth and discontinuous functions, whereas NSGA-II proved to be efficient, especially in highly non-linear and discontinuous design spaces [151]. Hence, the most appropriate approach to optimize the design of an injection moulding system is a MOGA, like NSGA II, which performed well in multi-objective optimization. It is also important to mention that the mould design space is a discontinuous non-convex set. Therefore, it will be impossible to have 100% certainty that the optimal solution found is a global optimum. However, one important issue in mould's design optimization is to assure the feasibility of the design. In fact, an improved design solution is better than not finding the optimal solution, reinforcing the GA choice. The computational times presented in Table 3.32 also highligth the effort involved in the simulation of each feasible solution with the MOLDFLOW code. Since the objective was only to evaluate the potential application of the framework, that effort justified the adoption of the simplified mathematical model to describe the physical pheneomena associated to the injection mould design. It also emhasizes that the computational effort associated to more accurate models is not proihibitive for the reinforcement of the proposed framework.

Table 3.32: Computational time (seconds): simplified version.

Method	CPU computation time (s)	Functions	Evaluations	Number of feasible designs
GRG2	50	Single objective	57	41
NSGA-II	2406	Three objective	2501	1493
MOLDFLOW Baseline	3416.53		-	
MOLDFLOW Optimal	3764.33		-	

In summary, the results attained highlight the great potential of the proposed framework to achieve mould design improvements, with consequent reduction of rework and time-saving for the entire mould design process. Based on that, it is possible to assume that the proposed approach can become an essential tool for future quality enhancement in 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. Considering its strong scientific basis, it is also possible to assume that the developed approach can turn into a global methodology to support more rationally different product design processes.

However, the inclusion of more accurate and realistic models will be essential to enhance the previous framework, in order to reach even more improvements in the mould design and operation. The development of a more realistic model for injection moulds involves the optimization model refinement, by including all important variables, in particular the categorical ones, and to expand its scope in order to cover the design of all mould's systems. Furthermore, it is necessary to integrate in the framework CAE models with sufficient accuracy and efficiency (as well as CAD tools) to be able to visualize the design solutions.

These are fundamental to achieve a fully integrated mould optimization. For that reason, computer-aided modelling will be used to represent the injection moulding process mathematically and to assist the mould design by simulation analysis. The best known examples of CAE tools are MOLDFLOW [222], and ABAQUS version 6.10-1 (ABAQUS), from Simulia [255]. The next chapter describes the reinforced platform developed, combining the optimization model refinement and the integration of CAD and CAE tools.

CHAPTER 4

Developed framework: generalization

4.1. Introduction

The development of a fully integrated optimization framework, based on the IDOV DFSS roadmap to support mould design, is the main focus of this chapter. As was described in the previous chapters, the IDOV approach encompasses a four stages framework: Identify, Design, Optimize and Validate. Based on that, on the previous chapter a first attempt was carried out, which tackles the design of an injection mould in a global and quantitative approach, starting with a full understanding of customer requirements and converting them into optimal mould solutions. To that end, an integrated platform was built, where all different analysis modules were inserted and optimized through an overseeing code system. The results attained highlight the great potential of the proposed framework to achieve mould design improvements.

Nevertheless, this first attempt adopted simplified mathematical models to describe the injection model phenomena (e.g. cycle time computation model). Thus, considering the importance of having more realistic models, as well as the inclusion of all important design variables, such as categorical and geometrical variables, a new and reinforced platform must be enhanced. For that purpose, the platform described in Chapter 3 will be reinforced through two main aspects. The first one involves the substitution of the analytical models, previously used, by high-fidelity models. In this sense, MOLDFLOW and ABAQUS were integrated in the platform aiming to model the thermal and rheological behaviour of injection phenomena, and the structural behaviour of the mould's components, respectively. In addition, a CAD tool (SolidWorks® v.11 software - SolidWorks) was also included in the platform as a geometry handler module, to help the generation and visualization of the design solutions. Similarly to the strategy adopted in the first attempt, all these analysis codes are managed by an overseeing code. In this case, the code adopted was ModeFRONTIER version 4.4.1 from ESTECO (ModeFRONTIER) [144]. This code is responsible for running the analysis codes, accessing the outputs and changing the input data according to the pre-defined mathematical exploitation and optimization schemes.

The second aspect of the platform's improvement was to include in the optimization model all the critical design variables. Although this inclusion increases the complexity of the optimization problem, it was considered essential to provide a more realistic model, as well as to support the design of the typical components of injection moulds. These variables are mostly categorical and geometrical variables, as is the case of the type of feeding layout, which can be symmetrical or circular, or the position of gates, which involves a geometric position on the cavity.

Considering the high potential of the proposed framework, highlighted by the first attempt to achieve mould's improvements, it was assumed that a more accurate and realistic platform can be a good way to overcome the current weakness of design procedures. Thus, the main objective of this chapter is to present a new and reinforced platform, aiming to provide more accurate results and to be closer to practical implementation in an industrial environment. Throughout this chapter each submodule of the reinforced platform is described and tested using as a reference an existing mould, the key holders mould. Thus, after this introduction, a brief description of this mould is presented. Finally, in order to evaluate its applicability, the reinforced platform will be validated using as baseline also the key holders existing mould. Moreover, since it is expected that its main weakness will be the high computational effort, we also evaluate if the proposed approach is computationally viable.

4.2. Case study: key holders mould

In order to test the reinforced platform submodules and validate their integration, an existing injection mould will be used as baseline. Figure 4.1 presents the selected mould, which is used to produce four key holders in each cycle. This mould was selected to be used as baseline since although it was designed according to best practice guidelines, experience designer's foresee some potential improvements.

The selected plastic part's material is Moplen HP 500N, produced by Basell Polyolefins. The application of the developed platform to this mould required information concerning the injection material properties. The necessary material's properties, which must be introduced in the platform, are presented in Table 4.1.

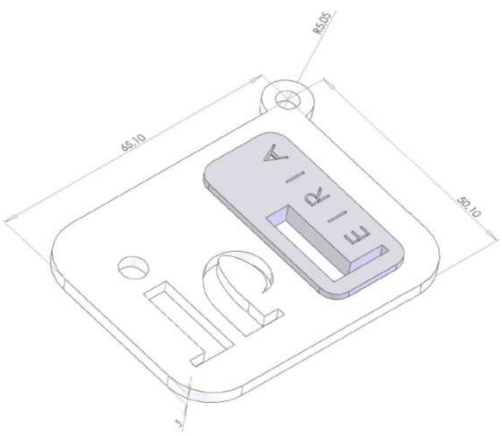


Figure 4.1: Key holders parts: a schematic view (left) and a view of the four injected parts in the mould (right).

Table 4.1: Moplen HP500N properties.

$E_{plastic}$	Young's Modulus of plastic material	1340	MPa
CTE	Coefficient of thermal expansion	9.05E-5	1/°C
T_{trans}	Transition temperature (Tc onset ASTM 3418)	112	°C
T_{eject}	Ejection temperature (Tc end pint ASTM 3418)	103	°C
T_{melt}	Melt temperature (recommended)	235	°C
T_{mould}	Mould temperature (recommended)	35	°C
τ_{max}	Maximum shear stress	0.25	MPa
$\dot{\gamma}_{max}$	Maximum shear rate	1E5	1/s
υ	Poisson ratio	0.392	-
G	Shear Modulus of material	481.3	MPa

The existing mould is a 2-plate mould, with nine plates, where a DME standard structure made of 1.1730 steel was adopted. Figure 4.2 presents the existing mould, highlighting the fact that the cavities impressions were directly machined on the mould plates. Since most of the ejector pins and sleeves are made of hardened materials, the fatigue limit stress was assumed as 800MPa. A smooth core surface is assumed that results in a static friction coefficient of 0.5, between the plastic part and the cavities, which has a draft angle of 1°.

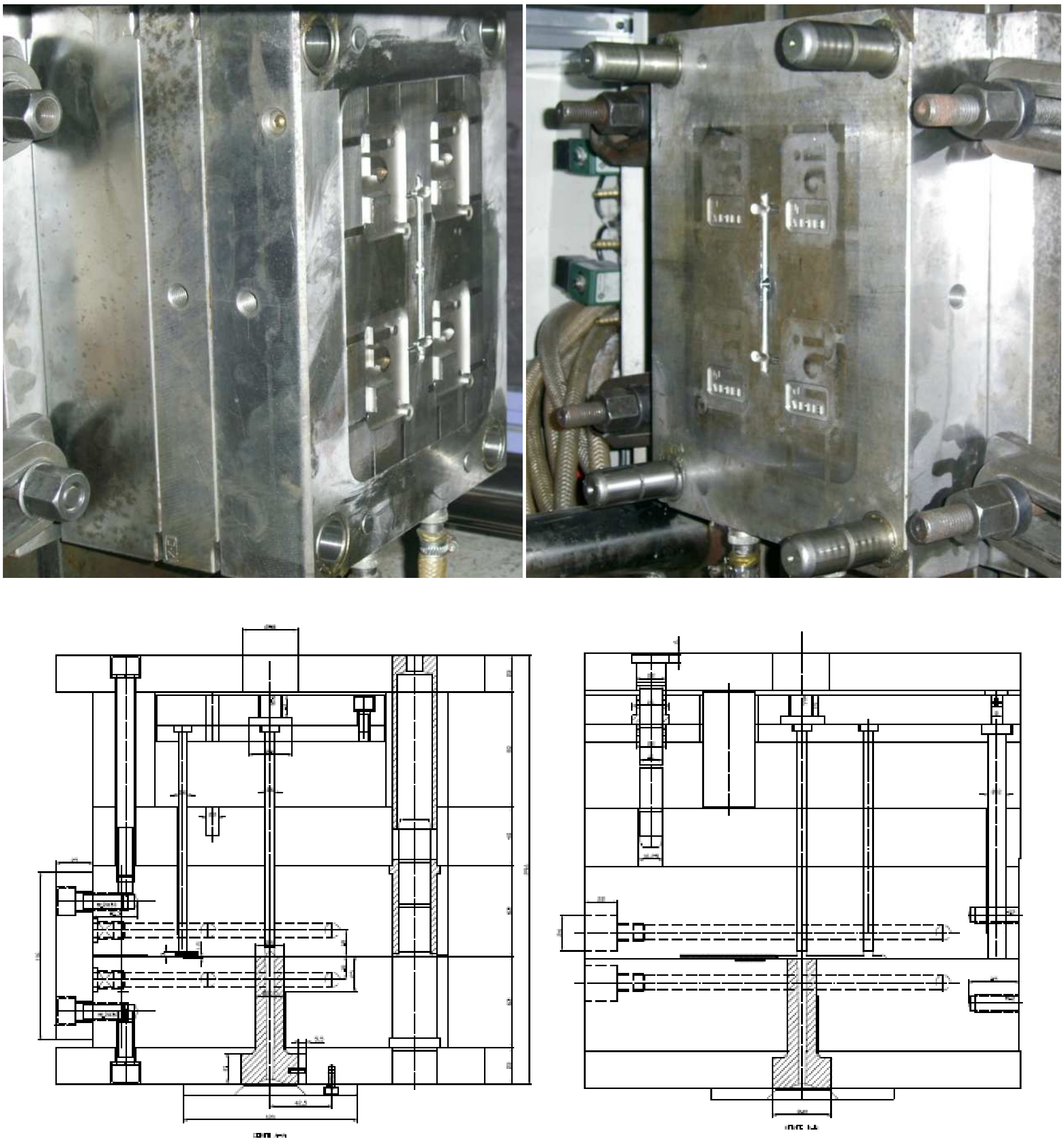


Figure 4.2: Existing mould for key holders (top) and a schematic representation of it (bottom).

Regarding the injection moulding machine, a EuroInj was employed, with a maximum locking force of 7.84E5N and a screw diameter of 32mm. A summary of its main characteristics is presented in Table 4.2.

Table 4.2: Injection moulding machine characteristics.

Space between tie bars	mm	360x360
Min mould height	mm	130
Max mould height	mm	400
Max Daylight	mm	720
Max Opening stroke	mm	320
Max Injection pressure	bar	2180
Max Injection rate	g/sec	67
Diameter of nozzle	mm	3

Figure 4.3 presents the CAD of the plastic part. This model was used to define the part in the platform but also to determine the effective area (A_{eff}) of each moulding, based on the area of its cross section, which is equal to 4.25E3mm^2. All these geometric, material parameters, and operational data, were introduced in the platform, in order to define the constraints according to this particular mould.

Figure 4.3: Geometric data regarding the injected key holder.

4.3. Reinforced platform structure

Similarly to the first attempt, the new reinforced platform follows a global and systematic approach to support the design of an injection mould. For that purpose, the proposed IDOV approach will be once more followed as a roadmap for the design process. Regarding the first IDOV stage, Identify, no special alterations were made. In fact, customer satisfaction auscultation is established mainly by the determination of mould customers' attributes importance in two levels. Therefore, no changes were introduced at the macro level where the ECSI model, previously estimated, will be used again as a reliable model. Assuming that globally the main drivers of mould's customers remain unchanged, which is theoretically consistent, both ECSI and Loyalty structural equations are the same used in chapter 3 (see Eq. 15 and Eq. 16).

The second level of customer's auscultation concerns detailing and evaluating customers' requirements, regarding the quality of mould design. In fact, for each specific mould order there are always specific needs, as well as different ratings regarding customer's importance of these needs. Thus, the second level of the Identify stage aims to determine the critical items for achieving high levels of customers' satisfaction and loyalty, through mould design construct. In this sense, similarly to the procedure adopted in chapter 3, it is necessary to refine and prioritize these particular customer attributes by determining the importance of each attribute.

For that purpose, AHP will be also used to rank the customer's preferences. This rank is achieved by customer's comparison of each attribute, two at a time, using a 1-9 scale, with three levels: 1 - Equal importance; 3 – Moderately more important; 9 - Extremely more important. For each specific mould's order, the attributes previously identified in Table 3.17, which are inherent to any injection mould, must be compared taking into account its specificities. Based upon this comparison, it is possible to mathematically express customer satisfaction as a function of the identified attributes. This function will be used in the next stages of the IDOV approach, namely in the Design and Optimize stages, as a single objective function (e.g. utility function).

Afterwards, subsequently to clearly understanding and evaluating customer's needs, it is time to design the mould. Two main stages will be carried out to execute the design of an injection mould. Firstly, at the Design stage, which is mainly supported by AD theory [7], a few number of conceptual solutions must be generated and the most ranked is selected. Then, at the Optimize stage, this conceptual solution will be optimized in order to get the best solution according to customer satisfaction criteria.

Both stages involve design decisions regarding the functional systems of injection moulds, namely, Impression, Feeding, Heat-Exchange, Structural and Ejection systems. Thus, in order to design each functional system it is important to define its design variables, bounds and constraints, as well as its specific objective functions. Therefore, a brief analysis regarding these systems will be now undertaken.

4.3.1. Structural system

The main function of the structural system is to aggregate all mould's components in a robust ensemble, which must be strong enough to resist to high levels of pressure during millions of injection cycles. This function is attained by a metallic structure where several components are assembled (e.g. guide pins, pillars, screws, ejector pins, etc.) forming a compact body. This structure is composed by a small number of plates[21], typically, nine for the two-plates mould type (Figure 3.31). These plates are widely available in the market.

Injection moulds are exposed to very high mechanical loadings, such as forces resulting from the pressure exerted by the melt against all surfaces of the mould cavities. This pressure results in both compressive and shear stress exerted in the cavity and the core inserts, as well as in the support plates. It is important to highlight that each mould plate is subjected to a load on one face, while their sides are constrained by the surrounding plates. Hence, the applied loads are carried by compressive and shear stresses transmitted through the thickness and across the plate. In general, to design the structure of a mould, three main objectives are considered, namely: minimize stress; minimize deflection under load and minimize volume.

Minimize stress

There are different kinds of stress regarding each component of the injection mould. Regarding the cavity insert, which is supported by plate 1 (top clamping plate) and by plate 2 (stationary plate), it is in a state of pure compression (due to mould clamping) while bending can be neglected. On the other hand, for the movable half of mould, due to the presence of the ejector pins house there is no support for core insert and its connecting plates. Thus, they transmit load via both compressive and shear stresses, which results in plates bending. For this reason, the stationary plates and the moving plates must be dimensioned distinctly.

A special issue regarding stress is the existence of stress concentration, due to the existence of coolant lines and ejector holes in the structural plates. An example of an analytical analysis of this effect can be found in Kazmer (2007) (see page 322)[226], where the author developed a model of the stress concentration factor, designated by K. This model was obtained by fitting some data gathered by performing analyses with finite elements (see

[21] Plate refers to a prismatic or rectangular structural member with a length and width typically greater than the thickness.

Eq. 48), where K is a function of hole's diameters (d_{hole}) divided by the distance of the centre of the hole from the cavity surface (Z_{hole}). This model was used as a constraint in the simplified analysis, presented in chapter 3. However, in the reinforced framework the stress concentration is taken into account through ABAQUS.

$$K = 3.1 + 0.75\left(\frac{d_{hole}}{Z_{hole}}\right)^{2.29}$$ ***Eq. 48***

Minimize deflection

As mentioned, the core insert and its connecting plates transmit load which results in plate's bending. This is, typically, the case of plates located between the ejector housing and the mould's cavity on the moving side of the mould. This load can cause excessive mould deflection, and then, originate flashing at the parting line, as well as part dimensions out of the specifications. Therefore, an important constraint of mould structure design is that transverse deformation of the mould (i.e. deformation transverse to the demoulding direction) must be lower than the corresponding shrinkage of the part's moulding. If this mould deflection assumes critical values, then it is necessary to reduce it through the use of support pillars located between the bottom clamping plate and the support plate. These support pillars are normally standard elements, as schematically represented in Figure 4.4. In this case, it is also necessary to analyse the number, location and size of the support pillars. This analysis must take into account some geometrical considerations in order to avoid interference with other mould's components, such as the ejections system components.

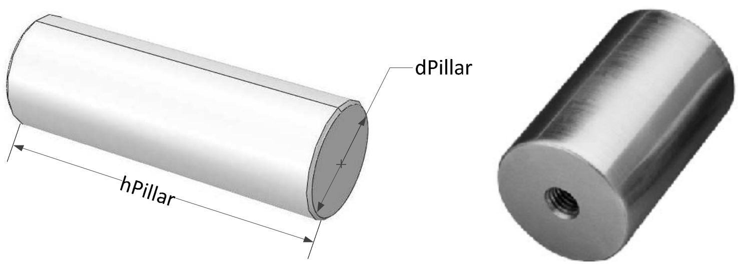


Figure 4.4: Support pillars (Z57 in HASCO Catalogue [256]).

Based on that, there are two additional variables that must be included in the structural module of the proposed platform. These variables are the pillars diameter, d_{Pillar}, and height, h_{Pillar}, which must respect standard dimensions. The pillars height is a variable dependent upon the other structural design variables. Also in the reinforced framework the number of pillars and their relative location is assumed as fixed, since these are conceptual decisions.

Nevertheless, if the back face of bottom clamping plate and the support plate are not fully supported, shear stresses will develop and cause the plate to bend. A reasonable estimate for the shear stress, τ, developed, is described in Kazmer (2007) [226], where this variable is determined using the following expression:

$$\tau = \frac{P_{inj}\,A_{proj}}{(2\mathrm{X_{cav}} + 2\mathrm{Y_{cav}})(\mathrm{Z_3} + \mathrm{Z_4} + \mathrm{Z_e})} \qquad \textit{Eq. 49}$$

This expression assumes a uniform distribution of the melt pressure around the perimeter of mould cavity, where $\mathrm{Y_{cav}}$ is the width of mould´s cavity (or its dimension along the Y direction), $\mathrm{X_{cav}}$ is the length of mould´s cavity (or its dimension along the X direction), $\mathrm{Z_3}$ and $\mathrm{Z_4}$ are the height or thickness of plates 3 and 4 (or their dimension along the Z direction), respectively. $\mathrm{Z_e}$ is the height of the core cavity.

Assuming that the entire load is applied in the centre of the mould section (i.e. adopting a conservative procedure) and that mould plates can be modelled as beams under bending, the maximum deflection can be determined through bending equation with a central load. Considering the conditions described, the maximum deflection $\delta_{bending}$ can be estimated as:

$$\delta_{bending} = \frac{P_{inj}\,A_{proj}(Y_4 - 2Y_5)^3}{4E_{mould}\mathrm{Y_{cav}}(\mathrm{Z_3} + \mathrm{Z_4} + \mathrm{Z_e})^3} \qquad \textit{Eq. 50}$$

Where Y_4, Y_5 are the widths of plates 4 and 5, respectively. Thus, $Y_4 - 2Y_5 = Y_{span}$ is the length of the span. Note that in Eq. 50 the moment of inertia was determined assuming a rectangular section.

Furthermore, regarding the deflection (δ_{mould}) across the entire mould (plates under compression), it can be estimated as:

$$\delta_{mould} = \frac{F_{clamp}\,Z_{mould}}{A_{compression}\,E_{mould}} \qquad \textit{Eq. 51}$$

Note that the mould is assumed as a monolithic block subject to a uniform state of compression, where Z_{mould} is the sum of all plate's thickness (i.e. it is the maximum distance on Z axis for the designed mould). $A_{compression}$ is the area of plates subject to compression, which can be computed as the product between the length and the width of the plate's mould faces. F_{clamp} is the maximum clamping force allowable for a specific injection moulding and

E_{mould} is the Young modulus of the selected mould's material. Both these variables are important to define the constraints for the structural system.

Minimize mould's volume

One simple method to reduce mould's deflection is to increase the thickness of its plates. However, the use of large and thick plates can result in an overly heavy and expensive mould. Furthermore, this solution will also result in a higher stack height which can be unviable due to the injection machine characteristics.

As mentioned before, mould's structure is constituted by nine plates typically acquired according to standard suppliers. Hence, according to each plate's specification it is possible to know its cost. Based on that, and through a supplier data base (e.g. HASCO Catalogue [256]), a cost model for the mould's structure was obtained through regression. This analysis was carried out through Minitab 16, where the results were obtained with a confidence level of 95% and validated by ANOVA analysis. The regression equations are summarized in Table 4.3 and Figure 4.5 presents the scatter plots of cost of plates as a function of its dimension. As expected, the results obtained show that the cost of plates is a function of plate's dimensions.

Table 4.3: Regression equations for cost of plates.

Cost of plates	R^2	R^2 (adj)
Cost_1_9 = - 39.3 + 3.56 Z1 + 0.00106 Area_1	R^2= 98.6%	R^2 (adj) = 98.5%
Cost_2_3 = - 52.8 + 2.40 Z2 + 0.00157 Area_2	R^2= 99.3%	R^2 (adj) = 99.2%
Cost_4 = - 45.1 + 2.71 Z4 + 0.00116 Area_4	R^2= 95.9%	R^2 (adj) = 95.4%
Cost_5_6 = - 14.3 + 0.831 Z5 + 0.00104 Area_5	R^2= 98.2%	R^2 (adj) = 98.0%
Cost_7_8 = 55.5 + 0.00175 Area_7	R^2= 90.4%	R^2 (adj) = 89.6%

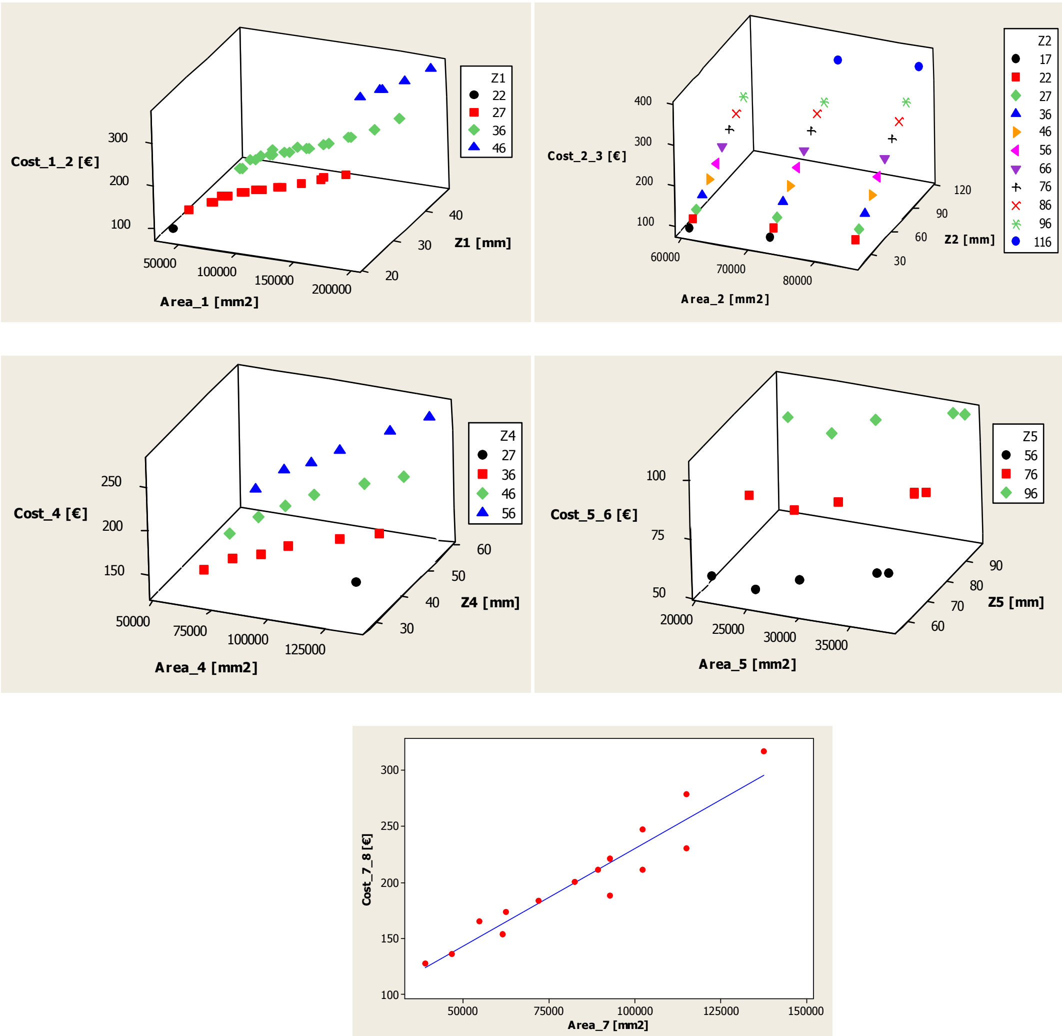


Figure 4.5: Scatter plots of cost of plate's function of its dimension.

The three objectives of the structural system optimization are to minimize stress, deflection and mould's volume. The structural design was previously defined as DP2.3., and linked with FR2.3.: Mould's size (see FRs-DPs mapping in chapter 3.3.2). The set of design variables defined to completely design this mould system at the optimize stage is presented in Table 4.4. Finally, it is important to highlight that the minimization of stress and deflection are included in the problem as constraints.

Table 4.4: Design variables regarding structural system at optimize stage: reinforced platform.

Design variables	Description	Units
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 support pillars	mm

Regarding the plates, they are widely available in the market as standard plates. The dimensions of the several structural elements are mainly dependent of the X_3 and Y_3 dimensions. In order to exemplify this interdependence, in the proposed framework, medium range dimensions were assumed for plate 3. Thus, the platform assumes that each design variable presents the following lower and upper bounds[22]:

$$246 \leq X_i \leq 296 \text{ i=1,..,9}$$ ***Eq. 52***

$$196 \leq Y_i \leq 296 \text{ i=1,..,4,9}$$ ***Eq. 53***

$$27 \leq Z_1 \leq 36$$ ***Eq. 54***

$$36 \leq Z_2 \leq 86$$ ***Eq. 55***

$$36 \leq Z_3 \leq 86$$ ***Eq. 56***

$$36 \leq Z_4 \leq 56$$ ***Eq. 57***

$$56 \leq Z_5 \leq 96$$ ***Eq. 58***

$$Z_7 = 12$$ ***Eq. 59***

$$Z_8 = 17$$ ***Eq. 60***

$$27 \leq Z_9 \leq 36$$ ***Eq. 61***

Additionally, the model optimization must also include standard constraints for plate's dimensions, as follows:

$$X_2 = X_3 = X_4 = X_5 = X_7 = X_8$$ ***Eq. 62***

[22] Nevertheless, these values can be easily change in the platform by updating in each mould's order the intended values.

$$Y_2 = Y_3 = Y_4 \qquad \textit{Eq. 63}$$

$$X_1 = X_9 \qquad \textit{Eq. 64}$$

$$Y_1 = Y_9 \qquad \textit{Eq. 65}$$

where X_i is the length of plate *i*, Y_i is the width of plate *i* and Z_i is the height of plate *i*, with *i*=1,..,9. Regarding the optimization of the structural systems, some additional constraints must be included in the developed platform, namely:

$X_1 \leq X_{bars} - 10$	The maximum dimensions of mould on X must be lower that the distances between tie bars imposed by injection machine $(\boldsymbol{X_{bars}})$ [257]	***Eq. 66***
$Y_1 \leq Y_{bars} - 10$	The maximum dimensions of mould on Y axis must be lower than the distances between tie bars imposed by injection machine $(\boldsymbol{Y_{bars}})$.	***Eq. 67***
$X_2 - X_{part} n_{cav_x} - p_1 (n_{cav_x} + 1) \geq 0$	The plate's dimensions must overcome moulding impressions and necessary compression area, along the X direction.	***Eq. 68***
$Y_2 - Y_{part} n_{cav_y} - p_1 \left(n_{cav_y} + 1\right) \geq 0$	The plate's dimensions must overcome moulding impressions and necessary compression area, along the Y direction.	***Eq. 69***
$Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_9 + d_{release} \leq MaxStroke$	The mould's height must be lower than the maximum stroke of the selected injection machine.	***Eq. 70***
$Shot\ size = \left(n_{cav} * V_{part}\right) + V_{feed} \leq 0.8\ Shot\ size\ of\ machine$	The shot size, which corresponds to the amount of melt that can be conveyed into mould with one stroke of the screw or the plunger, must not overcome 80% of the whole shot size of the machine, for practical operation reasons.	***Eq. 71***
$F_{clamp} \geq A_{proj} P_{inj}$	The clamping force must compensate the reactive force from maximum cavity pressure.	***Eq. 72***
$Z_2 - 3d_{cool} - Z_i \geq 0$	The thickness of plate 2 must be greater than 3 times the diameter of cooling lines, since the cooling lines will impose stress concentrations.	***Eq. 73***
$Z_3 - 3d_{cool} + Z_e \geq 0$	The thickness of plate 3 must be greater than 3 times the diameter of cooling lines, since the cooling lines will impose stress concentrations.	***Eq. 74***

$\delta_{bending} < Shrink$	The maximum deflection must be lower than the corresponding shrinkage of part's moulding. Following ABAQUS nomenclature, this constraint was defined based on COPEN.	*Eq. 75*
$d_{Release} - 1.5h \geq 0$	The distance of mould opening must assure the part's release.	*Eq. 76*
$-d_{release} + MaxOpen - Z_{mould} \leq 0$	The distance of part's release must not surpass the maximum free open distance of the mould.	*Eq. 77*

n_{cav} is number of cavities while $n_{cav_x}$and n_{cav_y} are the number of cavities on PP, on X, and Y direction, respectively; X_{part} and Y_{part} are the part's dimensions on X and Y directions, respectively; p_1 is the lateral distance between the impressions cavities; d_{cool} is the diameter of the cooling lines, Z_i is the height of moulding on the injection side (cavity plate) while Z_e is the height of moulding on the ejection (core plate); M_{int} is the minimum thickness of the moulded part.

4.3.2. Impression system

The impression system is composed by both the cavity and the core inserts, which are responsible for conferring the required shape to the part. In general, the cavity insert is responsible for the external impression of the plastic part, while the core insert produces the internal impression. Therefore, an important aspect of the design of the impression system is to take shrinkage into account, in order to conform to the part dimension. This issue is particularly important in applications that require tight tolerances. Thus, the impression system and the packaging conditions were previously mapped to the FR 1.2.: Shrinkage and the design variables for the different stages were listed in Table 3.19. Table 4.5 resumes the design variables associated with the impression system.

Table 4.5: Design variables regarding impression system: reinforced platform.

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	***position_parts***	Position of each part relatively to the PP	Geometrical
	partition_plane	Position of the PP	Geometrical
Optimize	***draft_angle***	Draft_angle	Continuous (° degrees)

4.3.3. Feeding system

Considering the most basic mould´s structure configuration (i.e. the two-plates mould configuration), the typical components of the feeding cold runners systems are: the sprue, the runners and the gates. As it was already described, the melt enters the mould via the sprue, which is generally machined in the sprue bushing as shown in Figure 4.6. This figure also presents the design variables associated to the sprue, which are summarized in Table 4.6.

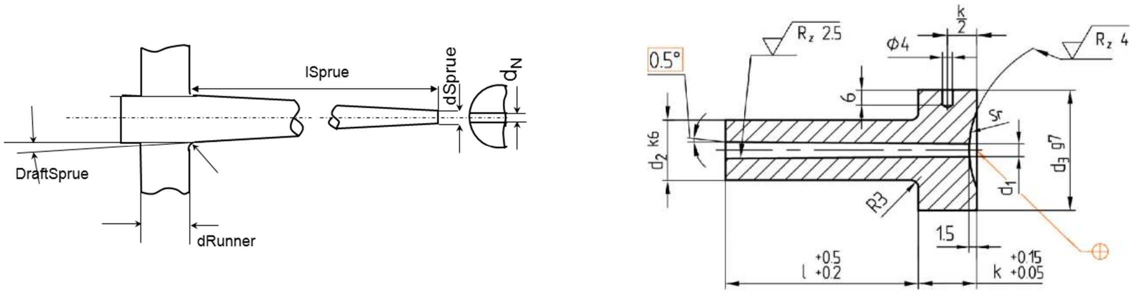


Figure 4.6: Design variables associated to the sprue design (left) and a sprue bushing standard (Z512) proposed by HASCO Catalogue [256] (right).

Table 4.6: Design variables regarding the sprue design: reinforced platform.

IDOV stage	Symbol	Design variable definition	Type of design variable
Optimize	d_{Sprue}	Diameter of the sprue	Continuous (mm)
	draft_sprue	Draft angle of the sprue	Continuous (° degrees)
	l_{Sprue}	Length of the sprue	Continuous (mm)

Regarding these design variables, some rules must be followed in order to assure its function, namely: (i) the diameter at the foot of the orifice should be roughly 1 mm greater than the gated moulded part at its thickest point, or greater than the diameter of the connecting runner (to ensure that it freezes last and that the orifice remains open for the holding pressure); (ii) the orifice must be tapered (> 0.5° and < 2°) in order to allow the sprue to be pulled out of the orifice when the mould is opened; and, (iii) given the sprue’s position on the mould’s structure, its length must be lower than the sum of the heights of plates 1 and 2, minus the distance of the cavity on the injection side plus the diameter of the injection nozzle of the injection machine, and greater than the previous summation minus the required height to fit the locating ring. Figure 4.7 presents a standard locating ring in order to highlight its dimensions. Based on the previously mentioned rules, some additional constraints must be included in the optimization model (see Eq. 79 to Eq. 82).

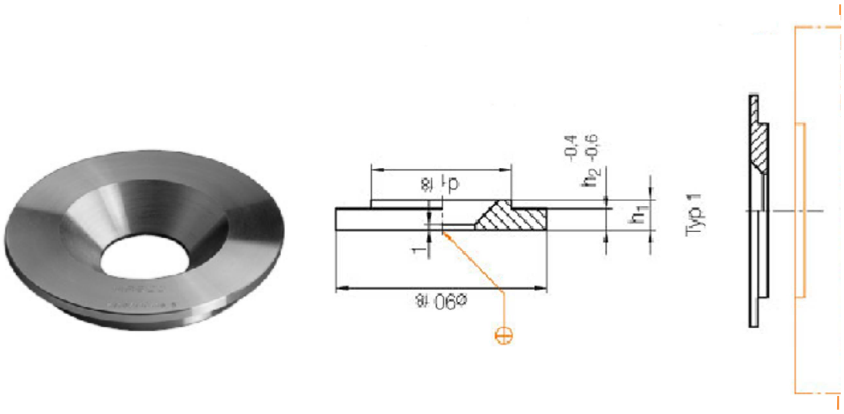


Figure 4.7: Locating ring (K100) available in HASCO Catalogue [256].

The runners connect the sprue with the cavity(ies) via the gate. Thus, their main function is to distribute the melt in such a way that it arrives (ideally) under the same pressure, at the same time, in all cavities. Based on that, an important feature regarding the runner's design is its layout, which depends mostly of the PP and the cavities' location on it, as well as on the number of gates per cavity. Given that, there are two main possible layouts: the symmetrical or series layout, and the circular layout. Both types have the possibility to use primary or secondary levels of runners channels, as exemplified in Figure 4.8. Of course, if one adopts secondary levels, the diameters of the secondary runners must be lower than the one of the primary runners, in order to get a uniform flow. Taking this limitation into consideration and for simplicity reasons, multiple branching is limited to a maximum of two ramifications in the developed framework.

At the conceptual design stage, the runners' layout and the respective number of secondary levels ramifications is decided. It is important to note that this decision is coupled with gates' position (i.e. if the number of cavities is four, one can opt for a circular layout with four runners with a single ramification, or for a layout in series with two runners with two levels, as shown in Figure 4.8).

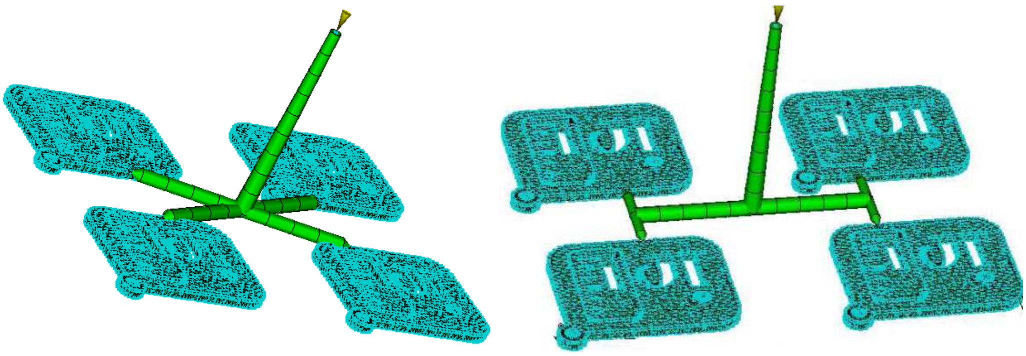


Figure 4.8: Circular layout with four runners (left) or layout in Series with two runners with two levels (right).

If one opts by using secondary levels, some additional design constraints must be considered, in order to maintain the same linear velocity in the branched runner system. For instance, the melt velocity can be preserved in a branched runner system by setting the diameter of the downstream diameters, d_{Runner_2}, equal to ([226] page 132):

$$d_{Runner\_2} = \frac{d_{Runner\_1}}{\sqrt{n_{ramif}}}$$ ***Eq. 78***

where d_{Runner_1} is the upstream runner diameter and n_{ramif} is the number of downstream runners branching off the upstream segment. Note that if the runners layout assumes a single level, then $d_{Runner\_2} = d_{Runner\_1} = d_{Runner}$. There are other possible configurations for the feeding layout, including the so-called hybrid layouts which combine series and circular layouts. Nevertheless, this type of configuration is not included in the platform.

Regarding the runners' geometry, there are several types of cross section. However, the non-circular runners give non-uniform shear rates and shear stresses around the perimeter of the cross-section, where additional material is necessary to provide the same pressure drop as a full round runners [243]. For that reason, the platform adopts a Full Round cross section (FuR). Given that, the design variables that are included in the model for the Design and the Optimize stages are summarized in Table 4.7.

Table 4.7: Design variables regarding the design of runners: reinforced platform.

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	***type_layout***	Type of feeding layout	Categorical (Circular, Symmetrical)
Optimize	d_{Runner_1}	Diameter of the upstream runner, i.e. runner 1	Continuous (mm)
	d_{Runner_2}	Diameter of downstream runner, i.e. runner 2	Continuous (mm)

Despite the fact that the primary function of the gates is to connect runners to mould cavity, gate's design has a significant impact on mould's operation, namely through its location and its dimensions. In fact, an important function of the gates is to control the post-filling time or packing time [226]. There are several types of gates' geometry. Regarding its geometrical simplicity, and mostly due to the need for a small size in order to provide a minimal gate vestige, the PiP gate type will be adopted as gates' geometry [244]. A schematic representation of this type of geometry can be observed in Figure 4.9. It is also assumed that the gates are typically located eccentrically with runners.

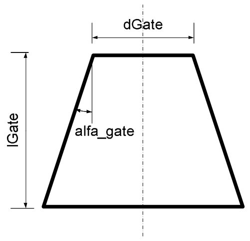


Figure 4.9: PiP gate geometrical characteristic.

The design variables included in the reinforced platform associated to the gates design are summarized in Table 4.8, for both the Design and the Optimize stages.

Table 4.8: Design variables regarding gate's design: reinforced platform.

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	n_{Gates}	Number of gates per part	Integer
	position_gates	Position of each gate relatively to the PP	Geometrical
Optimize	d_{Gate}	Diameter of the gates	Continuous (mm)
	l_{Gate}	Length of the gates	Continuous (mm)
	alfa_gate	Draft angle of the gates	Continuous (° degrees)

Table 4.9 summarizes the complete set of design variables that must be defined, regarding the feeding system and respective components, for both the Design and the Optimize stage.

Table 4.9: Design variables regarding feeding system that will be included in the reinforced platform.

IDOV stage	Symbol	Design variable definition	Type of design variable
Design	***type_layout***	Type of feeding layout	Categorical (Circular, Symmetrical)
	n_{Gates}	Number of gates per part	Integer
	position_gates	Position of each gate relatively to the PP	Geometrical
Optimize	d_{Sprue}	Diameter of the sprue	Continuous (mm)
	draft_sprue	Draft angle of sprue	Continuous (° degrees)
	l_{Sprue}	Length of the sprue	Continuous (mm)
	d_{Runner_1}	Diameter of the upstream runner, i.e. runner 1	Continuous (mm)
	d_{Runner_2}	Diameter of downstream diameters, i.e. runner 2	Continuous (mm)
	d_{Gate}	Diameter of gates	Continuous (mm)
	l_{Gate}	Length of gates	Continuous (mm)
	alfa_gate	Draft angle of gates	Continuous (° degrees)

Regarding the specific constraints and bounds, concerning the design of feeding system, a set of additional conditions must be included in the optimization model. Some of them were already mentioned, but they are now summarized.

$d_{Sprue} - h - 1 > 0$	The diameter at the foot of the sprue orifice should be 1mm greater than the gated moulded part at its thickest point.	***Eq. 79***
$d_{Sprue} - d_{Runner\_1} > 0$	The sprue's diameter must be greater than the diameter of the connecting runner.	***Eq. 80***
$d_{Sprue} - d_N > 0$	The sprue's diameter must be greater than the diameter of the connecting runner of the injection machine ($\boldsymbol{d_N}$).	***Eq. 81***
$l_{Sprue} - Z_1 - Z_2 + Z_i + 3 = 0$	The sprue's length must be greater than the sum of the height of plates 1 $(\boldsymbol{Z_1})$ and plate 2 $(\boldsymbol{Z_2})$ minus the distance of the cavity on the injection side $(\boldsymbol{Z_i})$ and the length of the injection nozzle (=3mm).	***Eq. 82***
$d_{Gate} - (Z_e + Z_i)/2 \leq 0$	The diameter of the sprue may be lower than one-half the wall thickness of the moulding.	***Eq. 83***
${d_{Gate}}^2 - \frac{4(1+h)}{\pi} \geq 0$	The gate cross-section must be roughly 1mm larger than the thicker moulded parts [243].	***Eq. 84***
$d_{Runner\_2} - \frac{\sqrt[4]{{m_{part}}^2 l_{Runner\_2}}}{3.7} \geq 0$	The downstream runner must have enough capacity to fulfil the part.	***Eq. 85***
$d_{Runner_1} - \frac{d_{Sprue}}{\sqrt{n_{ramif\_1}}} \geq 0$	The sprue must have enough capacity to fulfil the upstream runner.	***Eq. 86***
$d_{Runner\_2} - \frac{d_{Runner\_1}}{\sqrt{n_{ramif\_2}}} \geq 0$	The upstream runner must have enough capacity to fulfil the downstream runner.	***Eq. 87***
$\Delta P_{Feed} - 0.5 P_{inj} < 0$	The pressure drop through the feeding system $(\boldsymbol{\Delta P_{Feed}})$ must be lower than 50% of the pressure required to fill the mould's cavities [2].	***Eq. 88***
$V_{feed} - 0.3 V_{part} n_{cav} \leq 0$	The volume of the feeding system $(\boldsymbol{V_{feed}})$ must be lower than 30% of the volume of the mould cavities [226].	***Eq. 89***
$t_{feed} - t_{part} \geq 0$	The time to cool the largest diameter of the feeding system component (usually, the base of the sprue) must be greater than the time to cool the thickest mould cavity section.	***Eq. 90***

Where m_{part} is the mass of the moulding part, t_{feed} is the time to cool the feeding system, and t_{part} is the time to cool the moulded part. It is also possible to define some lower and upper bounds for the design variables, based on guidelines. However, since the runner's length depends upon the part's characteristics and type of layout *(type_layout)*, its lower and upper bounds must be imposed according to each particular case, in order to respect the position of the gates. Therefore, the following bounds refer only to the generally admissible ones:

$$4 \leq d_{Sprue} \leq 8$$ ***Eq. 91***

$$1 \leq draft\_Sprue \leq 1.5$$ ***Eq. 92***

$$4 \leq d_{Runner\_1} \leq 8$$ ***Eq. 93***

$$2 \leq d_{Runner\_2} \leq 6$$ ***Eq. 94***

$$0.5 \leq d_{Gate} \leq 2$$ ***Eq. 95***

$$15 \leq alfa\_gate \leq 30$$ ***Eq. 96***

$$0.5 \leq l_{Gate} \leq 2$$ ***Eq. 97***

4.3.4. Heat-exchange system

The heat-exchange system (or cooling system) is extremely important to the economic and operational performance of the designed mould. In fact, mould cooling accounts for more than two-thirds of the total cycle time in the production of injection moulded thermoplastic parts [230]. This system is composed by a few number of cooling channels, where a coolant is pumped. Typically, water is used as coolant but there are other options, namely: Oil and Ethylene glycol. The main function of the coolant is to remove heat from the mould, so that - once filled - the part is sufficiently rigid to be demoulded. Nevertheless, adequate temperature control of the core and cavity surfaces is important for producing quality parts, since uniform cooling improves part quality, by reducing residual stresses and maintaining dimensional accuracy and stability [258]. Thus, there are many different designs of heat-exchange systems that are used in practice[23], aiming to maximize heat-transfer and assuring the required quality of plastic parts. The reinforced platform assumes only straight cooling lines with a few number of turns (maximum of 4 turns), placed on both cavity and core plates. This imposition is assumed only for simplicity reasons, since it is very easy to change it in the reinforced platform. Figure 4.10 presents two cooling circuits adopting two or four turns. The design variables that must be defined regarding the design of the cooling system are summarized in Table 3.18. The design variables associated to the Optimize stage are highlighted in Figure 4.10.

[23] Currently, there are other alternatives to drilling cooling lines (e.g. conformal cooling).

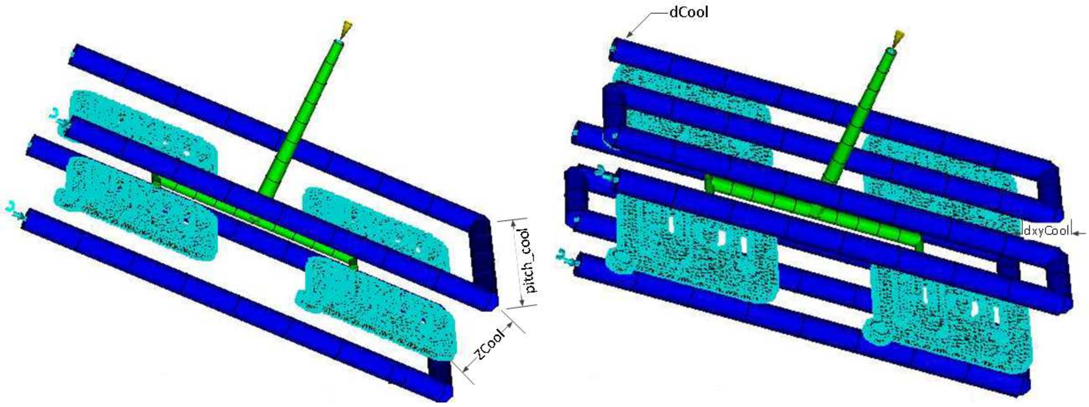


Figure 4.10: A cooling circuit with two turns (left) and with four turns (right).

Considering that the main function of the heat-exchange system is to maximize heat transfer rate in order to achieve shorter cycle times, there are some constraints that must be included in the model. These constraints are necessary to assure the adequate temperature gradients, aiming to reduce the shrinkage and the warpage of the plastic part.

$\Delta T_{coolant} = \frac{\dot{Q}_{line}}{\dot{V}_{coolant}\rho_{coolant}Cp_{coolant}} \leq 1$	The temperature's increase in coolant along the cooling line ($\Delta \boldsymbol{T}_{\boldsymbol{coolant}}$) must be lower than 1°C.	***Eq. 98***
$d_{Cool} - \frac{\rho_{coolant}\dot{V}_{coolant}}{1000\pi\mu_{coolant}} \leq 0$	The coolant must present with a turbulent flow (i.e. Reynolds number must be greater than 4000) to ensure adequate heat transfer from the mould to the coolant through a turbulent flow in the coolant.	***Eq. 99***
$d_{Cool} < Z_{Cool} < 2d_{Cool}$	The distance between the part and the cooling line (on the Z direction) must be great enough to ensure structural stiffness, as well as smaller enough to maximize heat conduction.	***Eq. 100***
$Z_{Cool} < pitch\_cool < 5Z_{Cool}$	This condition is imposed to provide a faster and more uniform cooling, as well as more structural stiffness and less geometrical conflicts with the other mould's components.	***Eq. 101***

Where $\dot{Q}_{line}$ is the heat transfer rate per cooling line and $\dot{V}_{coolant}$ is the volumetric flow rate of the coolant; regarding coolant's properties, $\rho_{coolant}$ is its density, $Cp_{coolant}$ is its specific heat capacity and $\mu_{coolant}$ is its viscosity. Also in this case it is possible to define some lower and upper bounds for the heat-exchange system design, based on guidelines, which are the following:

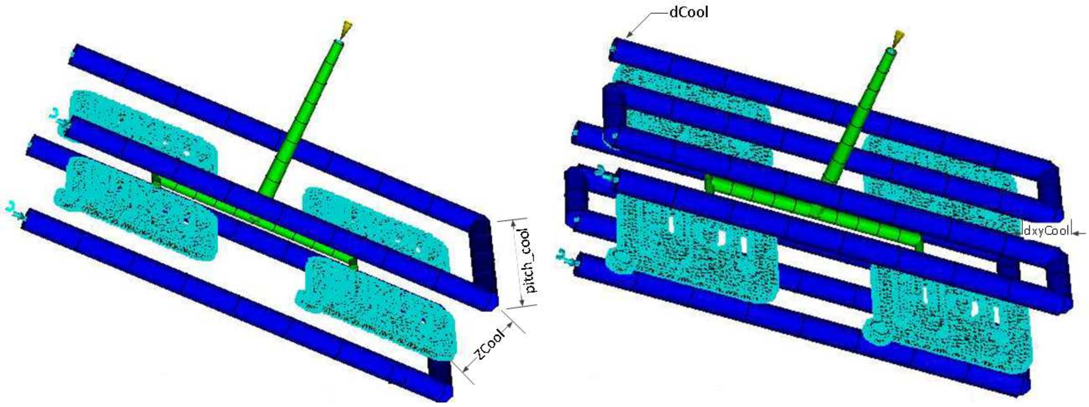


Figure 4.10: A cooling circuit with two turns (left) and with four turns (right).

Considering that the main function of the heat-exchange system is to maximize heat transfer rate in order to achieve shorter cycle times, there are some constraints that must be included in the model. These constraints are necessary to assure the adequate temperature gradients, aiming to reduce the shrinkage and the warpage of the plastic part.

$\Delta T_{coolant} = \dfrac{\dot{Q}_{line}}{\dot{V}_{coolant}\rho_{coolant}Cp_{coolant}} \leq 1$	The temperature's increase in coolant along the cooling line ($\boldsymbol{\Delta T_{coolant}}$) must be lower than 1°C.	***Eq. 98***
$d_{Cool} - \dfrac{\rho_{coolant}\dot{V}_{coolant}}{1000\pi\mu_{coolant}} \leq 0$	The coolant must present with a turbulent flow (i.e. Reynolds number must be greater than 4000) to ensure adequate heat transfer from the mould to the coolant through a turbulent flow in the coolant.	***Eq. 99***
$d_{Cool} < Z_{Cool} < 2d_{Cool}$	The distance between the part and the cooling line (on the Z direction) must be great enough to ensure structural stiffness, as well as smaller enough to maximize heat conduction.	***Eq. 100***
$Z_{Cool} < pitch\_cool < 5Z_{Cool}$	This condition is imposed to provide a faster and more uniform cooling, as well as more structural stiffness and less geometrical conflicts with the other mould's components.	***Eq. 101***

Where $\dot{Q}_{line}$ is the heat transfer rate per cooling line and $\dot{V}_{coolant}$ is the volumetric flow rate of the coolant; regarding coolant's properties, $\rho_{coolant}$ is its density, $Cp_{coolant}$ is its specific heat capacity and $\mu_{coolant}$ is its viscosity. Also in this case it is possible to define some lower and upper bounds for the heat-exchange system design, based on guidelines, which are the following:

$$8 \leq d_{Cool} \leq 12$$ ***Eq. 102***

$$8 \leq Z_{Cool} \leq 30$$ ***Eq. 103***

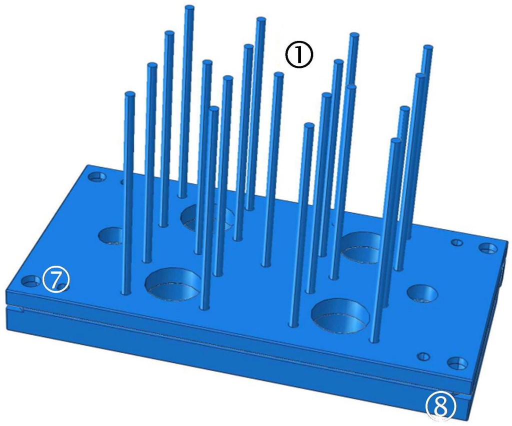
$$20 \leq pitch\_cool \leq 100$$ ***Eq. 104***

$$2 \leq n_{turns} \leq 4$$ ***Eq. 105***

4.3.5. Ejection system

According to Pontes *et al.* (2005) [259], the ejection system design requires special considerations, namely the prediction of the ejection force, in order to guarantee the integrity of the mouldings. Note that the ejection system is responsible for removing the moulded part(s) from the mould, after the mould opens. While it seems to be a simple function, it is important to note that once the plastic is injected into the cavity, it begins to cool and shrink. This shrinking develops a significant pressure on the mould's core, as mentioned before. Then, the ejection system must push off the plastic part from the core. If the pressure made by the ejection system is too high it can lead to the damage of the plastic part. To avoid these damaging or catastrophic effects it is necessary to optimize the number, location and dimensions of the ejector pins (Z. Wang *et al.* (1996) cited by [260]). Also some concerns regarding the quality of the mouldings must be considered, such as the vestige in the part caused by the ejector pin and flashing made by an incorrect adjustment and tolerancing of the ejection system, particularly for low viscosity injection materials. It is important to note that a poorly designed ejection system may over-deform or damage the plastic part, and may also buckle or even break during operation, incurring production shutdown and maintenance costs.

Typically, the ejection system consists of one ejector plate, one ejector plate retainer, return pins, ejector pins and stop pins, which are housed between the bottom clamping plate and the retainer plate, as shown in Figure 4.11. These components are typically located in the movable half of the mould. It is also important to highlight that, sometimes, there are additional components, such as slides and lifters. This type of components is only necessary when the plastic part is geometrically complex (i.e. when the parts include internal and external undercuts). Therefore, the design of slides and lifters does not fall within the scope of the proposed framework.



1	Ejector pins
7	Ejector plate
8	Ejector retainer plate

Figure 4.11: Typical components of the ejection system: reinforced platform.

In brief, the design of the ejection system must consider the following issues:

- Minimize distortions of plastic part mouldings (i.e. the ejection force must be uniformly distributed across the mould cavity);
- Minimize cycle time by reducing the mould's release time;
- Minimize impact on part surfaces. The most common approach is to locate, if possible, ejector pins on the non-visible surfaces and in the low stress area of the part moulding;
- Respect other mould's components location in order to avoid conflicts, specially the effect of cooling interference which can result in the reduction of the cooling effectiveness[24];

Taking these features into consideration, it is important to analyse the ejection forces that must be applied to the plastic part, through the ejection components, in order to release it from the core without causing part's damage. However, no specific commercial software code includes the analysis of these phenomena. Also, there are only a few research studies focusing on the ejection systems design.

One of the exceptions is the Wang *et al.* (2000)[261] work, where the influence of different layouts of the ejector pin system is studied, considering the number, location and size of its pins. They concluded that the ejection-induced stresses in the product depend significantly on the layout of the ejector pins. A more complete model for ejection force prediction can be found in Pontes *et al.* (2005) [259], where they define a simulation algorithm, based on a thermo-mechanical model, for determining the ejection force.

[24] Typically, the ejection components are less thermal conductive.

The principle adopted in this work to determine the ejection force considers the technical literature for mould design [226]. Thus, it is assumed that the ejection force (F_{eject}) required to remove a plastic part moulding from a mould core is a function of the normal force between the surface of the moulding and the surface of the mould (F_{normal}), together with the associated draft angle ($draft\_angle$) and the coefficient of static friction (μ_s), according to:

$$F_{eject} = \mu_s \cos(draft\_angle)\, F_{normal} \qquad \textit{Eq. 106}$$

As previously mentioned, for the selected example the draft angle is 1° and the static friction coefficient was assumed as 0.5. It has been demonstrated that some processing variables, such as cooling time, melt temperature and packing pressure, as well as surface roughness and contact temperatures have a significant influence on the coefficient of static friction [260]. Nevertheless, a simplified analysis will be undertaken in order to determine the major shear and compressive forces that are applied to the ejection system components in order to design it (i.e. a conservative simplifying assumption will be applied to estimate the ejection force). Given the geometric characteristics of the ejection system, buckling will be also considered in this analysis.

The normal force acting between the moulded part and the core is driven by the internal tensile stresses in the plastic, which causes the plastic part moulding to hug to the core. Then, this force can be estimated assuming that the tensile stresses in the moulding are the result of the thermal contraction of the plastic moulding, which over predicts the ejection forces[25]. Therefore, considering that the plastic melt only supports tensile stress as a solid, its thermal strain (ε) can be computed according with:

$$\varepsilon = CTE\left(T_{trans} - T_{eject}\right) \qquad \textit{Eq. 107}$$

Where CTE is the coefficient of thermal expansion of plastic at room temperature, T_{trans} is the transition temperature and T_{eject} is the ejection temperature. Then, the resulting tensile stress (σ) can be calculated as:

$$\sigma = E_{plastic} \cdot CTE\left(T_{trans} - T_{eject}\right) \qquad \textit{Eq. 108}$$

[25] A more accurate analysis can assume that the ejection forces can be determined by the integral of residual stress in the moulded part, taken across the effective area of the moulded part. However, this estimation is a complex function of the processing conditions, mould geometry and material properties.

Where $E_{plastic}$ is the Young's modulus of the plastic material. Based on that, the normal force can be expressed as the product of tensile stress times the effective area, A_{eff}, i.e. cross-sectional area of the plastic moulding:

$$F_{normal} = E_{plastic} \cdot CTE\left(T_{trans} - T_{eject}\right) \cdot A_{eff} \qquad \textit{Eq. 109}$$

Therefore, replacing Eq. 109 in Eq. 106, the necessary ejection force to release the plastic moulding $\left(F_{eject}\right)$ can be computed as:

$$F_{eject} = \mu_s \cos(draft\_angle)\, E_{plastic} \cdot CTE \cdot \left(T_{trans} - T_{eject}\right) \cdot A_{eff} \qquad \textit{Eq. 110}$$

Regarding compressive stress ($\sigma_{comp\_ejector}$), its value can be computed for each ejector pin, based on the applied force in each one, $F_{ejector}$, divided by its cross area. Considering that the ejector pins are typically cylindrical with diameter $d_{Ejector}$ to avoid failure the applied force in each ejector pin must be lower than:

$$F_{ejector} < \frac{\sigma_{fatigue\_limit}}{n_{safety}} \frac{\pi}{4} \left(d_{Ejector}\right)^2 \qquad \textit{Eq. 111}$$

Where $\sigma_{fatigue\_limit}$ is the fatigue limit stress of the ejectors material and n_{safety} is a safety coefficient.

Finally, an important subject regarding the pins dimensioning is that they tend to buckle under compressive load, due to their slim shape. Therefore, following Euler theory, the critical load regarding buckling $\left(F_{buckling}\right)$ is given, for each pin, by:

$$F_{buckling} = \frac{\pi^2 E_{pin} I}{\left(0.7 l_{Ejector}\right)^2} \qquad \textit{Eq. 112}$$

Where E_{pin} is the Young's modulus of the ejector pin's material and I is the moment of inertia. Assuming a circular ejector pin of diameter $d_{Ejector}$ its moment of inertia is $\frac{\pi}{16} d_{Ejector}^4$. Thus, taking into account the PP location and the necessary opening distance to release the mouldings ($d_{Release}$), in order to avoid buckling, the diameter of each ejector pin must be greater than:

$$d_{Ejector} = \sqrt[4]{\frac{7.84 F_{ejector} d_{Release}^2}{\pi^3 E_{pin}}} \qquad \textit{Eq. 113}$$

Based on the previous equations, it is possible to design each ejector pin. However, it is also necessary to define the number of pins and their locations. These conceptual decisions will be made, once more, at the Design stage. Afterwards, it is possible to define each pins' size, i.e. its diameter and its length. Ejector pins are available from several suppliers, which offer quite a lot of pins with coupled diameters and lengths, as exemplified in Figure 4.12. Therefore, its design must be constraint to availability on the market.

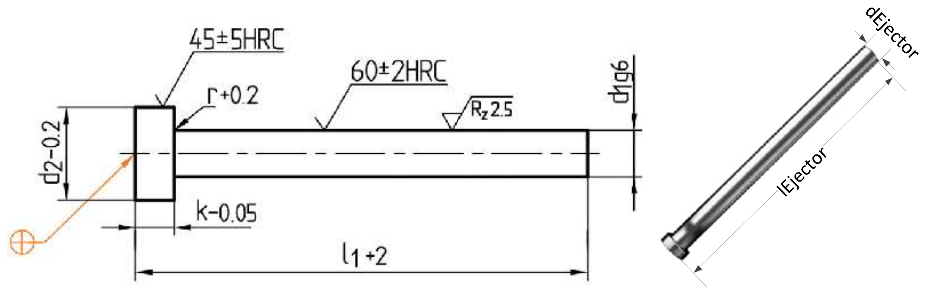


Figure 4.12: Ejector pins dimensions: standard from HASCO Catalogue [256] (left) and by platform (right).

Since plates 7 and 8 designs are already included in the structure design, the design variables that must be defined regarding the design of the ejection system are summarized in Table 3.22. It is important to note that the number of ejectors is assumed to be 2 or 4 per part, only for simplicity reasons, since this can be easily changed in the platform. Finally, the cost of ejector pins is also as an important issue, since it is necessary to encompass the trade-off between adopting several ejectors with lower diameters or a shorter number with greater diameters. Therefore, based on price of the ejector's available on the market, a function was estimated. The Hasco 2010 Digital Catalogue [256] was used as a reference, showing that the price is a function of ejector pin diameter and length, as illustrated in Figure 4.13.

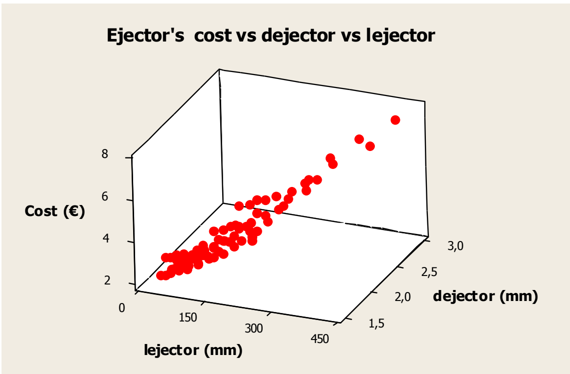


Figure 4.13: Ejector's cost versus ejector's diameter and length.

Based on these values, a regression analysis was carried out and the results are summarized in Table 4.10 and Figure 4.14.

Table 4.10: Regression analysis for ejector's cost estimation.

Predictor	Coefficient	SE Coefficient	t	p
Constant	2.1895	0.1690	12.96	0.000
$d_{Ejector}$	-0.36982	0.0840	-4.40	0.000
$l_{Ejector}$	0.0144	0.0005	31.39	0.000

S = 0.335415 R-Sq = 93.1% R-Sq(adj) = 92.9%

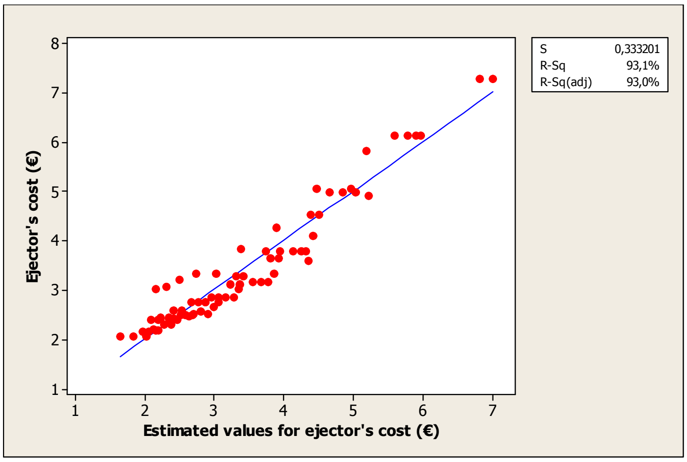


Figure 4.14: Estimated cost of ejectors versus real costs.

The cost function estimated explains 93.1% of the variability of the data, and can be expressed by:

$$Cost\_Eject = 2.19 - 0.37d_{Ejector} + 0.014l_{Ejector} \quad \textit{Eq. 114}$$

In addition, an analysis of variance and residuals confirms that this function is statically significant, as shown in Table 4.11 and Figure 4.15. Consequently, this cost function can be used in the optimization model to evaluate the cost of the ejectors pins.

Table 4.11: Analysis of variance of regression function: ejectors' cost.

Source	DF	SS	MS	F	p
Regression	2	113.602	56.801	504.88	0.000
Residual error	75	8.438	0.113		
Total	77	122.040	31.39	0.000	

DF – Degree of freedom, SS – Sum of squares, MS – Mean of square (MS=SS/DF), F is F-test statistic and p is the p-value.

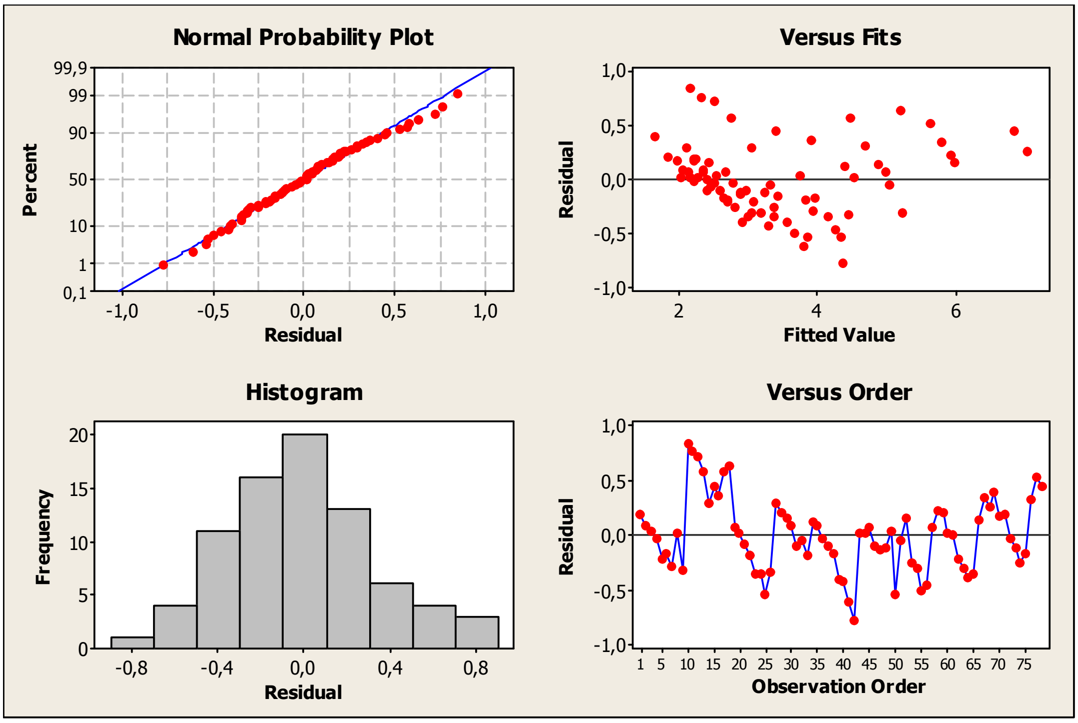


Figure 4.15: Plots of residuals: normal plot, residuals versus fits, and histogram versus order: ejector's cost.

In brief, the ejection system must be designed in order to minimize distortions of plastic part mouldings, as well as to minimize the impact on part surfaces. To that end, the ejector force must be the most uniformly possible distributed across the mould cavity. Therefore, based on the previous discussion, some constraints must be included in our ejection system design optimization model.

$$\sum_{i=1}^{n_{Ejectors}} \frac{\pi}{4} d_{Ejector}^2 \sigma_{fatigue_{limit}} - F_{eject} > 0$$
$$= \frac{\pi}{4} d_{Ejector}^2 n_{Ejectors} \sigma_{fatigue\_limit} - \mu_s \cos(draft\_angle)\, E_{plastic} \cdot CTE \cdot (T_{trans} - T_{eject}) \cdot A_{eff} > 0$$

The total push area of all ejectors pins must be enough to support the necessary ejection force to release the plastic moulding in order to avoid failure regarding compressive stress. ***Eq. 115***

$$d_{Ejector} = \sqrt[4]{\frac{7.84 F_{ejector} d_{Release}^2}{\pi^3 E_{pin}}}$$

The minimum value for the ejector pin diameter, in order to avoid buckling (following Euler theory). ***Eq. 116***

$$l_{Ejector} > Z_7 + Z_4 + Z_3 + d_{Release} - Z_e$$

The ejector's pin length must be greater enough to guarantee the release of the plastic moulding. ***Eq. 117***

$$l_{Ejector} < Z_7 + Z_4 + Z_3 + d_{Release} - Z_e + Z_5$$

The ejector's pin length must fit on the movable part of the mould. ***Eq. 118***

Finally, based on guidelines, the lower and upper bounds for ejectors' diameter and length are the following:

$$5 \leq d_{Ejector} \leq 7 \qquad \textit{Eq. 119}$$

$$100 \leq l_{Ejector} \leq 250 \qquad \textit{Eq. 120}$$

4.3.6. Interaction between functional systems

Based on the previous analysis of moulds functional systems, it is possible to conclude that the design of an injection mould involves a considerable number of design variables, with a significant number of categorical and geometrical types. Moreover, since most of these design variables are coupled with each other, assuming the design of an injection mould as an optimization problem presents a significant degree of complexity.

To deal with that, similarly to the first attempt, the reinforced platform follows a multidisciplinary approach to support the design of an injection moulding. The integrated domains are the structural, thermal, rheological and mechanical, where structural, thermal, and rheological processes are modelled by high-fidelity models.

In the platform, all different analysis codes are connected through the integration software, which is at this stage ModeFRONTIER. This overseeing software automates the iterative procedure of the optimization process, according to a predetermined optimization scheme. The loop of the reinforced framework starts with the Design stage, where a few number of conceptual mould solutions will be proposed by the mould designer, according to his experience and the best practice guidelines. A brief description of these practical rules can be found in the design's manual established by mould's Portuguese association [245]. It is important to highlight that these initial design decisions are described as the combination of each design variable alternative, included at the conceptual stage. Then, based on the previous FRs-DPs map and by assigning different values to each conceptual variable, the generated conceptual solutions will be evaluated, in order to select the solution which has the most well ranked customer satisfaction level.

The major weakness of the approach is the largest computational time associated to the high fidelity analysis. In fact, the computational expense necessary for an optimal design search in the conceptual stage is impractical, special due to the highly discontinuous and non-convex feasible space, originated by the categorical and geometrical design variables. Therefore, according to some authors [35, 87, 89], a good alternative is to employ DoE methods to evaluate potential designs. In fact, since much of the platform design analysis is performed through computer simulation models, and with the level of uncertainty prevalent in both these models and the injection mould problems themselves, 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 Eq. 17, being the design space defined by a DoE. Through DoE, a design matrix 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 one to assess the performance and quality of each studied design solution, in order to determine the most ranked, according to customer satisfaction.

In the Optimize stage, the geometry handler module (carried out by SolidWorks) calculates the geometrical and physical dimensions of the selected conceptual solution. For each combination of design variables, the geometry handler module generates a universal file (in this case IGES[26] format) to be used in the subsequent analysis. Phenomena are, then, undertaken by MOLDFLOW, responsible for the thermal and rheological behaviour analysis, and by ABAQUS, in charge of the structural analysis. As previously mentioned, 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 modules.

In order to differentiate the two stages, the developed platform was also structured into two levels, as schematically shown in Figure 4.16. In the first stage, the Design one, conceptual solutions are generated and selected based on their value regarding the Feeding, Heat-Exchange, Structural and Ejection system. This allows taking design decisions about the conceptual solutions. In the second stage, the Optimize one, the selected conceptual solution is detailed and optimized in order to maximize customer satisfaction. Note that, this is achieved by determining the values of design variables included at the Optimize stage, also shown in Figure 4.16.

[26] IGES means Initial Graphics Exchange Specification.

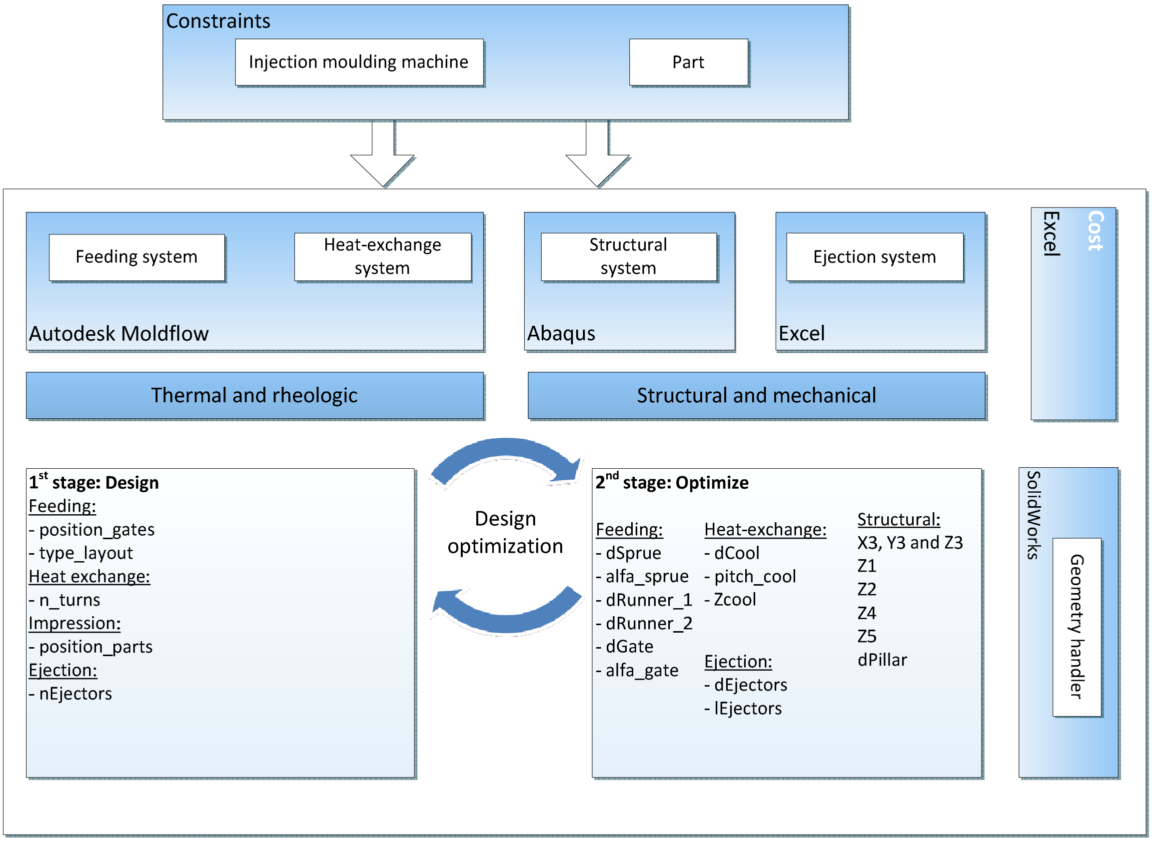


Figure 4.16: The two stages of the reinforced platform structure.

4.4. Design stage

As mentioned, the main objective of this stage is to conceive rough design layouts, where each concept is generated through the combination of each design variable alternatives. The design variables considered in the Design stage are summarized in Table 4.12. Then, by assigning different values to each conceptual variable, a number of different conceptual solutions for the mould can be accomplished. It is important to note that, as it was previously justified, some conceptual design variables were considered fixed in order to simplify the model, as shown in Table 4.13.

Table 4.12: Design variables considered in the Design stage: reinforced platform.

	Symbol	Design variable definition	Fixed value
Heat-exchange	***n_turns***	Number of turns of each cooling line	Integer
Impression	***position_parts***	Position of each part relatively to the PP	Geometrical
Gate's design	***position_gates***	Position of each gate relatively to the PP	Geometrical
Ejection	***position_ejectors***	Position of the ejectors regarding the PP	Geometrical
	$n_{Ejectors}$	Number of ejectors per part	Integer

Table 4.13: Fixed variables at the Design stage: reinforced platform.

	Symbol	Design variable definition	Fixed value
Gate's design	***type_gate***	Type of gate's geometry	Pin Point (PiP)
	partition_plane	Position of the PP	Geometrical (Existing)
Ejection system	***type_ejectors***	Type of ejectors	Cylindrical
Feeding system	***type_runner***	Type of runners cross-section	Full-Round (FuR)
Structural system	***mould_material***	Mould's material	1.1730
	cavity_material	Material for cavity's inserts	1.1730

Based on the design variables presented in Table 4.12, there are some additional decisions that must be undertaken at this stage, regarding the design of an initial baseline solution for the mould. Similarly to the strategy adopted in chapter 3, a few number of conceptual solutions must be generated combining the alternative options proposed by the mould designer. Afterwards, these solutions will be evaluated and compared, in order to select the conceptual solution that has the highest rank customer satisfaction level, through a full factorial DoE.

The structure of the module included in the reinforced platform, regarding the Design stage, can be observed in Figure 4.17, where the design variables and the objective functions are highlighted. Some important considerations were taken into account in its construction, namely customer's impositions are included and defined as *Material_part* and *Geometric_part* restrictions. About design variables that are assumed as fixed, their values are considered constant. For this reason, they are assumed as parameters in the platform. Nevertheless, they can be easily included as design variables in the platform, by altering its status from constant to variable and introducing their bounds. Finally, taking into account the type of design variables included in this stage, only thermal, rheological and mechanical analysis will be performed at this design stage.

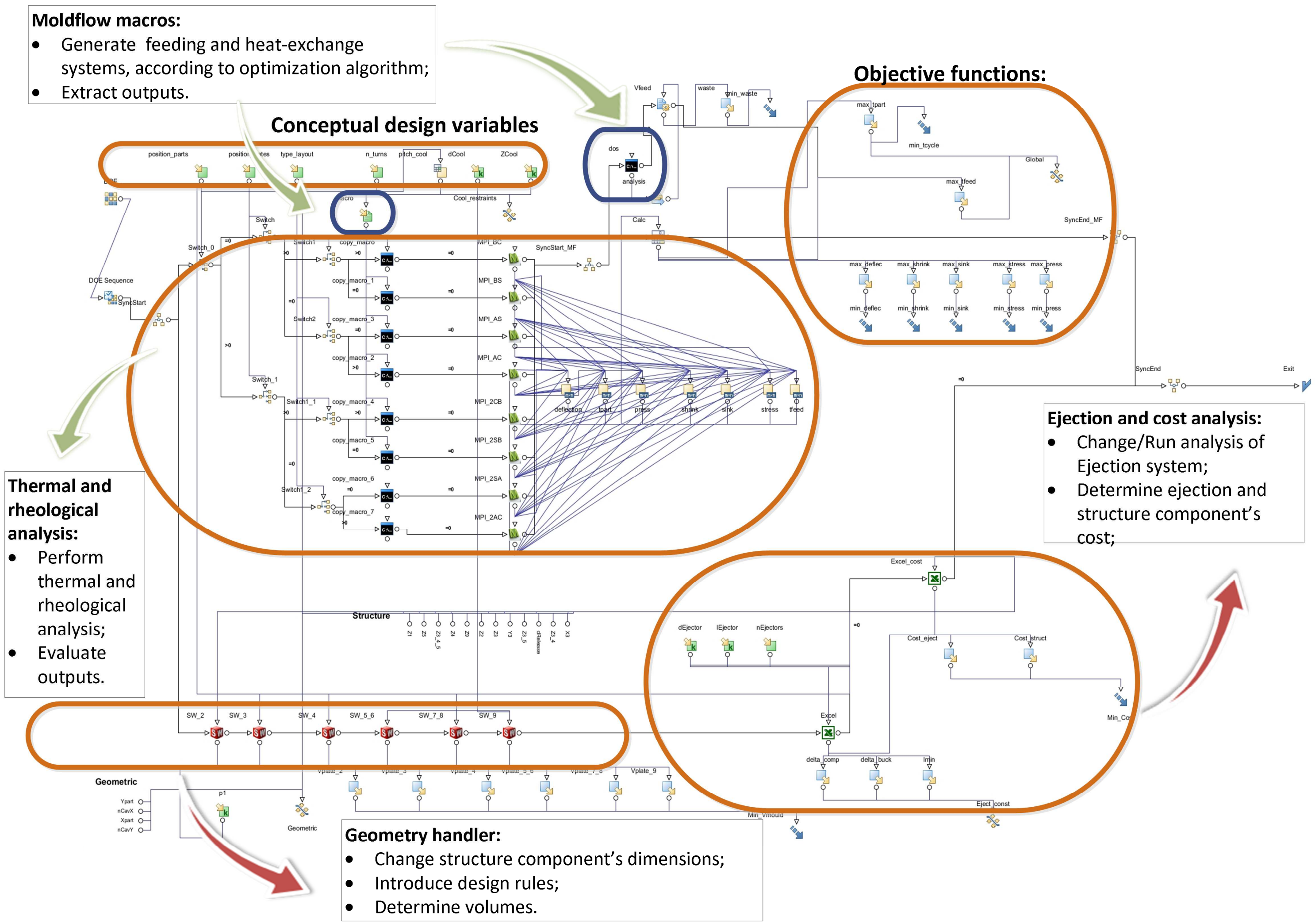


Figure 4.17: View of the Design module built in the reinforced platform (ModeFRONTIER).

Given the number and the type of design variables considered at the Design stage, mostly categorical with at least two possible values each one, a minimum of 32 conceptual solutions must be evaluated. Since the evaluation of a single conceptual solution takes in average 30 minutes, the complete evaluation of the generated conceptual solutions will take approximately 16 hours.

As it was previously mentioned, despite steady advances in computing power, the expense of running the analysis codes remains non-trivial. Therefore, it is important to assure that the computation time is feasible. In fact, one important request of the injection sector is the short period of time available for mould design and manufacturing. For that reason, the design space must be reduced by identifying the combination of conceptual variables that can increase the customer satisfaction level. For that purpose, DoE is adopted to allow the construction of an efficient set of computer runs. In addition, based on this DoE analysis, it will be also possible to select the most ranked conceptual solution regarding the levels of customer's satisfaction. This can be computed through the values attained for each functional requirement, regarding each generated solution. Afterwards, the selected conceptual design solution will be detailed and optimized in the next IDOV stage, the Optimize stage.

4.5. Optimize model

After the conceptual solution was found, it must be detailed and optimized through MDO. Then, the platform was redefined in order to include all the design variables regarding the Optimize stage, which is summarized in Table 4.14. Since all functional mould systems are included, and because each individual system has its own objective functions, these objectives will be included in the model as constraints.

Table 4.14: Design variables regarding injection mould at the Optimization stage: reinforced platform.

	Design variables	Description	Units
Structure	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

The structure of the module included in the reinforced platform, regarding the Optimize stage, can be observed in Figure 4.18 highlighting its individual submodules. This module also includes SolidWorks in order to generate the geometrical definition of each structural component of the solution. The outputs of this code are universal files (IGES format), which will be used in the subsequent structural analysis carried out by ABAQUS. These geometrical features are also considered for the rheological and thermal analysis. This analysis is performed in parallel with the geometry handler, by MOLDFLOW code. Finally, the mechanical analysis of the ejection system and cost's assessment are carried out by EXCEL. For each design solution the cycle ends with its evaluation taking into account the predefined constraints. In order to clarify how the platform works, the previously mentioned submodules will be detailed in the following sections.

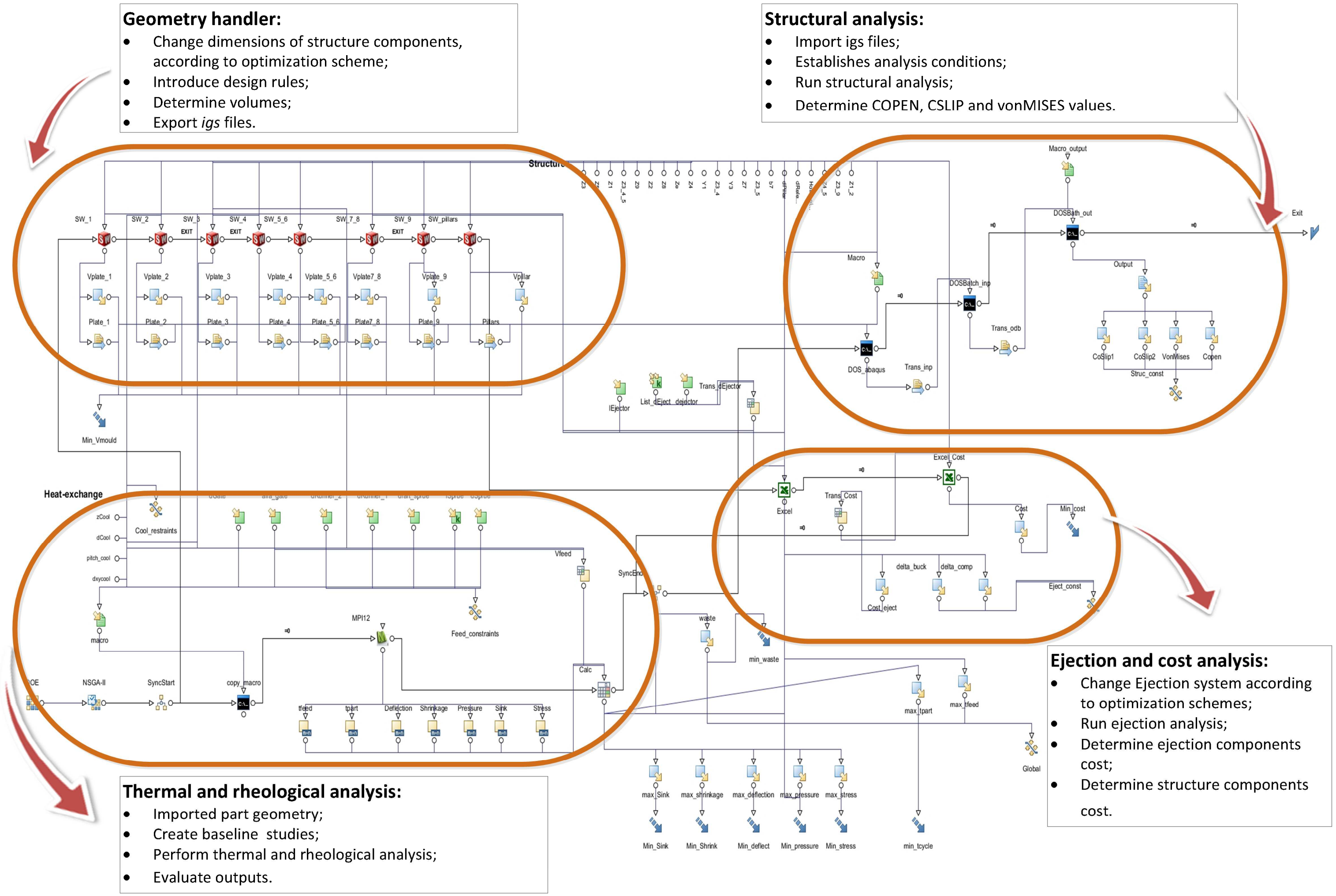


Figure 4.18: View of Optimization module in the reinforced platform (ModeFRONTIER).

4.5.1. Structural module

The reinforced platform includes a structural module, as illustrated in detail in Figure 4.22, which takes into account the previously described design variables, constraints and specific objectives regarding the structural system. To better explain how this module works, in this section we will analyse it independently of the remaining functional mould systems. For that purpose, the coupled design variables are assumed to have constant values. At the same time, only the constraints regarding the structural module were included, because the remaining constraints are verified by the feasibility of the coupled design variables values.

As previously mentioned, the three objectives of the structural system optimization are to minimize stress, deflection and mould's volume. The main goal of the structural module is to determine the plate's dimensions, in order to minimize the mould's volume (*Min_Vmould*) and cost (*Min_Cost*). However, at the same time, it is necessary to minimize stress and deflection. These variables are evaluated using the CAE software. In this particular case, the deflection can be analysed based on the variables COPEN (i.e. contact opening) and CSLIP (relative tangential motions), which represent the relative positions normal and tangential to the interface, respectively. They are both contact output 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 leads to outputs including the minimum value for contact opening, which reflects the smallest opening in the model. 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 master (plate 3) along the contacting plane. Thus, ABAQUS outputs include the two values along the principal directions (CSLIP1 and CSLIP2).

The conditions regarding stress distribution minimization are controlled imposing that the von MISES stress generated by the model must be smaller than the yield stress of the mould's material. ABAQUS provides the output of the von Mises stress maximum, minimum and average values. In brief, element based field outputs are written to the output database as the maximum value for nodes of the variables COPEN and CSLIP, on principal directions (CSLIP1 and CSLIP2), while for the von MISES, it was defined as the mean value determined for the centroid.

The kick-off of the structural module consists on a DoE random sequence, where the design space is filled randomly with a uniform distribution. Thus, unfeasible and repeated designs are rejected. For each design solution, the geometry handler module builds a CAD format for each plate and determines their volumes. Finally, it exports all the generated geometries through a universal file. It is important to note that several geometric relations regarding mould's components were introduced in the geometry handler (e.g. Eq. 68 to Eq. 71 and interference constraints) in order to respect design rules, as well as to avoid geometric interferences. For example, the geometric relations introduced in plate 3 are illustrated in Figure 4.19.

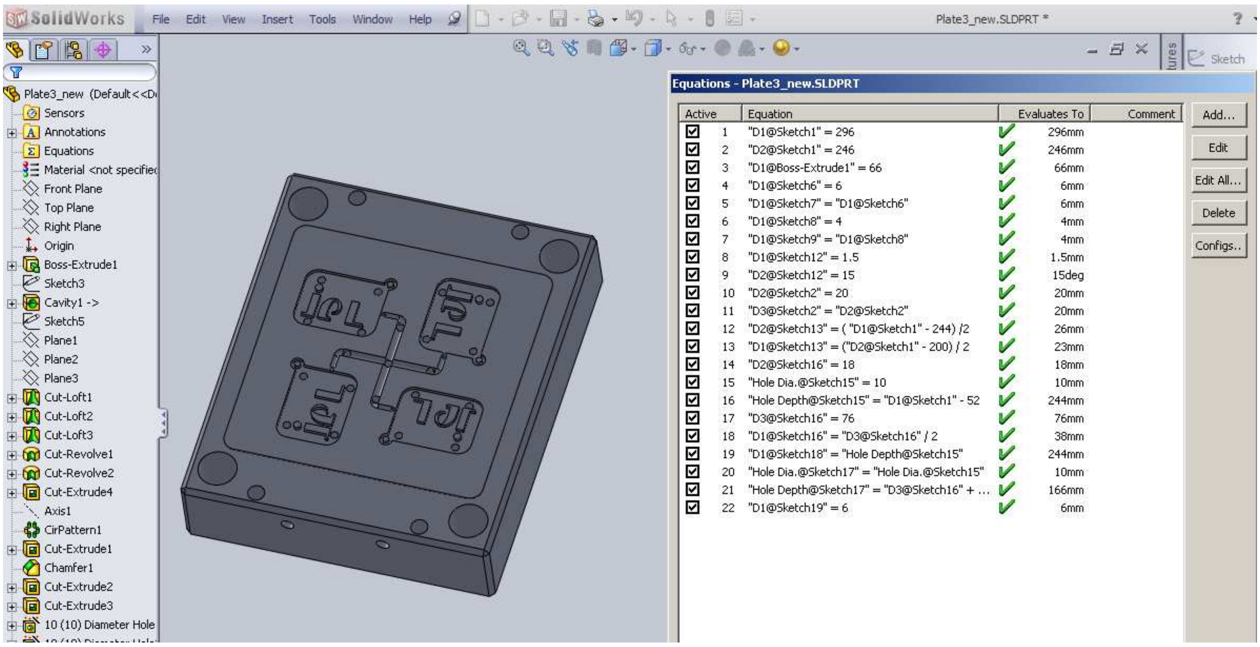


Figure 4.19: View of geometric relations introduced in geometry handler regarding plate 3 (Solidworks).

All the universal files produced by the geometry handler 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 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[27], resulting in approximately 392 code lines.

[27] Python is the standard programming language for Abaqus.

In each ABAQUS analysis, the boundary conditions are imposed to the top surface of the injection clamping plate (plate1), for which all displacements are constrained, as shown in Figure 4.20. 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.

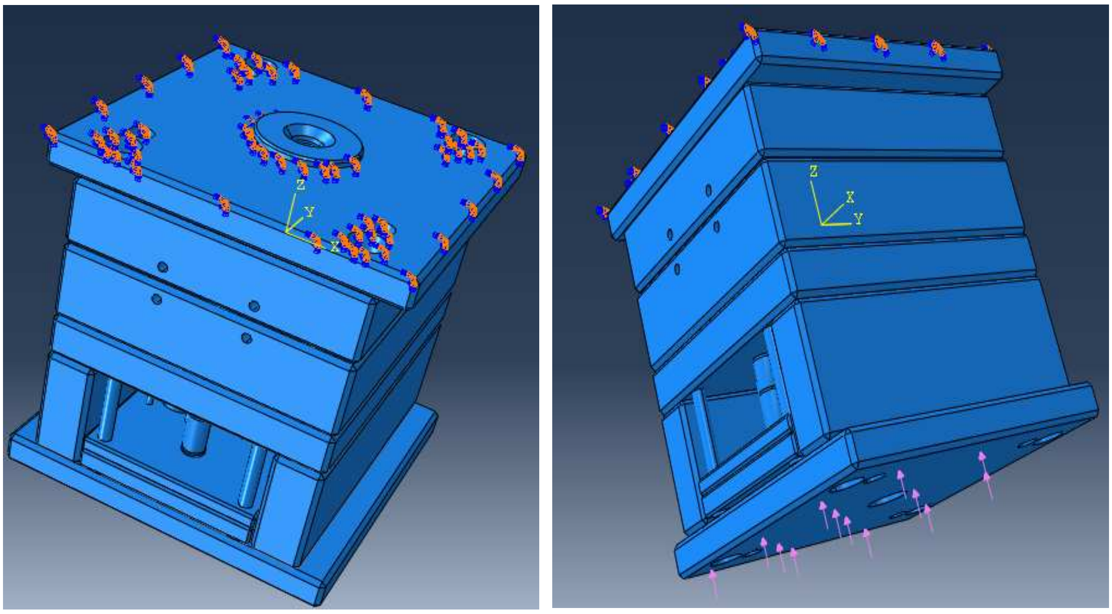


Figure 4.20: The boundary conditions and the clamping force applied (ABAQUS).

Regarding the remaining structural components, tie contacts are adopted, as contact interaction between the following surfaces: bottom of Plate 1 and top of Plate 2, bottom of Plate 3 and top of Plate 4, bottom of Plate 4 and top of Plates 5 and 6, bottom of Plate 4 and top of the support pillars, top of Plate 9 and bottom of Plates 5 and 6, top of Plate 9 and bottom of the stop pins, and top of Plate 9 and bottom of the support pillars, as well as between the guide space which connects plates 2 and 3. The injection pressure is applied in the cavity and the core areas of plates 2 and 3, respectively, as presented in Figure 4.21. Each structural element is discretized with tetrahedral solid elements, which are known to result in efficient mesh generation algorithms for solid components. Regarding 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 submodule 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 using EXCEL.

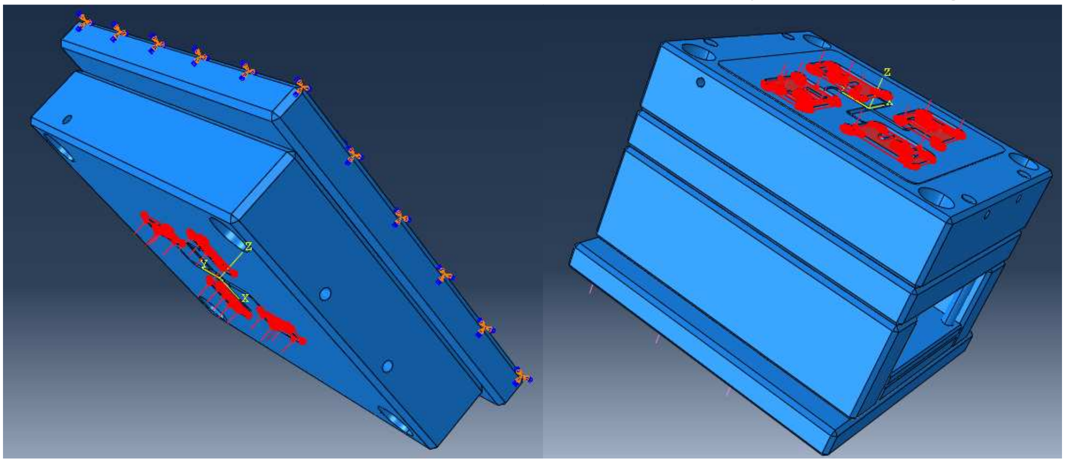


Figure 4.21: Application of the injection pressure in the cavity and the core areas of plates 2 (left) and 3 (right) (ABAQUS).

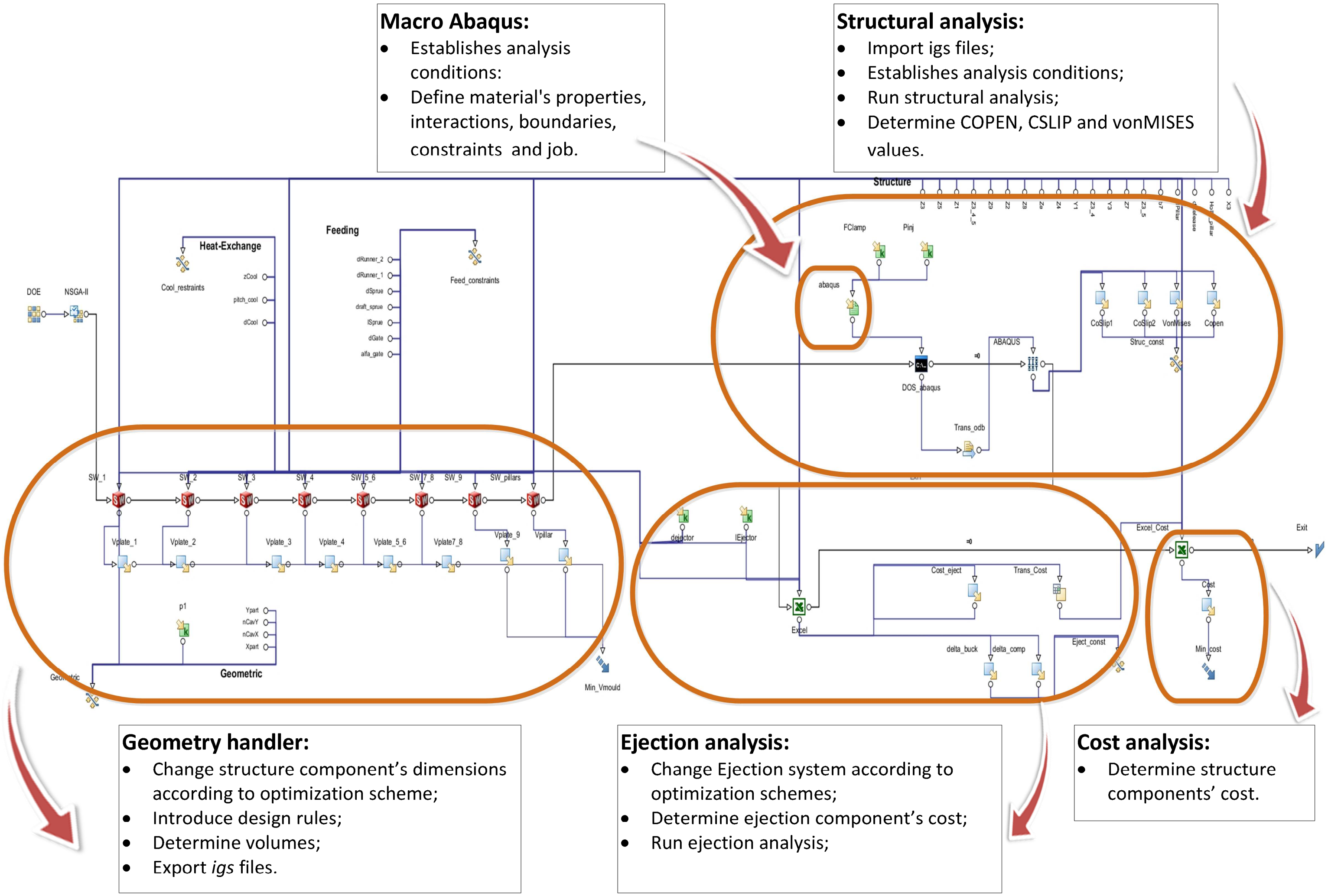


Figure 4.22: Main functions of the Structural module included in the reinforced platform.

The characteristics of the structural design problem, in particular the number and type of design variables and constraints; the feasibility of the design space; the type of initial solution and the adequate simulation runtime, are summarized in Table 4.19. Given these characteristics, a NSGA-II based on the one proposed by Deb *et al.* (2000)[262], was adopted to carry out the optimization procedure. The main reasons for this option are as follows: (i) it allows both continuous and discrete variables to be used; (ii) it allows user defined discretization (base); (iii) it implements elitism for multi-objective search; (iv) the diversity and spread of solutions is guaranteed without the use of shared parameters; and (v) it allows concurrent evaluation of the *n* (i.e. the number of individuals per generation) independent individuals.

Table 4.15: Main characteristics of structural module optimization problem: reinforced platform.

Criteria	
Number of design variables	Low (<20)
Number of constraints	Low (<1000)
Type of design variables	Real/Discrete
Objective/Constraints functions	Linear/Non-linear
Constraints type	Inequality/Equality
Feasible space	Non-convex and discontinuous
Initial point	Feasible
Simulation run time	Shortest

The number of individuals (*n)* of the initial population corresponds to the DoE values obtained by a random sequence, where the design space is filled randomly, with a uniform distribution. The sequence of points is determined by the value of the Seed, which was assumed as 1. Moreover, three additional parameters were defined:

1) Number of experiments to be generated: 10
2) Unfeasible designs are rejected;
3) Random seed for sequence repeatability: 1

The other tuning parameters adopted in the NSGA II algorithm are summarized in Table 4.16.

Table 4.16: Adopted parameters for NSGA II optimization: structural system.

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

A set of solutions was obtained, which can be observed with their respective objective values in Figure 4.23. The vertical bands in the parallel coordinates plot indicate the range of feasible or Pareto design variables values. There are a few possible Pareto solutions, which are highlighted in green.

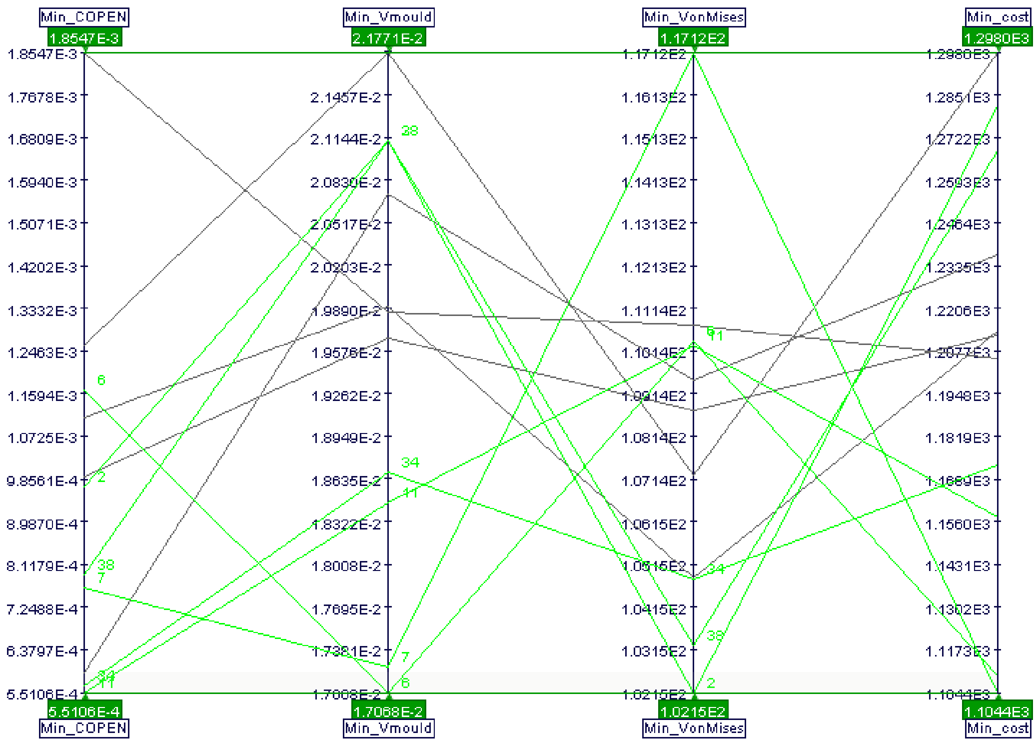


Figure 4.23: Structural design solutions achieved with Pareto solutions highlighted in green.

Nevertheless, the choice of the final structural design should be made from the set of Pareto optimal designs, using customer preferences. The aggregator software (ModeFRONTIER) has a Multi Criteria Decision Making (MCDM) tool to assist in finding the best solution from among a set of reasonable alternatives. It is important to note that MCDM allows the correct grouping of outputs into a single utility function. This utility function is coherent with the preferences expressed by the user through pairwise comparison of solutions or direct specification of attributes importance. For that purpose, modeFRONTIER has actually available four algorithms, namely Linear MCDM, GA MCDM, Hurwicz MCDM and Savage MCDM[28] [263]. For example, GA MCDM uses GA to generate utility function and weights of each customer criteria in order to respect customer preferences. Based on that, mould's customer can make better decisions, and then, consequently, make coherent evaluation of its different design objectives. This tool was used to determine a ranking between the achieved Pareto solutions. One possible relationship between the structural objectives can be established through direct comparison (see Table 4.17). The three objectives correspond to the minimization of the stress, deflection and mould's volume. These objectives are evaluated through the variables von Mises, COPEN, CSLIP1 and CSLIP2. Once more, a 1-9 scale with three levels was considered, the relationships between the objectives being defined according to Table 4.17.

Table 4.17: Relationships between objectives: structural system.

Objective 1	Type	Weight	Objective 2
COPEN	>	3	**vonMises**
Cost	>	3	**vonMises**
COPEN	>	1	**CSLIP1**

A linear algorithm is selected to assist the decision maker to find the best solution, among the set of reasonable alternatives, as well as to verify the coherence of the expressed preferences and generate a valid utility function and ranking. Note that this algorithm can only be used when the number of criteria is small. Finally, in order to create a MCDM, using the linear algorithm, three additional parameters were defined, namely, training cycles = 10, Preference Margin = 0.05 and Indifference Margin = 0.02. The results obtained are illustrated in Figure 4.24, which presents the weight of each criteria, as well as the utility function evolution along the range of the criteria. It is important to highlight that COPEN and Cost have the same importance (weight of 0.33), which is the highest value, followed by CSLIP1 (weight of 0.25) and by Von Mises (weight of 0.08). These results are in agreement with the imposed relationships defined in Table 4.17.

[28] They are computationally complex algorithms developed by ESTECO and integrated in ModeFRONTIER.

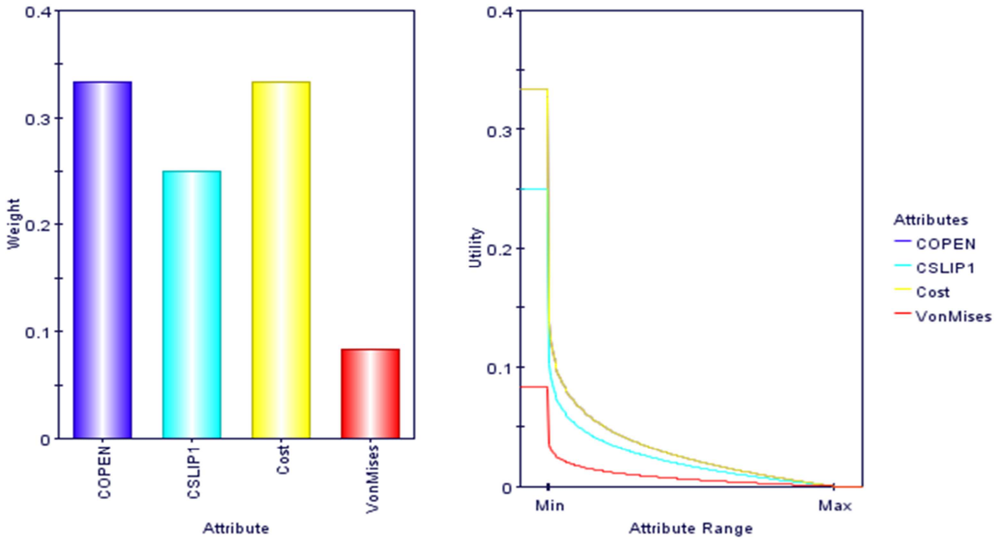


Figure 4.24: Weight and utility function obtained by MCDM tool regarding the structural system.

It is possible to verify that the algorithm can very quickly generate a valid ranking between alternatives (about 30 seconds), where the weights computed for the utility function respect the preference relationships expressed by the decision maker, as shown in Figure 4.24. Figure 4.25 presents the ranking achieved for the generated solutions, where it is possible to observe that the most ranked solution is ID 7.

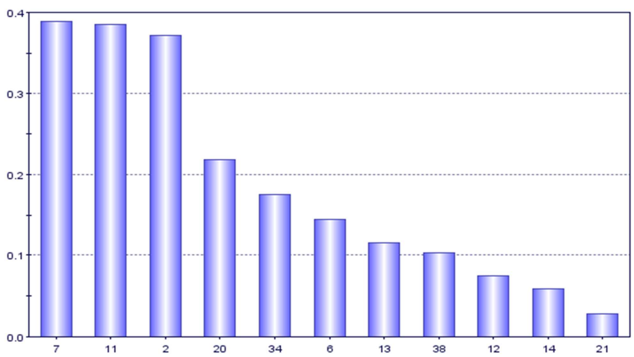


Figure 4.25: Ranking achieved for the structural solutions.

Even though multi-objective optimization problems do not yield an unique solution, it is possible to have an idea about the potential improvement of the initial solution when compared with the most ranked solution. This comparison is described in detail in Table 4.18. It is possible to verify that significant improvement was achieved in COPEN (-24%), Cost (-10%) and CSLIP2 (-11%). By the contrary, the achieved solution has an increase in CSLIP1 (2.9%) and von Mises (6.5%). Considering the importance of each objective, defined in Figure 4.24, it is possible to verify that this solution has a global improvement regarding the initial solution of 8.7%, and a small impact on CSI (increase of 0.11%). Nevertheless, it is important to highlight that this module only has a smaller influence on CSI since only mould's volume is assumed as a critical item to customer's satisfaction (see Eq. 18).

Table 4.18: Comparison between the best solution achieved (ID 7) and the selected conceptual solution: structural system.

	Conceptual	ID 7	Comparison
X_3	296	296	-
Y_3	246	246	-
Z_1	27	27	-
Z_2	66	66	-
Z_3	66	46	-
Z_4	46	36	-
Z_5	96	56	-
Z_7	12	12	-
Z_8	17	17	-
Z_9	27	27	-
d_{Pillar}	32	32	-
***COPEN* (mm)**	1.01E-03	7.65E-04	**-24.2%**
***CSLIP1* (mm)**	3.66E-3	3.8E-3	**2.9%**
***CSLIP2* (mm)**	2.34E-3	2.07E-03	**-11.3%**
***Cost* (€)**	1233.3	1104.4	**-10.4%**
***von Mises* (MPa)**	110	117.1	**6.5%**
***Vmould* (m^3)**	0.024	0.0173	**-15.4%**
Performance improvement			**8.7%**
Quality of Design improvement			**0.7%**
Impact on CSI through *Vmould*			**0.11%**

4.5.2. Feeding and heat-exchange modules

As it was previously mentioned, an important characteristic of the developed platform is the inclusion of two stages of design in the platform, namely, Design and Optimize stages. This feature is particularly important for these submodules, since the majority of conceptual variables are related with feeding system design. Therefore, feeding and heat-exchange modules are divided in two distinct and complementary parts regarding the two stages of design. Regarding the feeding and heat-exchange submodules, the reinforced platform includes the structures illustrated in Figure 4.26 and Figure 4.27, for the Design and Optimize stages, respectively. Since both feeding and heat-exchange systems are modelled by MOLDFLOW [264], some important considerations were taken into account during the construction of these submodules, in the reinforced platform. 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 configuration for the feeding and heat-exchange systems, Visual Basic scripts (VBScript) corresponding to the macro shown in Figure 4.26 were written using an Application Programming Interface (API) language[29]. 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 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 [264]. The VBScript macro was built in order to generate each feed and heat-exchange systems configurations imposed by optimization schemes. The macro allows the generation of a dual domain mesh on the part geometry, imported from an universal file (in this case 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.

In the Design stage the submodules encompass the conceptual decisions, which involve categorical and geometrical design variables of these two functional systems. As a result, several MOLDFLOW studies were required in order to cover, for example, different geometrical locations for 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 4.26 the MPI_2CB corresponds to the second position of the parts, on the PP, a B position of gates and a circular layout. The conceptual designs are generated based on DoE, in order to determine the variables for the Design stage presented in Table 4.9, for the feeding system, and in Table 3.18 for the heat-exchange system.

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

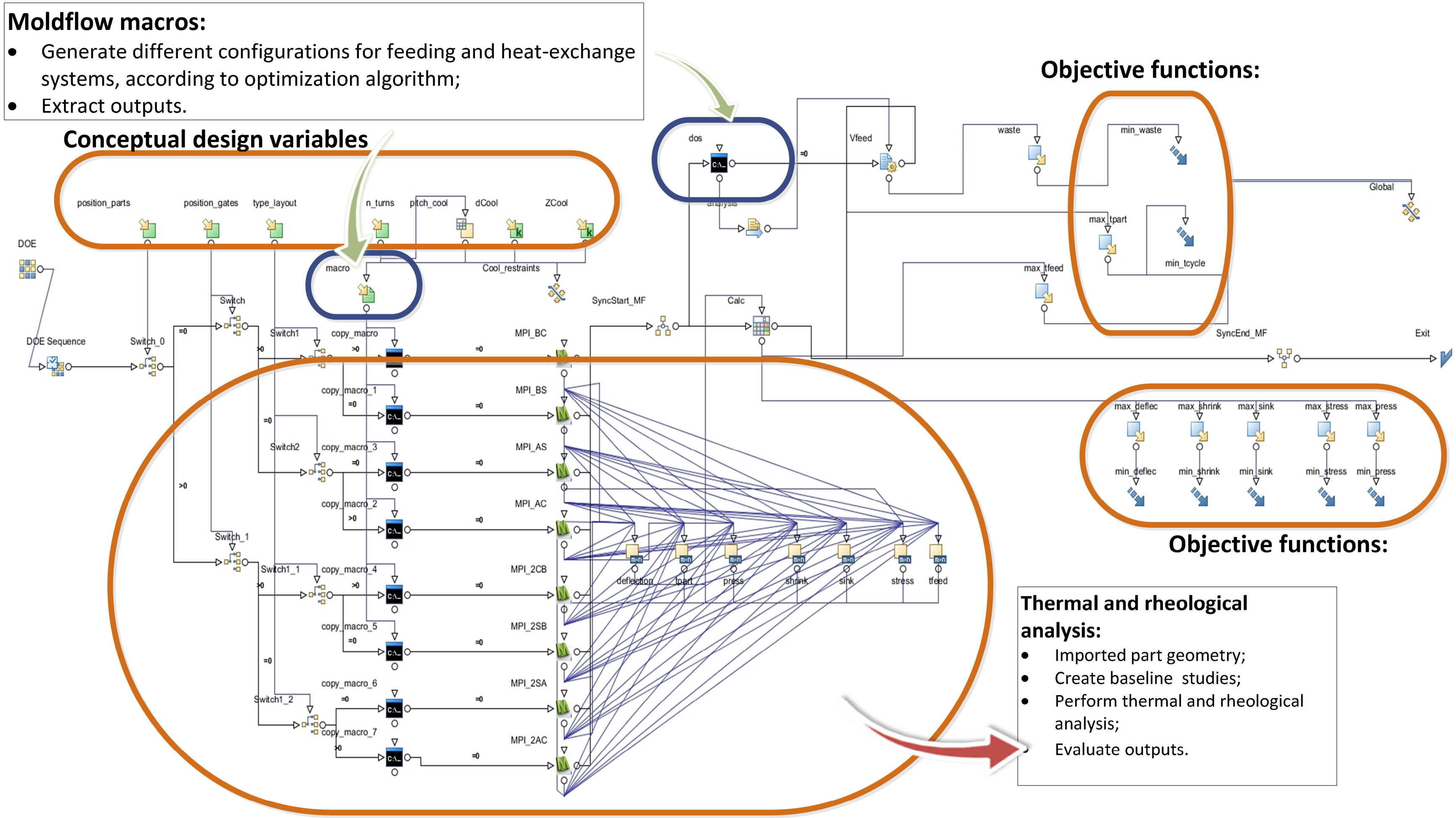


Figure 4.26: Feeding and heat-exchange modules included in the reinforced platform: Design stage (ModeFRONTIER).

After the conceptual solution selection, 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 4.27. The goal is to determine the most well ranked solution, through optimization, in order to define the variables selected for the optimize stage in Table 4.9, for the feeding system, and in Table 3.18 for the heat-exchange system. These variables include the sprue's dimensions, namely diameter, length and draft angle. Regarding the feeding system, the diameters of the main and secondary runners are also considered, as well as diameter and draft angle of gates. At the same time, regarding the heat-exchange system, the diameter of the cooling channels, as well as its distance regarding the PP and the distance amongst the cooling channels are also determined.

In the Define stage, it was established that the critical to quality items regarding feeding and heat-exchange systems are as follows: Deflection *(Min_Deflection)*, Shrinkage (*Min_Shrinkage*), Sink index (*Min_Sink*), Residual stress (*Min_Stress*), Cycle time (*Min_tCycle*), Pressure drop (*Min_Pressure*) and Volume of material's waste (*Min_Waste*). For that reason, these items were considered in the platform as objectives functions. They are mostly evaluated based on MOLDFLOW results. Therefore, it is important to describe how these items are calculated in the platform. 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. Shrinkage is computed as the volumetric change for each area of the dual mesh, as a percentage of the original volume. The Sink index is computed directly by MOLDFLOW using the following relation:

$$Sink\ index = \frac{(x^{+} - x^{-})\rho_{\delta}(T_{trans}P_{atm}) - \int_{x^{-}}^{x^{+}} \rho(z)dz}{2h \cdot \rho_{\delta}(T_{trans}P_{atm})} \qquad \textit{Eq. 121}$$

Where T_{trans} is the transition temperature of the polymer, x^{+} is the upper interfacial location when 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. This parameter indicates the likely presence and location of sink marks and voids in the part, and reflects how much material is still melt and left unpacked. Thus, the larger the volume that freezes under low pressure, the higher the sink index and the greater the likelihood of a sink mark.

The Residual stress is also directly estimated by MOLDFLOW, where the first direction in-cavity residual stress corresponds to the stresses in the orientation direction before ejection, resulting of the shear stresses generated during mould filling and packing. In MOLDFLOW

Cycle time is determined taking into account the time required for the part to fill and 80% of the part thickness to freeze. An open/release/close time is also imposed. In the case under analysis a value of 5 seconds was estimated. 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. 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, as shown in Figure 4.27 (Calc) in mm^3.

Moreover, some of the constraints previously defined for these systems were also introduced in the module. For example, *Feed_constraints* encompass the previous Eq. 85 to Eq. 87, while *Cool_restraints* include Eq. 100 and Eq. 101, and, finally, *Global* involves Eq. 89 and Eq. 90.

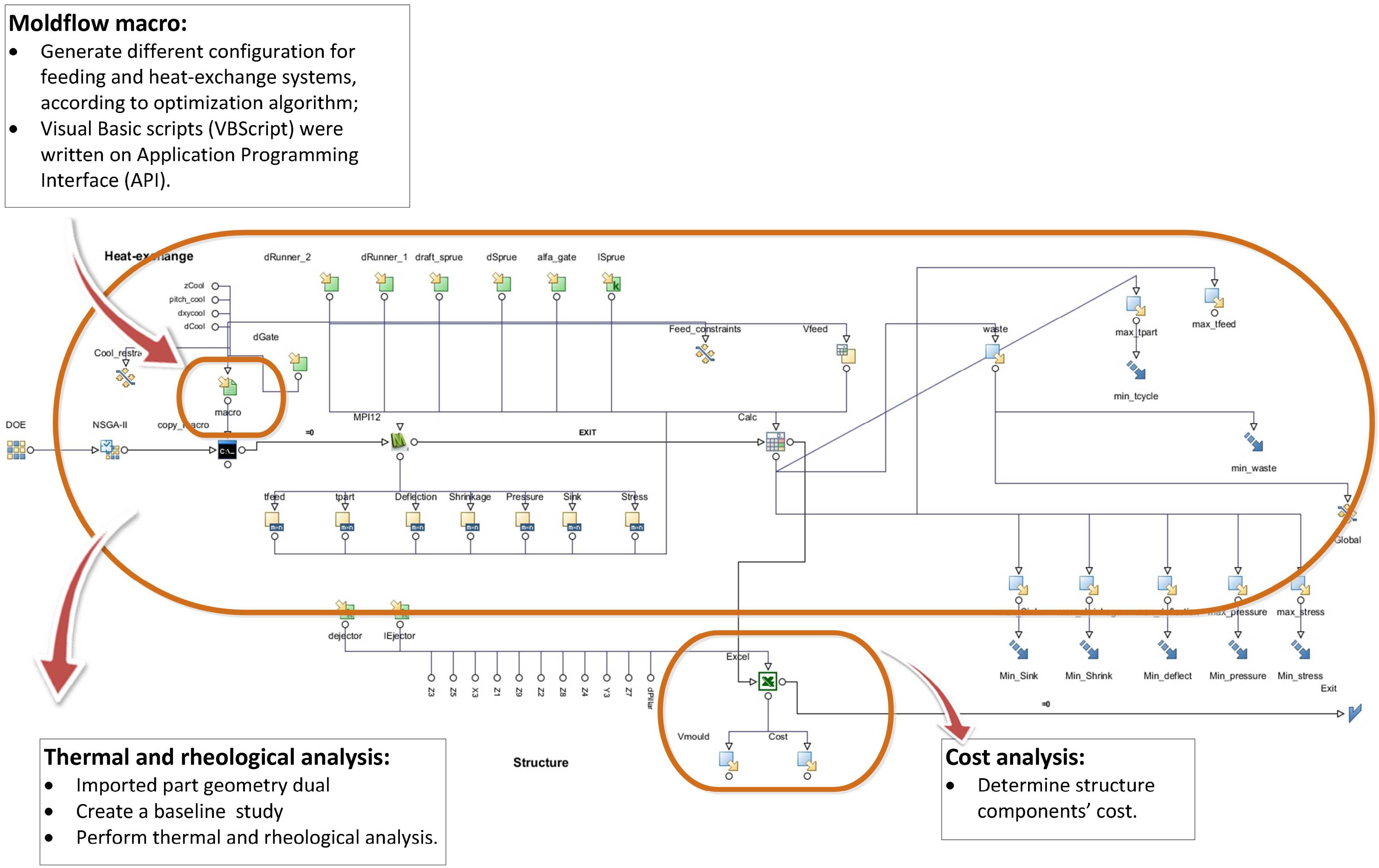


Figure 4.27: Feeding and heat-exchange modules included in the reinforced platform: Optimize stage (ModeFRONTIER).

The characteristics of the feeding and the heat-exchange design problem are summarized in Table 4.19, covering the number and type of design variables and constraints; the feasibility of design space; the type of initial solution and the adequate simulation runtime, and we again adopted a NSGA-II algorithm [262]. The main reasons for this option are the same previously described for the structural module.

Table 4.19: Main characteristics of the feeding and heat-exchange module optimization problem.

Criteria	
Number of design variables	Low (<20)
Number of constraints	Low (<1000)
Type of design variables	Real
Objective/Constraints functions	Linear/Non-linear
Constraints type	Inequality/Equality
Feasible space	Non-convex and discontinuous
Initial point	Feasible
Simulation run time	Shortest

As shown in Figure 4.27, the *n* individuals of the initial population are DoE values obtained by a random sequence, i.e. the design space is filled randomly, with an uniform distribution. The sequence of points is determined by the value of the Seed, which was assumed as 1. Moreover, three additional parameters were defined:

1) Number of experiments to be generated: 20
2) Unfeasible designs are rejected;
3) Random seed for sequence repeatability: 1

As shown in Table 4.20, the tuning parameters adopted for the NSGA II algorithm are similar to the ones of the structural module, except that in this case a higher number of generations was chosen.

Table 4.20: Adopted parameters for NSGA II optimization regarding feeding and heat-exchange systems.

Number of generations	20
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

Figure 4.28 presents the set of solutions obtained, and their respective objective values are shown in Figure 4.29. A few number of Pareto solutions can be found, which are highlighted in green. The vertical bands in the parallel coordinates plot of Figure 4.28 indicate the range of feasible or Pareto design variables values and unfeasible designs are highlighted in red.

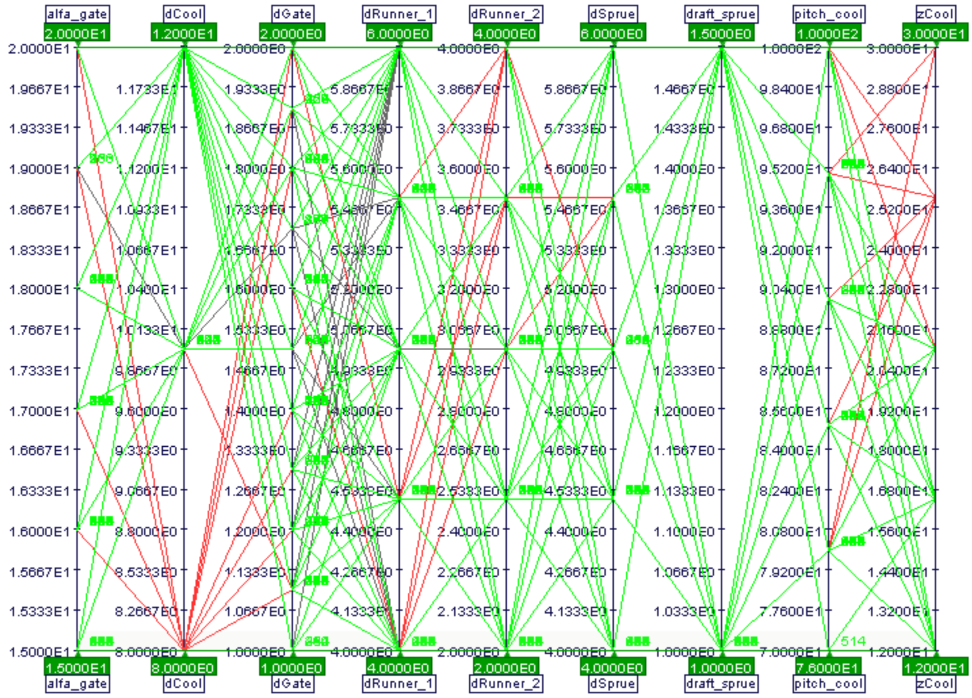


Figure 4.28: Feeding and heat-exchange design solutions achieved with Pareto solutions highlighted in green.

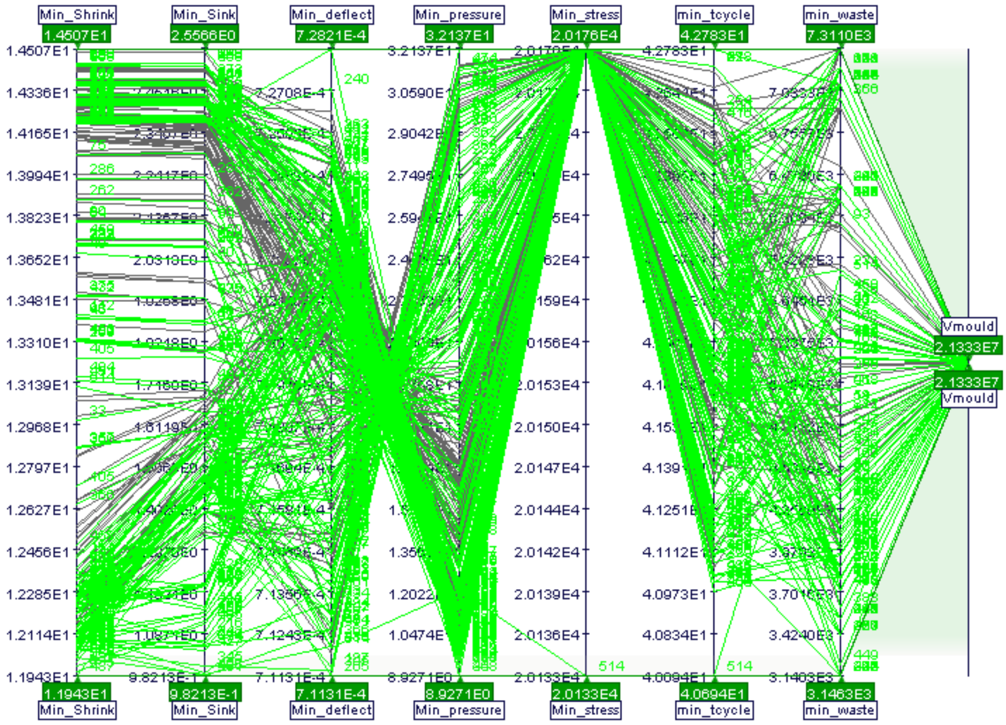


Figure 4.29: Objective values achieved for the generated solutions: feeding and heat-exchange systems.

It is important to note that the design variables present a lower variation than the majority of the objectives. This occurs mostly due to the high coupling between the objectives, which overdue the imposed lower and upper bounds of the design variables. Consequently, despite the small admissible interval of values for the design variables, a large diversity of performance levels can be achieved by the design solutions.

In order to evaluate possible trade-offs, a scatter matrix for objectives was built. It is presented in Figure 4.30, from which it is possible to identify six significant linear correlations, four of which are positive: Shrinkage and Sink, Sink and Waste, Shrinkage and Waste and Deflection and Waste. And two of them are negative: Deflection and Pressure and Pressure and Waste. These correlations can be observed in more detail in Figure 4.31, where the Pareto solutions are highlighted in green.

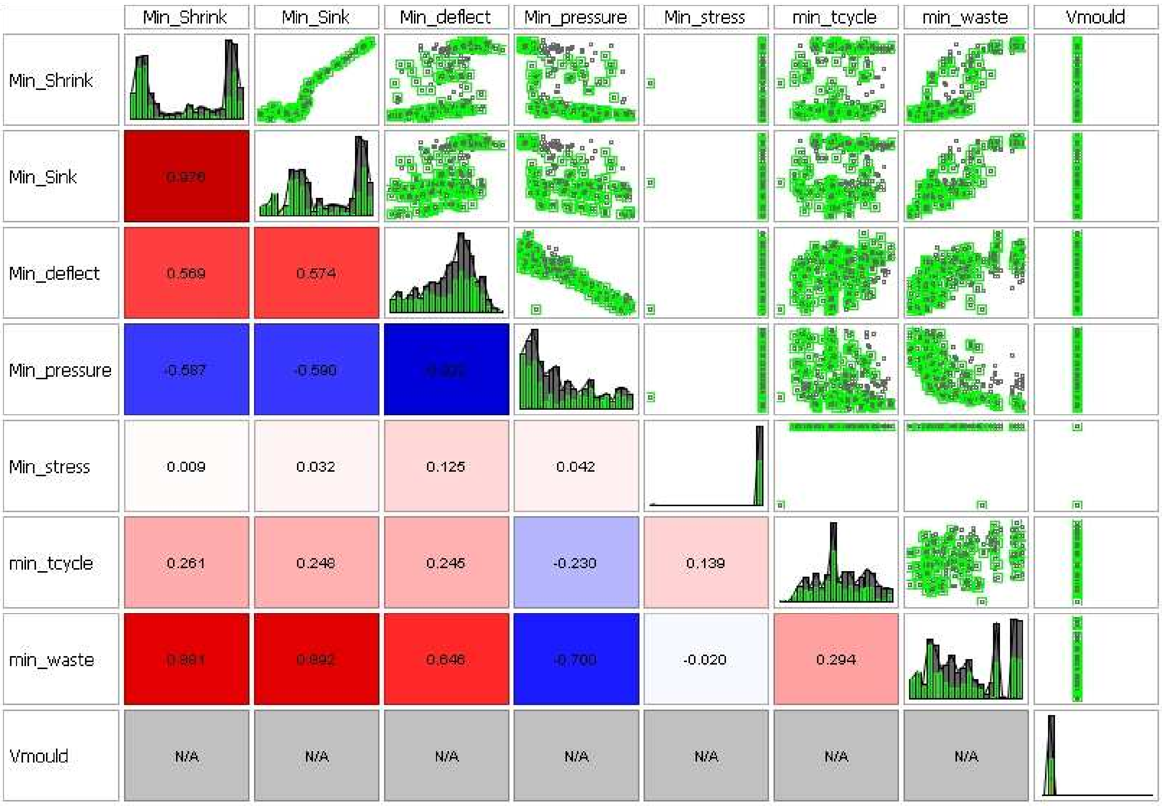


Figure 4.30: Scatter matrix of feeding and heat-exchange objectives with respective Pearson[30] coefficients.

The pairwise Pareto fronts shown in Figure 4.31 indicate that there are significant trade-offs that are necessary to take into account. For example, a decrease in Deflection of about

[30] Pearson value is a coefficient that measures correlation (linear dependence) between two variables X and Y.

5E-5 mm requires an increase of Pressure of nearly 12MPa, which is a very important value, since the Pressure ranges between a minimum of 8.9MPa and a maximum of 32MPa. About Pressure and Waste, a significant trade-off also exists, whereas a reduction in Waste of 3.5E3mm^3 will represent an increase of 12MPa on Pressure. Regarding the remaining objectives presented in Figure 4.31, they are correlated positively, meaning that when one is minimized the other will also decrease.

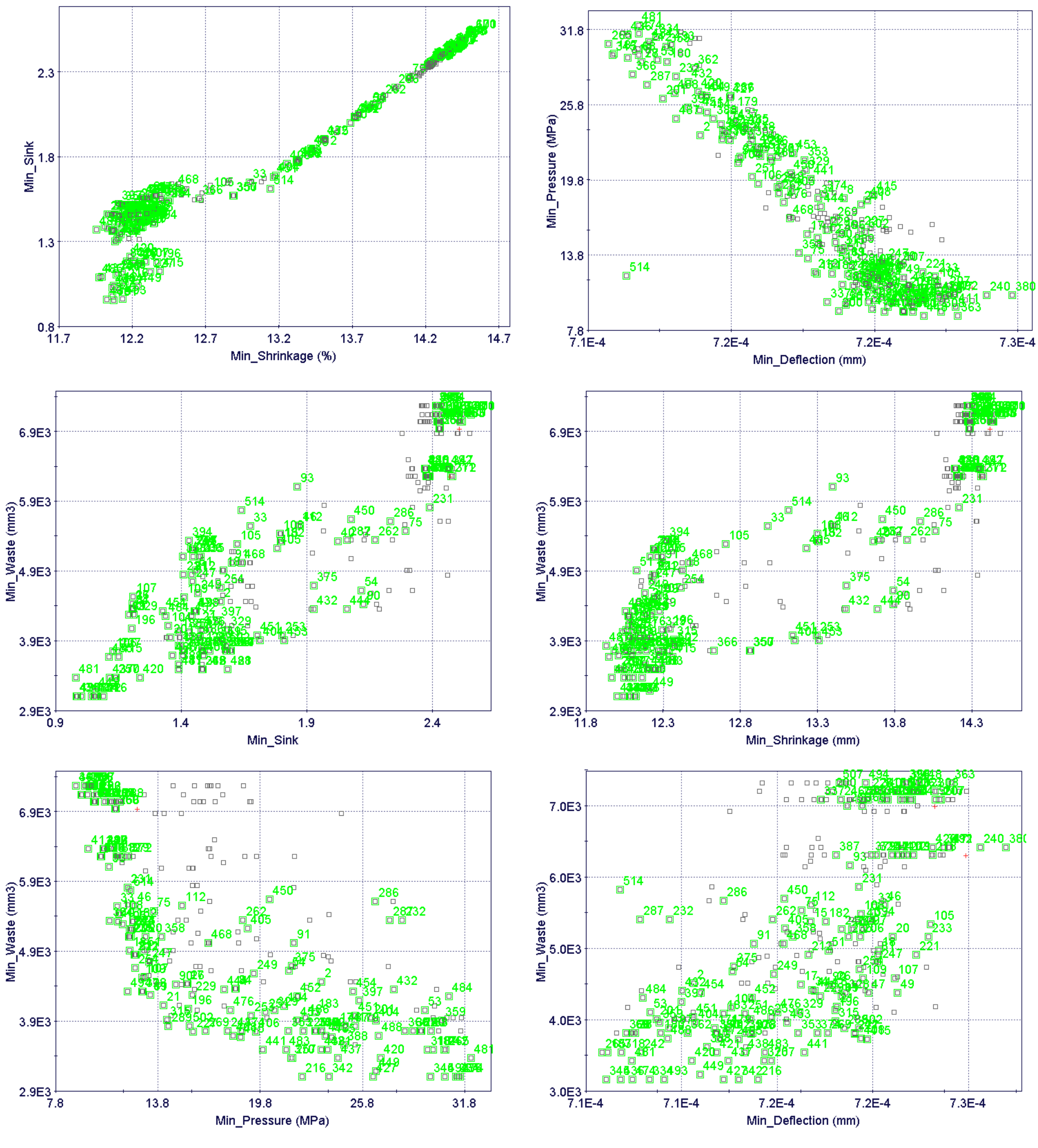


Figure 4.31: 2D Scatter plots for correlated objectives: feeding and heat-exchange systems.

In order to find the best choice of the feeding and heat-exchange systems design, the MCDM tool was used again to determine the ranking between the achieved Pareto solutions. The relationship between the objectives, namely, minimizing the Sink, Deflection, Shrinkage, Stress, Cycle time (*tCycle*), Pressure, Waste and Volume of mould (*Vmould*), were established through direct comparison, as shown in Table 4.21.

Table 4.21: Relationships between objectives of feeding and heat-exchange systems.

Objective 1	Type	Weight	Objective 2
Sink	>	9	***Stress***
Pressure	>	3	***Deflection***
Pressure	>	3	***Shrinkage***
Sink	>	9	***Vmould***
Sink	>	3	***Waste***
Deflection	>	3	***Waste***
Shrinkage	>	3	***Waste***
Pressure	>	9	***Stress***
Waste	>	3	***Vmould***
Sink	>	1	***Pressure***
Sink	>	9	***tCycle***

In this case, a GA is selected to assist the decision maker in finding the best solution from among the set of reasonable alternatives. This algorithm also allows one to verify the coherence of the expressed preferences and generate a valid utility function and ranking. The main reason for this option is that this method uses a GA to generate utility functions and weights, and it allows the use of any number of criteria. Finally, in order to create a GA MCDM three additional parameters were defined, namely, training cycles = 20, Preference Margin = 0.05 and Indifference Margin = 0.01. The results obtained for the weights and the utility function evolution along the criteria range can be observed in the Figure 4.32. It is observable that weights computed by the algorithm for the utility function respect the preference relationships expressed by the decision maker. Moreover, it is important to highlight that Sink received the highest weight (0.63), followed by Pressure (0.23), Deflection (0.04) and Shrinkage (0.07).

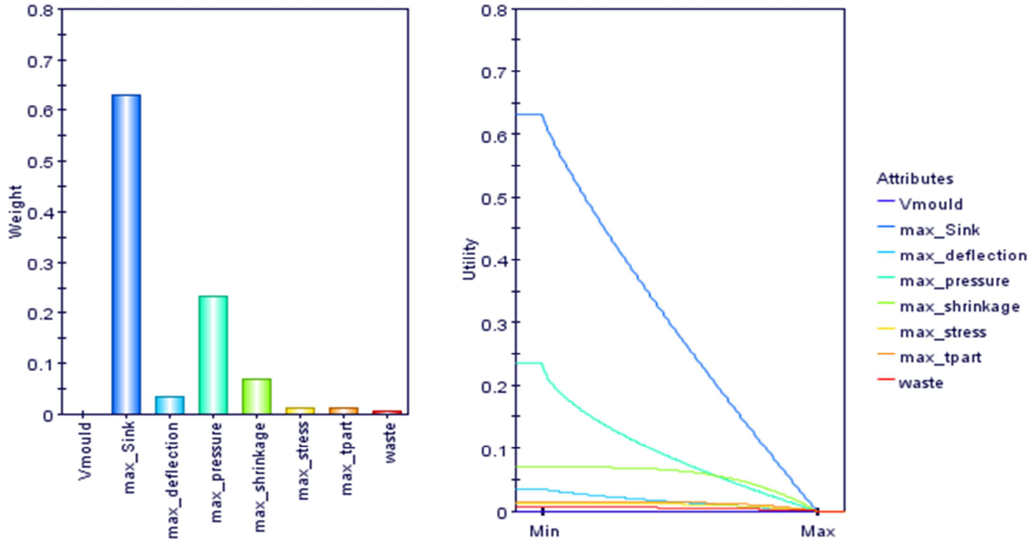


Figure 4.32: Utility function obtained by MCDM tool regarding the feeding and the heat-exchange systems.

Figure 4.33 presents the ranking between alternatives, where it is possible to observe that the best solution is ID 11 with a rank value of 0.76. It is also important to note that the baseline solution, with ID 514, has a rank value of 0.62. Thus, the baseline can also be considered as a good solution, when taking into account the previous criteria weights. These two designs are compared in Figure 4.34, where it is possible to verify that ID 11 has better performance on Sink, Shrinkage and Waste, while it presents a worst accomplishment than baseline on Deflection, Pressure and *tCycle*.

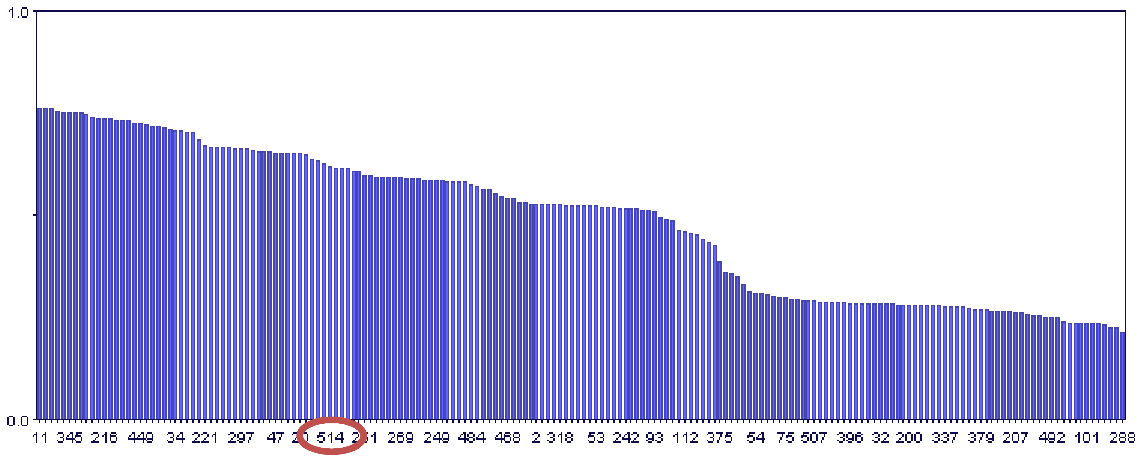


Figure 4.33: Design ranking obtained by MCDM tool with baseline (ID 514) solution assigned – Feeding and heat-exchange systems.

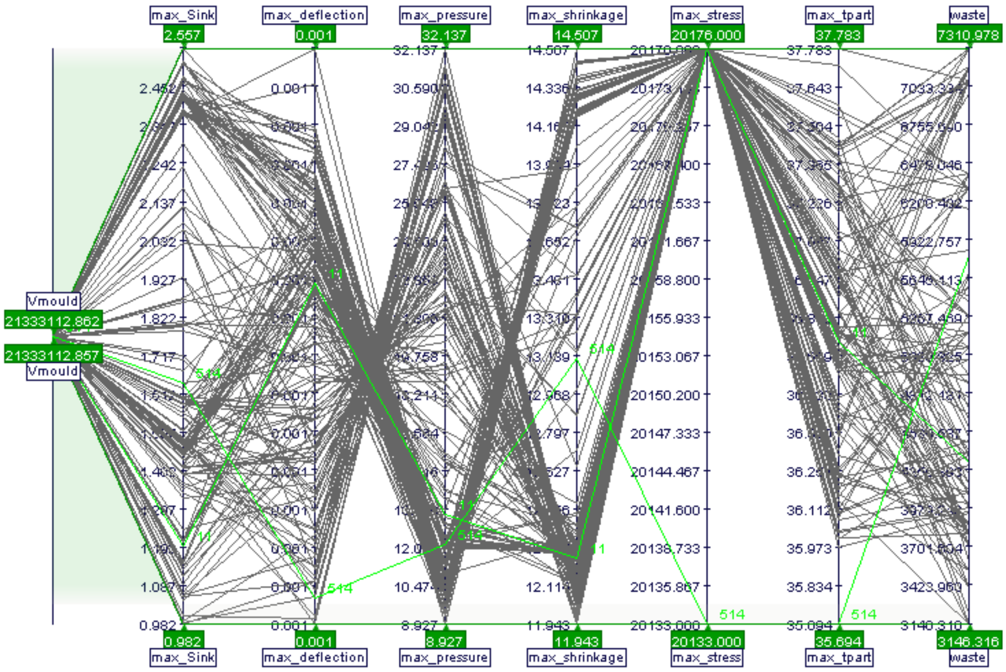


Figure 4.34: Parallel coordinates regarding objectives with selected solution (ID 11) and baseline (ID 514) highlighted in green - Feeding and heat-exchange systems.

To have an idea about solution well the potential improvement over the initial baseline solution, when compared with the most ranked alternative (ID 11), a detailed comparison between these two design solutions is presented in Table 4.22.

Table 4.22: Comparison between the best solution achieved (ID 11) and the baseline (ID 514) - Feeding and heat-exchange systems.

	ID 514	ID 11	Variation
alfa_gate (º)	15	16	-
d_{Cool} (mm)	10	10	-
d_{Gate} (mm)	1.5	2	-
d_{Runner_1} (mm)	6	5.5	-
d_{Runner_2} (mm)	4	3.5	-
d_{Sprue} (mm)	4.5	4	-
draft_sprue (º)	1.5	1	-
pitch_cool (mm)	76	80	-
Z_{Cool} (mm)	16.5	16.5	-
Vmould (mm^3)	2.13E7	2.13E7	**0.001%**
Min_Shrinkage (%)	13.13	12.13	**-7.8%**
Min_Sink	1.641	1.195	**-27.2%**
Min_Deflection (mm)	7.12E-4	7.21E-4	**1.3%**
Min_Pressure (MPa)	12.12	13.32	**9.9%**
Min_Stress (MPa)	20113	20176	**0.21%**
Min_tCycle (s)	40.69	41.72	**2.5%**
Min_Waste (mm^3)	5.81E3	4.32E3	**-25.8%**
Performance improvement	-	-	**5.9%**

It is possible to verify that significant improvements were achieved in Sink index (-27%), Waste (-26%) and Shrinkage (-8%). By the contrary, the achieved solution has a very important increase in Pressure (9.9%) and minor increases in Cycle time (2.5%), Deflection (1.3%) and Stress (0.2%). These results are consistent with the previously identified trade-offs. Thus, it is possible to conclude that ID 11 obtained the highest rank value due to the relative weight importance defined for each objective. Considering the ECSI model estimated, previously presented in chapter 3, in special Eq. 17, for this MCDM the rank is adapted for the previous MCDM rank to the following expression:

$$CSI = 0{,}157\text{Design} = 0.157[(0.04\text{Deflection} + 0.07\text{Shrinkage} + 0.63\text{Sink} + 0.012\text{Stress}) + (0.014\text{tCycle} + 0.23\text{Pressure} + 0.006\text{Waste})]$$ ***Eq. 122***

Applying this expression, it is possible to verify that the ID 11 solution presents a positive impact on quality of Design of 15.5%, which results in an increase of CSI of 2.4%. Although this CSI value seems to be relatively small, it is important to highlight that quality of design has a minor influence in CSI (see factor 0.157 in Eq. 17), when compared with other constructs, e.g. Image (has a factor of 0.535). Therefore, the improvement achieved by adopting solution ID 11, when compared with the baseline, must be considered significant.

Nevertheless, if other relationships between the objectives were established, different solutions will be achieved. In order to highlight this fact, the relationship between the objectives presented in Table 4.23 was also tested.

Table 4.23: New relationships between objectives – Feeding and heat-exchange systems.

Objective 1	Type	Weight	Objective 2
Sink	>	9	***Waste***
Sink	>	3	***Deflection***
Sink	>	3	***Shrinkage***
Sink	>	1	***Pressure***
Deflection	>	1	***Shrinkage***

A GA is used once more, adopting the same parameters used in the previous MCDM rank. Figure 4.35 presents the weights and utility function along the range of the attributes, obtained by the GA algorithm. In this case, it is possible to observe that Sink received the highest weight (0.43), followed by Pressure (0.36), Deflection (0.11), Shrinkage (0.06) and, finally Waste (0.04). The different solutions were ranked and the results are shown in Figure 4.36. It is possible to observe that the best solution is the baseline solution (ID 514) with a rank value equal to 0.865. This figure also highlights that now the previously selected solution

(ID 11) does not even appear in the first ten best rank values. In fact, ID 11 occupies the 14th position of the ranking (before ID 61, which assumes the 15th position).

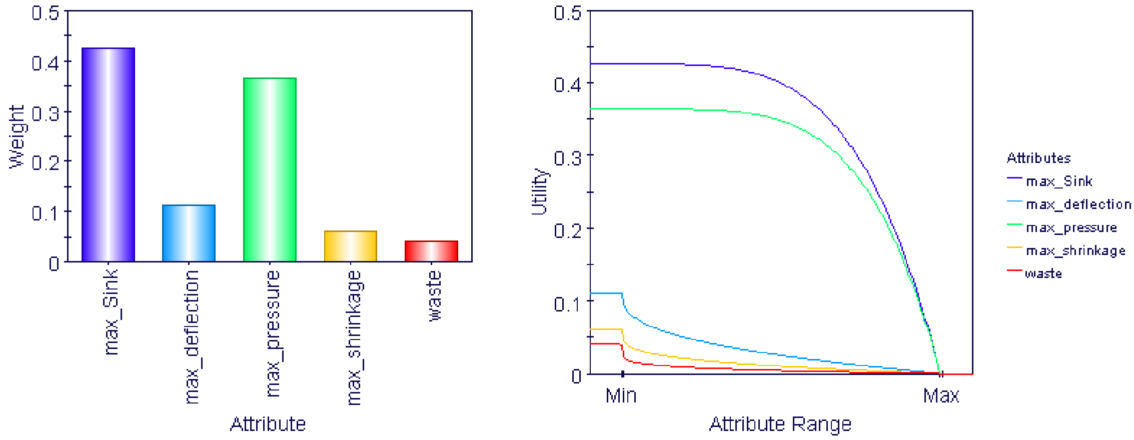


Figure 4.35: Utility function obtained by MCDM tool regarding feeding and heat-exchange systems: conventional.

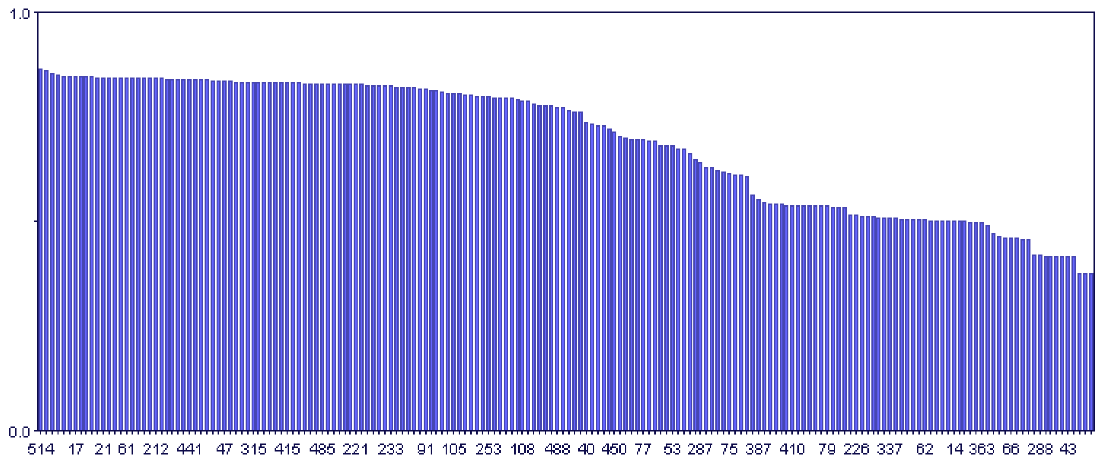


Figure 4.36: Design ranking obtained by MCDM tool where ID 514 has the highest rank value (feeding and heat-exchange systems).

Given this ranking, which has smaller differences in importance's weights when compared with the previous analysis, one can conclude that the developed platform is working well, since baseline (ID 514) has detached from the remaining 184 generated solutions, with the highest rank value.

4.5.3. Mechanical module

Regarding the mechanical submodule, the reinforced platform includes the structure presented in Figure 4.37.

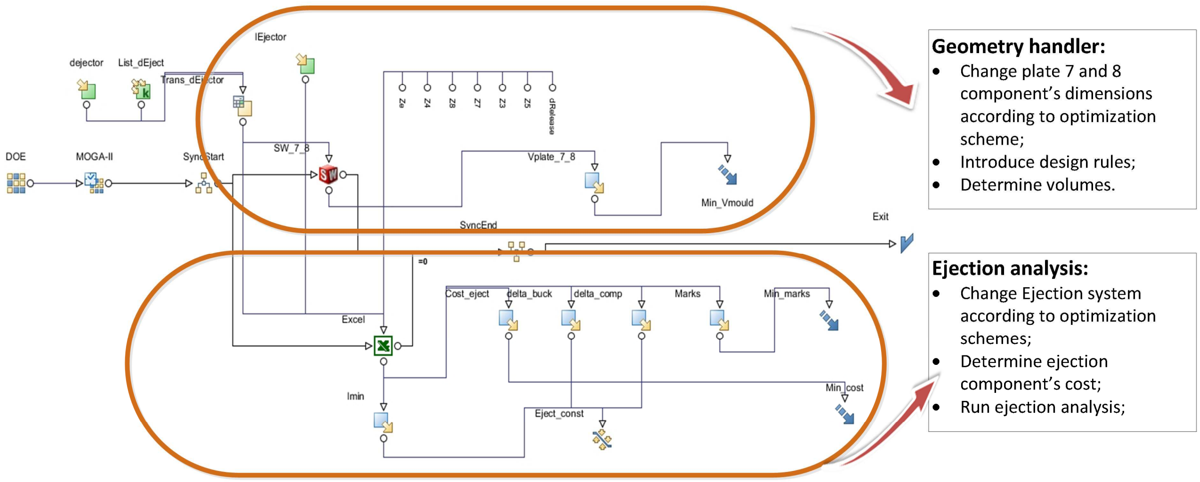


Figure 4.37: Mechanical module included in the developed platform (ModeFRONTIER).

This module allows to determine the diameter and the length of the ejectors, in order to minimize the distortions of the plastic part mouldings (*Min_Marks*), minimize the volume of the mould (*Vmould*) and minimize 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 (i.e. *Eject_const* defined in Figure 4.37, according to Eq. 115 and Eq. 116). In this case, the only structural elements that 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 ejector pins are widely available in the market, they should be selected according to standard dimensions. As previously mentioned, the standard dimensions used are accessible in the Hasco Catalogue [256]. Therefore, the list of available dimensions was included in the mechanical submodule (indicated by *List_dEject* in Figure 4.37).

Finally, it is important to note that the number of ejectors and their relative positions were previously established in the Design stage (see Figure 4.16). This strategy is adopted aiming to minimize objectives and to avoid conflicts, especially regarding cooling interference. In the Optimize stage, this concern is assured by the geometry handler module (SolidWorks), through several geometrical rules, and confirmed by its interference detection tool. Moreover, constraints regarding the geometrical positions of some mould's components are also imposed (i.e. *Eject_const*).

The characteristics of the ejection design problem are summarized in Table 4.24, in particular, the number and type of design variables and constraints; the feasibility of design space; the type of initial solution and the adequate simulation runtime.

Table 4.24: Main characteristics of ejection module optimization problem.

Criteria	
Number of design variables	Low (<20)
Number of constraints	Low (<1000)
Type of design variables	Real/Discrete
Objective/Constraints functions	Linear/Non-linear
Constraints type	Inequality/Equality
Feasible space	Non-convex and discontinuous
Initial point	Feasible
Simulation run time	Shortest

A MOGA was adopted to carry out our optimization procedure. As it was previously mentioned, this optimization algorithm allows for a fast Pareto convergence and enforces user defined constraints by objective function penalization. The initial population, with *n* individuals, is constructed using DoE values obtained by a random sequence. Thus, the sequence of points is determined randomly by the value of the seed, guaranteeing that the design space is filled randomly, with an uniform distribution. For that purpose, three parameters were defined:

1) Number of experiments to be generated: 100
2) Unfeasible designs are rejected;
3) Random seed for sequence repeatability: 1

The tuning parameters adopted for the MOGA algorithm are presented in Table 4.25

Table 4.25: Adopted parameters for MOGA optimization – Ejection system.

Number of generations	20
Probability of selection	0.05
Probability of mutation	0.1
Treat constraints	Penalising objectives

The mechanical submodule structure was tested considering the possibility of using two or four ejector pins. A set of solutions was obtained, through the platform, which can be observed in Figure 4.38. The variable corresponding to the ejector diameter is labelled

Trans_dEjector to highlight the fact that it is selected from a list of standard values. The vertical bands in the parallel coordinates plot indicate the range of feasible or Pareto design variables values, as well as the corresponding range for objectives. A few number of Pareto solutions can be selected, which are highlighted in green. It is important to observe that ejector's diameters vary less than its length. The platform uses standard values for both dimensions. However, the standard values for the diameter are constrained by geometrical relations, while the standards for the lengths are only assumed for cost evaluation. Consequently, the diameter of ejector pins (*Trans_dEjector*) varies less than its length ($l_{Ejector}$).

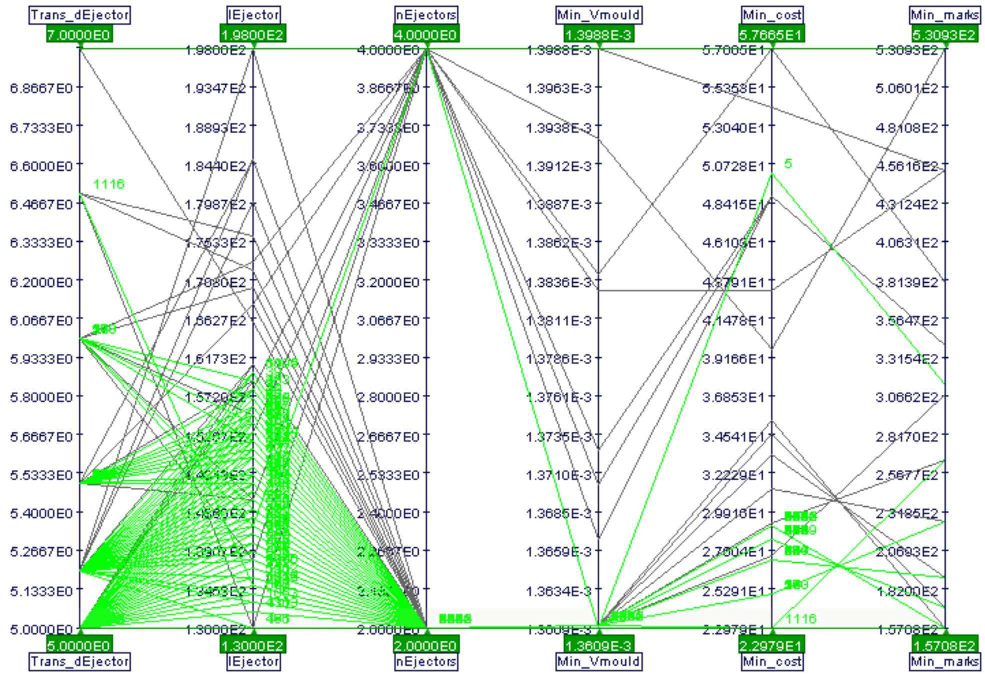


Figure 4.38: Ejection design solutions and objectives achieved for ejection system, with Pareto solutions highlighted in green.

Figure 4.38 presents the pairwise Pareto fronts for the marks and the cost objectives, where the Pareto solutions are indicated by a green line. The blue colour corresponds to the two ejector pins per part ($n_{Ejectors}$=2), while the four ejectors pins per part ($n_{Ejectors}$=4) correspond to the red colour. This figure shows that there is a significant trade-off between the two objectives, although two distinct sets can be observed. These sets are related with design variable $n_{Ejectors}$. For the two ejector pins per part, a decrease in the objective Marks of 100mm^2 corresponds to a cost increase of 5€, which represents of about 15% of cost increase.

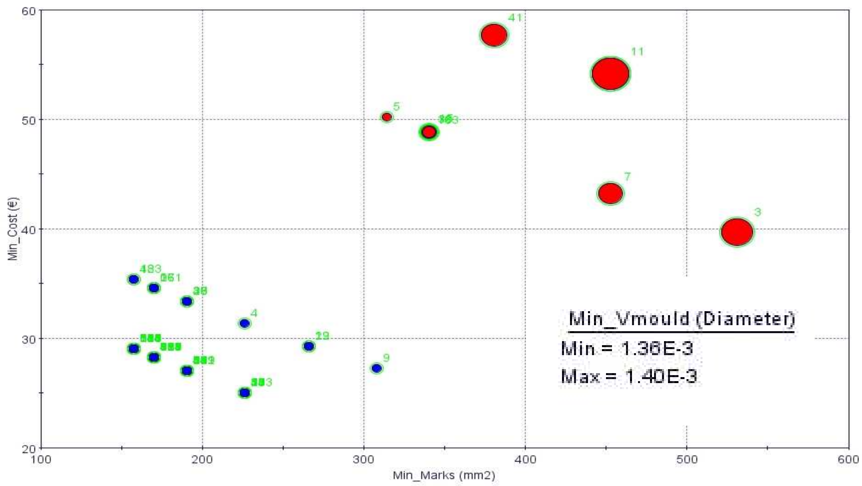


Figure 4.39: Pairwise Pareto front between objectives of Ejection system.

Nevertheless, the choice of the final ejection design should be made from the set of Pareto optimal designs, using customer preferences, through ModeFRONTIER MCDM tool. One possible relationship between the objectives, namely, Marks, Cost and *Vmould*, was established through direct comparison using a 1-9 scale with three levels. This relationship is shown in Table 4.26.

Table 4.26 – Relationships between objectives for Ejection system.

Objective 1	Type	Weight	Objective 2
Marks	>	3	**Cost**
Cost	>	1	***Vmould***

A linear algorithm is selected to assists the decision maker in finding the best solution from among the set of reasonable alternatives, as well as to verify the coherence of the expressed preferences and generate a valid utility function and ranking. In order to create a linear MCDM, three additional parameters were defined, namely, training cycle=20, Preference Margin=0.05 and Indifference Margin=0.02. Figure 4.40 presents the weights and the utility function evolution along the objectives range, obtained by MCDM. It is possible to verify that the weights computed for the utility function respect the preference relationships expressed by the decision maker. Moreover, it is important to highlight that M*arks* is the most important objective (weight=0.6), while Cost (weight=0.2*)* and *Vmould (*weight=0.17*)* play a secondary role.

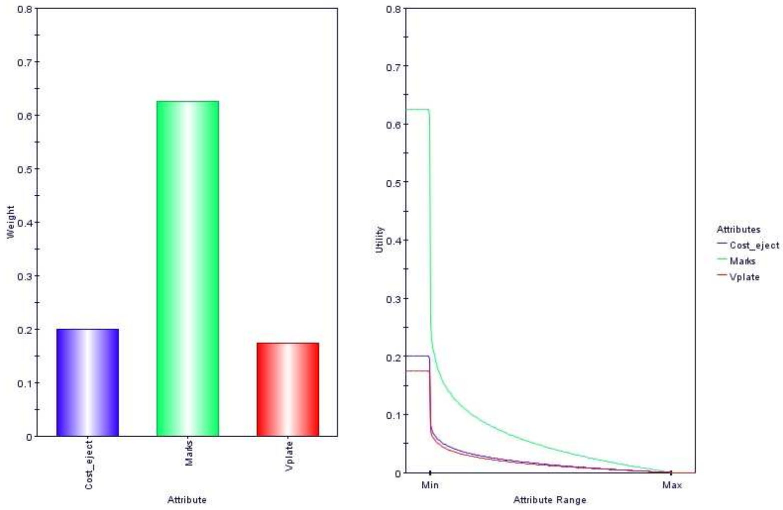


Figure 4.40: Utility function obtained by MCDM tool regarding ejection system.

In this case, the algorithm can very quickly generate a valid ranking between alternatives (about 10s). The design ranking is presented in Figure 4.41, where it is possible to observe that the designs solutions are grouped into a few number of classes of values. This results from the small range of imposed standard values for ejector pin diameters. In fact, for simplicity reasons, it was assumed that the standard diameters comprise only values between 5 and 7mm. This leads to a small variation of the objectives. Nevertheless, it is possible to select as best solution ID 22, which is shown in detail in Figure 4.42.

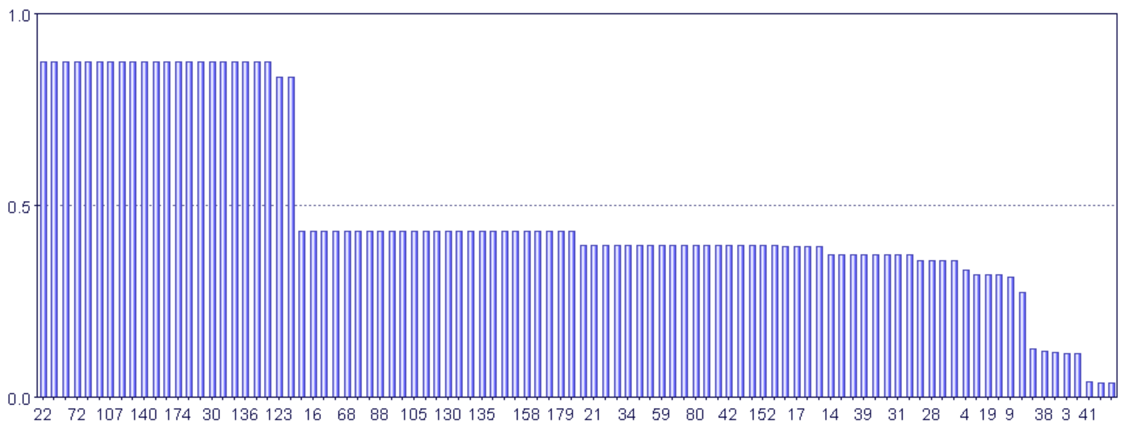


Figure 4.41: Design ranking obtained by MCDM tool regarding ejection system.

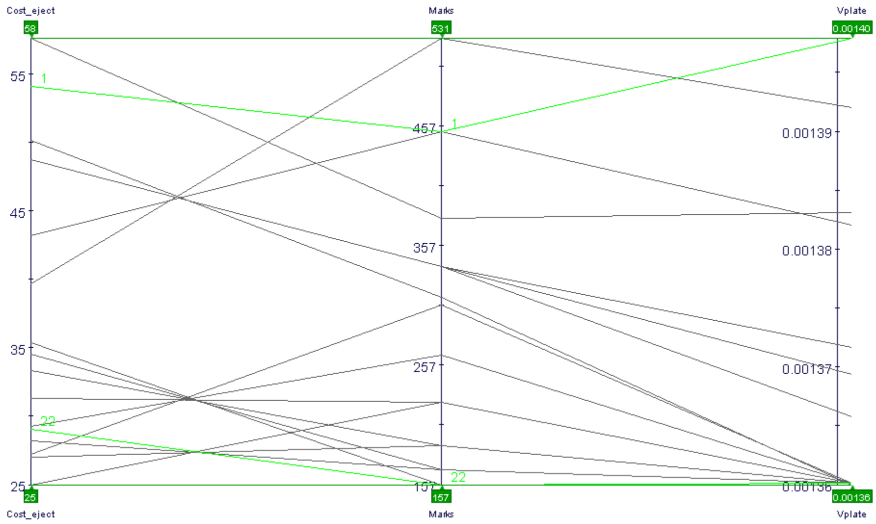


Figure 4.42: Objectives ranges obtained by MCDM tool with selected solution (ID 22) and baseline (ID 1) highlighted in green.

Table 4.27 presents the comparison between the initial baseline solution (ID 1) and the most well ranked solution (ID 22), in order to analyse the proposed framework, for the mechanical submodule.

Table 4.27: A description of a best solution achieved by MCDM tool regarding the ejection system.

ID	$d_{Ejector}$	$l_{Ejector}$	$n_{Ejectors}$	Cost_eject (€)	Marks(mm^2)	*Vmould(m^3)*
Baseline	6.0	173.0	4	5.42E+01	4.52E+02	1.40E-03
22	5.0	145.0	2	2.91E+01	1.57E+02	1.36E-03
		Reduction		**-86.2%**	**-188.0%**	**-2.8%**

It is possible to verify that improvements were achieved for all objectives. Also, they represent significant improvements, since a reduction of almost 25.4€ is achieved in cost (86% reduction), with a lower mould's volume (2.8% reduction) and considerable impact on marks (188% reduction). Nevertheless, it should be mentioned that this solution is illustrative, and is presented here only for demonstration purposes. In fact, for this simple submodule the results achieved can be easily found out without making of the platform.

4.6. Key holders mould design through IDOV platform

In this chapter the integration of the submodules for both the Design and the Optimize stage will be validated, using as baseline the exiting key holders mould. The selection of this mould allows for a comparison between the results produced by the reinforced platform and the reference, represented by the existing mould. According to the IDOV approach, the first step is to detail the estimated ECSI model for Portuguese mould makers (presented in Eq. 17), in order to include the specific requirements regarding the characteristics of this particular mould. Since the only latent variable under analysis is quality of design (Design), the impact on the ECSI model can be evaluated based on the variation of:

$$\Delta CSI = 0.157\Delta \mathrm{Design} \qquad \textit{Eq. 123}$$

Thus, we requested this mould customer to compare each CAs, two at a time, using a 1-9 scale with three levels. Hence, through AHP, each attribute was ranked according to its relative importance to the customer, aiming to build a weighted objective function. The results achieved can be observed in Table 4.28.

Table 4.28: Relative priority of each CA regarding key holders mould.

Customer Attributes (CAs)	Functional Requirements	Relative weights
Geometrical accuracy	Deflection	12.2%
Dimensional accuracy	Shrinkage	12.2%
Aesthetic aspects	Sink marks	22.9%
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	MDT	5.8%
Reliability of solutions	MTFB	5.0%
Accessibility	Information content	13.7%

Based on that, it is possible to observe that the most important attributes are the aesthetic aspects and mouldability. This ranking is a little bit different from industrial practice, where the most important attributes are usually also aesthetics aspects, but where, typically, cycle time, geometrical and dimensional accuracy have at least a similar importance. However, since the selected mould is not a commercial application, the attained values are coherent. In fact, this also highlights the importance of this first stage of the IDOV approach.

Based upon these values, it was possible to detail Eq. 17 into the CSI for this particular mould:

$$\begin{aligned} CSI = 0.157[&(0.122\mathrm{Geometrical} + 0.122\mathrm{Dimensional} + 0.229\mathrm{Aesthetic} + 0.02\mathrm{Properties}) \\ &+ (0.028\mathrm{Capability} + 0.163\mathrm{Mouldability} + 0.018\mathrm{Adaptability} \\ &+ 0.053\mathrm{Efficiency}) + 0.058\mathrm{Maintainability} + 0.05\mathrm{Reliability} \\ &+ 0.137\mathrm{Accessibility}] \end{aligned} \qquad \textit{Eq. 124}$$

Since the CAs are already mapped with the FRs, according to Table 4.28, Eq. 124 can be rewritten as a function of FRs as:

$$CSI = 0.157[(0.122\text{Deflection} + 0.122\text{Shrinkage} + 0.229\text{Sink} + 0.02\text{Stress}) + (0.28\text{tCycle} + 0.163\text{Pressure} + 0.018Vmould + 0.053Waste) + 0.058\text{MDT} + 0.05\text{MTBF} + 0.137\text{Information}] \quad \textit{Eq. 125}$$

Therefore, since customer's preferences are completely defined, it is now possible to start with the Design stage.

4.6.1. Design stage for the key holders mould

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 [245]. For this specific case, different alternatives were proposed, which are summarized in Table 4.29. Figure 4.43 exemplifies the two possible alternatives for the number of turns of each cooling line. Two different positions of the parts, relatively to the PP, are exemplified in Figure 4.44. Figure 4.45 shows different positions for each gate, relatively to the PP, for the same parts positioning. Figure 4.46 exemplifies the two alternatives for the type of feeding layout, also considering the same parts positioning. Finally, Figure 4.47 shows the two possible alternatives for the number of ejector pins, per part. These figures are shown to highlight the geometrical complexity of these conceptual solutions.

Table 4.29: Design variables regarding the Design stage – key holders mould.

Mould system	Symbol	Design variable definition	Type of design variable
Heat-exchange	***n_turns***	Number of turns of each cooling line	Integer (2, 4)
Impression	***position_parts***	Position of each part relatively to the PP	Geometrical (I, II)
Gate's design	***position_gates***	Position of each gate relatively to the PP	Geometrical (A, B)
Ejection	$n_{Ejectors}$	Number of ejectors per part	Integer (2,4)
Feeding	***type_layout***	Type of feeding layout	(Circular, Symmetrical)

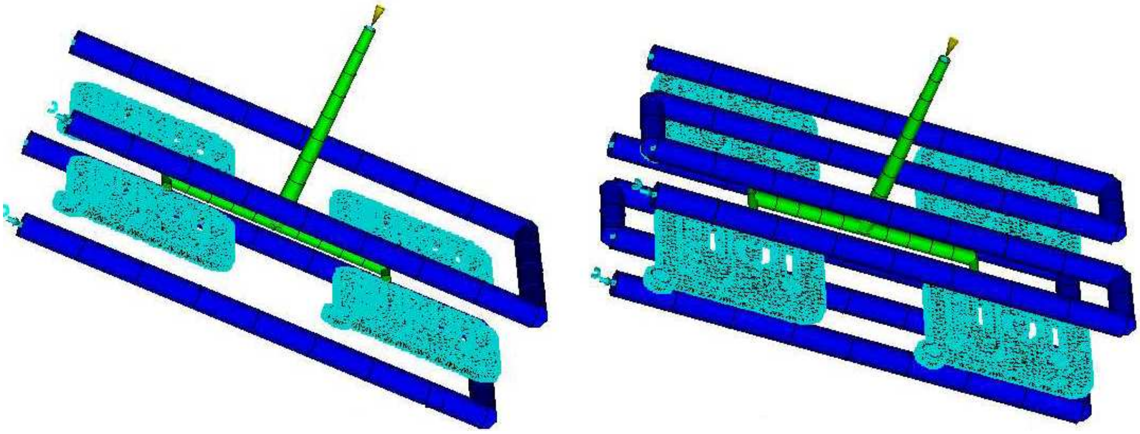


Figure 4.43: The two possible alternatives for n_turns: two turns (left) or four turns (right).

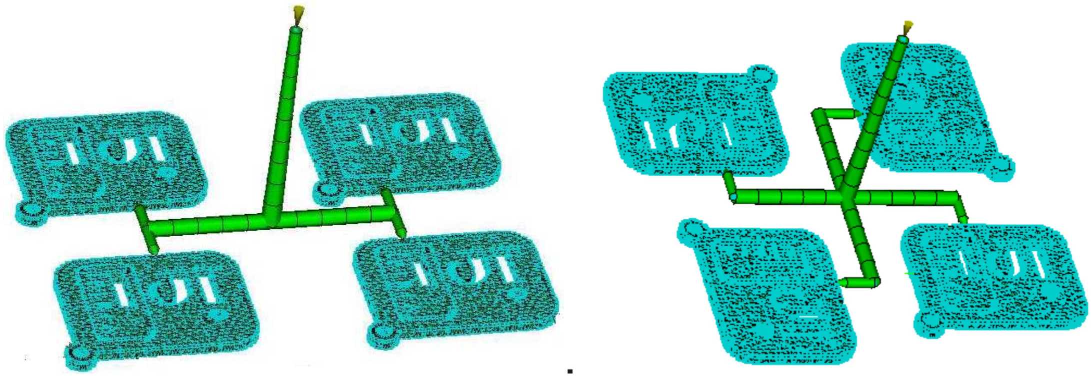


Figure 4.44: The two possible alternatives for position_parts: Position I (left) or Position II (right).

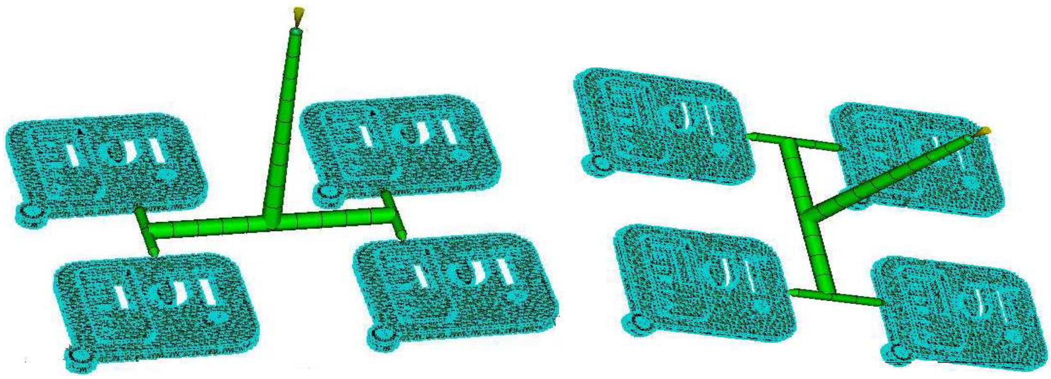


Figure 4.45: The two possible alternatives for position_gates: Position A (left) or Position B (right).

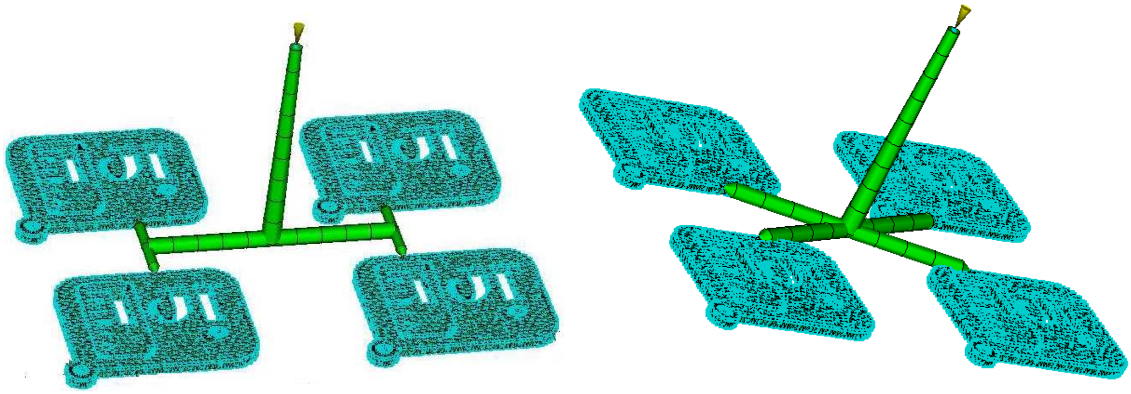


Figure 4.46: The two possible alternatives for <u>type_layout</u>: Symmetrical (left) or Circular (right).

Figure 4.47: The two possible alternatives for $n_{Ejectors}$: two pins per part (left) or four pins per part (right).

In this study, some variables were considered fixed, mostly due to the characteristics of the existing mould, in order to allow for a better comparison between the results attained by the platform and the reference. The variables that were assumed as fixed are presented in Table 4.30, which shows also the fixed value considered.

Table 4.30: Values for fixed variables at Design stage: key holder mould.

	Symbol	Design variable definition	Fixed value
Gate's design	***partition_plane***	Position of the PP	Geometrical (Baseline)
Ejection system	***type_ejectors***	Type of ejectors	Full-Round (FuR)
Structural system	***mould_material***	Mould's material	1.1730
	cavity_material	Material for the cavity's inserts	1.1730

Due to the number and type of design variables considered at this stage, a total of 32 conceptual solutions must be evaluated. Since a single evaluation run takes in average 30 minutes, the complete evaluation of the generated conceptual solutions will take approximately 16 hours. Hence, in accordance with Design stage purpose, all the previous described objectives are investigated as output responses. Based on that, each solution is evaluated using its impact on CSI (Eq. 125), as well as the variation attained in the objectives performance.

The five conceptual design variables, presented in Table 4.29, are considered as factors of the DoE study. A full factorial design was carried out, since it permits to experiment all combinations of factor levels. For that reason, a full factorial design of five factors, with 2 levels each one, will be adopted as a way to study the effects of each conceptual variable in the CSI. The aim is to determine the most well ranked conceptual solution, based on the DoE model presented in Table 4.31. For that purpose, the DoE analysis focused on the main effects and first order interactions. Therefore, 32 randomized virtual runs were generated and evaluated using the proposed reinforced platform.

Table 4.31: ***The DoE model (Full factorial design) – key holder mould.***

Design: Full factorial 2^5 design					
	n_turns	***position_part***	***type_layout***	***position_gates***	$n_{Ejectors}$
Min	2	I	Circular	A	2
Max	4	II	Symmetrical	B	4

Table 4.32 presents the results of the DoE analysis that show statistically significant effects. Through the analysis of variance for each objective, it is possible to identify, with a significance level of 5%, the design variables that have a significant influence in the observed outputs. In addition, it is also possible to verify that mould’s volume (*Min_Vmould*) only depends on the number of ejectors, since the parts positioning relatively to the PP present a neglectable influence on the mould’s volume. Consequently, since cost quantifies the cost of mould’s components, which are a function of its size, mould’s cost (*Min_Cost*) does not present considerable changes.

Table 4.32: Results of DoE model (only statistically significant effects).

Objective	Design variable	R-sq	R-sq (adj)
Pressure	position_parts	76.12%	53.74%
	position_gates*type_layout		
	position_parts*type_layout		
Shrinkage	position_gates*type_layout	88.02%	76.79%
	position_parts*type_layout		
Sink	position_gates	81.91%	64.96%
	position_gates*position_parts		
	position_gates*type_layout		
	position_parts*type_layout		
Stress	position_gates	66.67%	60.26%
	position_parts		
	position_gates*position_parts		
Waste	position_parts	71.30%	44.33%
	position_gates*type_layout		
	position_parts*type_layout		
Deflection	position_parts	71.90%	66.50%
	position_gates		
Cycle	n_turns	85.63%	72.16%
	type_layout		
	position_parts		
	position_gates		
	position_gates*position_parts		
	position_gates*type_layout		
	position_parts*type_layout		

In order to visualize in detail the main effects of the factors, regarding output responses, respective main effects plots were built and can be observed in Figure 4.48.

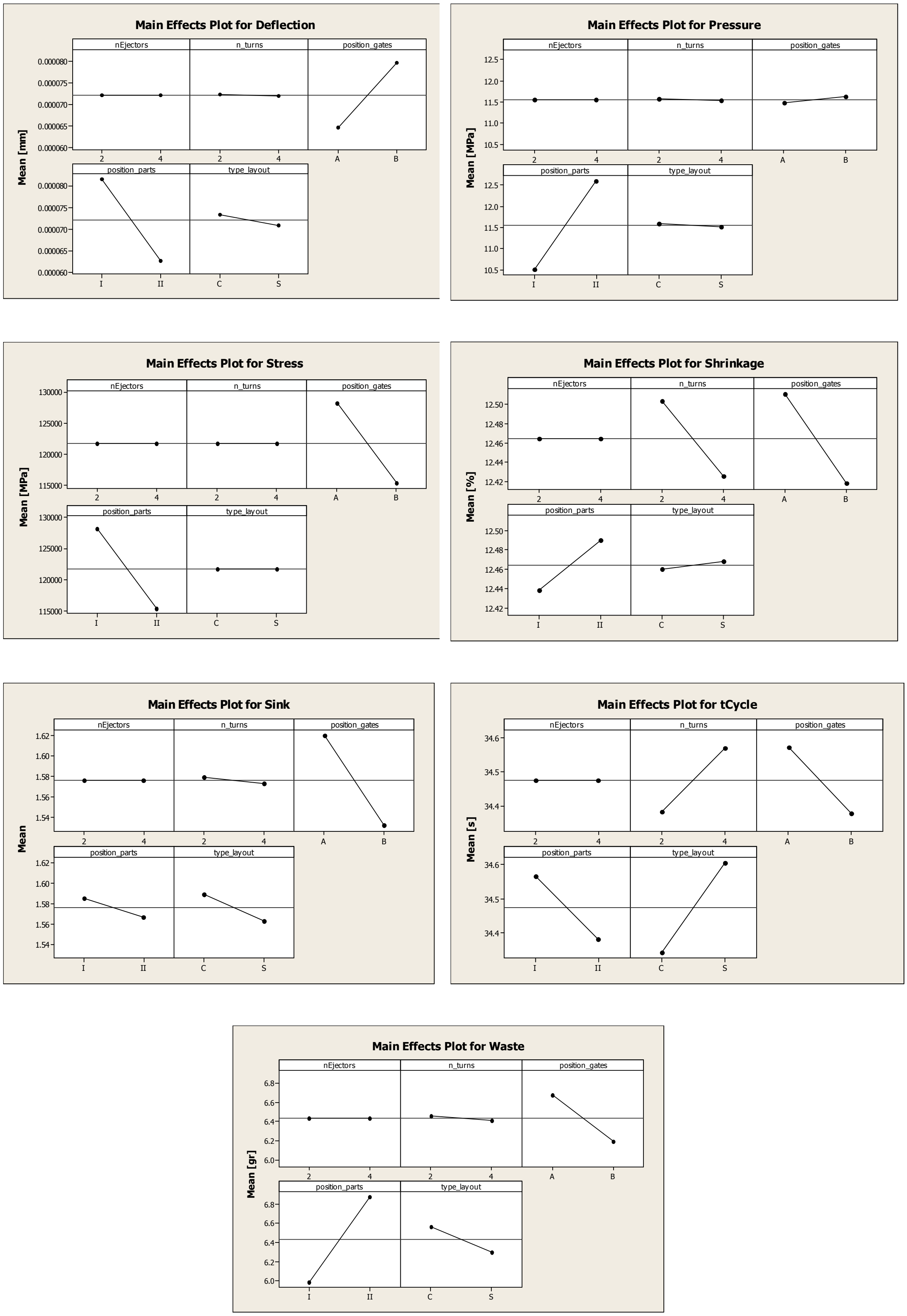


Figure 4.48: Main effects of each factor (design variable) into output response (objectives).

The conceptual solution was selected taking into account interaction effects. This selection considered also the importance weights of each attribute in customer satisfaction level (Eq. 125). Figure 4.49 presents the most well ranked conceptual solution, which has two turns of cooling channels, position II of the parts on the PP, symmetrical feeding layout and gates positioned on point B. Based on the DoE study, the number of ejectors has no statistically significant effect over the studied responses outputs. Thus, one can assume four ejectors per part, as defined in the baseline solution, as starting point for the Optimize stage.

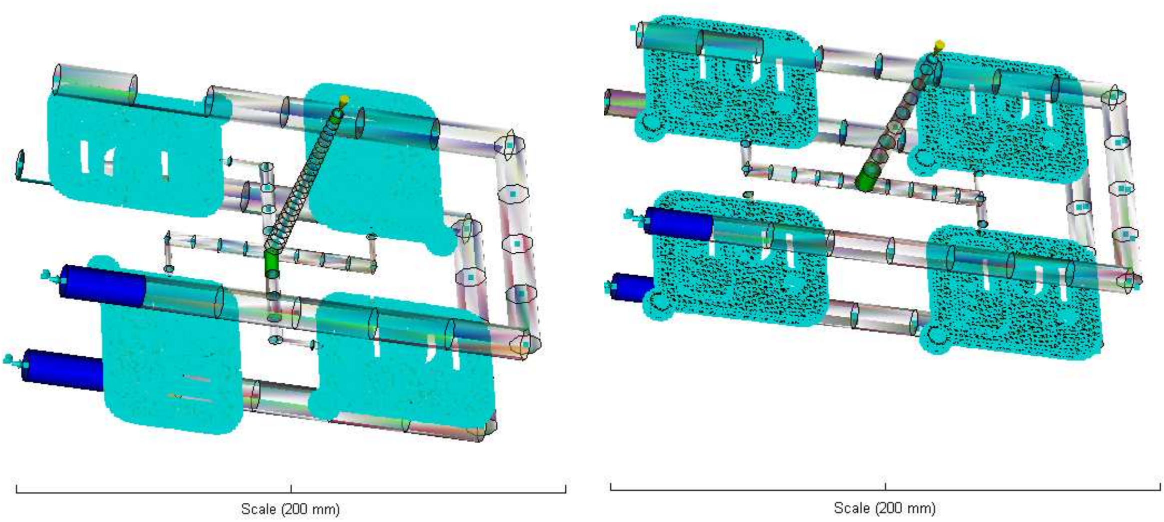


Figure 4.49: Most well ranked conceptual solution (left) versus baseline solution (right).

A comparison between the most well ranked conceptual solution and the baseline is presented in Table 4.33. It is possible to verify that the selected solution allows for a significant reduction on Pressure drop and Waste of material. By the contrary, it leads to higher levels of Sink index and Shrinkage a minor increase in Stress, Deflection and Cycle time. Mould's volume and cost are linearly proportional. As previously mentioned, the mould's volume depends only upon the number of ejectors. Thus, these objectives do not present any change, when compared with the baseline.

Table 4.33: Comparison between selected conceptual solution and baseline for the key holders mould.

	Baseline	Selected 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-04	8.21E-04	0.98%
Shrinkage [%]	12.24	12.77	4.33%
Sink [%]	1.54	1.64	6.49%
Stress [MPa]	1.280E+04	1.281E+04	0.10%
tCycle [s]	34.44	34.47	0.09%
Pressure drop [MPa]	11.14	9.82	-11.85%
***VMould* [m^3]**	1.98E-02	1.98E-02	0.00%
***Waste* [gr]**	6.27	5.68	-9.41%
Cost [€]	1163	1163	0.00%
Global improvement			**1.03%**
Quality of design improvement			**0.30%**
Impact on CSI			**0.05%**

Taking into consideration the weights of each attribute, assumed as drivers for customer's satisfaction (Eq. 126), it is possible to determine the impact of adopting the new design solution instead of the baseline. Thus, it is possible to verify that the selected solution presents a global improvement of 1% on its performance, and leads to an increase of 0.05% over customer satisfaction levels (assuming that the remaining objectives do not change). As previously mentioned, although this seems a small value, it can result in a significant improvements, since the model adopted considers that the Design does have a relatively small impact over CSI. This selected conceptual solution must be detailed in the Optimize stage of the IDOV roadmap.

$$CSI = 0.157\text{Design} = \\ = 0.157[(0.122\text{Deflection} + 0.122\text{Shrinkage} + 0.228\text{Sink} + 0.02\text{Stress}) \\ + (0.28tCycle + 0.163\text{Pressure} + 0.018Vmould + 0.053Waste)] \quad \textit{Eq. 126}$$

4.6.2. Optimize stage for the key holders mould

Based on the previously described characteristics of the injection mould design problem, NSGA II will be once more adopted. The NSGA II optimization uses the DoE values obtained by random sequence as the number of *n* individuals of the initial population. The design space is filled randomly, with an uniform distribution. For that purpose, three parameters were defined:

1) Number of experiments to be generated: 10
2) Unfeasible designs are rejected;
3) Random seed for sequence repeatability: 1

The tuning parameters adopted for the NSGA II algorithm are summarized in Table 4.34. Figure 4.50 and Figure 4.51 presents the set of Pareto solutions found and the objectives values attained. The vertical bands in the parallel coordinates plot indicate the range of feasible, unfeasible (red lines) or Pareto design variables values (green lines).

Table 4.34: Adopted parameters for NSGA II optimization regarding the key holders mould.

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
Evaluated repeated design	No
Evaluated unfeasible design	No

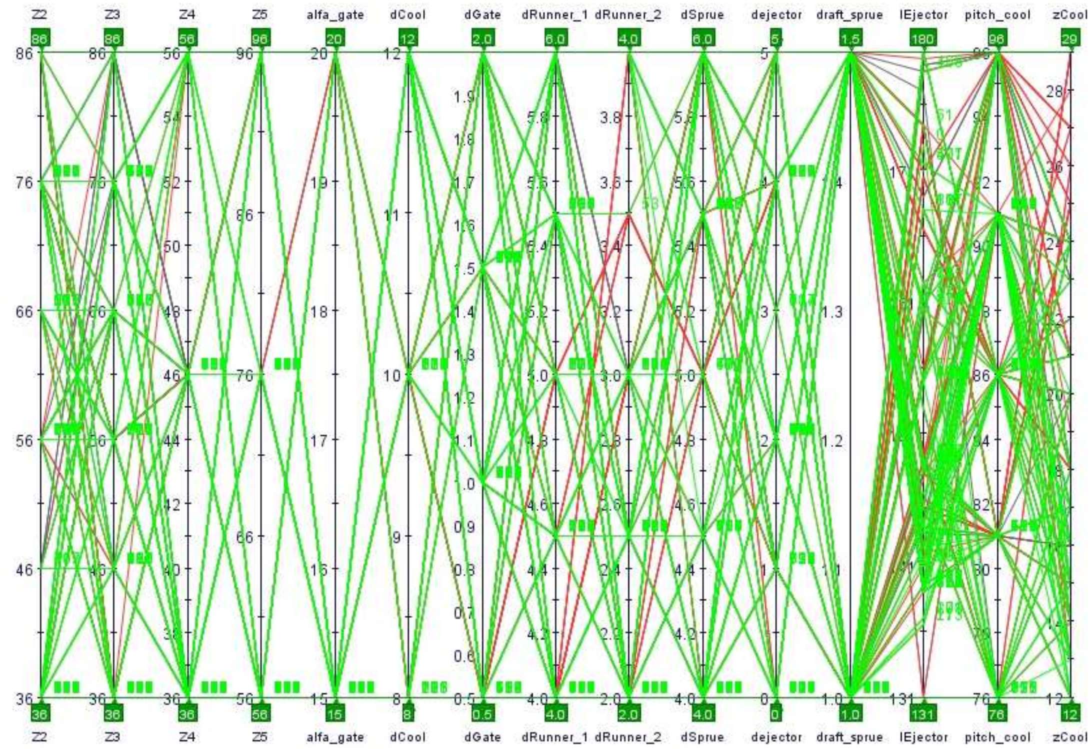


Figure 4.50: Parallel coordinates regarding the solutions achieved for the key holders mould with Pareto solutions in green.

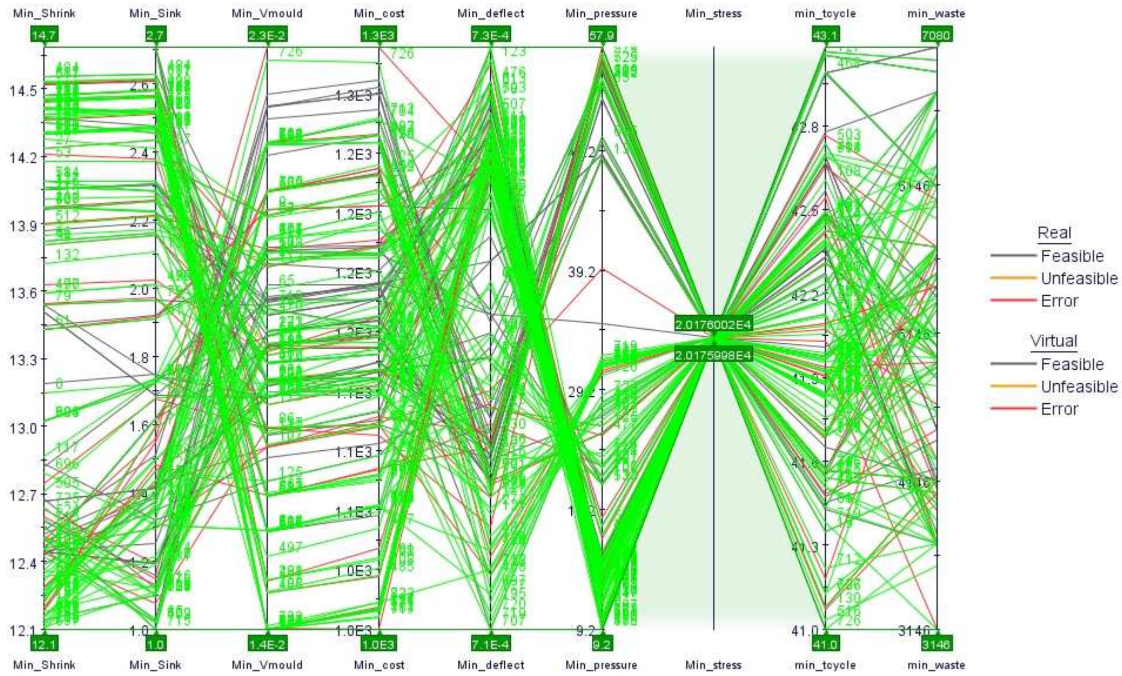


Figure 4.51: Parallel coordinates regarding the attained objectives values, with Pareto solutions in green.

Figure 4.52 ilustrates the correlation matrix between objectives, which was built in order to evaluate possible trade-offs. It is possible to identify six significant linear correlations, which are detailed in Figure 4.53. Four correlations are positive: mould's Volume and Cost, Shrinkage and Sink, Shrinkage and Waste and Sink and Waste. The other two ones are negative: Deflection and Pressure and Sink and Pressure.

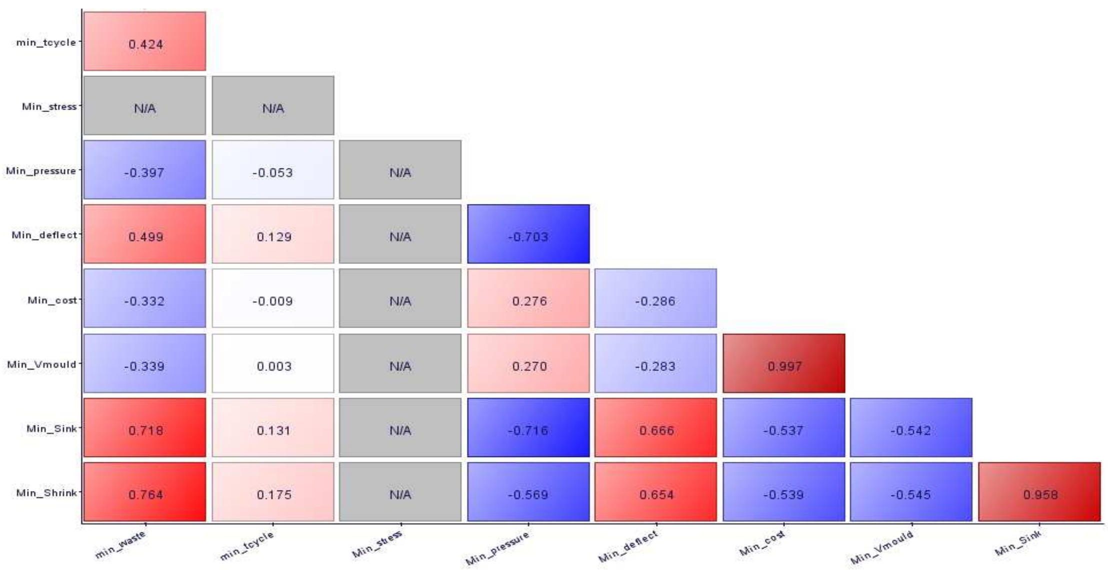


Figure 4.52: Correlation matrix between objectives using Pearson correlation values – key holders mould design.

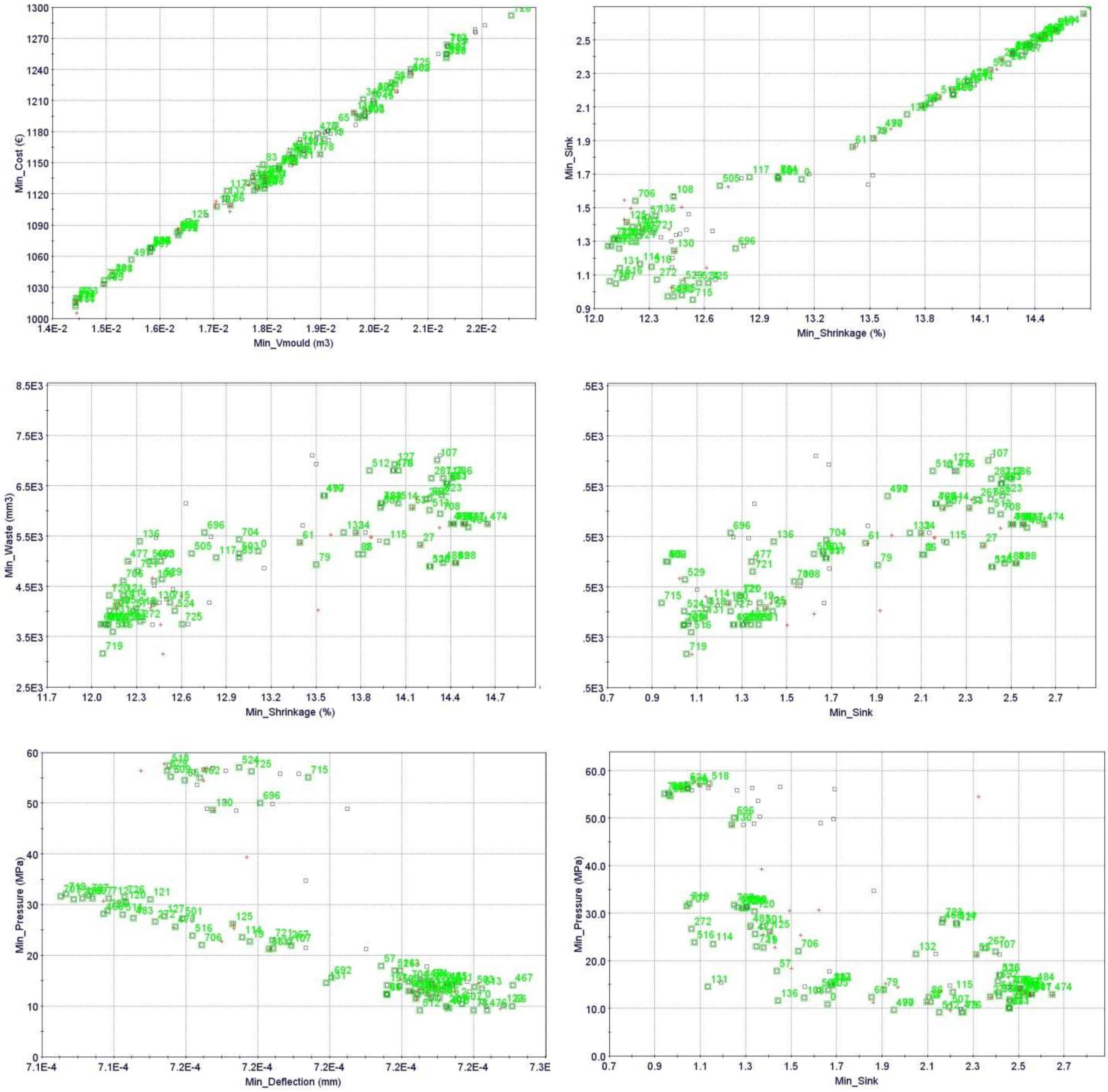


Figure 4.53: Scatter plots of objectives regarding the key holder mould design solutions.

The choice of the final injection design should be made from the set of Pareto optimal designs, using customer preferences. Based on the MCDM tool and assuming the relationship between objectives expressed by Eq. 126, a GA is selected to assists the decision maker to find the best solution from among Pareto solutions, as well as to verify the coherence of the expressed preferences and generate a valid utility function and ranking. Figure 4.54 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 as ID 0, has a rank value of 0.679, showing that a significant improvement was achieved through optimization.

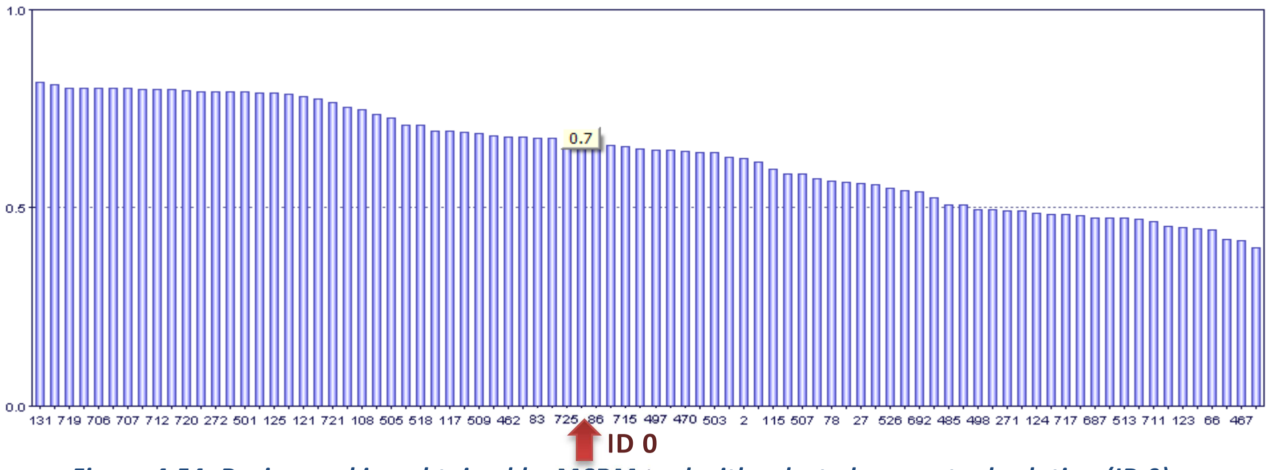


Figure 4.54: Design ranking obtained by MCDM tool with selected conceptual solution (ID 0) assigned – key holders mould.

Figure 4.55 presents the comparison of the objectives attained with both solutions. 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 Pressure drop.

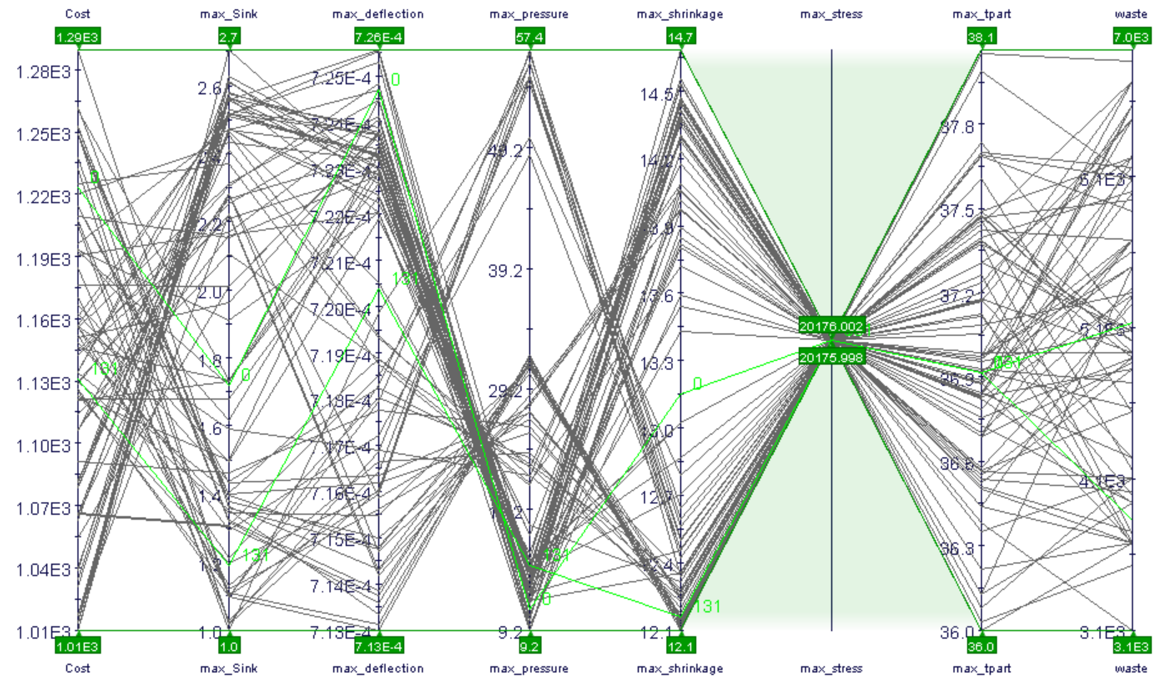


Figure 4.55: Parallel coordinates regarding objectives with selected solution (ID 131) and selected conceptual solution (ID 0) highlighted in green.

The selected solution (ID 131) is fully characterized in Table 4.35 and in Figure 4.56.

Table 4.35: Description of solution achieved (ID 131) and the selected conceptual solution (ID 0).

Stage	Design variable	ID 131	Conceptual solution (ID 0)
Design	$n_{Ejectors}$	4	4
	n_turns	2	2
	position_gates	B	B
	position_parts	II	II
	type_layout	S	S
Optimize	X_3 *(mm)*	296	296
	Y_3 *(mm)*	246	246
	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
	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

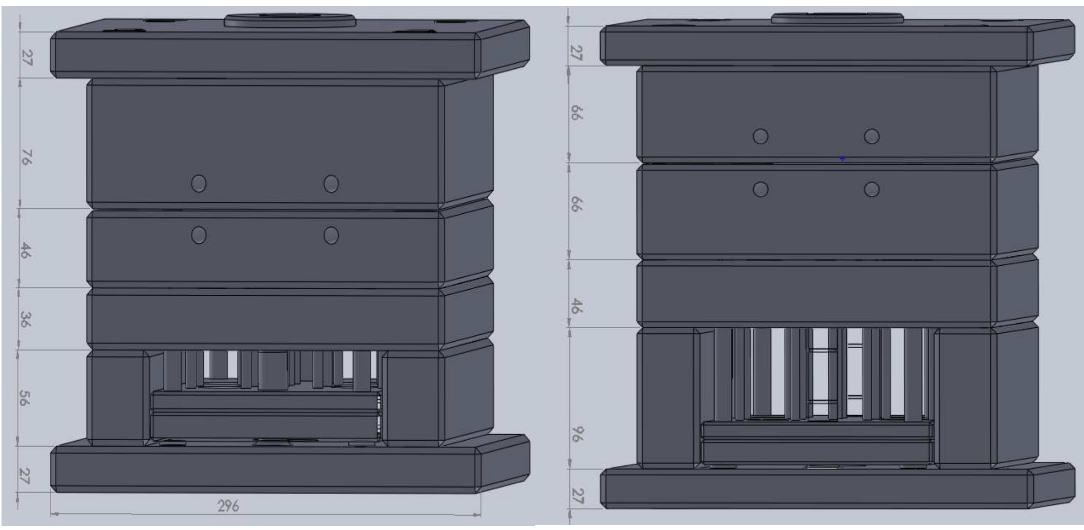


Figure 4.56: Structural system comparison between ID 131 (right) and conceptual solution (left): Solidworks

Table 4.36 presents a comparison between the optimized and the selected conceptual solution in terms of the improvements achieved in each of the objectives considered. An example of one output obtained by the platform is illustrated in Figure 4.57 showing the corresponding Sink index for the conceptual and ID 131 solutions, respectively.

Table 4.36: Comparison between the best solution achieved (ID 131) and the selected conceptual solution (ID 0).

	ID 131	Selected Conceptual (ID 0)	Comparison (%)
Deflection (mm)	7.20E-04	7.25E-04	**-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-02	2.04E-02	**-11.8%**
***Waste* (mm^3)**	**3.88E+03**	**5.18E+03**	**-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%**

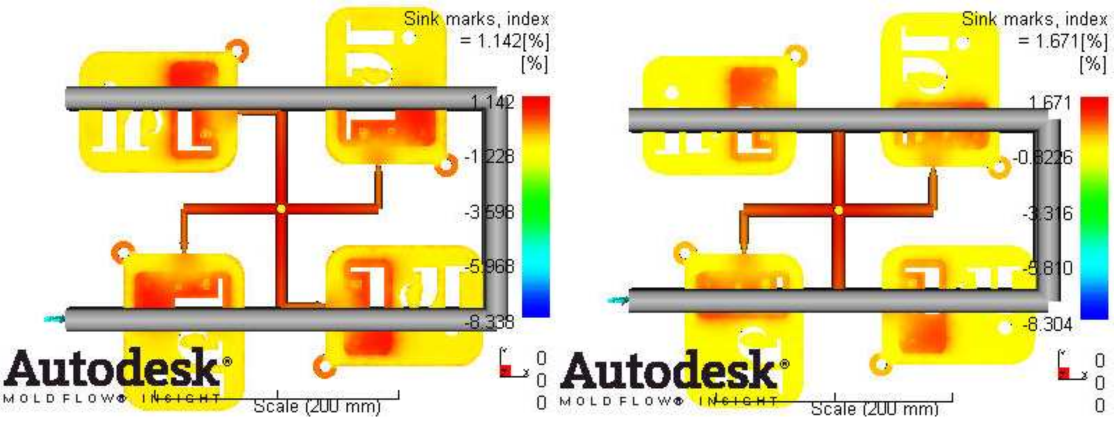


Figure 4.57: Sink index comparison between ID 131 (right) and conceptual solution (left): Moldflow.

Comparing solution ID 131 with the selected conceptual solution, it is possible to verify that significant improvements were achieved in all the objectives, except for Pressure drop. As shown in Table 4.36, the selected solution presents a reduction of the Sink index of 31.7%, of the Waste of 25.1%, of the mould's Volume of 11.8%, and of about 7.5% on Shrinkage and Cost. By the contrary, the achieved solution has a very important increase in Pressure drop (33%). 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 allows for an improvement on performance of about 5.7%. This enhancement can result in an increase of quality of Design of 4.4% which represents a positive improvement in

CSI of 0.7%. These results are consistent with the identified trade-offs. Therefore, due to the importance weights previously assigned, ID 131 obtained the highest rank value.

Comparing solution ID 131 with the baseline, it is possible to verify that major improvements were achieved in all the objectives, expect Pressure drop and Cycle time. As shown in Table 4.37, the selected solution presents a reduction on Sink index of 26%, on Waste of 25.1%, on mould's Volume of 11.8%, on Deflection of 11.4%, on Cost of 7.6%, and a drop on Shrinkage of about 0.8%. By the contrary, the achieved solution has a very important increase in Pressure drop (31%) and in Cycle time (7.2%). In average, ID 131 allows for an improvement on performance of about 5%. This enhancement can result in an augment of quality of design in almost 4%, which results in an increase of CSI of almost 0.6%.

Table 4.37: Comparison between the best solution achieved (ID 131) and the baseline (existing mould).

	ID 131	Baseline	Comparison (%)
Deflection (mm)	7.20E-04	8.13E-04	**-11.4%**
Shrinkage (%)	12.14	12.24	**-0.8%**
Sink	1.14	1.54	**-26.0%**
Stress (MPa)	2.02E+04	2.02E+04	**0.0%**
***tCycle* (s)**	36.933	34.44	**7.2%**
Pressure (MPa)	14.59	11.14	**31.0%**
***Vmould* (m^3)**	1.80E-02	2.04E-02	**-11.8%**
***Waste* (mm^3)**	3.88E+03	5.18E+03	**-25.1%**
Cost (€)	1133.1	1225.9	**-7.6%**
Global improvement			**4.94%**
Quality of design improvement			**3.73%**
Impact on CSI			**0.59%**

4.7. Conclusions

A reinforced and more realistic platform was developed in order to guide the mould design process [167]. For that purpose, the platform described in Chapter 3 was reinforced through two main aspects. The first one involved the substitution of the simplified models by high-fidelity models. In this sense, MOLDFLOW and ABAQUS were integrated in the platform aiming to model respectively thermal and rheological phenomena associated to the injection process, and the structural behaviour of the mould's components. A CAD tool (SolidWorks) was also included in the platform as a geometry handler module, helping to generate and visualize the design solutions. The second aspect of the reinforcement corresponds to the inclusion of all the critical design variables. These variables are mostly categorical and geometrical variables, as is the case of the type of feeding layout, which can be symmetrical or circular, or the position of gates, which involves a geometric position on the cavity.

The developed platform starts with a full understanding of the critical customer requirements. Afterwards, at the Design stage, it is necessary to define a few number of conceptual solutions for the mould. These solutions are proposed by the mould designer, according to his experience and to the best practice guidelines. It is important to highlight that these initial design decisions are described as the combination of each design variable alternative, included in the Design stage. Due to the increase of the model complexity, caused by its reinforcement, DoE methods were employed to evaluate potential designs. These methods are considered a good alternative to the optimal design search. Thus, a DoE analysis is carried out in order to determine the most well ranked solution regarding customer satisfaction. This solution was then detailed and optimized in the Optimize stage.

In the Optimize stage, thermal, rheological and structural analyses are undertaken by high-fidelity codes. 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 results obtained, a Pareto optimal frontier, $\mathcal{P}$, is determined. These Pareto optimal solutions, also known as non-dominated or efficient solutions, are ranked according to customer's preferences. For that purpose, a MCDM tool available on the overseeing code is adopted. This tool allows the correct grouping of outputs into a single utility function. This utility function is coherent with the preferences expressed by customers through pairwise comparison of attributes importance.

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, $n_{Ejectors}$, *n_turns*, *position_gates*, *position_parts* and *type_layout*. Thus, 32 randomized virtual solutions were generated and evaluated through the reinforced platform. The most well ranked conceptual solution, when compared with the baseline, allows for a global improvement on the objectives of 1%. This solution showed better performance on Pressure drop and Waste of material. By the contrary, it leads to higher levels of Sink index and Shrinkage, and a minor increase in Stress, Deflection and Cycle time. Mould's volume and Cost do not present significant changes. Assuming that the remaining objectives do not change, an increase of 0.05% on customer satisfaction level can be reached with the most well ranked conceptual solution.

In the Optimize stage, the selected conceptual solution was 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. The results attained highlight the potential of the proposed framework to achieve mould design improvements. In fact, an improvement of 0.7% on CSI was achieved through the optimization of the conceptual solution. Regarding the baseline solution, the best solution found corresponds to an improvement of 0.6% on CSI. 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 get quickly an early improved design solution. Based on that, it is possible to assume that the reinforced approach 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.

CHAPTER 5

Conclusions and future work

5.1. Introduction

The analysis presented in Chapters 1 and 2 allows one to identify the current challenges of the moulds makers industry and shows that nowadays the current practices for mould design are not efficient enough to assure its competitiveness. Also, it was demonstrated that the product development stage is crucial for companies' success. Based on that, academia and industry have been locking for different procedures to support the mould design process, which contributes for time reduction and higher levels of quality. In this sense, it was assumed that the development of a more quantitative and systematic approach will be needed to support it. For that purpose, a new approach, based on IDOV and complemented by high value tools, which were never used aggregated, was proposed as a roadmap for building a platform capable of supporting the design of injection moulds. Two versions of this platform were built with different purposes. The first one aims to explore its potential value and its feasibility, while the second one encompasses an enhanced model that includes the aggregate design of functional mould systems: Structural, Feeding, Heat-Exchange, Ejection and Impression systems.

In chapter 3 the first attempt was described and tested, by undertaking two optimization examples. As a result, it was concluded that the platform has high potential to optimize mould design solutions. Thus, it was decided to reinforce this platform in order to get more realistic results, by the inclusion of high-fidelity models instead of the simplest one used in the first endeavour. Chapter 4 describes the enhanced platform and demonstrates the platform value, through a comparison of the results achieved by the platform with an existing mould solution, which was considered as the baseline for optimization. In this last section, a summary of the insights achieved will be described, as well as some remarks about future work-made.

The driving factor for the development of this work was our strong conviction that the support of the product design stage by a more quantitative and systematic approach can greatly contribute for increasing companies' competitiveness. The fact that the decision making process is supported by sustainable process data will lead to a reduction of the iterative try-out of designs. Thus, better solutions will be achieved in a shorter time. This is especially important for the design of complex engineering systems, as it is the case of injection mould tools.

The proposed IDOV approach, powered by the developed platform, will automate much of the design process and drive the engineering analysis to the centre of the design process. This is clearly an advantage also for assessing quantitative process data, which can help the designer to take better design decisions. Regarding the injection mould design, although a mould can be considered as a prototype (i.e. rarely there are two identical moulds), it was demonstrated that the process design has a common structure that must be explored.

Based on that, a platform was developed, capable of generating, evaluating and optimizing mould solutions for simple plastic parts (i.e. without undercuts). In order to attain the complete integration of the major injection mould's disciplines, an integrated environment was built. This reinforced framework allows the analysis of the design solutions by evaluating the performance of the different design alternatives in two stages: the conceptual and the optimize stage.

The modular structure of the proposed framework includes the interaction among the different disciplines, which allows exploiting the coupling relations between the different functional systems of moulds. This option also ensures, at least conceptually, that other mould systems can be easily included in the framework. This can be the case of specific modules to integrate, for instance, the design of auxiliary components needed for more complex moulds, or new mould components resulting from technological advances. This modular characteristic is also true for the adopted high-fidelity codes, since the software packages can be replaced by other ones, with the same features, depending for instance on mould makers availabilities. This is particularly important for CAD software, given the several options available in the market. In this case, the framework can be easily adapted for other CAD software, due to the use of universal file formats. Regarding the thermal, rheological and structural phenomena analysis codes, the integration of other software can involve more complex rearrangements, due to the fact that different codes use different interchanging programming languages. Therefore, in that case, it may be required to build new macros for data exchanging with the overseeing code, ModeFRONTIER.

Typically, mould designers define the mould according to their experience and by following the practical guidelines. As a result, it is not sure that the achieved solution adequately responds to customer needs. For example, typically mould makers design moulds in order to attain the minimum cycle time. But, as it is the case of the key holder mould example used in this work, sometimes this is not a customer major concern. For this reason, the first stage of the adopted IDOV approach, Identify, drives mould designers to customers' auscultation, in order to evaluate their needs and to quantify relative importance's. This procedure allows to establish an utility function, specific for each mould order, providing designers with the necessary information to understand customer's preferences and implications over design.

It is also important to highlight that the developed platform can also be reinforced by adding, at any time, additional mould' attributes regarding internal and external customer´s needs. Although the utility function is pre-defined, the definition of the Pareto front provides a way to help designers or customers to visualize and understand the trade-offs, through the application of the MCDM tool. Therefore, it is possible to study different scenarios and, through customers consent, select the best solution for each particular scenario.

Given its ability to design products rapidly, and the emphasis on design assessment and improvement offered by the developed platform, it will lead to better mould design solutions, according to customer needs. In fact, it is assumed that a flowing design process, aligned with customer needs, is important for the mould maker's industry competitiveness. At the same time, since the platform allows to test several mould solutions through high-fidelity models, it provides valuable information to sustain the designer decisions on engineering analysis. As a result, the traditional problems arising from mould design will be reduced, as well as avoiding later problems detected only on the mould's experimental try-out.

One important key to the success of the design stage derives from the designers' ability to take advantage of process design, in order to reduce the iterations and errors committed in this crucial stage of moulds development. In fact, the majority of poor quality costs (68% of total costs) have their origins in errors committed in the mould design stage and in the transposition of the design to the production stage. The consequences of these errors are delays in mould deliveries and the increase of costs, due to mould repairs and to the payment of customer compensations. Thus, it is expected that by adopting the proposed IDOV procedure, shorter lead time and cost reductions will be achieved. The cost reduction will be a consequence of internal cost savings, due to the reduction of the iterative procedure, typically necessary to correct errors after the mould production. In parallel, savings are also expected regarding the monetary compensations for delays.

Although the new product development environment is enabled by an automated framework, it is important to bear in mind that it starts based on mould designer experience. In fact, the baseline solution of the platform is a preliminary mould conceived by the mould designer. Only then a few number of mould conceptual solutions will be evaluated and compared, in the Design stage. Afterwards, the best conceptual solution is optimized, according to customer's preferences, in the Optimize stage. This division in two stages was deliberate, and aims to exploit human capabilities for creative innovation. In this sense, the first stage of design is a conceptual stage, where vital decisions are made, and the knowledge acquired is considered essential. Thus, at this stage it is essential to exploit new and different alternatives for the design solutions.

Finally, since this methodology is based on scientific principles and quantitative tools, we consider that there should be no significant barriers in adapting it to other sectors.

5.2. Research phases and methods

A new and global approach based on the integration of well-known quantitative techniques was the main focus of this research. For that purpose, several methods have been studied in order to develop a more systematic and scientific approach to support the design process. As a result, DFSS was adopted as the main methodology.

Despite the great success of DFSS, which made out of it a phenomenon regarding its wide acceptance in industry, this DFSS boom has not been accompanied in the academic field [73]. In fact, as was shown in the literature review, DFSS lacks a theoretical underpinning and a basis for other research rather than "best practice" studies [74, 75]. Therefore, the reduction of the gap between the DFSS theory and practice was one of the main motivations for our DFSS adoption. Additionally, given the systematic and well-structured basis of DFSS, which provides an established and data-driven methodology based on analytical tools, DFSS's option was reinforced as an enhancement to the current product design practices.

Based on the developed work, it is possible to substantiate that the DFSS methodology works very well in supporting process design, mostly due to its well-structured and methodical manner to sustain product development stages. In fact, due to the connection between the DFSS principles and the different stages of a systematic design process, this methodology allows for a logical and comprehensible arrangement and integration of all design tasks.

In addition, the DFSS particularity of not having a single roadmap must be also considered an advantage, since it allows for the selection of the most appropriate roadmap according to the company practices. At the same time, the possibility of selecting a different number of roadmap stages is also beneficial, because the DFSS roadmap can be established according to specific particularities of each product design process. For example, the four stages of the IDOV roadmap adopted for the injection mould cases result from the lack of a project definition stage. Typically, the first stage of a five stages DFSS roadmap aims to define the business foundations of a design project, which includes tasks such as the establishment of the business goals, the strategy, market and segments, market trends forecasting, competitive benchmarking, as well as team memberships, roles and responsibilities definition and a preliminary project plan execution. Based on the characteristics of the mould design process, where each mould design is unrepeatable, the process flow is always identical and does not involve the previous tasks. Therefore, the Definition stage has not been included in the adopted IDOV roadmap.

Although the DFSS benefits are important, on the contrary it was not clear which DFSS methods or techniques are the most appropriate to use. In fact, since DFSS offers an advanced toolbox containing a large collection of well-tried best practice tools, it is hard to find out which tools or techniques are the most adequate. For that reason, after the process of injection mould's design was completely structured, with each stage's objectives and tasks clearly defined, it was necessary to identify which techniques are the most adequate to hold each stage. Thus, to support the ***Identify*** stage, ECSI was adopted as a reliable and independent way of assessing customer satisfaction. In fact, based on the obtained results, and although the estimated model is not perfect, there is a good reason to be satisfied with its estimation, because it has internal consistency, convergent validity and a very good capacity of prediction. Nevertheless, some limitations can be pointed, namely:

– The high effort to conduct data collection, mostly due to the lower predisposition of mould maker customers to answer questionnaires. Thus, in order to obtain a sufficient number of answers, it was necessary to promote mould customer's participation;
– Considering the characteristic of Portuguese mould makers customers (summarized in chapter 3 by customers chain analysis value tool), which are typically international leading

companies, a bigger communication effort was done to increase foreign survey's participation. In this regards, one attempt was made aiming to auscultate USA companies, which are important customers of Portuguese mould makers. However, this action has not entirely successful, since only 7 answers to the questionnaire were received;

- Due to the high effort to carry out the ECSI survey, which involved significant time and financial resources, one single ECSI evaluation was made during the Spring of 2007. This aspect limits the access to customer's updated data. Nevertheless, and since customer's can change their priorities, some adjustments are expected on the estimated ECSI model;
- Moreover, the limitation associated to the ECSI model is also minimized through the second step of customer auscultation, provided by IDOV approach, since it allows to identify the importance of each customer attribute, specific for a particular mould's order;
- Nevertheless, regarding the importance of an update of ECSI model estimation, it is important to undertake an effort to get the sponsorship of Portuguese mould makers companies and respective associations, in order to carry out the ECSI survey periodically, similarly to what is done by other Portuguese economic sectors (e.g. banks, mobile communications, etc.).

In spite of the mentioned limitations, an ECSI model specific for injection mould sector was estimated, through a component-based approach, based upon PLS. This option was based on PLS advantages when compared with Covariance-based methods (e.g. Robust Maximum Likelihood), namely: the fact that it can be used with relatively small sample sizes; it is free from the independence and multivariate normal distribution assumptions; it avoids the indeterminacy problem; it provides an exact definition of component scores; it can estimate models with both formative and reflective modelling, which is the case of the adopted ECSI model. Nevertheless, both approaches were used to estimate a reduced version of the ECSI model and they produced similar results.

Based on the estimated ECSI model, it was possible to build one single objective function regarding customer's satisfaction level, defined as a weighted function of specific customer attributes. In order to detail and refine the previously identified attributes, a focus was put on the quality of design items through AHP.

AHP is a measurement method that uses pairwise comparisons to deal with a set of mostly qualitative criteria, aiming to establish a multi-criteria decision-making solution. Based on the work done, it is possible to highlight that this technique is a very easy way to evaluate the relative importance of each attribute, according to customers. In fact, since they compare each attribute, two at a time, using a 1-9 scale, with three levels, it is possible to easily obtain an evaluation of the importance of each objective. Thus, AHP proved to be an efficient method for setting priorities and selecting alternatives, using for that purpose subjective evaluations obtained by human comparison.

The ***Design*** stage was mainly supported by the AD methodology [7, 31, 32]. Thus, following AD main guidelines, a few number of conceptual solutions was generated by mapping specific items to drivers for the quality of mould's design. For that purpose, these items are firstly translated into functional requirements, and then mapped with mould's design variables (i.e. the so-called design parameters). Thus, preliminary mould solutions are defined by assigning different values to these design variables, aiming to generate several conceptual solutions. These values are established by designers according to their experience and following practice guidelines. Afterwards, all these conceptual solutions were evaluated through a DoE study in order to select the most promising one. DoE was considered as a good alternative to optimal search, due mostly to the highly discontinuous and non-convex feasible space, resulting from the use of the categorical and geometrical design variables at this stage. The high computational resources needed for an optimal design search were considered to be impractical, at this stage.

Based on the results achieved, it is possible to conclude that AD is helpful to facilitate the physical structure generation, as well as to identify potential system interactions (i.e. couplings). Nevertheless, one recommends adopting AD to support only the top level decisions. This is particularly true for complex products, as it the case of injection moulds. In fact, since the hierarchical decomposition in one domain cannot be performed independently of the evolving hierarchies in the other domains, the imposition for zigzagging mapping becomes too complex when the design progresses to more detailed levels.

For that reason, this methodology appears to work better with abstract concepts. It has been demonstrated that AD can help to generate more adequate solutions regarding its key functions. It also helps to think in different ways to answer the key functions, aiding to increase the degree of mould's innovation. It is important to note that at the top level of product definition, theoretically all design solutions are possible. In fact, early in the design process, there is a complete freedom for decision making, since there are no limits caused by previous decisions. On the other hand, knowledge about the implications on product performance of these design decisions is scarce. Thus, it becomes even more important to conceive and evaluate different conceptual solutions, in order to understand and identify the critical aspects of the design and its implications on product's performance.

According to AD guidelines, the generated solutions must guarantee functional independence. However, as other authors point out, our perception is that this is not achievable in the case of injection moulds, mostly due to technological and lead time restrictions. Therefore, as explained in chapter three, it was assumed that if some remaining coupled relations subsist, they are not considered to be prohibitive at the Design stage, because they will be exploited in the Optimize stage.

After the most promissory conceptual solution is found, in the Design stage, it will be detailed in the ***Optimize*** stage. This stage is supported by the MDO framework, which shows to be an appropriate methodology to exploit the coupling phenomena. In fact, MDO works well in synergism exploration of the interdisciplinary couplings, mostly between thermal, rheological and structural disciplines, through the combination between analyses and optimizations in the individual disciplines. In fact, the results presented demonstrate that the optimal of each functional system is not the global optimum.

Regarding the computational time involved, this can be considered as a weakness of the developed platform, particularly when high-fidelity models are adopted. In fact, these models involve lot of computational resources and time. Nevertheless, the MDO reveals a good performance, since it takes advantage of parallel computation regarding individual modules. The MDO ability to search on multidimensional spaces presents a high potential for bringing a baseline mould to an improved mould's solution. In that search for an optimal solution, Pareto methods were preferred, since they rely on the concept of dominance to distinguish between inferior and non-inferior (i.e. non-dominated) solutions. Thus, the search does not depend on customer's preferences regarding each objective, which reveals to be useful by helping the designer to understand the impact of each design decision.

Among the Pareto approaches, the NSGA-II proved to be efficient. Nonetheless, taking into account the discontinuous and non-convex mould design space, it is impossible to assure that the optimal solution found is a global optimum. However, the more important issue in mould's design optimization is to assure the feasibility of the design. In fact, an early improved design solution is better than finding the optimal solution, but too late.

Finally, in the last stage, ***Validate*** stage, the goal is to verify if the optimized design achieves the established levels of performance. Regarding the work developed, two main issues must be evaluated differently. The first one is related with the main objective of this research, which involves the development of a more systematic and scientific approach to support the design process, which must be validated. For that purpose, the framework was conceptually validated, aiming to demonstrate that the injection mould design problem was properly conducted, allowing for a high degree of matching between model and reality. The primary validation technique used was face validation and traces. In fact, during this project, a main concern was to have experts to sustain the options made, as well to support decisions about the conceptual model. On the other hand, it is important to note that the platform was developed with the final goal of conceiving and optimizing injection moulds. Therefore, it must be operationally validated by evaluating if the designed system responds adequately. To that end, several techniques were adopted, namely: comparisons between platform's simulation outputs and already validated simulation models (e.g. comparison of first attempt with MOLDFLOW simulations); model exploration through parameter variability-sensitivity analysis, as well as by using sets of experimental conditions from the space domain of the model's for comparison with an existing model baseline.

Finally, the mould solution obtained by the platform must be evaluated in order to verify if it can achieve the established levels of performance, as well as being able to reach high levels of customer satisfaction. The most appropriate way to make this validation requires for the construction of the best mould solution, in order to perform experimental tests under similar conditions of use. This procedure allows measuring its performance, as well as its assessment by customers. However, due to financial constraints, it was not possible to build the optimal mould achieved for the key holder case. Therefore, the validation was performed using an alternative way, which consisted on comparing the results obtained by the tested and validated high-fidelity simulation codes, for both the mould baseline, and the new and improved virtual solution. This strategy allows one to assess the achievements in mould's performance, as well as regarding customer satisfaction index results.

5.3. Main insights achieved

Throughout the present work, the conclusions considered as potential insights were appointed based on the attained evidences. Now, in coherency with the IDOV approach, they will be summarizing under the following topics:

Identify:

- To support the Identify stage, ECSI was adopted as a way of assessing customer satisfaction and loyalty [30]. Hence, an ECSI model, regarding system specificities, was built, in order to encompass the particular factors for quality of injection moulds. Based on the data collected through a survey, the ECSI model was estimated and validated. This model demonstrates internal consistency, convergent validity (the AVE scores are greater than 0.5) and a very good capacity of prediction (more than 65% of ECSI variation is explained by its drivers);
- Based on the estimated model, it was possible to observe that the most important variable over customer satisfaction is *Image* (with a total effect of 0.535), followed by *Expectations* (with 0.354), *Quality of mould's manufacturing* (with 0.273), *Quality of service* (with 0.233) and finally, *Quality of mould's design* (0.157). Since the estimated indexes for each of these latent variables are, respectively, 74.8, 70.7, 74.5, 67.4 and 75.0, it is possible to conclude that *Quality of service* and *Expectations* are the items that must be, firstly, improved in order to achieve higher levels of customer satisfaction and loyalty;
- Regarding the construct Value, it is possible to verify that it has no significant impact on customer satisfaction (with a total effect of 0.032). This is not a very typical situation in ECSI studies, and may indicate that the mould's value is not a main concern for customers;
- Due to one single ECSI evaluation, during the Spring and Summer of 2007, the ECSI estimated model can suffer some adjustments regarding customer updated information;
- Due to the absence of data information regarding foreign customers of Portuguese mould's makers, it was impossible to test possible differences in preferences between Portuguese customers and other customers. However, as future research work, one intends to try different approaches to get their participation, such as having ould association sponsorships.

Design:

- According to AD guidelines, the identified functional requirements were mapped into design parameters, for the first three levels of decomposition. Mostly due to theoretical reasons, a single map was obtained (described in chapter 3). Nevertheless, the identified map can be easily updated to take into account future changes on customer's preferences. The existing platform can also be easily adapted to take into account these updates, since it only implies changing the objective items and making the new links between objectives and design variables;

- Three functional requirements were not included in the platform, namely *Mean Down Time (MDT), Mean Time Between Failure (MTBF)* and *Information content*. The main reason for that was because there is no support on the literature to be able of express these items as functions of injection mould design variables. As a result, the Maintainability and Reliability concepts, as well as the Accessibility item must be studied in future work, in order to establish models for a MDT, MTBF and Information content evaluation;
- We demonstrated the high importance of achieving a good preliminary solution, particularly when considering its novelty and degree of response to customer's needs. In fact, conceptual design decisions, which establish the set of values that can be assumed by each conceptual variable, are essential for the success of the final mould design solution and manufacturing;
- Based on the developed platform, it is also possible to verify that different design solutions with similar performance along one criterion can exist. However, they present different performance for at least another criterion. Also, small changes on customer's preferences can change drastically the optimal solution selected;
- It was also demonstrated, that design solutions with good performance attribute levels in many criteria represent a tiny subset of the design space;
- The majority of the generated designs are characterized by an acceptable performance, when compared with the final solution, especially on the Design stage;
- Traditional design practices result, typically, in a poor design space exploitation, usually as a consequence of the shorter lead time and due to technical resources constraints. Moreover, given time constraints, the main concern of mould designers is to achieve an acceptable mould solution, instead of looking for the best one. Nevertheless, mould designer know-how and experience reveal to be an important factor to indicate the best design areas to explore at the Design stage.

<u>Optimize:</u>

- Since the design space is discontinuous and characterized by geometrical feasibility zones (i.e. for instance the ejection pins cannot be located next to the cooling lines), GA with explicit Pareto optimality management, properly fed with an initial population of feasible solutions, generate feasible solutions and are able to locate the Pareto front efficiently;
- The developed platform has the potential to generate and optimize solutions with performance attributes levels much higher than the ones obtained with current design processes, mainly due to: (i) time and cost saving in experimental try-outs; (ii) exploration of other design solutions (only possible with the automated computational process); (iii) 24h

per day of possible design activity, since design exploration can occur without human intervention. In the key holder example, one design was accomplished in 2h, against the several days that it would be required if performed manually (note that the structural analysis is usually not performed in the design process);

- Mould's attributes that are important for achieving higher levels of customers satisfaction are not intuitively obvious, neither its importance weight. In fact, it was verified that typically the solution is generated in order to achieve the lowest cycle time, which sometimes is not the main objective of mould customers. Consequently, the designer follows its intuition and goes in the wrong directions. This has been demonstrated by the different optimal solutions achieved by the platform, when it used the typical CSI instead of the specific CSI adjusted for that particular mould's order;
- One advantage of the developed platform is its ability to explore the design space without having a pre-definition of the moulds customer's utility function. Since this exploitation involves running complex simulations, highly demanding in time and computational resources, this effort is not wasted. The platform allows for selecting effective designs by exploiting the characteristics of the Pareto fronts. Additionally, this characteristic also helps to understand the implications of the trade-offs;
- Given the different ways of articulating customer's preferences in order to select the best conceptual solution, and considering that engineering design is clearly about making decisions with multiple conflicting criteria, a *Priori articulation of DM* preferences seems to be the most adequate to guide designers on customer's preferences direction. Nevertheless, since optimization engineering problems are very time consuming, mostly due to CAE analysis, the search for the optimal solution must be carried out by Pareto methods. In fact, these methods are independent of customer's preferences allowing for an independent optimal search of solutions. Therefore, analysis runs must be performed once, to get a Pareto set, which will be presented to customers, helping them to make a decision.

Validate

The 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 reinforced platform. Based on the results achieved, through the comparison between the existing mould and the solutions generated at the conceptual and detailed design 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;
- 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 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 for customer's satisfaction degree. In fact, as described in chapter 4, a global improvement on performance of almost 5% resulting in an increase in quality of design of about 4% was achieved (with a positive impact on CSI of 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.

5.4. Future work

As demonstrated, the Design stage has a significant importance for achieving a superior final solution. In the developed approach, conceptual decisions are mostly dependent on the designer's knowledge for defining the baseline solution, as well as the feasible values for these conceptual variables. Therefore, it will be important to include in the platform some embedding design rules aiming to help designers with less experience. For that purpose, a Knowledge-Based System (KBS) can be built to support the conceptual design stage. Although such an approach has been an important area of mould injection research, as pointed out in the literature review chapter, it has not yet been directed to this stage of design. Nevertheless, a simple and fast design exploration tool, based on a KBS, can be an efficient way of establishing the initial solution, helping inexperienced people to define the mould design space and to have a preliminary design.

Additionally, in coherency with the last MDO advances [265], it will be also important to integrate in the platform manufacturing requirements. This aspect is particularly important due to the existence of several couplings between design and process parameters. Finally, a more complete cost function must be also included in the platform, in order to provide decision makers with an economic analysis of design decisions. This goal can be attained by extending the existing cost model in order to include processing costs, expressed as functions of the design variables. To that end, a two stages cost model will be necessary to provide a quick and rough cost estimation regarding the preliminary design solution, followed by a more detailed cost analysis concerning the final mould solution.

On the topic of assessing the platform's value, the underlying question is how to measure the impact of a modified solution generated by the platform, if it has not been constructed and validated. In fact, due to the high cost of mould's construction, testing both solutions is impractical. Unfortunately, this question is not valid only within injection design mould´s scope. In fact, it is consensually accepted for all the major industries that use MDO methods that this is a non-trivial issue [265]. Therefore, a significant amount of work is required in order to provide a basis where MDO methods can be validated, in a manner that provides limits beyond which MDO results either cannot be accepted or may only be interpreted as merely trend pointers. However, in our opinion more important that having a platform capable of generating optimal mould solutions, is for one to have a platform able to test several design solutions, mostly at the conceptual design stage, and to give quantitative information to aid in the design decision making.

Nonetheless, the application of the developed platform in an industrial context is a way to test it in a real context, since the platform can be applied in parallel in mould design and manufacturing. This is the next goal in order to assess the real impact of the proposed framework, as well as to evaluate possible earnings in development time and cost. Furthermore, this will also allow us to assess the degree of acceptance of the platform as a tool for supporting injection mould design processes.

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APPENDIX I

Interview script

The purpose of this interview is, primarily, to identify the needs and expectations of clients industries of Portuguese mould makers. In this sense, we believe that your long experience as a client of this industry must be assessed in order to have your perspective regarding this subject.

Note that this interview is the first step of a global project aiming to identify the factors that contribute to mould makers customers' satisfaction and loyalty. The next step, which will be undertaken only after the analysis of these interviews, will include a complete questionnaire that will be sent to all customers of Portuguese mould makers. By opposition, this interview will be only conducted to a small number of customers.

The theoretical basis for this research is the European Customer Satisfaction Index (ECSI), which aims primarily to determine customer satisfaction in the industry with metrics capable of international comparison.

This interview should take about 1 hour, and with your permission, it will be recorded. Nevertheless, the contents of the interview will be kept confidential and only accessible to the authors of this research project, namely Eng. Irene Ferreira, Professors Pedro Saraiva and José Cabral. Later this interview will be transcribed for analysis and identification of main ideas. It is also important to highlight that only the global conclusions resulting from the analysis of interviews will be published.

This interview consists of three parts. The first part seeks to understand the importance of the quality of mould (design and manufacturing) regarding the specificities of your process, as well as to identify the main requirements imposed by you.

The second part of the interview aims to understand your needs and expectations regarding additional services related to mould (such as payment terms, transportation, technical resources, monitoring of production, among others).

The final part of the interview focuses your future expectations and concerns regarding the injection mould sector, as well as to evaluate your overall satisfaction and loyalty with your mould suppliers.

Part I (Mould's Quality)

Assuming that the mould is critical to your process; Could you describe how the quality of the mould may influence the performance of your process? (Q1)

Bearing in mind all that you said, what are your main requirements when using/ordering/testing a mould? (E)

You usually transmit these concerns to your mould supplier/customers? How? (E)

Therefore, what are the requirements that you consider basic in order to obtain a mould that would guarantee quality in your process? (Q1)

Taking into account these requirements, and assuming a scale of priorities, how do you rate them? (From most important to least important) (Q1)

Considering your long experience with moulds, can you describe examples of typical problems with moulds? (Q1) How often do they occur? (C) How do mould's makers usually manage these problems? (C)

Do these problems usually result in formal complaints? (C) What type of complaints do you present to your mould's suppliers? How are these complaints usually handled by your mould supplier? (C)

Part II (Service Quality)

What other criteria do you take into account to work with a mould supplier of moulds? (Q2)

These criteria are taken into account to evaluate and qualify your moulds suppliers? How? (Q2)

On average with how many suppliers do you usually work? Can you characterize your relationship with them? (L) How do you differentiate them?

Now, thinking in the future, would you keep these criteria? If I asked you to describe your ideal mould's supplier, how would you characterize it? (Q2) If this supplier exists elsewhere in the world, do you hesitate to work with him? Why? (L)

Part III (Future trends)

Holistically, could you describe what is your image of the Portuguese moulds makers sector? (I)

In a global view, and considering a scale of 1-10, could you define your satisfaction level with moulds and respective moulds suppliers? What are the main reasons for this classification? (S)

Considering your answer, do you think that the value paid by the moulds is fair? Why? (V)

Now, to finish this interview, can you tell what your future prospects for this sector are? How do you think the plastic injection sector will progress in the medium and long term? Given your prediction, which are, in your opinion, the consequences of future changes to the mould sector? And to its companies? How? Do you plan to keep working with them? (L) What are the changes that they need to suffer to make this true? (E)

Is there something more that you want to add to this interview?

Thank you for your attention and availability.

Legend:

Q1 - Quality of product

Q2 - Quality of service

E - Expectations

I - Image

C - Complaints

L - Loyalty

S - Satisfaction

V - Perceived value

APPENDIX II

EUROPEAN CUSTOMER SATISFACTION INDEX (ECSI)
Mould Makers Version

The main objective of this survey is to assess the customer satisfaction, in an accurate way, regarding designers and mould makers for plastic parts injection. This work is part of a PhD research project developed by Irene Ferreira (isofia@mit.edu) at the **MIT Strategic Engineering** Group led by Prof. Olivier de Weck (deweck@mit.edu) in conjunction with the **Engineering Faculty of Porto University** and **Chemical Department of Coimbra University** (Portugal).

This survey will allow the determination of customer satisfaction factors, and more importantly, the development and validation of a model based on the European Customer Satisfaction Index (ECSI) that are specific for the mould maker sector, which will provide useful insights regarding mould producers and their customers' evaluation of their quality and services. The ECSI model is a framework, adapted from the Swedish Customer Satisfaction Barometer and American Customer Satisfaction Index (ACSI), which aims to harmonize the national Customer Satisfaction Index in Europe.

This inquiry will not take more than 5 minutes to answer. Therefore, we would appreciate that you answer this questionnaire within the following two weeks. We guarantee that your responses will be treated with confidence and at all times, the data will be presented in such a way that your identity will not be connected with any specific published data.

If you have any questions or comments about this project, please send us an e-mail.

We are especially thankful for your precious contribution in fulfilling this questionnaire.

Irene Ferreira
(isofia@mit.edu)

In order to answer this survey, please bear in mind your main Portuguese mould maker and remember all your experiences in the last three years with this mould maker.

If you want to give us the name of this mould making company, please write it in this space:

Q1. To answer the following questions, remember what your perceptions about this company are. Then, please indicate the degree of your agreement with the following statements (Please give me a rating on a 10 point scale on which "1" means your "total disagreement "and "10" means "total agreement" with the statement):

	1	2	3	4	5	6	7	8	9	10	NA
1.1 This mould makers is a reliable and trustworthy company											
1.2 This company is innovative and always looks ahead											
1.3 This company is a customer-oriented companies											
1.4 This company has lots of experience in moulds production											
1.5 This company is stable and well established											

NA means not applied

Q2. Before you ordered your injection mould, you probably knew something about this particular company. Based on this, think back and remember your expectations about the following items. Please give us a rating on a 10 point scale on which "1" means your expectations were "very low" and "10" means your expectations were "very high."

	1	2	3	4	5	6	7	8	9	10	NA
2.1 Overall quality of this company											
2.2 Company's capacity in offering moulds that answer to your needs											
2.3 Moulds maker's reliability and provided service											

NA means not applied

2.4 Considering your expectations, to what extent has this company fulfilled them?

1	2	3	4	5	6	7	8	9	10	NA

Q3. Up to this point we have asked you about your expectations, now we are going to ask about your recent experience with mould's design and construction, and overall performance of this company.

First, please considerer all your experiences in the last three years with the **mould's design** developed by this company. Using a 10 point scale, on which "1" means "very low" and "10" means "very high", how would you rate the following items:

Quality of design	1	2	3	4	5	6	7	8	9	10	NA
3.1 The capacity of the mould's design meeting your product requirements											
3.2 The mould's design capacity according to your specific injection process											
3.3 The use of adequate constructive solutions											
3.4 The companies' accessibility in discussing the mould's design											
3.5 The overall quality of mould's design											

NA means not applied

Secondly, please considerer all your experiences in the last three years with the **mould's construction** produced by this company. Using a 10 point scale, on which "1" means "very low" and "10" means "very high", how would you rate the following items:

Quality of construction	1	2	3	4	5	6	7	8	9	10	NA
3.6 The quality of the structural elements											
3.7 The reliability of the adopted constructive solutions											
3.8 The adequacy of manufacturing processes (type, parameters and tools) to your requirements											
3.9 The overall quality of mould's construction											

NA means not applied

3.10 How would you rate the overall quality of your mould maker products and service?

1	2	3	4	5	6	7	8	9	10	NA

Thirdly, please considerer all your experiences in the last three years with the moulds and services provided by this company. Using a 10 point scale, on which "1" means "very low" and "10" means "very high", how would you rate the following items:

Cooperation	1	2	3	4	5	6	7	8	9	10	NA
3.11 The company's accessibility in sharing responsibilities for the part's quality											
3.12 The accompaniment, by this company, of the mould performance during it's life cycle											
3.13 Company's pro-activity in collaborating in solving problems during mould's life cycle											
3.14 The company's capacity for integrating complementary services											

NA means not applied

Resources	1	2	3	4	5	6	7	8	9	10	NA
3.15 The technical staff's know-how											
3.16 The level of it's high-tech equipment											
3.17 The quality of the installations											

NA means not applied

Response capacity	1	2	3	4	5	6	7	8	9	10	NA
3.18 The response capacity to your requirements											
3.19 The capacity in answering quickly to your needs and problems											

NA means not applied

Contracts	1	2	3	4	5	6	7	8	9	10	NA
3.20 The companies' flexibility											
3.21 The fulfilment of the conditions previously agreed											

NA means not applied

3.22 Using a 10 point scale, on which "1" means "very far" and "10" means "very close," how close is this mould maker to your ideal moulds provider?

1	2	3	4	5	6	7	8	9	10	NA

Q4. Now we want you to consider the value of your moulds in terms of both price/quality and quality/price.

4.1 Given the quality of the moulds made by this company, how would you rate the price that you paid for these moulds? Please use a 10 point scale on which "1" means "very high price given the quality" and" 10" means "very low price given the quality".

1	2	3	4	5	6	7	8	9	10	NA

4.2 Given the price that you paid for your moulds, how would you rate their quality? Please use a 10 point scale on which "1" means "very poor quality given the price" and" 10" means "very good quality given the price."

1	2	3	4	5	6	7	8	9	10	NA

Q5. Now, please think about how often things gone wrong with this company in the last three years.

5.1 Using a 10 point scale on which "1" now means "very often," and "10" means "hardly ever," how often have things actually gone wrong with your mould maker?

1	2	3	4	5	6	7	8	9	10	NA

5.2 Have you ever complained about your mould maker within the past three years?

Yes No Don't know

If you answer in the last question **yes**, please ask the following question, otherwise go to next section.

5.3 Using a 10 point scale on which “1” means “handled very poorly” and “10” means “handled very well”, how would you rate the handling of your most recent complaint?

1	2	3	4	5	6	7	8	9	10	NA

6.1 The next time you are going to order a new mould, how likely will you place the new order to this company? Please use a 10 point scale, on which “1” means it’s “very unlikely” and “10” is “very likely”.

1	2	3	4	5	6	7	8	9	10	NA

6.2 If there was a competitive mould maker that could offer the same range and quality of moulds as this company, how much would they have to reduce their prices for you to change supplier? Please use a 10 point scale, on which "1" means it's "very little" and "10" is "very much".

1	2	3	4	5	6	7	8	9	10	NA

6.3 If anyone asked for your advice, how likely is that you would recommend this company? Please use a 10 point scale, on which "1" means it's "very unlikely" and "10" is "very likely".

1	2	3	4	5	6	7	8	9	10	NA

6.4 We would like to know how important the following technical requirements of injection moulds are to you, when you order a new mould to a mould maker. Using a 10 point scale, on which "1" means "very little" and "10" means "very high", how would you rate their importance:

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**NA**
6.4.1	Cycle time											
6.4.2	Mould's durability											
6.4.3	Dimensional reproducibility of the plastic parts											
6.4.4	Part's finishing											
6.4.5	Mould's reliability											
6.4.6	Dimensional accuracy of the plastic parts											
6.4.7	Mechanical properties of the plastic parts											
6.4.8	Number of injected parts											
6.4.9	Number of cavities											
6.4.10	Deliver dates											
6.4.11	Others:											

Your Company Information

7. Finally, to better understand our specific needs, we need to get more information about your company and your core business. Therefore, please give us the following information.

7.1 Company's Name (optional):

7.2 Function of survey respondent (optional):

7.3 What are the main industries supplied with our products?

7.3.1	Automotive	
7.3.2	Household Items	
7.3.3	Home Appliances	
7.3.4	Packaging	
7.3.5	Electr./Inform./Telec.	
7.3.6	Garden Furniture	
7.3.7	Agriculture/Irrigation	
7.3.8	Building Material	
7.3.9	Electrical Material	
7.3.10	Child-Welfare	
7.3.11	Others	

7.4 How many moulds, in average, do you order per year?

7.5 What are the main technical areas of your company?

7.5.1	Product Engineering	
7.5.2	Tools Engineering	
7.5.3	Production	
7.5.4	Others	

7.6 Have your company a quality system audited?

Yes No Don't know

7.7 If you want to give us any additional information or make any suggestions, please write it in this space:

Thanks for your precious contribution.