Proceedings of ICAD2009
The Fifth International Conference on Axiomatic Design
Campus de Caparica – March 25-27, 2009
ICAD-2009-19

A NEW AD/MDO APPROACH TO SUPPORT PRODUCT DESIGN

Irene Ferreira.
iferreira@estg.ipleiria.pt
Centre for Rapid and Sustainable Product Development,
INDEA, Campus 5
Rua das Olhalvas,
2414-016 Leiria, Portugal

José A. Cabral
jacabral@fe.up.pt
Department of Industrial Engineering and Management,
Faculty of Engineering,
University of Porto
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal

Pedro M. Saraiva
pas@eq.uc.pt
Department of Chemical Engineering,
University of Coimbra,
Pólo II - Pinhal de Marrocos,
3030-290 Coimbra, Portugal

ABSTRACT

Nowadays, due to its critical role regarding product cost and performance, as well as time to market, product design is considered to be at the new frontiers for achieving competitive advantage. Therefore, to face today's rapidly changing business environments, it is extremely important to adopt a systematic approach to product design, in order to avoid errors and consequently achieve shorter time-to market performances. In this context, we will describe a new approach to support product design, which links Axiomatic Design (AD) and Multidisciplinary Design Optimization (MDO), applied in an integrated way at the conceptual design and the detailed design stages, respectively. Firstly, the conceptual design stage is undertaken by AD, which is used to map Functional Requirements (FRs) with the corresponding Design Parameters (DPs). Even though we try to guarantee the Independence of FRs, as established by Axiom 1 of AD, if some remaining coupled relations subsist that is not prohibitive. Afterwards, the detailed design is carried out by MDO, considered to be an appropriate methodology to design complex systems through an adequate exploitation of interacting phenomena. The proposed approach is applied to the design of metallic moulds for plastic parts injection, since the mould makers sector involves constant design and production of unrepeatable moulds, where uncoupled design solutions, mostly due to technological and time reasons, aren't common (this sector is strongly influenced by customers who place enormous pressures on lead-time and cost reduction). This application points out the high potential of improvement that can be achieved through the simultaneous improvement of mould quality, reliability and time to market.

Keywords: Axiomatic Design, Multidisciplinary Design Optimization, moulds design, coupled designs.

1 INTRODUCTION

In general product development can be described as an iterative process, where some recursive and repetitive tasks, dominated by empirical knowledge, are performed until an acceptable solution is achieved. Due to today's market pressure to reduce costs and time-to-market of products, as well as to increase its quality, new design approaches must be adopted, leading to faster and more efficient product development.

One of these methodologies is Axiomatic Design (AD), which establishes a systematic and scientific basis for the product design process, with the final goal of determining the best design solution [Suh, 1990]. The basic postulate of the AD approach is that there are two fundamental axioms that must govern the design process: the Independence axiom and the Information axiom. The first axiom states that the independence of Functional Requirements (FRs), which are the specific requirements translated from customer's needs, must always be maintained. The second axiom establishes that the best design, amongst designed solutions that satisfy the independence axiom, is the one that has the smallest information content.

In addition, AD establishes that the design process must progress by mapping the FRs into Design Parameters (DPs), which characterize each design solution, in a top-down hierarchical manner. For each level of decomposition, the relationships between FRs and DPs can be described mathematically as a design matrix [A]. According to the structure of this matrix, there are three types of design: Uncoupled, Decoupled and Coupled. The Uncoupled design (most preferred) is characterized by a diagonal matrix, which indicates the independence of all FR-DP pairs [Jang, Yang et al., 2002]. The Decoupled design (second choice) is characterized by a triangular design matrix. Therefore, the FRs can be answered systematically, from FR1 to FRn, by considering only the first n DPs. Finally, the Coupled design (undesirable) is characterized by a design matrix with no specific structure. Therefore, a change in any DP may influence all FRs simultaneously, meaning that the independence axiom is not accomplished. Although this type of design is not promoted by AD, because it does not guarantee the first axiom, some authors (e.g. [Crawley, Weck et al., 2004]) believe that there are some cases where it should be applied, especially when performance, efficiency and packaging constraints dominate, where uncoupled/decoupled solutions might not be feasible. This is the case of metallic moulds for plastic parts injection [Ferreira, Cabral et al., 2006], where, by technological and time reasons, mould designs are generally a coupled solution, or has at least do have some coupled areas. In this sense, Multidisciplinary Design Optimization (MDO), which is considered appropriate to design complex systems trough an exploitation of interacting phenomena, can be undertaken in order to design faster and improved solutions, with minimal coupling vulnerabilities.

2 AXIOMATIC DESIGN APPROACH

According to AD theory, the world of design is made up of four domains (Figure 1): the customer domain, the functional domain, the physical domain and the process domain [Suh, 1990]. The starting point of process design is the identification of Customers Attributes (CAs) in the customer domain. Then, these CAs must be translated into specific requirements, designated as FRs, which are formalized in the functional domain. After that, considering that the objective of design is generated as a physical solution, characterized in terms of DPs (that meets FRs), the design must progress by interlinking these two domains (functional and physical) through a zigzag approach. Finally, the last step involves interlinking the DPs with the Process Variables (PVs), which assure product manufacturing.

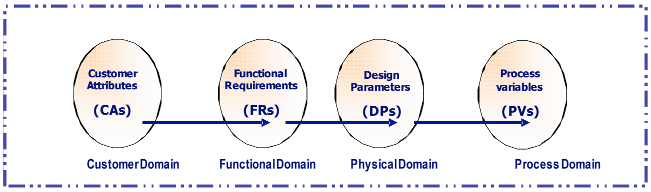


Figure 1. World of AD design: domains.

One first attempt to apply an AD approach to moulds design was carried out by Ferreira et al. [Ferreira, Cabral et al., 2006]. That application encompassed the identification and decomposition of the FRs and DPs into their respective hierarchies, following the traditional zigzagging approach to map FRs into DPs. To undergo that process, the authors considered that the main aim of an injection mould is to replicate the desired geometry of the plastic part, which involves the design of some typical functional systems (e.g. feeding system, ejection system, venting system, heat-exchange system, impression system and guide system). They also assumed, as a typical process of mould design, the one that is undertaken by the majority of mould makers. During this process, they found out that the design matrixes identified were mostly coupled (Appendix I).

Nevertheless, it is important to highlight that this mapping was obtained without linking first the CAs with the FRs (first task of the AD design process). This task is considered important, because when not done (or not correctly done), designers may initiate the design process without fully understanding customer requirements [Rose, Beiter et al., 1999; Chao and Ishii, 2004]. This can lead them to conceive good product solutions which do not however satisfy at all of customer needs. Since AD doesn't comprise special references to how this task should be carried out, two sequential steps were adopted to undertake it. The first stage involved semi-structured interviews and visits to an illustrative sample of Portuguese injection companies (customers of Portuguese moulds makers). This exploratory stage allowed us to identify the factors that might contribute to the perceived quality of moulds and to inherent service, and to elicit a comprehensive set of questions regarding the construction of a survey [Ferreira et al., 2007]. In a second stage, a survey based on the European Customer Satisfaction Index (ECSI) was developed, aiming to evaluate the impact of each factor over Customers Satisfaction (CS) and Loyalty. Therefore, each attribute was ranked according to its relative importance to customers, in order to address the critical items.

Based on the data gathered [Ferreira et al., 2008], it was possible to identify four main factors that contribute to mould's design quality. These factors are the satisfaction of Part's requirements, Injection process requirements, Constructive solutions and Accessibility (Table 1).

Table 1. Factor's importance regarding mould's design quality.

	Relative weights
The capacity of the mould's design to meet product requirements	0.20
The mould's design capacity to meet injection process requirements	0.19
The use of adequate constructive solutions	0.23
The company accessibility in discussing the mould design	0.18
The overall quality of mould design	0.19

For each factor, a team of seven mould designers defined the associated requirements (designated as CAs), which are typically required by injection mould customers, when they ordered the mould (Figure 2).

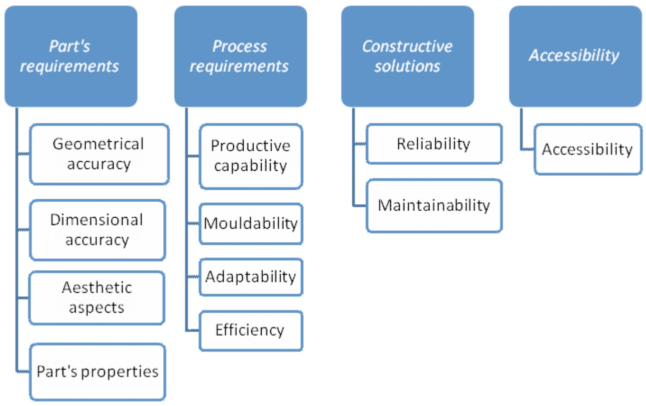


Figure 2. Typical CAs regarding injection mould design.

In order to refine and prioritize the identified CAs, it was assumed that CS is a linear function of CAs performance (i.e. performance does have a correlation with CS, and CS with CA). In this regard, the team was asked to compare each CAs previously identified, two at a time. They used in this comparison a 1-9 scale [Saaty, 1994], with three levels: 1 - Equal importance; 3 – Moderately more important; 9 - Extremely more important. To determine the relative priority of each item, the Analytical Hierarchical Process (AHP) was adopted (Table 2). This technique is widely used for addressing multi-criteria decision making problems, since it assures the consistency and stability of the forthcoming decisions [Lu, Madu et al., 1994]. 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 [Raharjo, Xie et al., 2007].

Table 2. CAs priorities

	Customer's attributes (CAs)	Ranking
Part's requirements	Geometrical accuracy	0,436
	Dimensional accuracy	0,234
	Aesthetic aspects	0,198
	Properties	0,132
Process' requirements	Productive capability	0,422
	Mouldability	0,289
	Adaptability	0,235
	Efficiency	0,054
Constructive solutions	Maintainability	0,568
	Reliability of solutions	0,432
Accessibility	Accessibility	1,000

Based upon these values, it is possible to express mathematically CS as a function of CAs, as well as a function of FR:

$$\begin{aligned} CS &= 0.2 Part's + 0.19 Process + 0.23 Solutions + 0.18 Accessibility \\ &= 0.2\left(0.436 Geometrical + 0.234 Dimensional + 0.198 Aesthetic + 0.132 Properties\right) \\ &+ 0.19\left(0.422 Capability + 0.289 Mouldability + 0.235 Adaptability + 0.054 Efficiency\right) \\ &+ 0.23\left(0.568 Maintainability + 0.432 Reliability\right) + 0.18 Accessibility \end{aligned} \quad (2)$$

The next step in our AD approach encompasses the translation of previously identified CAs into FRs, which are the minimum set of functional requirements states in the functional domain (Table 3). This step is considered helpful to facilitate the physical structure generation, through FRs-DPs mappings [Yang and El-Haik, 2003].

Table 3. Mapping CAs and FRs.

Customer attributes (CAs)	Functional Requirements (FRs)
Geometrical accuracy	Deflection
Dimensional accuracy	Tolerance
Aesthetic aspects	Visual marks
Properties	Specific property
Productive capability	Cycle time
Mouldability	Pressure range
Adaptability	Mould's size
Efficiency	Volume of scrap
Maintainability	MTTR
Reliability of solutions	MTBF
Accessibility	Information content

Several architectural concepts can be developed to fulfil the previous FRs. These alternative solutions are generated by mapping the FRs, in the functional domain, to a set of design parameters (DPs), in an adjacent physical domain, by the zigzag process. In theory, the number of plausible solutions, for any given set of requirements, is unlimited, depending only upon the designers. In this sense, when there are no constraints (e.g. time, resources, etc), designers must look for solutions that respect the independence axiom (axiom 1) and minimize information content (axiom 2). However, due to market pressure to reduce the time-to-market of products, the lead-time available for designing and making injection moulds is decreasing. Additionally, during the mould design process, customers often impose several changes to the plastic part geometry and other attributes, requiring fast modifications of the mould. Thus, mould makers are compelled to shorten both lead times and cost, as well to accomplish higher levels of mould performance, which can only be possible with new design approaches.

In this sense, the proposal here is that AD must be used as a support methodology for the conceptual stage, which is more focused on human creativity and intuition, aiming to guide the initial decisions in a more rational approach. Then, if some axiom 1 violations subsist, they will be addressed at the detailed stage, through an MDO application, since it is considered an appropriate methodology to explore the interacting phenomena. According to this proposal, firstly AD was undertaken in order to support the conceptual design. In this stage, the initial mould's design decisions were defined according to the FRs-DPs mapping developed for the upper levels (Figure 3 and Figure 4).

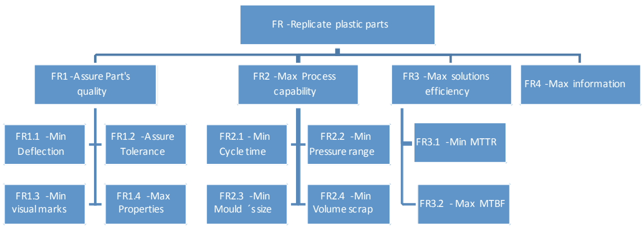


Figure 3. FRs defined for top levels.

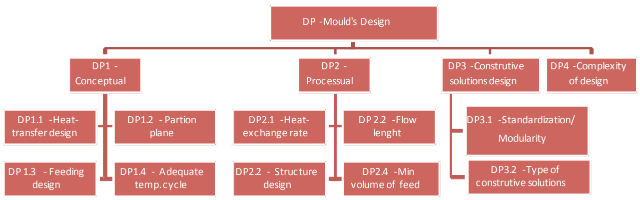


Figure 4. DPs defined for top levels.

For the previous levels of decomposition, the respective design matrixes were developed using X and 0 to express the relationships between FR and their associated DPs, where X indicates a mapping relationship and 0 a lack of mapping relationships (Figure 5).

	DP1. Conceptual	DP2. Processual	DP3. Construtive solutions design	DP4. Complexity of solutions
FR1. Assures Part's quality	X	X	X	X
FR2. Max Process capability	X	X	X	X
FR3. Max Solution's efficiency		X	X	X
FR4. Max Design acessibility	X		X	X

	Heat-exchange design	Partion plane location	Feeding design	Adequate temperature cycle	Heat-exchange rate	Flow lenght	Structure design	Min volume of feed	Standardization/Modularity	Type of constructive solution	Complexity of design
FR1.1. Min Deflection	X	X	X	X	X		X			X	
FR1.2. Assure Tolerance	X	X	X	X	X		X			X	
FR1.3. Min Visual marks	X	X	X		X					X	
FR1.4. Max properties				X	X		X			X	
FR2.1. Min Cycle time	X		X	X	X		X		X		
FR2.2. Min Pressure range		X	X			X	X				
FR2.3. Min Mould's size	X		X				X		X	X	
FR2.4. Min Volume of scrap		X	X			X		X		X	
FR3.1. Min MTTR		X							X	X	X
FR3.2. Max MTBF			X						X	X	X
FR4.1. Max Information	X	X	X				X		X	X	X

Figure 5. Design matrix for upper levels of an injection mould design.

Based on the previous figures, it is possible to verify, as was expected, that injection mould is a highly coupled design.

3 MDO FRAMEWORK

MDO is a powerful approach that exploits the synergies of the interdisciplinary couplings through a systematic and mathematically-based manner [AIAA, 1991]. 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 then 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 exploration of large design spaces, including those that may be characterized by discrete variables or discontinuous functions [Korte, Weston et al., 1997]. This procedure enables product designers to deal with complex interactions, due to the existence of several constraints (e.g. technology, time, resources, etc.), using quantitative mathematical models.

One major approach exploited in MDO is decomposing a large system into smaller subsystems, connected by information flows from outputs of one subsystem to the inputs of another. These information flows between subsystems are termed couplings [English and Bloebaum, 2008]. Regarding the injection mould design, five subsystems were identified: Conceptual, Feeding, Structural, Heat-Exchange and Ejection. The conceptual subsystem includes the preliminary design decisions, such as type of mould (Structure design), the types of feeding system (Feeding design) etc., which were previously identified in the conceptual stage through our FR-DP mapping. The feeding subsystem, which encompasses the Sprue, the Runners and the Gates as components, has the main function to assure melt distribution from the injection nozzle of the moulding machine into the mould cavities. The structural subsystem is responsible for moulds coupling into the injection machine and for the overall assembly of its components. This subsystem must also guarantee the alignment and guiding of the mould. The heat-transfer subsystem is composed by a system of cooling channels, through which a coolant is pumped, aiming to transfer heat between mould, melt, coolant and environment. Depending on the material, most of the times the objective is to remove heat from the mould, so that – once filled - the part is sufficiently rigid to be ejected. The ejection subsystem has the main function to knock out the injection moulded parts, in order to release them from the mould.

A block diagram (Appendix 2) was built in order to identify the feedforward and feedback paths between the different subsystems. It is important to note that the mapping is generic and was established independently of specific plastic part and injection machine characteristics (i.e. these modules and their relations are present in every mould design problem).

This approach facilitates the mathematical formulation of the mould design as a multidisciplinary system design problem. The multidisciplinary processes considered were ***rheological***, which seek to model and evaluate the mould filling process, ***thermal***, encompassing heat transfer between melt, mould and coolant, ***mechanical***, concerning the mould's physical movements of opening and closure and plastic part's push-out, and, finally, ***structural***, aiming to minimize the mould's deformation induced by compressive and bending stresses, as well as increase mould's life cycle by load cyclic reduction. Some assumptions have been made to simplify the MDO approach to injection mould design. For example, the design of more complex elements of moulds (e.g. sliders) was not taken into account.

4 CYCLE TIME OPTIMIZATION

In order to validate the proposed framework, based on AD and MDO interlinks, the cycle time was used as an example of one FRs which should be minimized, in order to increase process capability (CAs).

Theoretically, cycle time can be defined as the summation of the time for the different stages of the injection moulding process. Therefore, cycle time can be mathematically expressed by Eq.1 (for more details see [Ferreira et al., 2008]).

$$
\begin{aligned}
Cycle\ time = & \frac{\left[d_{Sprue} + \tan\left(\frac{DraftSprue.\pi}{180}\right) l_{Sprue}\right]^2}{23.1\alpha} \ln\left(0.692 \frac{(T_{melt} - T_{cool})}{(T_{demol} - T_{cool})}\right) \\
& + \frac{d_{gate}{}^2}{23.1\alpha} \ln\left(0,692 \frac{(T_{melt} - T_{cool})}{(T_{demol} - T_{cool})}\right) \\
& + 2 \times \frac{d_{Release}}{184 + 13\log\left(\frac{P_{inj} \times A_{proj} \times 10^{-3}}{g}\right)}
\end{aligned} \quad (1)
$$

Assuming that geometry and material of the plastic part, as well as injection machine parameters, are imposed by the mould customer (which is usually what happens in the mould design process), the design variables that must be optimized, in order to find the best solution, are:

d_{Sprue}	=	Sprue diameter [m]
l_{Runner}	=	Runner length [m]
l_{Gate}	=	Gate length [m]
d_{Gate}	=	Gate diameter [m]
DraftSprue	=	Sprue draft angle [º]
l_{Sprue}	=	Sprue length [m]
P_{inj}	=	Injection Pressure [Pa]
d_{Runner}	=	Runner diameter [m]
$d_{Release}$	=	Distance of part's release [m]

Since T_{melt} (i.e Melt temperature), T_{mold} (i.e Mould's temperature), T_{demold} (Demoulded temperature) and α (material coefficient of diffusivity) are dependent of material, and A_{proj} (Projected area of moulding) is a function of partition plane location, which was decided at the conceptual stage, these items are considered as parameters (invariable values). Nevertheless, it is important to note that mould's design is assumed as an integrated optimization problem (according to the MDO approach). Therefore, for solving the cycle time minimization problem, due to the existence of coupling relations between mould subsystems, there are several constraints and design variables that must be also included in the optimization problem. For instance, the minimal distance for cavity insert on the X coordinate (X_{ins_cav}) is function of P_{inj}, since the mould's cavity insert must be strong enough to withstand millions of cyclic internal loads from injection pressures. In this sense, this variable must be dimensioned in order to overcome this effort. At the same time, X_{ins_cav} is important to define cavity plates dimension, since the cavity plate must accommodate the cavity's insert, as well as the coolant lines of the heat-exchange subsystem. Therefore, as this example illustrates, the final optimal solution must be found taking in consideration the coupling relations and global constraints. In this context, the complete set of design variables, which will be used for our cycle time optimization problem, is summarized in the next table.

Table 4. Design variables for cycle time optimization problem.

Design Variables (DVs)	Symbol
Injection Pressure	Pinj
Distance X cavity Insert	Xins_cav
Distance Y cavity Insert	Yins_cav
Final distance X cavity and core	Xcav_core
Final distance Y cavity and core	Ycav_core
Height of core insert	Hcore_Ins
Height of cavity insert	Hcav_ins
Final distance Z for cavity	Zcav
Final distance Z for core	Zcore
Release distance	dRelease
Final distance Z for plate 1,9	Zplate_1,9
Final distance Z for plate 4	Zplate_4
Final distance Y for plate 5,6	Yplate_5,6
Final distance Z for plate 5,6	Zplate_5,6
Final distance Y for plate 7,8	Yplate_7,8
Final distance Z for plate 7	Zplate_7
Final distance Z for plate 8	Zplate_8
Length of sprue	lSprue
Diameter of sprue	dSprue
Draft angle of sprue	DraftSprue
Diameter of runner	dRunner
Length of runner	lRunner
Diameter of gates	dGates
Length gate	lGate
Diameter channel of coolant	dcool
Distance z from cavity surface to the center of cooling line	Zcool
Distance between turns in y	pitch_cool
Number of changes in position of coolant channel	nturns
Length of coolant line	lLine
Increase of temperature of coolant	ΔTcool

It is important to note that the space of design solutions is defined by all admissible values that each design variable can assume. In this sense, a specific design solution will be characterized by a set of DPs, where each DP value is equal to the optimal value determined for the respective design variable. Afterwards, applying the Generalized Reduced Gradient 2 algorithm (GRG2), it was possible to determine the optimal solution, which represents a cycle time reduction of 7% over the initial solution (Table 5).

Table 5. Optimal versus Initial solution.

DVs	Units	Initial	Optimal=DPs
Pinj	Pa	1,8E+08	1,55E+08
Xins_cav	m	0,258	0,27
Yins_cav	m	0,258	0,27
Xcav_core	m	0,296	0,296
Ycav_core	m	0,296	0,296
Hcore_Ins	m	0,043	0,0428
Hcav_ins	m	0,044	0,0443
Zcav	m	0,056	0,046
Zcore	m	0,056	0,046
dRelease	m	0,075	0,075
Zplate_1,9	m	0,046	0,022
Zplate_4	m	0,046	0,046
Yplate_5,6	m	0,046	0,066
Zplate_5,6	m	0,046	0,106
Yplate_7,8	m	0,202	0,252
Zplate_7	m	0,016	0,026
Zplate_8	m	0,026	0,026
lSprue	m	0,068	0,068
dSprue	m	0,013	0,0124
DraftSprue	º	1,000	1
dRunner	m	0,009	0,0088
lRunner	m	0,120	0,083
dGates	m	0,001	0,0019
lGate	m	0,001	0,001
dcool	m	0,01	0,0048
Zcool	m	0,025	0,010
pitch_cool	m	0,05	0,019
nturns		7	7
lLine	m	1,196	1,04
ΔTcool	ºC	0,5	1
Cycle time	s	121,47	112,43

The GRG2 optimization algorithm was adopted because it is widely used, since it is considered to be an effective method for addressing large-scale nonlinear programming problems, with mostly smooth non-convex nonlinear functions. It is better adapted to handle problems with infeasible initial designs and under the presence of equality constraints. Some advantages of this method are that its extension for determining the solution of large sparse problems is conceptually simple, as well as its availability and user-friendly nature.

Based on the previous values, it is possible to characterize the design solution that minimizes cycle time. Considering that CS increases linearly with cycle time (the additional improvement on CS, made by cycle time coupling with other FRs was, at this stage, neglected), it is possible to conclude that this solution, when compared with a baseline solution that was determined following practical guidelines [Centimfe, 2003], will lead to a 0.56% increase in CS (see Eq.2).

$$\begin{aligned} \Delta CS &= 0.19 \times 0.422 \times \Delta \textit{cycle time} \\ &= 0.08 \Delta \textit{cycle time} \\ &= 0.56\% \end{aligned} \tag{2}$$

5 CONCLUSION

The main objective of this paper was to describe a new approach, which links Axiomatic Design (AD) and Multidisciplinary Design Optimization (MDO), developed to support the product design process. This framework aims to help designers to achieve a faster and a more efficient design of complex products, as a way to face the current market challenges. In this sense, the framework proposes to carry out the conceptual design through an AD approach, aiming to map FRs with the corresponding DPs. Then, to support the detailed design stage, MDO is adopted with the objective to determine the best solution design through the exploitation of the design space established by the options made at the conceptual stage.

In this sense, the starting point of our approach involves CAs identification and its translation into FRs. This task was performed by conducting semi-structure interviews. The data gathered was validated by an ECSI survey. Then, the identified FRs were mapped into DPs regarding only the upper levels of design (conceptual level). At this stage, even seeking for the independence of FRs, some remaining coupled relations can subsist, and they are not considered to be prohibitive.

In relation to the detailed design, a framework based on MDO was developed, which tackled mould design in a global way, through structural, thermal, rheological and mechanical domain integration. This framework was validated, using the GRG2 algorithm, where a baseline solution was optimized regarding cycle time, allowing for a 7% reduction of cycle time. This result points out the potential for mould design improvements, since the developed framework can be used to search the best solution for mould design, amongst the design space established after initial decisions have been made at the conceptual stage.

It is also important to note that this framework encompasses the modules and the relationships that are present in every mould design problem, which means that it can be used for any mould design. Of course that the design of more complex elements, that can be present in moulds, has not yet been included in this framework. Nevertheless, the design of these elements will be the object of future research. Finally, in order to develop a more realistic model for mould's design and to get more accurate results, some high-fidelity models, like Moldflow, will also be integrated in our approach.

6 REFERENCES

AIAA (1991). "White paper on current state of art", Technical Committee on Multidisciplinary Design Optimization (MDO)

Centimfe (2003). *Manual do projectista para moldes de injecção de plásticos*, Centimfe.

Chao, L. P. and K. Ishii (2004). "Design process error-profing project quality function deployment". *ASME Design Engineering Technical Conferences, Salt Lake City*, ASME.

Crawley, E., O. d. Weck, et al. (2004). "The influence of architecture in engineering systems", MIT - Engineering System Divison: 29.

English, K. and C. Bloebaum (2008). "Visual dependency stricture matrix for Multidisciplinary Design Optimization tradeoff studies." *Journal of aerospace computing, information and communication* 5: 274-297.

Ferreira, I., J. A. Cabral, et al. (2008). "Customer´s satisfaction evaluation of Portuguese mould makers based on the ECSI approach". *RPD 2008 - Rapid Product Development, Oliveira de Azeméis - Portugal*

Ferreira, I., J. S. Cabral, et al. (2006). "Axiomatic Design applied to injection moulds for plastic parts". *RPD 2006 – Rapid Product Development, Portugal.*

Ferreira, I., J. S. Cabral, et al. (2007). "A new conceptual framework based on the ECSI model to support Axiomatic Design". *Virtual and Rapid Manufacturing*, Taylor&Francis.

Ferreira, I., O. d. Weck, et al. (2008). "Multidisciplinary Optimization of Injection Molding Systems." *Structural and multidisciplinary optimization* (Submitted).

Jang, B.-S., Y.-S. Yang, et al. (2002). "Axiomatic design approach for marine design problems." *Marine Structures* 15: 35-56.

Korte, J. J., R. P. Weston, et al. (1997). "Multidisciplinary Optimization Methods for Preliminary Design". *Future Aerospace in the Service of the Alliance*.

Lu, M. H., C. N. Madu, et al. (1994). "Integrating QFD, AHP and benchmarking in strategic marketing." *Journal of Business&Industrial Marketing* 9(1): 41-50.

Raharjo, H., M. Xie, et al. (2007). "A methodology to improve Higher Education quality using the Quality Function Deployment and Analytic Hierachy Process." *Total Quality Management* 18(10): 1097-1115.

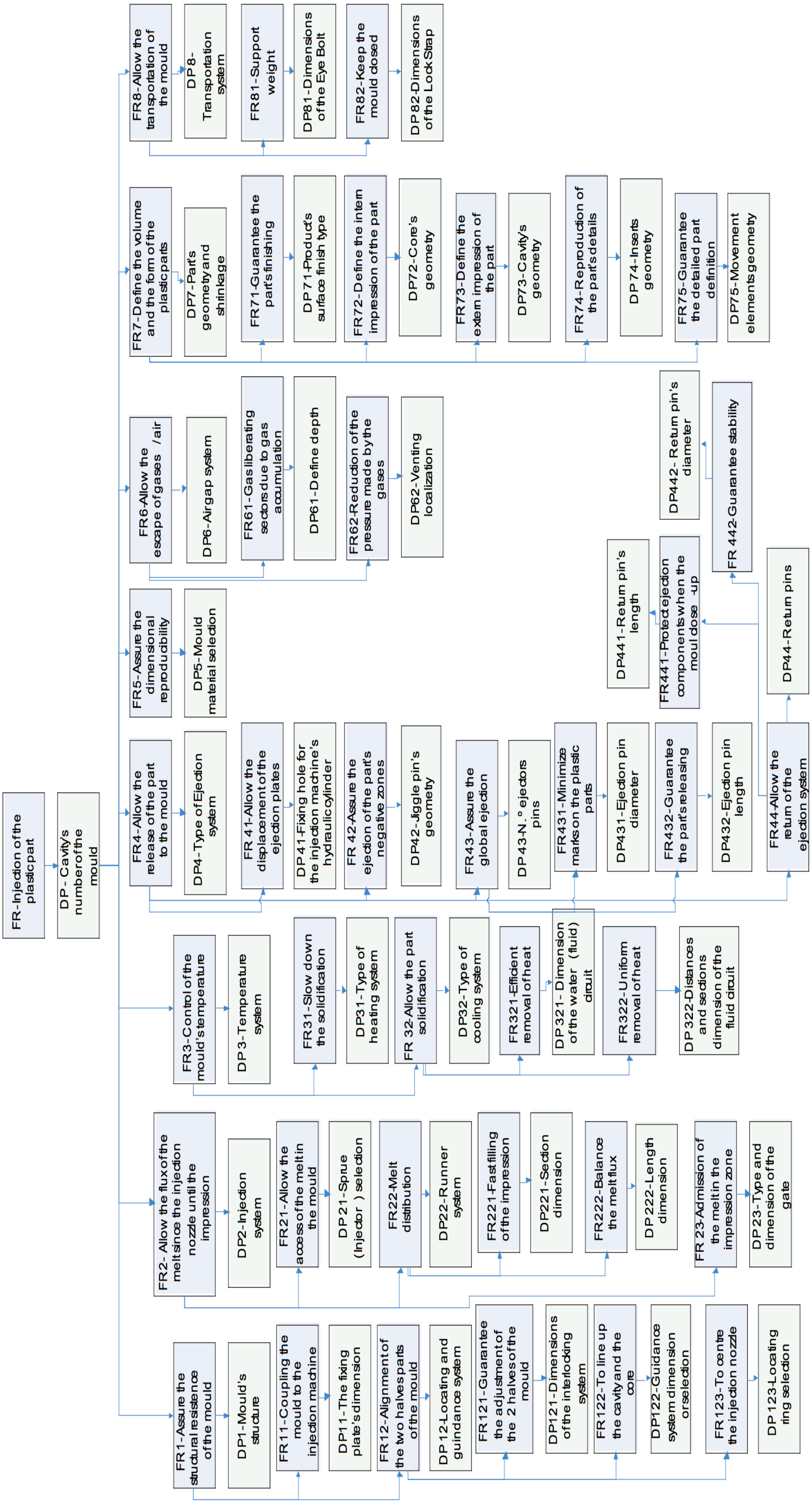
Rose, C. M., K. A. Beiter, et al. (1999). "Determining end-of-life strategies as a part of product definition". *IEEE International Symposium on Electronics and the environment Massachussets*, IEEE.

Saaty, T. L. (1994). "How to make a decision: the Analytic Hierarchy Process." *Interfaces* 24: 19-43.

Suh, N. P. (1990). *The principles of design*, Oxford University Press.

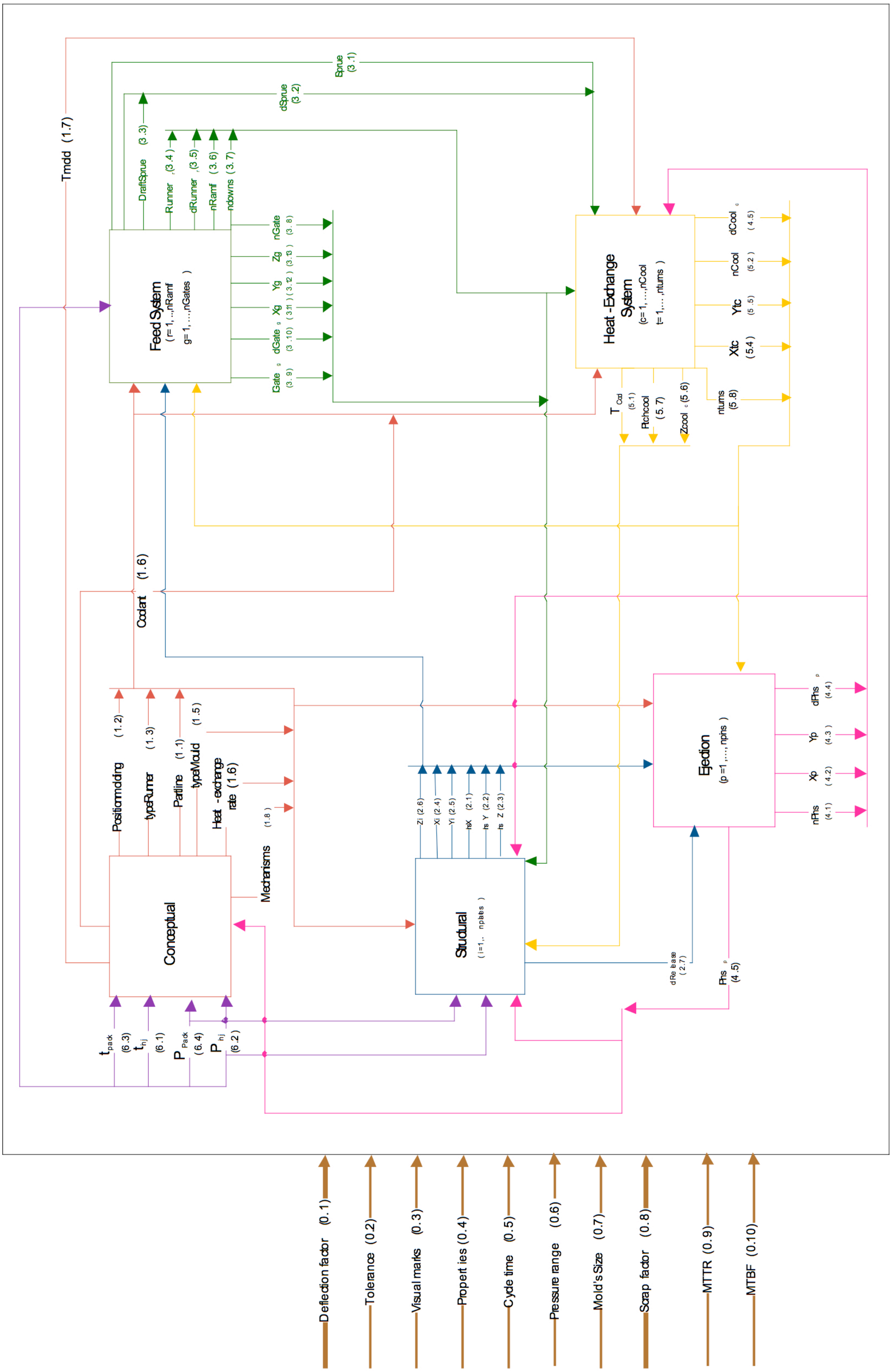
Yang, K. and B. El-Haik (2003). *Design for Six Sigma: A roadmap for product development*, McGraw-Hill.

APPENDIX 1


FR-Injection of the plastic part
DP - Cavity's number of the mould
FR1-Assure the structural resistence of the mould
DP1-Mould's structure
FR11-Coupling the mould to the injection machine
DP11-The fixing plate's dimension
FR12-Alignment of the two halves parts of the mould
DP12-Locating and guindance system
FR121-Guarantee the adjustment of the 2 halves of the mould
DP121-Dimensions of the interlocking system
FR122-To line up the cavity and the core
DP122-Guidance system dimension or selection
FR123-To centre the injection nozzle
DP123-Locating ring selection
FR2- Allow the flux of the melt since the injection nozzle until the impression
DP2-Injection system
FR21-Allow the access of the melt in the mould
DP21-Sprue (Injector) selection
FR22-Melt distribution
DP22-Runner system
FR221-Fast filling of the impression
DP221-Section dimension
FR222-Balance the melt flux
DP222-Length dimension
FR 23-Admission of the melt in the impression zone
DP23-Type and dimension of the gate
FR3-Control of the mould's temperature
DP3-Temperature system
FR31-Slow down the solidification
DP31-Type of heating system
FR 32-Allow the part solidification
DP32-Type of cooling system
FR321-Efficient removal of heat
DP321- Dimension of the water (fluid) circuit
FR322-Uniform removal of heat
DP322-Distances and sections dimension of the fluid circuit
FR4-Allow the release of the part to the mould
DP4-Type of Ejection system
FR 41-Allow the displacement of the ejection plates
DP41-Fixing hole for the injection machine's hydraulic cylinder
FR 42-Assure the ejection of the part's negative zones
DP42-Jiggle pin's geometry
FR43-Assure the global ejection
DP43-N.º ejectors pins
FR431-Minimize marks on the plastic parts
DP431-Ejection pin diameter
FR432-Guarantee the part's releasing
DP432-Ejection pin length
FR44-Allow the return of the ejection system
DP44-Return pins
FR441-Protect ejection components when the mould close -up
DP441-Return pin's length
FR 442-Guarantee stability
DP442- Return pin's diameter
FR5-Assure the dimensional reproducibility
DP5-Mould material selection
FR6-Allow the escape of gases /air
DP6-Airgap system
FR61-Gas liberating sectors due to gas accumulation
DP61-Define depth
FR62-Reduction of the pressure made by the gases
DP62-Venting localization
FR7-Define the volume and the form of the plastic parts
DP7-Part's geometry and shrinkage
FR71-Guarantee the part's finishing
DP71-Product's surface finish type
FR72-Define the intern impression of the part
DP72-Core's geometry
FR73-Define the extern impression of the part
DP73-Cavity's geometry
FR74-Reproduction of the part's details
DP74-Inserts geometry
FR75-Guarantee the detailed part definition
DP75-Movement elements geometry
FR8-Allow the transportation of the mould
DP8-Transportation system
FR81-Support weight
DP81-Dimensions of the Eye Bolt
FR82-Keep the mould closed
DP82-Dimensions of the Lock Strap

	DP_1	DP_2	DP_3	DP_4	DP_5	DP_6	DP_7	DP_8	DP_{11}	DP_{12}	DP_{21}	DP_{22}	DP_{23}	DP_{31}	DP_{32}	DP_{41}	DP_{42}	DP_{43}	DP_{44}	DP_{61}	DP_{62}	DP_{71}	DP_{72}	DP_{73}	DP_{74}	DP_{75}	DP_{81}	DP_{82}	DP_{121}	DP_{122}	DP_{1}[illegible]
FR_1	X																														
FR_2		X	X																												
FR_3			X		X		X																								
FR_4				X			X																								
FR_5			X	X	X	X	X																								
FR_6						X																									
FR_7						X	X																								
FR_8								X																							
FR_{11}									X																						
FR_{12}										X																					
FR_{21}											X	X	X																		
FR_{22}												X																			
FR_{23}												X	X																		
FR_{31}														X	X																
FR_{32}														X	X																
FR_{41}																X															
FR_{42}																	X														
FR_{43}																	X	X	X												
FR_{44}																			X												
FR_{61}																				X	X										
FR_{62}																				X	X										
FR_{71}																						X									
FR_{72}																						X	X		X	X					
FR_{73}																						X		X	X	X					
FR_{74}																						X	X	X	X	X					
FR_{75}																						X	X	X	X	X					
FR_{81}																											X				
FR_{82}																												X			
FR_{121}																													X	X	
FR_{122}																													X	X	
FR_{123}																															X
FR_{221}																															
FR_{222}																															
FR_{321}																															
FR_{322}																															
FR_{431}																															
FR_{432}																															
FR_{441}																															
FR_{442}																															

APPENDIX 2


Feed System
Heat-Exchange System
Ejection
Structural
Conceptual
Tmold (1.7)
Coolant (1.6)
Sprue (3.1)
dSprue (3.2)
Deflection factor (0.1)
Tolerance (0.2)
Visual marks (0.3)
Properties (0.4)
Cycle time (0.5)
Pressure range (0.6)
Mold's Size (0.7)
Scrap factor (0.8)
MTTR (0.9)
MTBF (0.10)