Multi-Objective Optimization of the Pneumatic Ejectors for Plastics Thin-wall Injected Parts

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In this paper a modern multi-objective optimization of the pneumatic ejectors of the plastic injection mold is presented. For this Pareto multi-objective optimization, two objective functions (volume and efficiency of the ejector) and four genes were taken into consideration and a set of twelve constraints were formulated. In solving the optimization problem we used an original two-phase evolutionary algorithm (2PhEA) inspired from the concept of "punctuated equilibrium". 2PhEA is implemented in Cambrian v.3.2 which is in operation at the Optimal Design Centre of the Technical University of Cluj-Napoca, Romania. The study on the individuals along the obtained Pareto front reveals some important conclusions useful in the design of the pneumatic ejectors.

Keywords: optimal design, evolutionary algorithms, pneumatic ejector, injected part

Plastic part injection (area of great interest of the current days and which has seen a tremendous development in recent decades) is conditioned mainly by three factors: characteristics of injection machine, plastic material characteristics and characteristics of injection mould. In this context there have been concerns in the optimization of laminated composite parts [11-13] or parts of polymer [21], in the optimization of the manufacturing process [7], as well as in the optimization of the machines used in plastic parts processing [15 - 17]. As one can find the optimal design of the mould problem is fewly approached. In this paper, the authors propose an original variant of multi-objective optimization with evolutionary algorithms of the ejector system of injection moulds for thin-wall parts. Optimal design of the ejector system leads to a reduction of total cycle time of injection and thus an increased productivity. The molud used in the manufacture of "Bucket of 10 l" was also used in following optimization of the ejector system.

The 10 *l* bucket is a general purpose product made by Napochim Company originated in Cluj-Napoca, Romania. This bucket encompasses two injected parts: body of bucket and the ear. Obviously, the main component of the product is the body which is a thin-wall injected part of taper shape. More often the bucket body is made of propylene.

For this bucket body there are supposed to be known the following data:

D_p – outer diameter of the part (core);
d_p – inner diameter of the part (core);
h – thickness of the injected part wall;
l_p – length (height) of the injected part;
characteristics of the injected part material (the modulus of elasticity, specific contraction, allowable bearing pressure, the coefficient of friction between the injected part and the core etc.);
parameters of the injection process (demoulding temperature, air-compressed pressure etc.).

The mold used to obtain this piece is presented in figure 1. The ejector system (necessary to eject the injected part from mould) is composed of an air valve and a double-action pneumatic ejector.


Fig. 1 Injection mold of 10 l bucket

In paper [2], a mono-objective optimal design of the pneumatic ejector is presented. The objective function for this case was the ejector volume. The assumed goal of the optimization was to minimize as much as possible the volume occupied by the ejector in the mould volume without affecting the mould efficiency. Any space economy inside the mould volume allows, for example, a larger volume of cooling system and consequently the piece will be cooled off faster. Six variables (genes) were taken into account in this approach: five different standardized O-rings and one stainless steel pipe (the piston cylinder is made of). The optimal pneumatic ejector obtained had a volume $V = 358146$ mm^3.

Using this result as starting point of the new research we made a step forward: the multi-objective optimal design with evolutionary algorithms of the pneumatic ejector. In the following paragraphs we will identify and propose the genes, the objective functions, and the constraints which will be aggregated in the multi-objective optimization program.

Genes of the optimization program

After a close analysis of the pneumatic ejector design (fig. 2) and having in mind the necessity of the unique description of the optimization problem we proposed 4 genes. It is worthy to note that al these genes are not simply real or integer numbers, but standardized machine elements and each of these elements encapsulates all sorts of parameters: material, dimensions, mounting and dismounting conditions etc. For example, each O-ring list

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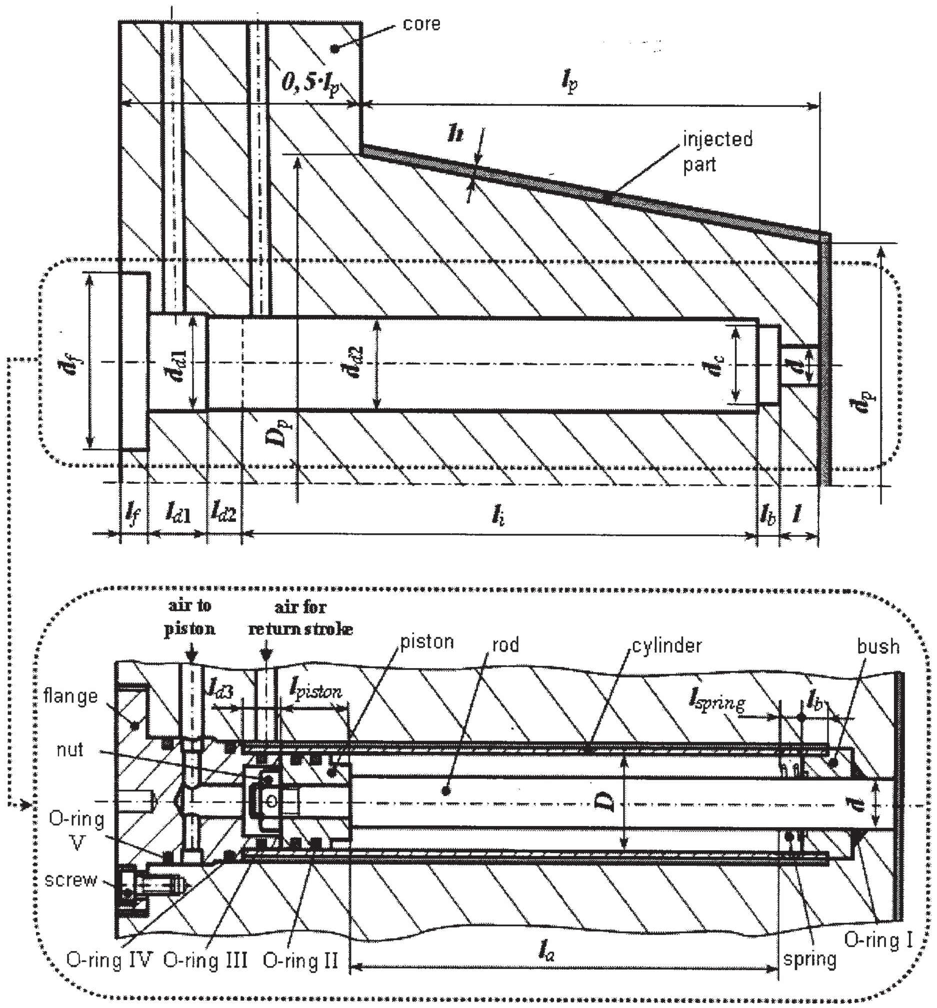

Fig. 2. Pneumatic ejector and its position in the mould

Table 1
GENES OF THE OPTIMIZATION PROGRAM

Gene	Part	No. of values in list	Parameter
1	Pipe (cylinder)	64	d_c - outer diameter of the stainless steel pipe h_c - thickness of the stainless steel pipe
2	O-ring I	64	d - rod diameter $d_{O\ ring\ 1}$ - diameter of the O-ring I
3	O-ring II	64	D - inner diameter of the cylinder $d_{O\ ring\ 2}$ - diameter of the O-ring II
4	O-ring V	64	d_{d1} - plug shoulder diameter $d_{O\ ring\ 5}$ - diameter of the O-ring V

consists of four standardized ring types, and for each type we considered the standardized diameters: 1.8, 2.65, 3.55 and 5.3 mm. For symmetry reasons, we proposed 64 types of pipes for the cylinder. The chosen genes used in solving of the optimal design problem are presented in table 1.

In comparison with the previous approach we have to mention that we reduced the number of genes since we developed an easier technique to design an ejector based only on the values of these four genes.

Seting the objective functions

In multi-objective optimization, it is preferably to choose objective functions with antagonist behaviour with respect to the same variables. That means that, for example, where one function reaches its desirable maximum, the other reaches its undesirable minimum (for the last function we want to capture its maximum, too). Obviously, it is a problem of compromise, and in order to obtain this settlement the authors used the well-known Pareto approach.

In this paper we set two goals since we intended to obtain an ejector (fig. 2) with the smallest possible volume and with the highest possible efficiency. Obviously these two requirements are in contradiction, since in the case of the pneumatic ejectors the efficiency increases with increasing piston diameter (and implicitly with increasing ejector volume).

The first objective function is the ejector volume and its equation is:

$$V_a = \frac{\pi \cdot \left[d_f^2 \cdot l_f + d_{d1}^2 \cdot l_{d1} + \left(d_c + 2 \cdot t_{sp}\right)^2 \cdot \left(l_i + l_{d2}\right) + d_c^2 \cdot l_b + d^2 \cdot l\right]}{4} \cdot n \rightarrow \mathbf{min} \qquad (1)$$

where:
d_f– flange diameter;
l_f– flange length;
d_{d1}– plug shoulder diameter;
l_{d1} – plug shoulder length;
d_{d2}– plug rod diameter;
l_{d2} – plug rod length;
d_c – cylinder outer diameter;
t_{sp} – clearance through which air circulates in the return stroke

$$t_{sp} = \frac{d_{d2} - d_c}{2} \qquad (2)$$

l_i – cylinder length;
l_b– bush length;
d – piston rod diameter;
l – length of the bush hole;
n – number of ejectors.

The second objective function is the ejector efficiency:

$$\eta = \frac{F_a - F_f}{F_a} \rightarrow \mathbf{max} \qquad (3)$$

where:
F_a – extraction force;
F_f– force of friction between the O-rings and the cylinder.

$$F_a = \frac{\pi \cdot D^2 \cdot p_a}{4} \qquad (4)$$

where:
D – piston outer diameter;
p_a – air-compressed pressure.

According to [1] the equation of force of friction is:

$$F_f = c_1 \cdot \mu \cdot p \cdot \pi \cdot D \cdot b \cdot i \qquad (5)$$

where:
c_1 – correction factor which depends on the number of gaskets (c_1 = 1 for single gasket, c_1 = 0.5 for package of gaskets);
μ – coefficient of friction between the O-ring and the cylinder;
p – effective pressure between gasket and the contact surface;

$$p = p_a - p_{atm} \qquad (6)$$

p_{atm}– atmospheric pressure (p_{atm} = 0.1 MPa);
b – O-ring contact width ($b_2 = 1.2 \cdot d_{O\ ring\ 2}$, [1]);
i – number of identical gaskets in package.

Using the above equation the friction force is given by:

$$F_f = \mu \cdot \left(p_a - p_{atm}\right) \cdot \pi \cdot D \cdot 1.2 \cdot d_{Oring2} \qquad (7)$$

Constraints

The following twelve constraints were identified and used in the optimization program:

R1 In order to allow the reversal stroke of the ejector piston (in initial position), the piston outer diameter D has to be larger than the piston rod diameter d with a certain amount (t_{ret}):

$$g_1 = \frac{2 \cdot t_{ret} + d}{D} - 1 \le 0 \qquad (8)$$

R2 In order to exist a clearance through which air circulates in the return stroke, the cylinder outer diameter d_c has to be larger than the plug rod diameter d_{d2} with a certain amount (t_{sp}):

$$g_2 = \frac{2 \cdot t_{sp} + d_c}{d_{d2}} - 1 \le 0 \qquad (9)$$

R3 The plug rod diameter d_{d2} has to be larger than the plug shoulder diameter d_{d1} with a certain amount (t_{mo}), enough to allow the fitting in of the O-ring IV without its damage:

$$g_3 = \frac{2 \cdot t_{mo} + d_{d2}}{d_{d1}} - 1 \le 0 \qquad (10)$$

R4 The inner diameter D of the pipe has to be less than its outer diameter d_c:

$$g_4 = \frac{D}{d_c} - 1 \le 0 \qquad (11)$$

R5 The difference (d_c–D) has to be less than $2 \cdot h_c$ (double of the thickness of the pipe wall):

$$g_5 = \frac{d_c}{2 \cdot h_c + D} - 1 \le 0 \qquad (12)$$

R6 The thickness of the pipe wall should be higher or equal to a minimum imposed value:

$$g_6 = \begin{cases} \frac{2 + D}{d_c} - 1 \le 0 & if \quad d_c \le 25 \\ \frac{3 + D}{d_c} - 1 \le 0 & if \quad d_c > 25 \end{cases} \qquad (13)$$

R7 The thickness of the flange wall, in the fitting in zone of the O-ring III, has to be higher or equal to a minimum imposed value:

$$g_7 = \frac{4 + d_{gol} + 2 \cdot t_1}{D} - 1 \le 0 \qquad (14)$$

R8, R9 The ratio d/d_p has to lie in a certain range:

$$g_8 = \frac{d}{d_p} - 0.2 \le 0 \qquad (15)$$

$$g_9 = 0.07 - \frac{d}{d_p} \le 0 \qquad (16)$$

R10 The ejector must not damage the bottom wall of the injected part:

$$g_{10} = \frac{\sigma_b}{\sigma_{ab}} - 1 \le 0 \qquad (17)$$

$$\sigma_b = \frac{4 \cdot F_a}{\pi \cdot d^2} \qquad (18)$$

where:
σ_b – bearing pressure;
σ_{ab} – allowable bearing pressure of the material of the injected part at the demolding temperature.

R11 The ejection length has to be a positive number:

$$g_{11} = -l_a < 0 \qquad (19)$$

$$l_a = l_i - l_{d3} - l_{piston} - l_{spring} - l_b \qquad (20)$$

R12 The ejection length has to be higher than a certain fraction of the injected part length:

$$g_{12} = \frac{0.6 \cdot l_p}{l_a} - 1 \le 0 \qquad (21)$$

Multi-objective optimization program

The authors of this paper conducted the evolutionary multi-objective optimization by means of the Pareto

Table 2
INPUT DATA OF THE OPTIMIZATION PROGRAM OF THE PNEUMATIC EJECTOR

Parameter	Denotation	Value
Large diameter of the part (core)	D_p	287 mm
Small diameter of the part (core)	d_p	205 mm
Part length	l_p	265 mm
Part wall thickness	h	2 mm
Demolding temperature	T	60 °C
Allowable bearing pressure of the material of the injected part at the demolding temperature	σ_{ab}	10 MPa
Air-compressed pressure	p_a	0.6 MPa
Coefficient of friction between the O-ring and the cylinder	μ	0.4

approach. In solving the optimization problem we used our original two-phase evolutionary algorithm (2PhEA) inspired from the concept of "punctuated equilibrium".

Punctuated equilibrium [23] a theory about how new species evolve was first advanced by paleontologists Niles Eldridge and Stephan Jay Gould in 1972 [6]. Before punctuated equilibrium, most scientists assumed that evolutionary change occurs slowly and continuously in almost all species, and that new species originate either by slow divergence of small, isolated groups or by slow evolutionary transformation of whole species. But studies of the fossil records have shown that the biological evolution is a strong non-equilibrium process with long periods of stasis interrupted by avalanches of large changes in biosphere. According to the proponents of punctuated equilibrium [6, 9], for the majority of time species are in evolutionary stasis, with little or no change occurring and hence little or no increase in adaptation to their environments. Occasionally, often due to some environmental catastrophe (or planetwide climatic change [10]), there will be punctuations, periods of rapid evolutionary change during which speciations occur. So, punctuationists claim that (i) except when speciation occurs, species are in stasis and do not become increasingly adapted to their environments, and (ii) gradual natural selection alone is insufficient for speciation, which requires a punctuation event. Therefore the biological evolution can be considered as a kind of self-organized criticality (SOC) dynamics [8] and, therefore, SOC gives an insight into emergent complexity in nature. Bak [2] contended that the critical state was the most efficient state that can actually be reached dynamically, and in this state, a population in an apparent equilibrium evolves episodically in spurts. Local change may affect any other element in the system, and this delicate balance arises without any external, organizing force.

In other words, in terms of evolutionary computation, evolution of a species consists of jumpings from one hilltop to another nearby in some fitness landscape. Naturally such jumps will be rare, separated by large time intervals where species are located at a fitness peak, and the resulting evolutionary pattern will show punctuations as indeed seen in the fossil record [3].

Probably punctuated equilibrium is the best known example of evolutionary metastability [5]. From the beginning, the theory of punctuated equilibrium has inspired many computational approaches [3, 18, 20, 22].

Unlike the above-mentioned researches, the authors of the present paper have a totally different point of view on implementing the concept of punctuated equilibrium in an evolutionary optimization algorithm 25. We think that the high level of stress in the population (which determines sudden and massive changes of the species) is comparable to the effect of constrains of an optimization problem. Therefore, the main idea behind our 2PhEA algorithm is its operation in two phases. In each phase, the individual fitness is determined by another factor. In *Phase 1*, the individual fitness depends only on the way in which an individual is more suitable (or not) in terms of constraints. In this phase, the population "fight for survival" and there is no interest for the best individual. For this reason, the number and level of mutations is high, respectively very high. We thought this phase as some kind of "feasible individual generator". The algorithm moves into the second phase when the number of feasible individuals of the population exceeds a preset threshold. Phase 2 is a common evolutionary algorithm (sometimes a simple genetic algorithm). Only in this second phase the Pareto front is collected.

The 2PhEA is implemented in Cambrian v.3.2 which is in operation at the Optimal Design Centre of the Technical University of Cluj-Napoca, Romania. During optimization, we used a population of 1000 individuals, and we set the cross-breeding probability p_c = 0.7 and the mutation probability p_m = 0.25 in Phase 1, and p_c = 0.8 and p_m = 0.1 respectively, in Phase 2. The best results were obtained when we used an acceptance threshold for feasible individuals of 0.4.

The input data of the optimization program are presented in table 2.

Optimization results

The optimization results are presented in table 3 and the optimal Pareto front is showed in figure 3. One can observe that there are several optimal ejector variants (all of them are good).

The first position in table 1 corresponds to an ejector with the piston diameter D = 7 mm and piston rod diameter d = 15 mm. The volume of this ejector is V = 358146 mm^3 (minimal volume) and its efficiency is η = 78.9 % (minimal efficiency). The last position in table corresponds at an ejector with the piston diameter D = 45 mm and the rod diameter d = 15 mm. The corresponding volume is V = 832706 mm^3 (maximal volume) and the efficiency is η = 87.3 % (maximal efficiency).

A minimal volume of pneumatic ejector will bring an economy in mould space, the saved space being used in order to obtain a better cooling system. This will decrease the cooling time and will implicitly decrease the injection cycle time and consequently, will dramatically increase productivity.

On the other hand, a maximal efficiency means a substantial decrease of friction losses that leads to the minimal energy consumption necessary to act the ejector. Unfortunately, choosing the ejector with maximum efficiency (D = 45 mm, d = 15 mm) implies an ejector volume that is unacceptable in terms of cooling system

Table 3

OPTIMIZATION RESULTS (ONLY SOLUTIONS WITH $V<10^6$ mm^3 ARE PRESENTED)

Pipe (REV INOX)			O-ring I (ISO 3601)				O-ring II (ISO 3601)				O-ring V (ISO 3601)				Volume of the ejector V_a, [mm^3]	Efficiency η
Position in list	d_c [mm]	h_c [mm]	Position in list	Symbol	d [mm]	$d_{O\text{-}ring1}$ [mm]	Position in list	Symbol	D [mm]	$d_{O\text{-}ring2}$ [mm]	Position in list	Symbol	d_{d1} [mm]	$d_{O\text{-}ring5}$ [mm]		
17	30	1.5	9	26501500	15	2.65	21	35502000	27	3.55	15	26503000	35	2.65	358146	0.789
17	30	1.5	9	26501500	15	2.65	21	35502000	27	3.55	28	35502800	35	3.55	358787	0.789
18	30	2	9	26501500	15	2.65	21	35502000	27	3.55	28	35502800	35	3.55	358787	0.789
22	32	2.5	9	26501500	15	2.65	23	35503340	29	3.55	29	35503000	37	3.55	400576	0.804
26	35	2	10	26501600	16	2.65	24	35502360	31	3.55	31	35503450	41	3.55	470353	0.816
27	35	2.5	9	26501500	15	2.65	24	35502360	31	3.55	31	35503450	41	3.55	470836	0.816
29	38	2	9	26501500	15	2.65	28	35502800	35	3.55	22	26503870	43	2.65	539441	0.837
30	38	3	9	26501500	15	2.65	28	35502800	35	3.55	32	35503650	43	3.55	540233	0.837
29	38	2	9	26501500	15	2.65	28	35502800	35	3.55	32	35503650	43	3.55	540233	0.837
32	40	2	9	26501500	15	2.65	29	35503000	37	3.55	33	35503870	45	3.55	591547	0.846
33	40	3	9	26501500	15	2.65	29	35503000	37	3.55	33	35503870	45	3.55	591547	0.846
35	42.4	2	10	26501600	16	2.65	30	35503150	39	3.55	35	35504370	50	3.55	664727	0.854
36	42.4	3	10	26501600	16	2.65	30	35503150	39	3.55	35	35504370	50	3.55	664727	0.854
38	45	2	9	26501500	15	2.65	33	35503450	42	3.55	35	35504370	50	3.55	730253	0.864
40	48.3	2	9	26501500	15	2.65	36	35503750	45	3.55	36	35504750	54	3.55	832706	0.873
42	48.3	3	9	26501500	15	2.65	36	35503750	45	3.55	36	35504750	54	3.55	832706	0.873

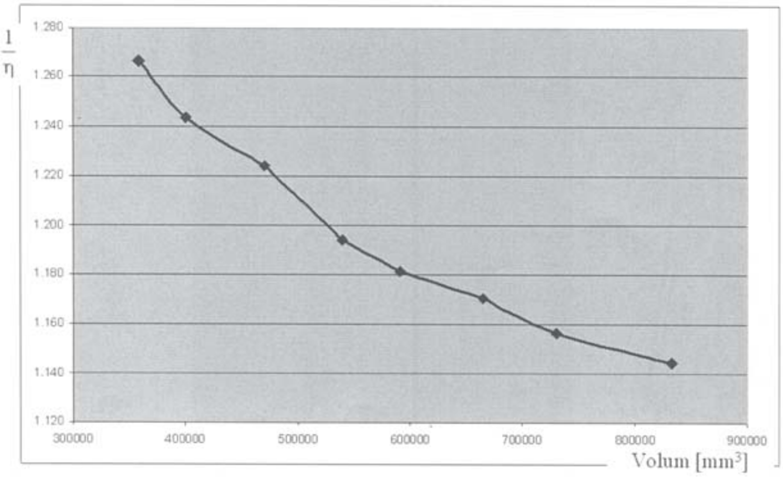

Fig. 3. Optimal Pareto front

design (an increase in efficiency by 10% will result in a doubling of the volume of the ejector).

An acceptable solution would be to choose the nearest point to the ideal point, which here is the origin. This design solution (in fact a very good technical solution) corresponds to a pneumatic ejector with a volume V = 539441 mm^3 and an efficiency η = 83.7 %. In this case the piston diameter is D = 35 mm and the rod diameter is d = 15 mm (the solution is shadowed in table 3).

Conclusions

For multi-objective optimization of mould ejector system was used *Cambrian*, an original software developed in the frame of Optimal Design Centre belonging to Technical University of Cluj-Napoca, Romania. The authors of this paper have made significant contributions to designing and implementing this program.

In *Cambrian* software is implemented 2PhEA our absolutely new and original evolutionary algorithm with two phases.

The ejector efficiency is not a very important factor of influence on the ejector design.

The ejector volume varies approximately linearly with its efficiency; a maximum efficiency brings an excessive ejector volume that is unacceptable.

The solutions from Pareto front with $V > 10^6$ mm^3 are not included in this report because, although the efficiency increases in these cases, the ejectors are totally improper.

Multiple choices of solutions to be achieved open new perspectives for selecting other optimization criteria.

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