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The application of metaheuristic algorithms in multi-objective optimization of engineering problems

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ABSTRACT

Comparative testing of three modified metaheuristic algorithms - the cyclic algorithm of the bat family (Loop BFA), the hybrid cuckoo search and the firefly algorithm (H-CS-FA) and the modified krill herd algorithm (MKH)was performed in the paper. The authors tested these algorithms in relation to original ones and the effectiveness of the modifications was confirmed for each individual algorithm. Here, the effectiveness of all three algorithms was verified on two engineering problems in the field of metal cutting - optimization of the body of the turning knife and optimization of the eccentric of the clamping tool. In both cases, multi-objective optimization with two objective functions was performed. By comparing the obtained optimization results as well as the speed of convergence, appropriate conclusions about the efficiency of the algorithms and recommendations for their application were made.

KEYWORDS

Metaheuristic, Multiobjective optimization, Modified algorithms, Turning knife, Eccentric of clamping tool

1. INTRODUCTION

Metaheuristic algorithms are widely used in modern engineering problems. They can be classified into biologically inspired and non-biologically inspired. Bio-inspired algorithms imitate phenomena and processes in nature (e.g. the evolution process), but they also find inspiration in animal systems (flocks of birds, colony of ants, bees, ...). Metaheuristic algorithms are being developed permanently and their number is constantly increasing. A detailed review of existing algorithms was given by Yang [1].

In order to obtain better characteristics of the algorithm, some modifications (improvements) and hybridization of algorithms are carried out. The paper compares the efficiency of three modified biologically inspired algorithms: the cyclic algorithm of the bat family (Loop BFA), the hybrid cuckoo search and the firefly algorithm (H-CS-FA) and the modified krill herd algorithm (MKH). The cyclic algorithm of the bat family (Loop BFA) represents a modification of the standard BA by including the loop search in the zone of solutions [2,19]. H-CS-FA represents a combination of two algorithms and it was used in the optimization of the dynamic quantities of the mechanism which is described in detail in[3, 4]. Modified krill herd algorithm (MKH) proposed by Bulatović et al [5] corresponds to an improved version of the standard krill herd algorithm.

In the text below, the mentioned algorithms will be used in the optimization of machining parameters. The problem of choosing optimal parameters, in order to improve the quality of machining process, reduce costs and increase the efficiency of production, dates back to the beginning of the XX century. The problem of choosing optimal machining parameters is actually a problem of multi-objective optimization, where the objective functions are often opposed to each other. Namely, it is clear that an increase in quality of machining process requires an increase in machining costs, while an increase in efficiency (use of more robust machining parameters: higher cutting speed, larger step and increased cutting depth) can lead to a decrease in quality of the process of machining. Different methods are used in optimization of machining parameters, from conventional optimization methods (geometric programming, dynamic programming, integer programming) to meta-heuristic algorithms [6-14].

Johari et al. [6] used a hybrid algorithm which combines firefly algorithm and particle swarm optimization to optimize the machining parameters in turning operation. A. R. Yildiz [7] presents a new hybrid optimization algorithm based on the algorithm of differential evolution (DE) and receptors for editing the properties of the immune system, which is applied in the optimization of the milling process. In order to obtain optimal machining parameters pattern search algorithm was applied in [8]. In addition to single-criteria optimization, the authors also use this algorithm for multi-objective optimization when determining the optimal machining parameters for EDM. A methodology based on multi-objective particle swarm optimization algorithm, for identifying the optimal parameters for machining a workpiece with a milling is presented in [9]. To solve the problem of multi-objective optimization when determining the optimal turning parameters, Deb and Datta [11] use the evolutionary multi-objective optimization (EMO) algorithm. In order to obtain better convergence properties, EMO is modified using a procedure of local search. Optimization of multi-pass face milling parameters using six metaheuristic algorithms are described in [13]. Hossain [14] applied five metaheuristic algorithms (Artificial Bee Colony, quick artificial bee colony, modified differential evolution, ant colony optimization and simulated annealing) for solving optimization problem of minimizing the machining time for end milling operation on hot die steel (H13).

The rest of the paper is organized as follows: Section 2 describes the problem of optimization of the body of the turning knife, while the optimization of the eccentric of the clamping tool is described in detail in Section 3. Conclusions are given in Section 4.

2. OPTIMIZATION OF THE BODY OF THE TURNING KNIFE

When machining metal by turning, the separation of the material is caused by the penetration of the cutting wedge of the turning knife into the material of the object of machining. It belongs to the group of oblique cutting, in which the main movement, which is rotary, is performed by the workpiece, while the auxiliary movement is straight and it is performed by the tool[19].

Three main cutting resistances occur during the turning process (Figure 1): F_1- main resistance to cutting, F_2- resistance to the penetration of the cutting wedge of the tool into the workpiece material, F_3 - resistance to auxiliary movement [15]:

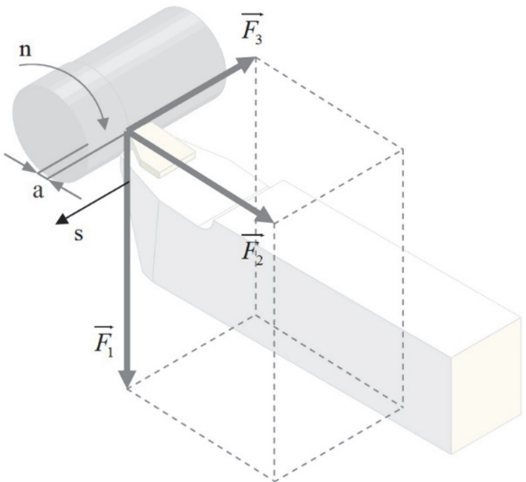

Figure 1: Model of cutting forces in metal turning

The basic parameters of machining process when perform turning are [15]: cutting depth *a*[mm], number of turns of the workpiece *n*[o/min], tool step*s*[mm/o].

The main cutting resistances (Figure 2) can be expressed as a function of the machining parameters, which is represented by equations (1) to (3).

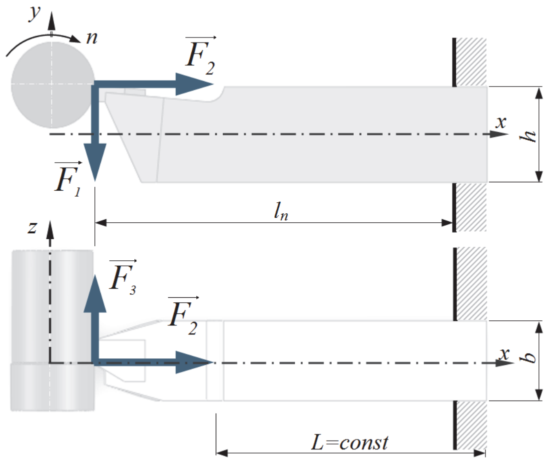

Figure 2: The main cutting resistances in the horizontal and vertical planes

$$F_1 = C_{k1} a^{x_1} s^{y_1} \tag{1}$$

$$F_2 = C_{k2} a^{x_2} s^{y_2} \tag{2}$$

$$F_3 = C_{k3} a^{x_3} s^{y_3} \tag{3}$$

where C_{ki}, x_i and y_i $(i = 1,2,3)$ are factors that depend on the type of workpiece material [15, 16].

Since the turning knife is clamped in the tool holder, it is necessary to check the resistance of the body of the knife to bending and pressure which occurs under the influence of the main resistance to cutting. The expressions for the stresses, which occur in the body of the turning knife, are given by equations (4) - (6).

$$\sigma_x = -\frac{F_2}{A} = -\frac{F_2}{b \cdot h} \tag{4}$$

$$\sigma_y = \frac{M_y}{W_y} \tag{5}$$

$$\sigma_z = \frac{M_z}{W_z} \tag{6}$$

where: σ_x [N/mm^2] is the pressure experienced by the knife body from penetration resistance F_2 [N], σ_y [N/mm^2] is a normal stress due to bending moments about the y-axis M_y [Nmm] - equation (7), W_y [mm^3] is a resisting moment of the knife body section for the y-axis -equation (8), σ_z [N/mm^2] is a normal stress due to bending moments about the z-axis M_z [Nmm] -equation (9), W_z [mm^3] is a resisting moment of the knife body section for the z-axis -equation(10), b, h [mm] are dimensions of the cross-section of the body of the knife.

$$M_y = -F_3 \cdot l_n \tag{7}$$

$$W_y = \frac{b^2 \cdot h}{6} \tag{8}$$

$$M_z = -F_1 \cdot l_n + F_2 \cdot \frac{h}{2} \tag{9}$$

$$W_z = \frac{b \cdot h^2}{6} \tag{10}$$

When equations (7) and (8) are included in equation (5), i.e. when equations (9) and (10) are inserted into equation (6), expressions for σ_y and σ_z represented by equations (11) and (12) will be obtained, respectively.

$$\sigma_y = -\frac{6 \cdot C_{k3} a^{x_3} s^{y_3} \cdot l_n}{b^2 \cdot h} \tag{11}$$

$$\sigma_z = -\frac{6 \cdot C_{k1} a^{x_1} s^{y_1} \cdot l_n}{b \cdot h^2} + \frac{6 \cdot C_{k2} a^{x_2} s^{y_2} \cdot h}{2 \cdot b \cdot h^2} \tag{12}$$

The total normal stress represents the sum of the absolute values of the stress σ_x, σ_y and σ_z, and it must satisfy the criterion of the allowed stress, equation (13).

$$\sigma = |\sigma_x| + |\sigma_y| + |\sigma_z| \leq \sigma_{allowed} \tag{13}$$

Due to the setting of restrictions related to the stress state of the body of the knife in the turning process, this analysis of the load of the body of the turning knife was necessary.

2.1. Objective functions and constraints

The optimization problem refers to the determination of the maximum amount of material during turning processing $MRR = f(v,s,a)$, at the minimum dimensions of the cross-section of the body of the turning knife $V = f(b,h,l_n)$. The mathematical model of the objective function with constraints is given by equations (14)-(20).

$$\max(MRR = v \cdot s \cdot a) \ \left[\mathrm{mm}^3 / \mathrm{min}\right] \tag{14}$$

$$\min(\mathrm{V} = \mathrm{b} \cdot \mathrm{h} \cdot \mathrm{l}_n) \tag{15}$$

Constraints:

$$g_1 = \sigma - \sigma_{allowed} \leq 0; \tag{16}$$

$$g_2 = F_1 - 2300 \leq 0; \tag{17}$$

$$g_3 = P - P_{\max} \cdot \eta \leq 0; \tag{18}$$

$$g_4 = 1.6 - \frac{h}{b} \leq 0; \tag{19}$$

$$g_5 = 1.6 - \frac{l_n}{h} \leq 0; \tag{20}$$

Multi-objective optimization is defined by equations (14) and (15). Namely, the idea is to choose the machining parameters (cutting speed -*v*, step -*s*, depth of cut –*a*) which will result in the maximum amount of processed material (MRR), while the dimensions of the cross-section of the knife are minimal. In equation (15), the total length of the knife body *L* is not taken into account, because it can be expressed as a function of the free length of the knife l_n and the length necessary for clamping $L = l_n + const.$

The constraint g_2 refers to the recommendation of the maximum cutting force $F_{1\max} = 5000 \ [\mathrm{N}]$, while constraint g_3 refers to the maximum cutting power $P_{\max} = 10 \ [\mathrm{kW}]$.The data for $F_{1\max}$ and $P_{\max}$, taken from [11], refer to the machining of a steel bar with a turning knife with a P20 plate on a CNC lathe with a motor power of 10kW and a degree of utility $\eta = 75\%$. Constraints g_4 and g_5 refer to the recommended values of the ratio of the dimensions of the cross-section of the knife body, i.e. the ratio of the free length of the knife body l_n and the height of the cross-section *h* [15, 16].

Design variables: cutting speed -*v*, step –*s*, cutting depth -*a*, body dimensions of the turning knife section –*b* x *h*are within the limits:

$$250 \leq v \leq 400;\ 0.15 \leq s \leq 0.55;\ 0.5 \leq a \leq 6 \quad [11]$$

$$6 \leq b \leq 40;\ 6 \leq h \leq 50;\ 9 \leq l_n \leq 80 \quad [16]$$

2.2. Optimization results

A comparative view of the results obtained by the cyclic algorithm of the bat family (Loop BFA), the hybrid cuckoo search and the firefly algorithm (H-CS-FA) and the modified krill herd algorithm (MKH) is given in Table1.

Table1:The optimization results of the body of the turning knife

	LoopFBA		H-CS-FA		MKH	
v	400.00		269.33896		396.54641	
s	0.55		0.15		0.4909	
a	0.8378628547		1.45836		1.55493	
$b \times h \times l_n$	6× 11× 32		6× 49× 80		6× 10× 16	
g_1	-4437.506512054349		-2500.859192700796524		-3796.969160138297	
g_2	-1.250043413696		- 0.578612316356966		-0.370862022226	
g_3	-25.219197149399		-190.310830811429		-22.737268160532	
g_4	-1.309090909091		-0.0326530612244897		0	
g_5	-0.23333333		-6.56666666666667		-0.0666666	
	MRR	V	MRR	V	MRR	V
The best	184329.82803274	2112.00	168511.0910474	2288.00	302692.3929835	960.00
Mean value	183979.56124019	3009.084	165766.029386	3479.672	299723.9669634	2322.4833
The worst	174427.75962776	13230.00	162150.580446	4800.00	242608.23611	13182.434
S.D.	1432.809543	1874.2335	3091.82371	1229.655	5751.79684722	1000.729

It can be seen (Table 1) that the values of the objective functions obtained by the modified krill herd algorithm (MKH) are the best compared to the other two algorithms. Also, the constraint functions $g_i\left(\, i=1,..,6\right)$ are satisfied for all three algorithms, because $g_i \le 0,\ \forall\ i=1,..,6$.

On the other hand, the fastest convergence is obtained by applying the cyclic algorithm of the bat (LoopFBA), i.e., the best solutions are reached the fastest. With the MKH algorithm, we also have a very fast convergence, and then frequent repetition of values close to or equal to the mean values of the objective functions, so the best results are obtained only at the end of the iterative process

3. OPTIMIZATION OF THE ECCENTRIC OF THE CLAMPING TOOL

Clamping with an eccentric is based on the principle of a wedge - an oblique plane. The eccentric is cylindrical (Figure 3.a) or the plate element (Figure 3.b) revolving around an axis that is placed eccentrically in relation to its axis of symmetry[17].

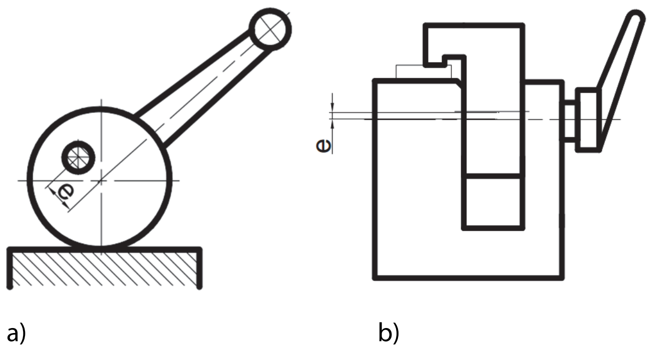

Figure3: Examples of eccentrics

Eccentrics are made of case-hardening steel and they are cemented to a hardness of 55-60HRC, while the contact surfaces of the eccentrics are ground. Due to a shorter service path (downward movement of the handle) eccentric clamping is performed in a short time interval. However, eccentrics have a narrower application. They are used in machining operations characterized by high stability of the clamping tool, lower cutting forces and machining with slight vibrations. In principle, there are two types of eccentrics - circular and curvilinear. A circular eccentric was chosen for the optimization problem, while the basic formulas for calculating the eccentric are given below.

One of the basic conditions that the eccentric must satisfy is the provision of self-braking. For this reason, it is necessary to consider the relationships that should be fulfilled in order for the friction angle to be greater than the angle of climb of the eccentric [17].

Looking at Figure 4, it is possible to establish the dependence between the angle of climb of the eccentric - α and the angle of rotation of the eccentric - β, equation (21).

$$\tan\alpha = \frac{e \cdot \cos\beta}{R + e \cdot \sin\beta} \tag{21}$$

where: e – eccentricity, $R = \frac{D}{2}$ - radius of the eccentric.

The clamping force F_s, which is achieved when clamping with a circular eccentric, can be calculated with sufficient accuracy assuming that the eccentric functions as a wedge. In principle, the problem can be presented as a static balance of forces in relation to the point of rotation of the eccentric arm (Figure4).

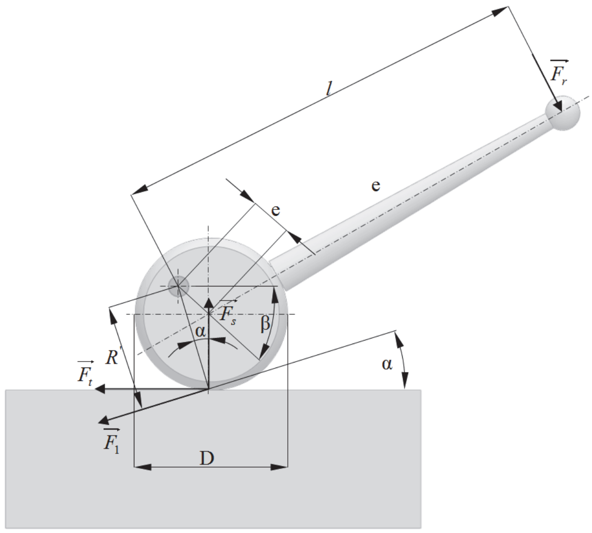

Figure4:Analysis of forces on a circular eccentric

Starting from the equilibrium equation of moments at the point of rotation of the eccentric sleeve (22), i.e., the equation of the distribution of forces at the wedge (23), it will be obtained the dependence of the clamping force on the force on the lever arm of the eccentric (24).

$$F_r \cdot l = F_1 \cdot R', \; F_t = F_1 \cdot \cos\alpha \tag{22}$$

$$F_s = \frac{F_t}{\mathrm{tg}(\alpha + \rho_1) + \mathrm{tg}\rho_2} \tag{23}$$

$$F_s = \frac{F_r \cdot l}{\left[\mathrm{tg}(\alpha + \rho_1) + \mathrm{tg}\rho_2\right] \cdot R'} \tag{24}$$

where: F_r - force on the eccentric lever (it can be adopted~ 150N), l - arm of force [mm], α - variable climbing angle of eccentric [rad], ρ_1 - friction angle on the contact surface of the eccentric and the workpiece [rad], ρ_2 - friction angle on the sleeve of the eccentric [rad], R' - distance of the pivot point of the eccentric from the point of contact $R' = \frac{\frac{D}{2} + e \cdot \sin\beta}{\cos\alpha}$, F_1 - resulting force acting on the object of processing.

3.1. Objective functions and constraints

Based on the previous analysis, an optimization model of the circular eccentric can be set up. In this case, it is a multi-objective optimization with two objective functions. The first objective function refers to determining the minimum dimensions of the eccentric, while the second objective function enables the achievement of the maximum clamping force.

The mathematical model and the corresponding constraint functions are given by equations (25) to (32).

$$\text{Minimize } V = \left(\frac{D}{2}\right)^2 \cdot \pi \cdot b \tag{25}$$

$$\text{Maximize } F_s = \frac{F_r \cdot l}{\left[\operatorname{tg}(\alpha+\rho_1)+\operatorname{tg}\rho_2\right]\cdot R'} \tag{26}$$

Constraints:

$$g_1 = F_R - F_s \le 0 \tag{27}$$

$$g_2 = p_{contact} - \left(p_{contact}\right)_{allowed} \le 0 \tag{28}$$

$$g_3 = \left(p - p_{allowed}\right)_{sleeve} \le 0 \tag{29}$$

$$g_4 = 14 - \frac{D}{e} \le 0 \tag{30}$$

$$g_5 = \frac{18.65 \cdot F_s}{K \cdot D \cdot b} + 41.4 - HRC \le 0 \tag{31}$$

$$g_6 = \left(p - p_{allowed}\right)_{eccentric} \le 0 \tag{32}$$

The constraint g_1 ensures that the clamping force is not less than the maximum cutting force. In this example, it was assumed that the maximum cutting force is $F_R = 2500\text{N}$.

The constraint g_2 checks whether permanent deformations will occur at the point of contact [17]. The contact surface pressure, $p_{contact}$, is calculated according to the equation (32),while the value $\left(p_{contact}\right)_{allowed}$ represents the 20% increased value of the stress at the yield point of the weaker material $\left(p_{contact}\right)_{allowed} = 1.2 \cdot R_e$.

$$p_{contact} = \frac{4}{\pi}\sqrt{\frac{E_e \cdot F_s}{R' \cdot b}} \tag{33}$$

where: $E_e = \frac{2 \cdot E_1 \cdot E_2}{E_1 + E_2}$ - the equivalent Young's modulus of elasticity, E_1, E_2 - Young's modulus of elasticity of eccentric and workpiece, respectively and b - width of the eccentric.

Furthermore, it is necessary to check the pressure values obtained on the contact line between the eccentric and the workpiece (equation (34)),as well as the pressure in the sleeve of the eccentric (equation (35)) in relation to allowed pressure values for the materials of the eccentric and the working material $p_{allowed}$.Since it is steel, the allowed pressure value in this case is $p_{allowed} = 150\left[N/mm^2\right]$.

$$p_{eccentric} = \frac{F_s}{D \cdot b} \tag{34}$$

$$p_{sleeve} = \frac{F_s}{D_r \cdot b} \tag{35}$$

where D_r is the diameter of the sleeve of the eccentric.

Equation (31) refers to the checking of surface deformation according to Levin and Reshetov, for line contact. In this equation, Krepresents the permissible contact load, which depends on the type of thermal treatment (fully hardened or cemented then hardened; induction hardened or nitrided) and on the type of contact (ball, short roller, long roller).For induction-hardened surfaces and a short roll $K = 18\left[N/mm^2\right]$, while $HRC = 96.4$ for steel Č3130.

Design variables: diameter of the eccentric - D, eccentric - e, angle of rotation of the eccentric - β, force arm - l, width of the eccentric - b and diameter of the sleeve of the eccentric - D_r are within the limits [18]:

$$40 \le D \le 115;\quad 4 \le e \le 10;\quad 30 \le \beta \le 90;\quad 60 \le b \le 120;\quad 15 \le D_r \le 35$$

3.2. Optimization results

A comparative view of the results obtained by the cyclic algorithm of the bat family (Loop BFA), the hybrid algorithm of the cuckoo search and firefly algorithm (H-CS-FA) and the modified krill-herd algorithm (MKH) is given in the Table2.

Table2: The results of the optimization of the eccentric

	LoopFBA		H-CS-FA		MKH	
D	56.00007347098426		68.86583		56.22869	
E	4		4.00000		4.01169	
B	90° (π/2)		90°(π/2)		85°(π·17/30)	
l	164.3		180.00000		174.13285	
B	10.039361		96.00000		110.47683	
D_r	31.0841824131		35.00000		20.12035	
g_1	-562.3928		-293.665770918547		-598.8392358535625	
g_2	-0.1095		-38.5151961538239		-1.3786958795177	
g_3	-149.0965		-149.168551853893		-148.6059051886784	
g_4	-0.0012		-3.2164575		-0.0162101259070	
g_5	-54.4804		-54.56216975549		-54.4831360914344	
g_6	-149.4985		-149.577429254628		-149.5011501150574	
	V	F_s	V	F_s	V	F_s
The best	268610.06705	3062.39278	292348.91465	2975.81491	274332.3369382	3098.8395451
Mean value	268930.13266	3058.82352	323218.03655	2815.65655	277164.7488624	3039.7645054
The worst	275779.70696	2996.54577	423905.92624	2231.86118	295327.5310168	2933.7663861
S.D.	707.52216565	6.56736132	45435.2027358	266.058509	2191.683067381	42.749816778

It can be seen, from the table above, that the highest clamping force is obtained by the MKH algorithm, while the smallest volume is obtained by applying the LoopFBA algorithm. All constraints $g_i \ (i=1,..,6)$ are satisfied because $g_i \leq 0, \ \forall \ i=1,..,6$.

4. CONCLUSION

The application of three biologically inspired algorithms- the cyclic algorithm of bat (LoopFBA), the hybrid algorithm of the cuckoo search and firefly algorithm (H-CS-FA) and the modified krill-herd algorithm (MKH)was tested in this paper. Testing of modified algorithms was performed on the examples of optimization of the body of the turning knife and eccentric.

Based on the obtained results, it can be concluded that the mentioned algorithms function correctly. Convergence is good, with a high value of standard deviation for both examples and all three algorithms. This can be explained by the fact that it is a multi-objective optimization of two contradictory objective functions. In the first example, the minimum dimensions of the body of the turning knife were requested, but with the achievement of the maximum amount of removed material during the machining. In the second example, the objective function was to achieve the maximum clamping force while obtaining the minimum dimensions of the eccentric.

Comparing the results, for both examples, it can be concluded that the MKH algorithm gives better results than the other two algorithms.

In the example of the optimization of the turning knife body, the MKH algorithm gave significantly better results than the Loop BFA and H-CS-FA algorithm (Table1). Unlike Loop BFA, MKH algorithm converged relatively quickly, but towards a value close to or equal to the mean value of the objective function, only to achieve the best result at the end of the iterative process.

A similar conclusion can be drawn for the example of optimization of the eccentric. The highest clamping force was obtained by using the MKH algorithm, while Loop BFA gives the smallest dimensions of eccentric with the achievement of a satisfactory clamping force (Table 2). The results obtained by the H-CS-FA algorithm are worse than the other two mentioned algorithms. Unlike the Loop BFA, the MKH algorithm converged relatively quickly to a value close to the mean value of the objective function, only to achieve the best result in the last third of the iterative process.

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