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HYBRID METAHEURISTIC ALGORITHM: A NOVEL APPROACH FOR INDUSTRIAL OPTIMIZATION CHALLENGES

Hammoudi ABDERAZEK[1,2], Aissa LAOUISSI[2,3], Mourad NOUIOUA[4], Ivana ATANASOVSKA[5,*]

[1]UR-MPE, M'hamed Bougara University, Boumerdes, Algeria

[2]Applied Precision Mechanics Laboratory, Institute of Optics and Precision Mechanics, Setif-1-University, Algeria

[3]Department of Mechanical Engineering, Faculty of Sciences and Technology, University of Mohamed El Bachir El Ibrahimi, Bordj Bou Arreridj, Algeria

[4]Mechanics and Structures Research Laboratory (LMS), Mechanical Engineering Dept, 1945 University, 24000, May Guelma, Algeria

[5]Mathematical Institute of the Serbian Academy of Sciences and Arts, Belgrade, Serbia

*Corresponding author: iatanasovska@mi.sanu.ac.rs, iviatanasov@yahoo.com

Abstract: *In this work, a new hybrid optimization algorithm is developed, specifically designed to address real industrial optimization challenges. Initially, we validate the proposed method by applying it to various industrial optimization problems, showcasing its versatility and effectiveness. The optimization results obtained with the introduced algorithm are rigorously compared against those produced by other state-of-the-art optimization methods cited in the literature. Our findings indicate that the proposed method not only converges more rapidly but also consistently delivers superior performance in terms of solution quality and computational efficiency across most test problems. Furthermore, we apply the algorithm to optimize the main cutting parameters in the turning operation of X210Cr12 steel. In this application, the fitness functions evaluated include the tangential cutting force, surface roughness, and cutting power. The mathematical expressions for these objectives were generated using the Response Surface Methodology (RSM). This application highlights the practical utility of our algorithm in improving industrial processes and achieving optimal operational parameters.*

Keywords: *Meta-heuristic algorithm; Multi-objective optimization; Eco-Friendly machining; Turning*

1. INTRODUCTION

Optimizing mechanical structural problems presents a formidable challenge to designers and researchers, owing to the intricate nature of their mathematical underpinnings. Furthermore, a significant portion of these structural optimization challenges entails intricate nonlinear objective functions, encompassing a multitude of considerations such as geometrical congestion, mechanical resilience, and operational performance requirements [1-4].

In the machining process, the desired final shape of the mechanical component is created by removing unwanted material from a larger piece of material using machines and cutting tools. During this process, selecting appropriate machining parameters is critical to ensuring product quality, low manufacturing costs, higher productivity, and short manufacturing time. Accordingly, over the last two decades, a lot of efforts have been devoted to optimizing the cutting conditions using several mathematical approaches to satisfy diverse criteria [5-7].

This article presents a novel hybrid evolutionary algorithm incorporating a local search technique, designed for optimizing real-world industrial optimization problems. In the initial phase, we applied ReDE-NM to address mechanical engineering problems. The optimization results unequivocally demonstrate the superiority of our proposed method over the other algorithms used for comparison. Subsequently, our developed algorithm was employed to optimize the primary cutting parameters during the turning process of X210Cr12 steel. These turning operations were conducted under the Minimum Quantity Lubrication (MQL) lubrication mode, employing a multilayer-coated carbide insert GC-4215 as the cutting tool. To model the two key performance metrics, namely the tangential cutting force (Fz) and surface roughness (Ra), a series of tests were conducted following the Taguchi L_27 experimental design.

2. DISCRETE AND INTEGER VARIABLES HANDLING

The fundamental approach for managing discrete variables involves utilizing their position index within an array of normalized values. For a more comprehensive understanding of this discrete variable handling principle, please refer to Fig. 1. It's worth noting that integer variables can be addressed in a similar manner to discrete ones.

More precisely, rather than directly optimizing the discrete and integer variables themselves, we optimize their corresponding index values, which are initially represented as real numbers and subsequently rounded to the nearest integer through truncation. Throughout the process of evaluating the objective function and constraints, it is the discrete values themselves, not their indexes, that are utilized [8].

3. PROPOSED METHOD: REDE-NM

The flowchart illustrating the ReDE-NM method is provided in Figure 2. As depicted, ReDE-NM consists of four primary steps: initialization, mutation, crossover, and selection. Below, we offer a concise description of each of these steps.

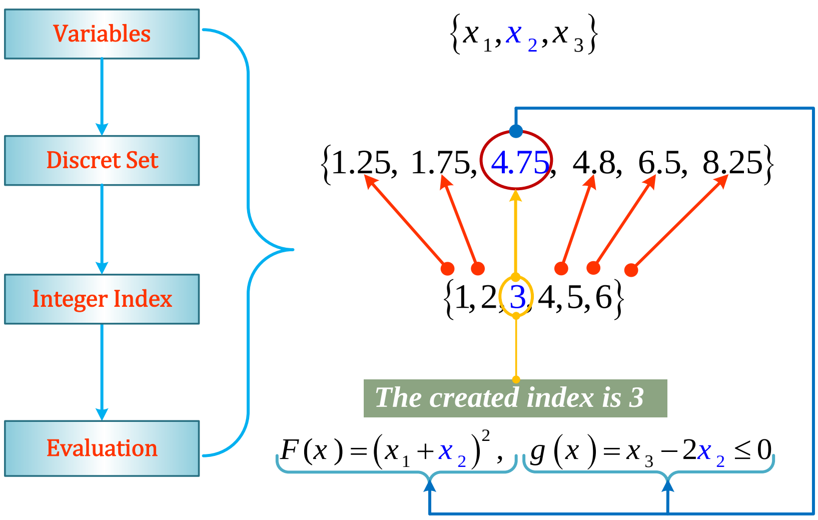

Figure 1. Discrete variable handling method

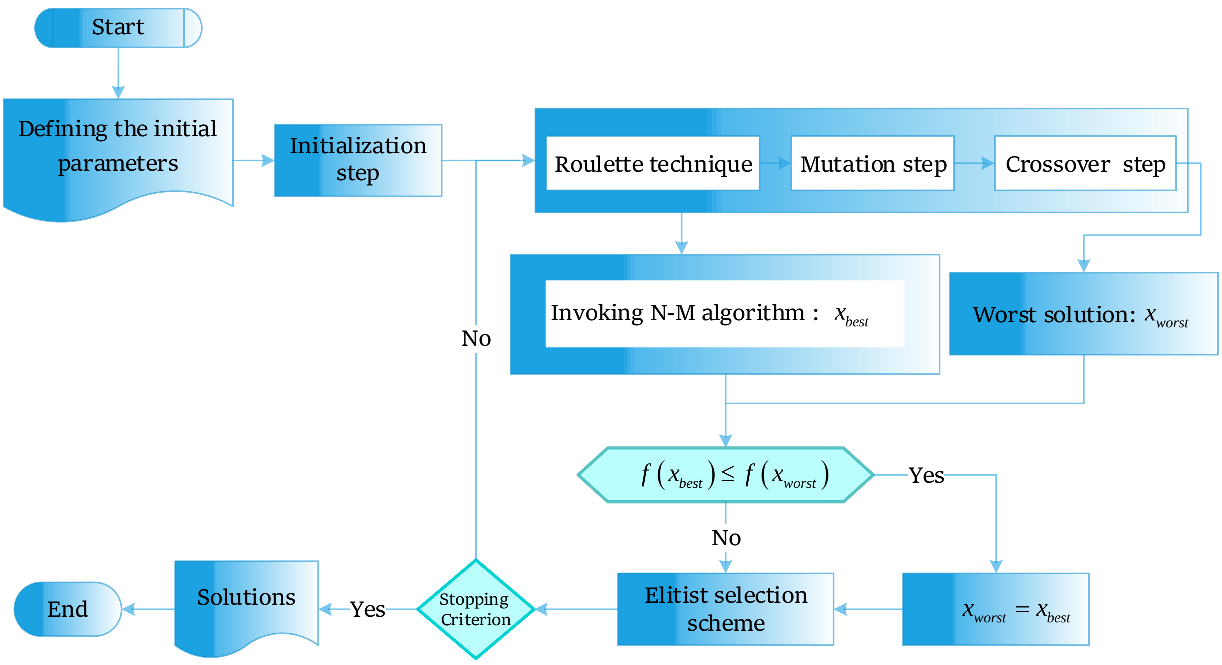

Figure 2. Flowchart of ReDE-NM

The incorporation of a local search algorithm not only enhances the method's ability to escape from local optima but also bolsters its exploitation capability. In the context of IDE, this technique is employed to improve the quality of the worst solution identified within each generation.

4. OPTIMUM DESIGN OF MULTIPLE DISC CLUTCH BRAKE AND SPUR GEAR SYSTEM

In this section, the resolution of two intricate mechanical design problems (multiple disc clutch brake and spur gear system) has been addressed to assess the efficiency of our newly developed algorithm. Schematic representations of the two mechanical problems are presented in Fig. 3 and Fig. 4, respectively. We benchmark the optimal outcomes achieved through ReDE-NM against those obtained by other optimization algorithms, as documented in references [9-12].

Tables 1 and 2 present the statistical outcomes of the compared algorithms, corresponding to the multiple disc clutch brake and the spur gear design problem, respectively. The tables clearly demonstrate that ReDE-NM outperforms the previously reported algorithms, notably exhibiting superior performance in terms of standard deviation for both of these optimization problems.

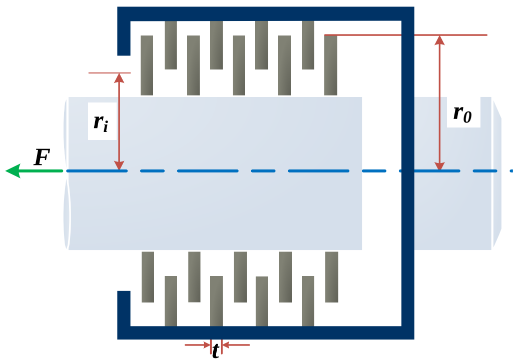

Figure 3. Schematic view of multiple disc clutch brake

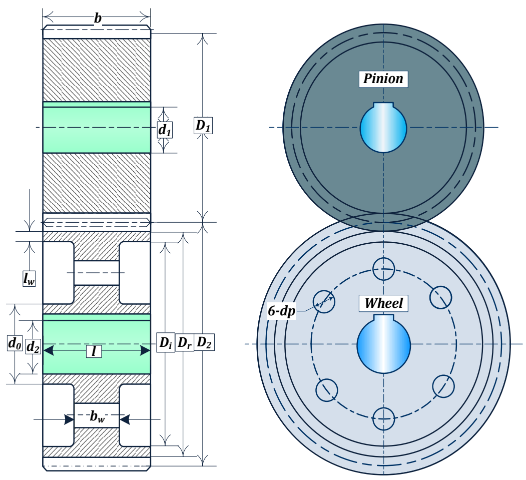

Figure 4. Schematic view of the spur gear system

Figures 5 and 6 depict the convergence rates of the solved problems. Notably, the proposed algorithm achieves convergence to the optimal solution in just 11 iterations for the multiple disc clutch brake problem. In contrast, for the spur gear system, the optimal solution is reached after 122 iterations. This observation underscores the effectiveness of incorporating the local search Nelder-Mead technique, as it significantly enhances the efficiency of the ReDE-NM method, leading to quicker convergence toward near-optimal solutions.

Table 1. Statistical results of the used algorithms for the multiple disc clutch brake problem

Algorithms	Best	Mean	Worst	SD	SR (%)
ReDE-NM	**0.313656611**	**0.313656611**	**0.313656611**	**5.60747E-17**	100
PVS	0.313657	0.328163	0.392071	NA	-
GA	0.313657	0.330712	0.401873	NA	-
WCA	0.313656	0.313656	0.313656	1.690E-16	-
TLBO	0.313657	0.3271662	0.392071	0.6700000	
ABC	0.352864	0.324751	0.313657	0.5400000	

Table 2. Statistical results of the used algorithms for the spur gear problem

Algorithms	Best	Mean	Worst	SD	SR (%)
ReDE-NM	**1538.9446818**	**1538.9446818**	**1538.9446818**	**0.000E+00**	**100**
NAMDE	1538.94468	1538.94468	1538.94468	1.6904E-08	-
MVO	1538.95376564	1539.02756935	1539.16664793	0.04791177	32
ASO	1624.22360200	1713.75053647	1827.07827573	49.4135992	0
EBO	1538.94468183	1544.54893767	1570.07778507	12.0822412	82
QSA	1538.94468183	1539.56734390	1570.07778507	4.40288568	98

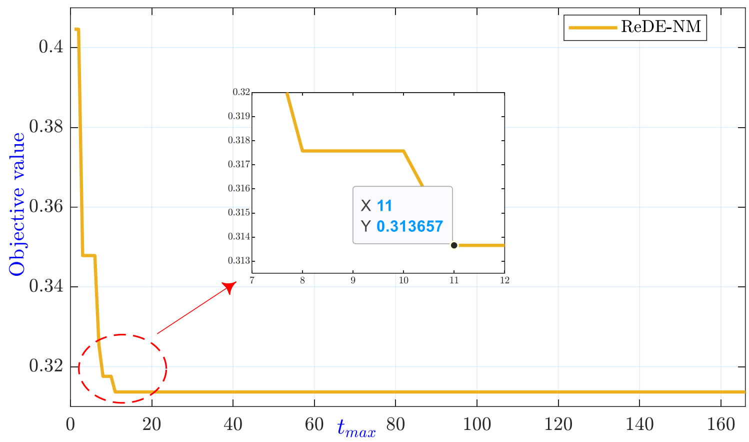

Figure 5. Convergence graph for the best solutions for the multiple disc clutch brake

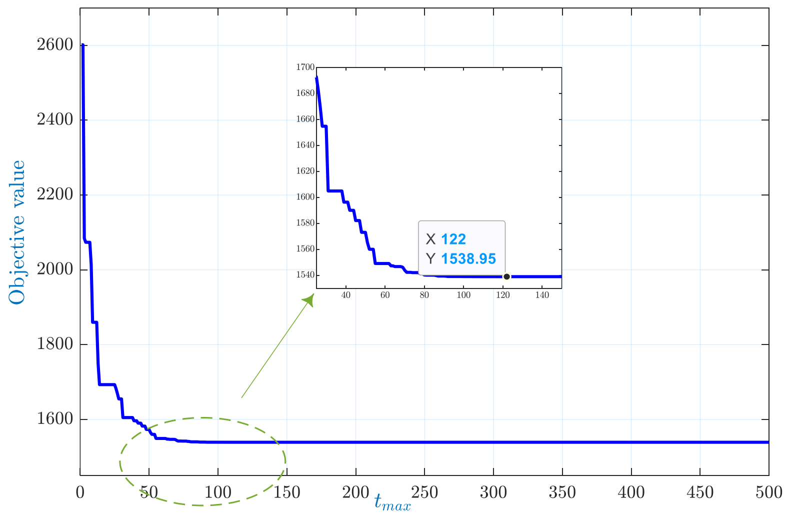

Figure 6. Convergence graph for the best solutions for the spur gear

5. OPTIMIZATION OF MACHINING PARAMETERS DURING THE TURNING OPERATION OF X210CR12 STEEL

This section focuses on the optimization of key cutting parameters during the turning process of X210Cr12 steel. These critical parameters include cutting speed (Vc, measured in m/min), feed rate (f, measured in mm/rev), nose radius variation (r, measured in mm), and depth of cut (ap, also measured in mm). We conducted a total of twenty-seven tests to measure the two optimized outputs, specifically the tangential force (Fz) and surface roughness (Ra). It's worth noting that the value of Ra represents the mean of three measured values, ensuring statistical reliability.

To model the objectives effectively, we employed response surface methodology (RSM). The objective functions can be expressed as follows:

$$F_z = 120.81 - 0.36Vc - 45.17f - 67.77r + 2.63ap + 0.03Vc \times f - 0.05Vc \times r - 0.06Vc \times ap + 295.62f \times r + 2573.75f \times ap + 17.62r \times ap + 7.9810^{-4}Vc^2 - 1819.27f^2 + 25.44r^2 + 20.97ap^2 \quad (1)$$

$$R_a = -3.77 + 5.26 \times 10^{-3}Vc + 29.38f + 3.21r + 0.60ap - 9.3710^{-3}Vc \times f + 1.31 \times 10^{-3}Vc \times r + 4.5 \times 10^{-3} \times Vc \times ap - 4.06f \times r - 3.12f \times ap + 0.18r \times ap - 1.55 \times 10^{-5}Vc^2 - 67.96f^2 - 1.28r^2 - 2.25ap^2 \quad (2)$$

The two objectives are evaluated under four distinct experimental conditions, as outlined below:

$$\begin{cases} g_1 = R_a - 0.41 \leq 0 \\ g_2 = -R_a + 0.40 \leq 0 \\ g_3 = -F_Z + 84 \leq 0 \\ g_4 = F_Z - 85 \leq 0 \end{cases} \quad (3)$$

where $Vc \in [150,\ 350]$, $f \in [0.08,\ 0.16]$, $r \in [0.8,\ 1.6]$ and $ap \in [0.2,\ 0.6]$

6. RESULTS AND DISCUSSIONS

To assess the algorithm's efficacy in tackling machining problems, we conducted extensive computer simulations involving various parameter configurations. These simulations were conducted in a Windows 10 environment, utilizing an HP Z8 G4 workstation equipped with an Intel(R) Xeon(R) Silver 4210 CPU @ 2.20GHz and 128 GB of memory. The compilation environment employed was MATLAB 2020b.

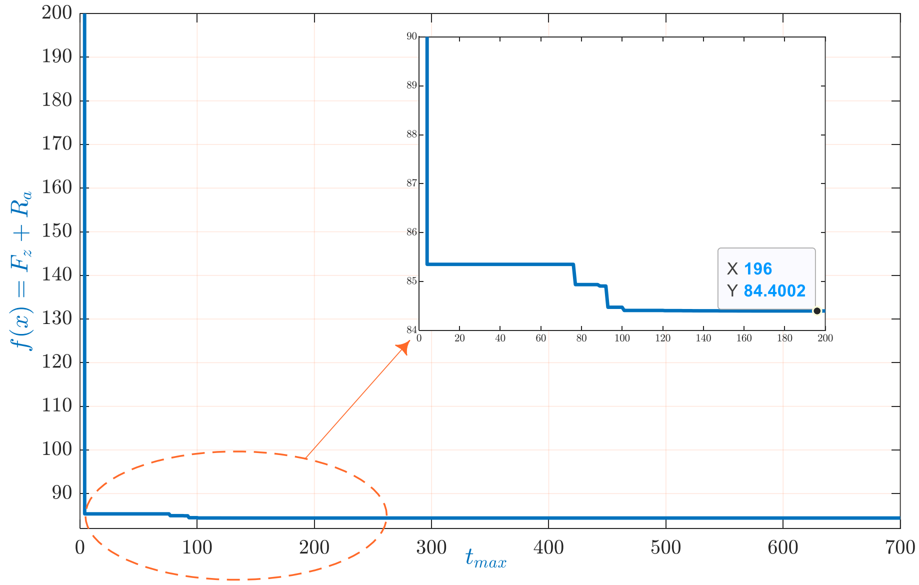

Figure 7. Convergence plot of the ReDE-NM for the turning problem

The plot in Figure 7 illustrates the algorithm's convergence history. Remarkably, ReDE-NM achieves the optimal solution with remarkable efficiency, accomplishing this milestone after just 196 iterations.

Table 3. The optimal solution for the machining parameters

Variables	ReDE-NM
Vc (m/min)	256.216393
f (mm/rev)	0.08366701
r (mm)	0.85700971
ap (mm)	0.21639342
Ra (μm)	0.40000000
Fz (N)	84.0000000

7. CONCLUSION

This paper introduces an innovative hybrid evolutionary algorithm termed Roulette Wheel Selection and Nelder-Mead-based Improved Differential Evolution (ReDE-NM). Through comprehensive numerical assessments, the supremacy and competitive edge of ReDE-NM over a spectrum of contemporary algorithms documented in existing literature are firmly established. ReDE-NM showcases its prowess by consistently attaining superior results for key metrics, encompassing the best value, mean, and standard deviation across all examined problem instances.

The efficacy of ReDE-NM extends beyond theoretical benchmarks, finding practical utility in tackling a complex challenge within the domain of machining – specifically, the turning operation of X210Cr12 steel. The investigation targets a design space characterized by four mixed variables and four constraints, embracing three pivotal objectives: minimizing tangential cutting force, refining surface roughness, and optimizing cutting power consumption.

Numerical analyses convincingly affirm the successful application of ReDE-NM in optimizing the turning operation, showcasing its aptitude as a potent tool for real-world applications and the resolution of multifaceted challenges across diverse domains.

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ORCID iDs

Hammoudi ABDERAZEK 0000-0001-8911-348X
Aissa LAOUISSI
Mourad NOUIOUA
Ivana ATANASOVSKA 0000-0002-3855-4207

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