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Increasing the Performance of Computer Numerical Control Machine via the Dhouib-Matrix-4 Metaheuristic

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Abstract: The Computer Numerical Control (CNC) machine represents a turning point in today's production which has high requirements for product accuracy. The CNC machine enables a high flexibility in work and time saving and also reduces the time required for product accuracy control. Moreover, the CNC machine is used for several activities, most often for turning, drilling and milling operations. Usually, the productivity of any CNC machine can be increased considering the minimization of the non-productive tool movement. In this paper, the results of a new metaheuristic named Dhouib-Matrix-4 (DM4) with an application on the NP-hard problem based on the Traveling Salesman Problem are presented. DM4 is used for increasing the performance of the CNC Machine by optimizing a tool path length in the drilling process performed on the CNC milling machine. The proposed algorithm (DM4) achieves a solution closed to the optimum, compared with the results obtained with others standard methods.

Keywords: Optimization, Metaheuristics, Computational Intelligence, Artificial intelligence, Drilling Path Sequence.

1 Introduction

Today's manufacturing industry demands the production of high accuracy products in the shortest possible time and at the lowest possible costs. In all projects, time plays a key role because the invested time represents the amount of money invested. Whether we are talking about finishing the project within the agreed deadline or increasing production efficiency, today it is important to be competitive and production facilities try to achieve competitiveness in all available ways in order to survive on the market. The production without CNC machines is unthinkable today, considering the required high accuracy that we want to achieve during the production process. In this view, the ways to increase the efficiency of numerically controlled machines are considered. There are several possible solutions that lead to a reduction cost of the production. It is possible to reduce production costs by taking into account the cutting tools life, reducing delivery time and reducing the total operating costs of the machine. In order to effectively control the CNC machine, it is necessary to take into account also the processing parameters. In this case, it is possible to increase the feed rates, depth of cut and cutting speed. All of the above, of course, certainly contributes to the tool wear, however, the long life of the cutting tool represents only 3% of the total production costs when working on CNC machines, so the previously mentioned reduction is still more significant.
Furthermore, as a possible solution for achieving the efficiency of the production process is the possibility of optimizing the operation scheduling on available machines (known as a job shop scheduling problem), which is also the subject of many research papers [1, 2, 3], minimize the cycle time of a NC program (includes machining and non-machining operations) and also the cutting tool path optimization. When we talk about the drilling process, especially for a large number of holes, it is possible to achieve significant reduction by minimizing the drilling cycle with tool path optimization which is the subject of this paper.

Many studies have been conducted on this topic, where various metaheuristic methods were used for optimization. Reduction of clear tool path length during pocket milling, according to [4], was performed using the Ant Colony

Optimization method. By using the rough processing technique so-called contour parallel machining, the cutting time is reduced to avoid increasing costs and tool damage at the example of the milling process. Reduction of the

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processing time in the amount of 6.87% and a reduction of the total tool path length in the amount of 6.81% were achieved. Tool path optimization in a production line with two CNC machines was carried out in the work [5]. A novel method that predicts the optimal tool path sequence with minimum time for a 2M production line for CNC machining time estimation has been implemented. The optimized sequence is determined using a genetic algorithm (GA). Optimization was done for hole making operation where multiple cutting tools are required to drill the hole to complete the process. Since each of the machines can perform a specific set of operations, the goal is to minimize the non-productive time between the two CNC machines. The tool path plays a significant role in the productivity of CNC machining operations. The possibility of parameters choosing for the GA optimization of the tool path for drilling tool was investigated in the paper [6]. The Matlab scientific computer environment was used for the analysis. The results indicate the behaviour of the genetic algorithm and the enormity of the solution space. The optimal values for the GA parameters were obtained and applied to the selected problem in the creation of G codes for the CNC program for a specific CNC machine. The research of tool path optimization for the drilling process was also investigated in the paper [7]. The two new algorithms were introduced and implemented, random start shortest distance permutation (RSSDP) and first point start shortest distance permutation (FPSSDP). The results, realized in the MATLAB environment, were compared with the shortest distance location algorithm (SDL) and the traveling salesman problem (TSP) algorithm, showing a significant reduction in non-productive processing time. In [8] a new algorithm was proposed for minimizing the tool path during drilling (which is considered as non-productive time), taking into account multiple constraints such as the location of the tool origin and the presence of obstacles along the tool path and also taking into account the collision. The obtained results were compared with the results generated by the HSMWorks CAM software, and the ability of the algorithm to find the optimal or suboptimal tool path during the drilling process with minimal time was confirmed. The authors in [9] were applied the bat algorithm to solve the problem of determining the optimal drilling path sequence when making multiple holes by using the CNC machines. Different case studies were made on different examples of hole layouts. The proposed algorithm also takes into account machining time, machining cost and non-productive costs of the associated drilling operation. Also, the possibility of implementing the algorithm in the MATLAB environment is investigated [10], which contains a combination of two well-known algorithms PSO and GA. The optimization of the tool path through the reduction of machining cycle time is based on the TSP principle. The movement of the tool was divided into cutting segments. An attempt was made to reduce the non-cutting movement by taking the position for cutting (milling), which must be performed in the next pass. At the same time, any two segments can be connected in 8 different ways, which represents quite a challenge. The proposed algorithm provides an improvement, i.e., it saves up to 40% of tool time during machining compared to the tested Inventor HSM and MasterCam software. Also, the possibility of reducing the cutting time in the milling process was investigated in order to avoid an increase in a production costs. In the paper [11], a travelling salesman problem (TSP) is used to generate a tool path in the drilling process without collision. The developed optimization model can process the objective function under multiple constraints, returning to the origin of the tool rather than the initial hole being drilled. In order to do the above, they take into account all dimensions/angles of the work-piece for the initial position of the tool, as well as the impediment constraint to generate a collision-free path. The performance of the proposed algorithm was obtained for the different starting positions of the tool at all corners of the work-piece. The results show that the proposed algorithm can give the solution of the problem in real time and it is able to generate the optimal tool path without collision.

In this field, a new metaheuristic named Dhouib-Matrix-4 (DM4) is developed by [12] in order to solve combinatorial problem. In this paper, the DM4 will be adapted to find the shortest drilling path in prismatic work-piece for 156 holes, and other complicated problems. The general structure of the paper is organized as follow. In the next section, the holes drilling problem is presented as Traveling Salesman Problem and mathematical formulation is given. In the third section the proposed method is described with details. The fourth section presents a different case studies of drilling holes and a comparison to other methods in literature are presented. Finally, the conclusion and the perspectives will be given in section five.

2 The holes drilling problem

The problem of finding the shortest holes drilling path can be formulated as Traveling Salesman Problem where the holes represent the cities and the salesman is simulated to the robot arm. Thus, minimising the movement of the salesman between all cities correspond to minimize the movement of the robot arm. Mathematically the problem can be formulated as Equation 1:

$$\text{Minimize } f(x)=\sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij}\, d_{ij} \tag{1}$$

$$\sum_{i=1}^{n} x_{ij}=1,\ j=1,2,..,n$$

$$\sum_{j=1}^{n} x_{ij} = 1,\ i = 1,2,..,n$$

Hence, the objective function is to minimize the total distance (d_{ij}) between all nodes (n) where the binary decision variable (x_{ij} = 1) only if node j is joint from node i otherwise (x_{ij} = 0).

Several optimization methods were developed to solve this problem. Two constructive heuristics are designed to generate rapidly a good initial basic feasible solution for the TSP are presented in [13, 14, 15] Moreover, an application of the novel greedy method DM-TSP1 is analysed to solve the TSP: under fuzzy environment in [16, 17, 18], with intuitionistic domain in [19] and neutrosophic area in [20, 21, 22]. The paper [23] describes the application of the differential evolution algorithm for the work path minimization problem for drilling operations which are computer numerically controlled. A new differential evolution heuristic algorithm was applied to the traveling salesman problem. In the mass production of a large number of products that is need to be drilled, such as printed circuit boards (PCB), the time which is need to travel of the drilling tool is a significant part of the overall production process. Therefore, the differential evolution algorithm-the heuristic traveling salesman problem can play a significant role in reducing production costs. In [24], three metaheuristic algorithms (GA, ACO and Hopfield neural network) were used to solve the traveling salesman problem. The used algorithms were compared in terms of time complexity, spatial complexity, advantages and disadvantages of the calculation results and the level of difficulty of implementation. The overall results that were achieved showed that the mentioned algorithms are useful for solving the traveling salesman problem. The best results were achieved by ACO, followed by GA and the lowest results were achieved by Hopfield network. According to [25], a multi-objective genetic algorithm with cyclic crossover, two-point mutation and a refinement operation, which was introduced as a new operator, was used to solve the traveling salesman problem. A reduction of total costs and time required for a complete tour was achieved.

In the paper [26], the multi-descendant genetic algorithm (MO-GA) was used and compared with the basic genetic algorithm (BGA) for solving the TSP problem. Compared to the basic BGA algorithm, in MO-GA the number of offsprings is increased, which leads to an increase of the probability of creating excellent individuals, and also makes the population more competitive, which leads to a significant improvement. The results showed that MO-GA has higher speed, and the number and time of the iterations are significantly reduced compared to BGA. The paper [27] investigated the problem of waste collection in the city of Tlemcen in Algeria. The problem is presented as a traveling salesman problem. Due to the complexity of this problem, the well-known metaheuristics, Tabu Search algorithm and the simulated annealing algorithm (SA) were integrated into a graphical decision-making interface. The results showed that SA has the best performance for reducing the travelled distance in the majority of cases.

The authors in [28], proposed a new meta-heuristic for solving TSP based on a new insight into network routing problems. The proposed algorithm attempts to improve algorithm performance and solution quality for TSP by using local search algorithms on behalf of 2-Opt and 3-Opt, at the end of each iteration. Another research paper [29] considers the algorithms based on the heuristic methods for the traveling salesman problem on a sphere (it is assumed that all vertices are on a spherical surface, which represents a special case of the conventional traveling salesman problem). First, the 28 test instances on the unit sphere, are generated. Then, using different methods such as genetic algorithm, ant colony optimization and fluid genetic algorithm, initial solutions are obtained for solving test instances of the traveling salesman problem in the Matlab program. The initial heuristic solutions were used as input for the 2-opt algorithm, and the performance and time complexity of the applied methods were analyzed.

In the paper [30], a hybrid two-phase metaheuristic algorithm, MACSGA, which is used to solve the TSP is presented. In the first stage, the TSP is solved by a modified ant colony system (MACS), in each iteration, while in the second stage, a modified genetic algorithm (GA) and 2-opt local search are used to improve the ant solution for that iteration. This approach avoids premature convergence and provides more favourable solutions. The results showed the effectiveness of the proposed algorithm in comparison with GA, ant colony optimization and other metaheuristic algorithms. The authors in [31] propose a new metaheuristic method for solving the traveling salesman problem - partial comparison optimization (PCO). PCO is a metaheuristic for solving combinatorial problems like TSP. To test PCO performance, it was used to solve TSPLIB instances. PCO algorithm gives a good optimal solution that is almost close to the optimal solution of each TSPLIB instance.

3 The proposed method

In this paper the novel multi-start metaheuristic Dhouib-Matrix-4 (DM4) is applied to find the shortest drilling path. In fact, DM4 is developed in [12, 32] and fundamentally executes in iterated structure two sequential methods where the output of the first method will be the input data for the second methods. The first method is a column-row heuristic named Dhouib-Matrix-TSP1 (DM-TSP1) used as diversification tools in order to explore several positions in the domain space (in each execution of DM-TSP1 different statistical metrics are used (such as: Sum, Standard Deviation, Average, Etc.) in order to generate different initial basic feasible solution). The second method is a local

search method entitled Far-to-Near (FtN) handled as intensification tools with the purpose of exploiting a specific region in the domain space.
Basically, the DM-TSP1 is designed in [14] and it is composed of four simple steps in order to generate a Hamiltonian cycle and this paper only the first three steps are considered (see Figure 1) viewing that the shortest drilling path (not a cycle) is required.

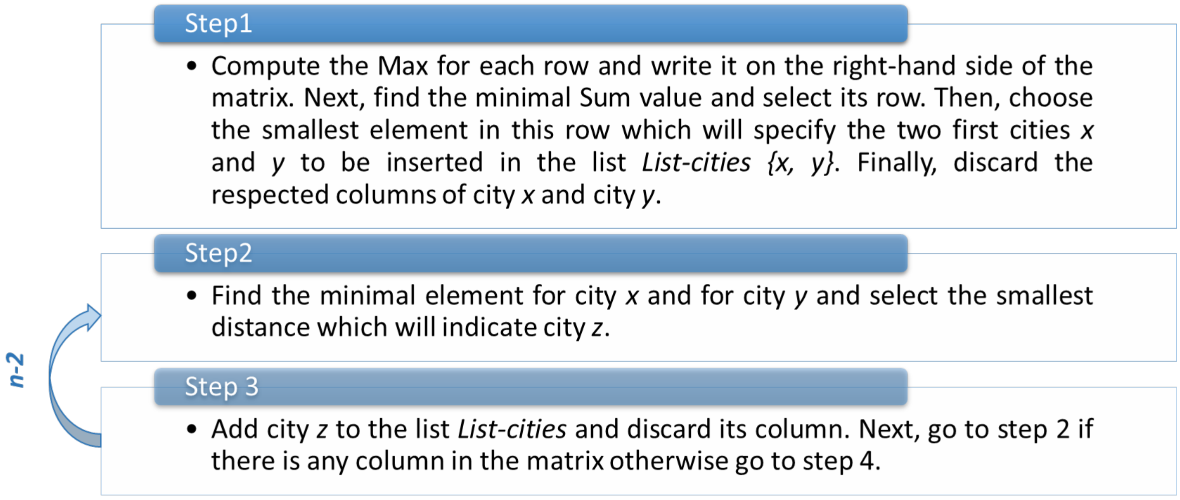

Figure 1. The three simple steps of the heuristic Dhouib-Matrix-TSP1 (DM-TSP1)

The local search FtN method is developed in [33] and used as intensification technique in [12, 34]. In fact, FtN is founded on organized choice of *k* nearest neighbours. Also, three perturbation are applied on the current solution (x_i) in order to create three neighbour (x_1,x_2,x_3) and their best one is affected to (x_4). Besides, the current solution will take the value of (x_4) with thresholding acceptation criterion (see Figure 2).

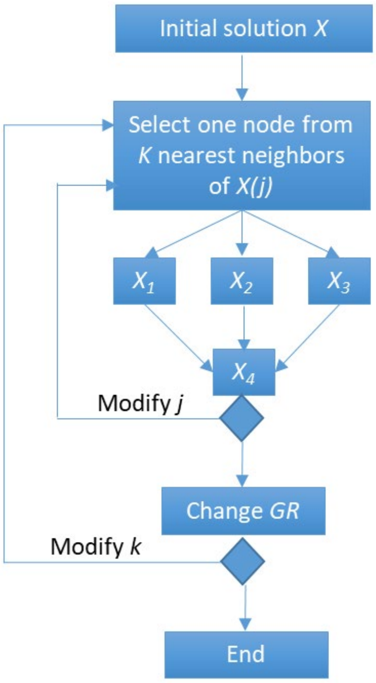

Figure 2. The flowchart of the novel Far-to-Near method (taken from [3])

Actually, all these method DM-TSP1, FtN and DM4 are developed under the concept Dhouib-Matrix where several other methods are designed such as: The greedy Dhouib-Matrix-AP1 heuristic (designed in [35] to solve Assignment Problem) and the column-row Dhouib-Matrix-TP1 (developed in [36, 37] to unravel the Transportation Problem).

4 Numerical Illustrations

The DM4 is developed under Python programming language and using a Laptop with Windows 10 Pro operation system, a processor of Intel® Core™ i5-320M CPU @ 2.50 GHz and 8 GB of memory. Several complicated case studies are used to prove the performance of DM4 and for each case study twenty five independent runs are executed and the average, maximum and best value is presented. Moreover, two indicators are computed the percentage of robustness (see Equation (2)) and the percentage of gap between DM4 and other methods (Equation (3)).

$$\%Robustness = 100 - (\frac{Max_{DM4} - Min_{DM4}}{Min_{DM4}} * 100) \tag{2}$$

$$\%Gap_{Meta\text{-}DM4} = (\frac{Min_{Meta} - Min_{DM4}}{Min_{DM4}} * 100) \tag{3}$$

4.1 Case study 1

Let us consider the case study developed by co-author in [38] where 156 holes need to be drilled (see Figure 3) on prismatic work-piece. The distance matrix is computed using the Euclidean distance metric between all holes.

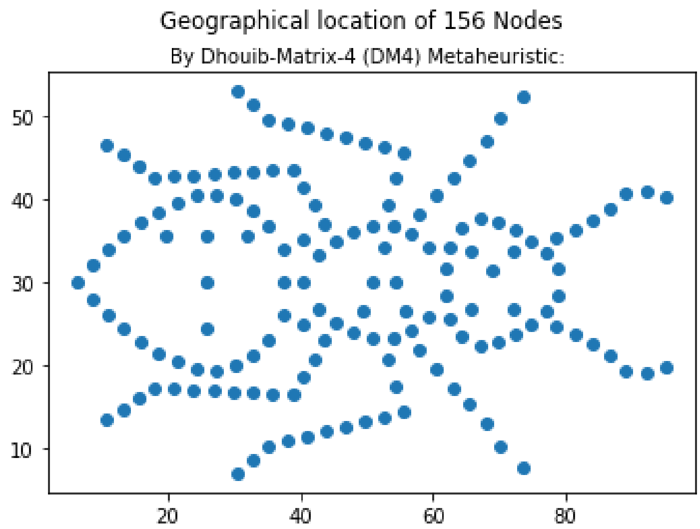

Figure 3. The 156 holes to be drilled

After twenty five independent runs of DM4, the found optimal solution is 543.4761 mm, where the average and the maximum values were respectively 553.3371 mm and 558.3973 mm. The optimal solution produced by DM4 is shown in Figure 4.

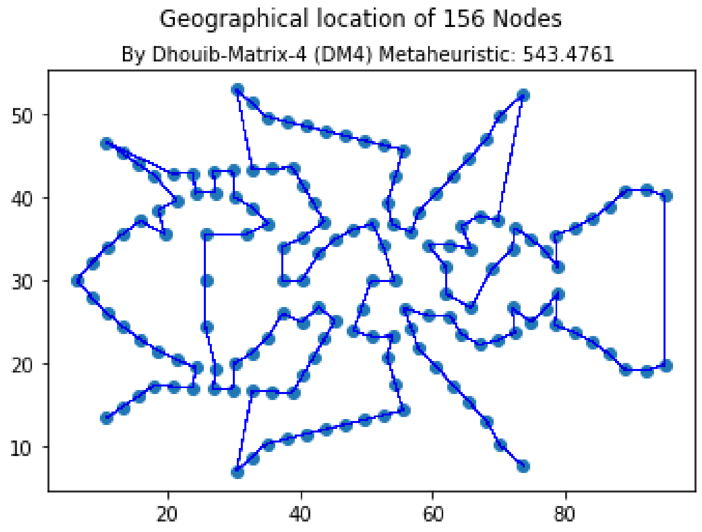

Figure 4. The shortest holes drilling path found by DM4

This optimal holes drilling path (543.4761 mm) achieved by DM4 presents a percentage of robustness (97.2524 %) and introduces a percentage of gap (5.4681 %) to the Ant Colony Optimization and (15.7982 %) to the Manual Programming (see Table 1).

Table 1. Comparing DM4 to other methods

Methods	Manual Programming	ACO algorithm	DM4		
			Max	Average	Min
Shortest Path, mm	629.3353	573.1939	558.3973	553.3371	543.4761

The graphical representation of the best result generated by DM4 and other methods are depicted in Figure 5.

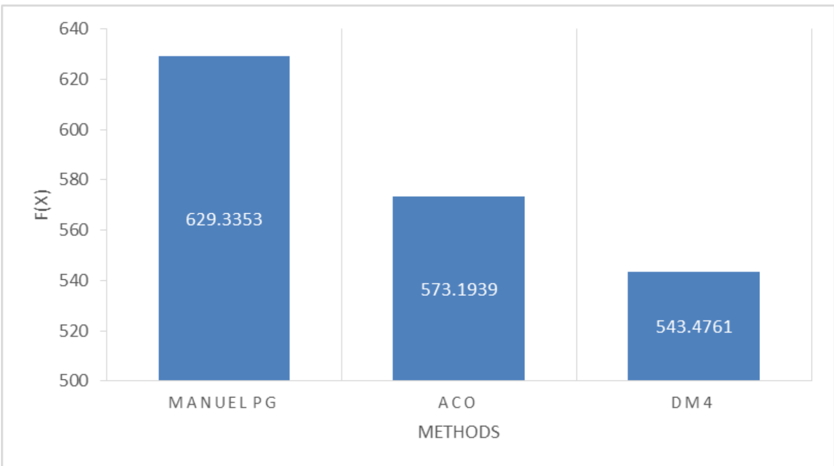

Figure 5. The gap between the proposed method DM4 and other methods

Figure 6 depicts the convergence speed of the DM4 metaheuristic. Obviously, the value of total distance of the generated path between all nodes converge through the iterations.

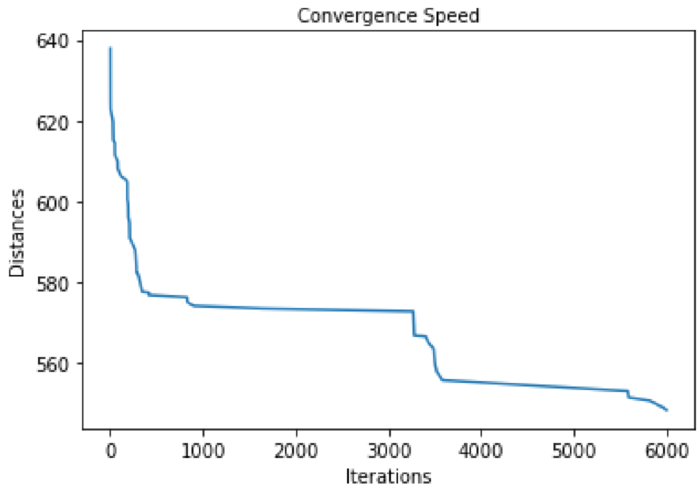

Figure 6. Convergence speed of the novel DM4 method

4.2 Case study 2

In this section, we apply the DM4 metaheuristic to a second case study (developed in [39]) where 100 holes need to be drilled. The distance matrix is computed using the rectilinear distance metric between all holes. After twenty five independent runs of DM4, the best solution is 94.569 mm, the average solution is 95.194 and the standard deviation is 0.766. The best solution produced by DM4 is depicted in Figure 7.

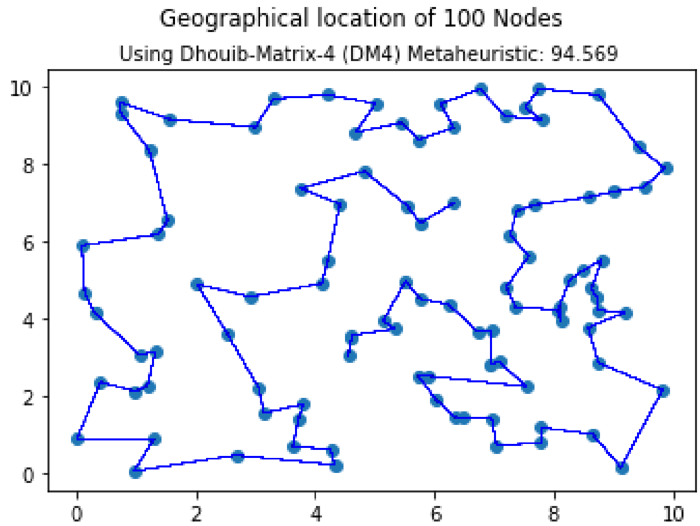

Figure 7. The shortest holes drilling path found by DM4

DM4 generates the best holes drilling path (94.569 mm) by means of percentage of robustness (97.4939 %) and outperforms the CS, GA and CSGA methods with respectively percentage of gap (53.2003 %), (12.7759) and (0.1311).

Table 2. Comparing DM4 to other methods

Methods	CS		GA		CSGA		DM4		
	Average	Best	Average	Best	Average	Best	Max	Average	Best
Shortest Path (mm)	156.298	144.880	109.576	106.651	97.783	94.693	96.939	95.194	94.569

The graphical representation of the best result generated by DM4 and other methods are depicted in Figure 8.

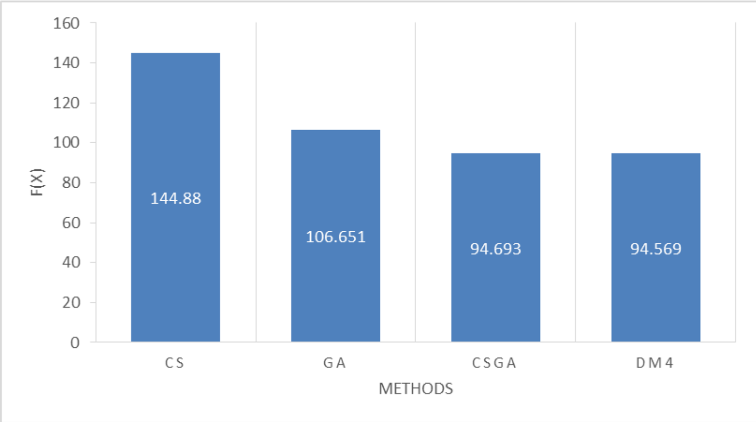

Figure 8. The gap between the proposed method DM4 and other methods

4.3 Case study 3

A third example taken from [39] is considered where 200 holes need to be drilled (the distance matrix is computed using the rectilinear distance metric between all holes). After twenty five independent runs of DM4, the best solution achieved is 137.539 mm, the average solution is 138.313 mm and the standard deviation is 0.766. The best solution produced by DM4 is shown in Figure 9.

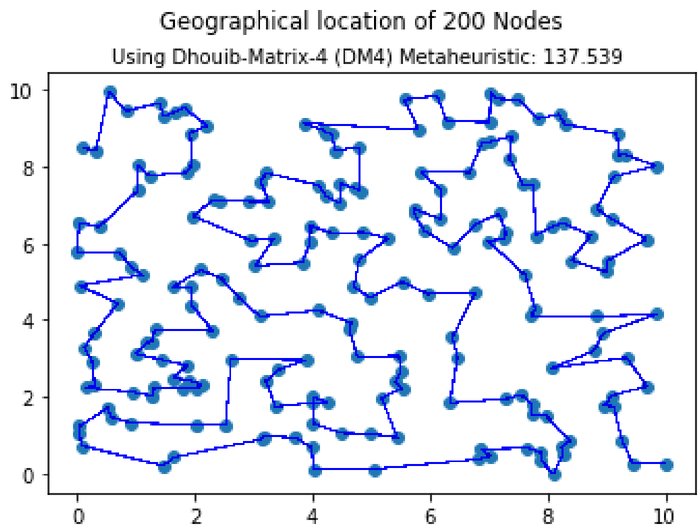

Figure 9. The shortest holes drilling path found by DM4

Table 3 depicts the results generated by the DM4 and the three methods (Cuckoo Search (CS), Genetic Algorithm (GA) and hybrid method Cuckoo Search Genetic Algorithm (CSGA)) developed in [39]. DM4 presents a percentage of robustness (98.4274 %) and introduces a percentage of gap (266.9825 %) to the CS, (69.4574 %) to GA and (4.2199 %) to the CSGA.

Table 3. Comparing DM4 to other methods

Methods	CS		GA		CSGA		DM4		
	Average	Best	Average	Best	Average	Best	Max	Average	Best
Shortest Path (mm)	511.086	504.744	243.168	233.070	152.157	143.343	139.702	138.313	137.539

The graphical representation of the best result generated by DM4 and other methods are depicted in Figure 10.

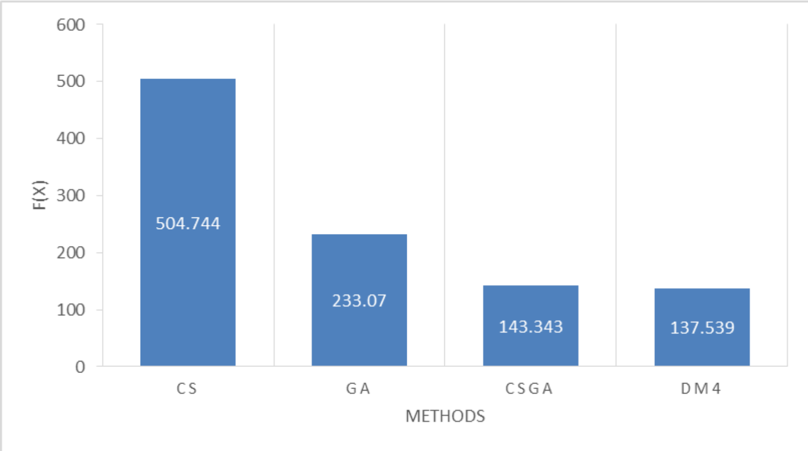

Figure 10. The gap between DM4 and other methods

5 Conclusion

This paper presents the application of the novel metaheuristic Dhouib-Matrix-4 (DM4) to find the shortest drilling path. DM4 is composed of two techniques, first generates an initial basic feasible solution by the novel heuristic Dhouib-Matrix-TSP1 (DM-TSP1), then, intensifies the generated solution through the original Far-to-Near (FtN) local search method. In fact, DM-TSP1 is executed with different statistical metric in order to generate several starting points. The performance of DM4 is tested on several complicated problems and the generated results by DM4 are compared with other methods (CS, GA, CSGA). A novel DM4 method is effective in finding the optimal solution of tool path drilling holes, compared to the previously mentioned methods (for the case of 200 nodes and introduces a percentage of gap 266.9825 % to the CS, 69.4574 % to GA and 4.2199 % to the CSGA method. As perspective, the adaptation of DM4 metaheuristic for the holes drilling path in Multi-Objective and in uncertain environment will be considered.

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