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Hierarchical Coverage Repair Policies Optimization by Dhouib-Matrix-4 Metaheuristic for Wireless Sensor Networks using Mobile Robot

S. Dhouib*

Department of Industrial Management, Higher Institute of Industrial Management, University of Sfax, Tunisia

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ABSTRACT

The wireless sensor networks represent a wide range of potential application, they are composed of a set of energy-constrained sensors used for detecting events and then sending information. In this paper, the novel metaheuristic Dhouib-Matrix-4 (DM4) is enhanced to optimize the coverage repair policies for wireless sensor networks using a mobile robot with different moving speeds. Hierarchically, two conflicted criteria are considered: at first the number of sensors to be visited in time is maximized, then at second, the trajectory distance of the mobile robot is minimized. Therefore, maximizing the lifetime of sensors and minimizing the path of the mobile robot is a challenging issue. DM4 is a multi-start method which uses at each start the novel greedy heuristic Dhouib-Matrix-TSP1 in order to generate an initial basic feasible solution which will be intensified by the new local search technique entitled Far-to-Near. DM4 is applied on several TSP-LIB standard instances from the literature where the moving speed (*w*) of a mobile actor varied from 0.4 to 1. The performance of DM4 is proven by comparing its results to those generated by the Evolutionary Algorithm (EA). DM4 is developed under Python programming language and a graphical representation of the generated solution is illustrated.

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NOMENCLATURE

WSNs	Wireless Sensor Networks	TSP	Travelling Salsmen Problem
DM4	Dhouib-Matrix-4 metaheuristic	EA	Evolutionary Algorithm
w	Static moving speed	d_i	Distance
α_i	Residual survival	β_i	Requested time for mobile robot to join sensor *i*
r_i	Current remaining energy	x_{ij}	Binary decision
c_i	Consumption of energy by time		

1. INTRODUCTION

The Wireless Sensor Networks (WSNs) are composed of a set of sensors used for detecting, measuring and collecting information from real world environments in order to offer a virtual layer for physical world. Indeed, the performance of the WSNs depends on several device parameters such as transmission range, battery and memory which highly constrained the wireless sensors. For that, the use of mobile robots can nicely enhance the performance of the wireless sensor through simultaneously (or separately) collecting information form sensor nodes and (or) delivering energy to these sensor nodes.

The WSNs have many applications in different domains such as prolonging the network lifetime under probabilistic target coverage via localized algorithm based on mobile nodes introduced by Zorbas and Razafindralambo [1], restoring of physical layer failure in the wireless sensor and actor networks using the Grey Wolf metaheuristic with Lagrangian Relaxation [2]. Moreover, a review of the three techniques (collection,

*Corresponding Author Email: souhail.dhouib@gmail.com (S. Dhouib)

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delivery and combination) related to mobile robots in order to enhance the wireless sensor networks performance is presented by Huang et al. [3]. A Bat Algorithm is designed by Kim and Yoo [4] to optimize the target coverage problem with sensor node activation method and a greedy algorithm was proposed by Li and Shen [5] to solve the barrier coverage problem. An integrated algorithm is developed to unravel the scalability problem of robot formation [6] and a biomimetic robotic arm is designed for Teleoperation & Biomedical Applications [7]. Also, Sinks and sensors placement were studied in order to improve the coverage of WSNs by Kabakulak [8] and an enhanced Genetic Algorithm was developed by Harizan and Kuila [9] to improve the coverage and the connectivity for WSNs. A review on several applications of WSNs was considered by Rashid and Rehmani [10] and a survey on WSNs lifetime maximization was studied by Yetgin et al. [11]. Furthermore, a state-of-the-art dedicated for wireless sensor networks with mobile robots summarized by Boukerche and Sun [12] and a survey for the coverage problem in wireless sensor networks under uncertain domain was addressed by Wang et al. [13] and Tian et al. [14].

In this paper, we mainly focus on adapting the novel Dhouib-Matrix-4 (DM4) metaheuristic in order to solve the coverage repair policies hierarchically for wireless sensor networks using a mobile robot with different moving speeds. Originally, DM4 was designed by Dhouib [15] to solve the Travelling Salesman Problem with single objective (only the distance criterion was considered). However, in this current research work DM4 is enhanced to solve hierarchically two criteria: The hierarchical resolution emphasis on the one hand to move the robot mobile to the sensor node and repairs it before its energy runs out (the first goal is to maximize the number of sensors to be visited in time: Therefore, maximizing the number of cover sets lifetime) and on the other hand to minimize the movement of the mobile robot (the second goal is to minimize the trajectory distance: Consequently, improve the performance of the mobile robot). The experiments show the superiority of the proposed DM4 method compared to the Evolutionary Algorithm (EA).

The rest of this manuscript is organized as follows. The second section introduces the coverage repair policies for wireless sensor networks using a mobile robot problem. The third section is the synopsis of basic knowledge related to the novel metaheuristic Dhouib-Matrix-4 (DM4). The experiment will be given to a standard case study developed in the literature with seven scenarios of changing the moving speed from 0.4 to 1 for mobile robot. Finally, the fifth section is the summary of this article.

2. PROBLEM DESCRIPTION

The coverage repair policies in wireless sensor networks using a mobile robot with different moving speeds is a famous combinatorial problem. It deals about a set of static sensors responsible for monitoring a specific area where their battery is reduced through the time and their network coverage will be degraded. For that, energy analysis is considered and every sensor reports its current energy left to the base station. Hence, each sensor with less survival time will be reached via a mobile robot (located at the base station) in order to replenish its energy. This problem is considered as a Travelling Salesman Problem where the sensors are the nodes and the mobile robot is the salesman: The Travelling Salesman Problem is composed of several cities to be visited by a salesman; in fact, the objective is to create a Hamiltonian cycle joining all nodes where each city is visited only once except the starting city which will be the ending one.

Moreover, two criteria are hierarchically considered: maximizing the active sensor (repair the sensor before that its node energy runs out) and minimizing the total trajectory distance. The mathematical formulation of this problem can be described as follows: the wireless sensor networks can be represented by a graph $G=(V,E)$ where V is the set $\{v_1,..,v_n\}$ of vertex (set of sensors) and E is the set $\{e_{ij}\}$ of edges (distances between two sensors i and j, $\forall i, j \in \{1,..,n\}$).
The first objective Equation (1) is to maximize the number of active sensors:

$$
\begin{aligned}
& Max\ f_1(x)=\sum_{i\in V}(\delta_i) \\
& where \\
& \delta_i=\begin{cases}1, \text{ if } (\alpha_i-\beta_i)>0 \\ 0, \text{ if } (\alpha_i-\beta_i)\leq 0\end{cases} \\
& \alpha_i=\frac{r_i}{c_i} \\
& \beta_i=\frac{d_i}{w}
\end{aligned} \tag{1}
$$

α_i represents the residual survival time for node v_i: This node will die if its energy is not added after α_i time. Hence, α_i can be computed by r_i/c_i where r_i is its current remaining energy and c_i its consumption of energy by time.

β_i is the requested time for mobile robot to join sensor i from its current position. Indeed, the mobile actor presents a static moving speed w and needs to cover the distance d_i to join the sensor *i* from its current position.

The second objective Equation (2) is to minimize the total trajectory distance:

$$
\begin{aligned}
&Min\ f_2(x) = \sum_{i=1}^{n}\sum_{j}^{n} x_{ij} d_{ij} \\
&\sum_{i=1}^{n} x_{ij} = 1,\ j = 1,..n \qquad (2) \\
&\sum_{j=1}^{n} x_{ij} = 1,\ i = 1,..n
\end{aligned}
$$

x_{ij} is the binary decision variable: if vertex *j* is visited from vertex *i* $(x_{ij} = 1)$ and if not $(x_{ij} = 0)$.

3. THE PROPOSED METHOD

In this paper, the new metaheuristic named Dhouib-Matrix-4 (DM4) is applied to hierarchically solve the coverage repair policies for WSNs. DM4 has been firstly invented by Dhouib [15] and performed to optimize the shortest path joining all nodes as reported in literature [16-18]. Hence, DM4 is a multi-start technique (see Figure 1) and for each start two independent methods are applied: At first, the novel column-row heuristic Dhouib-Matrix-TSP1 (DM-TSP1) is used to create several initial feasible solutions with different statistical metrics (Min, Max, Mean, Standard deviation etc.); at second, this solution will be used as a starting point by the second method namely the Far-to-Near (FtN). Essentially, DM-TSP1 and FtN are applied in a relay process where the output of the first method will be the input for the second one (For more information about DM-TSP1 and FtN see respectively Dhouib's work [19, 20]).

Hence, DM-TSP1 is a novel greedy method and its performance was tested on different standard problems under crisp, fuzzy, intuitionistic and neutrosophic domains [21-26]. Basically, FtN is a local search method characterized by its organized perturbation process (for more details see literature [20]).

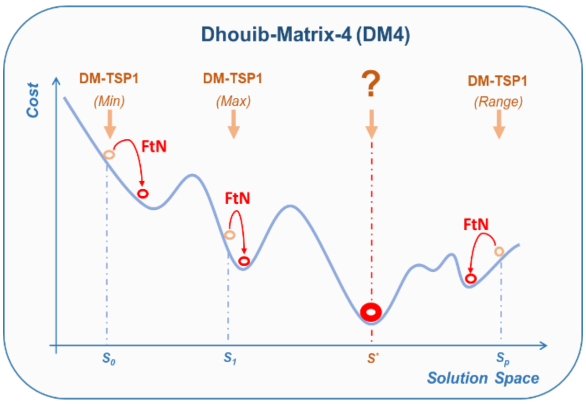

Figure 1. The proposed multi-start DM4 method

Besides, DM4, DM-TSP1 and FtN belong to the concept of Dhouib-Matrix where several other methods are developed such as: the greedy heuristic Dhouib-Matrix-TP1 designed to unravel the transportation problem [27, 28]; the constructive methods Dhouib-Matrix-AP1 [29-31] and Dhouib-Matrix-AP2 [32] which are dedicated to solve respectively the balanced and unbalanced assignment problem. Moreover, an iterative stochastic metaheuristic entitled Dhouib-Matrix-3 is designed and tested by Dhouib [33], Dhouib and Zouari [34, 35]. Lastly, an optimal technique called Dhouib-Matrix-SPP is invented to rapidly unravel the shortest path problem [36].

In this paper, the coverage repair policies for WSNs will be considered with two hierarchical criteria (f_1 and f_2) where the first criterion (see Equation (1)) aims to maximize the number of active sensors (repairing the sensor before that its node energy runs out) and the second criterion (see Equation (2)) targets to minimize the total trajectory distance. Thus, for hierarchical criteria the first criterion is considered first then only in the case of equality the second criterion will be considered: for example, for two realizable solutions (x_1 and x_2), the solution (x_1) is better than the solution (x_2) in two cases: on the one hand, if $f_1(x_1) > f_1(x_2)$ (nevertheless the value of $f_2(x_1)$ and $f_2(x_2)$); on the other hand, if $f_1(x_1) = f_1(x_2)$ and $f_2(x_1) < f_2(x_2)$. Figure 2 illustrates the pseudo-code of the proposed DM4 method for the hierarchical coverage repair policies for WSNs.

The novel greedy method DM-TSP1 is depicted in Figure 3.

Figure 4 represents the flowchart of the innovative local search FtN method.

DM4 algorithm for Hierarchical Coverage Repair Policies for WSNs

Input: Distance matrix (*Matrix*), Residual survival time (α_i)
Output: Optimal solution

1. Set $S^*\_f_1$ and $S^*\_f_2$
2. *List-Metrics {Min, Max, Range, Mean, Mode, Sum, Q3, StDev}*
3. Set *Ctp-Start* (the number of metrics in the *List-Metrics*)
4. Set *Step* := 1
5. Repeat
   a. Select the metric number *Step* in the *List-Metrics*
   b. (S'_f_1, S'_f_2) := DM-TSP1 (*Matrix*, α_i, *List-Metrics[Step]*)
   c. (S''_f_1, S''_f_2) := FtN (*Matrix*, α_i, S'_f_1, S'_f_2)
   d. If $(S^*\_f_1 < S''\_f_1)$ or $((S^*\_f_1 = S''\_f_1)$ and $(S^*\_f_2 > S''\_f_2))$
      i. $S^*\_f_1 = S''\_f_1$
      ii. $S^*\_f_2 = S''\_f_2$
   e. *Step* := *Step* + 1
6. Until termination condition is met (*Step* = *Ctp-Start*)
7. Return $(S^*\_f_1, S^*\_f_2)$

Figure 2. The pseudo-code of the proposed DM4 metaheuristic to optimize hierarchically the coverage repair policies for WSNs

Dhouib-Matrix-TSP1 (DM-TSP1) Algorithm

```
Input: Distance matrix, Residual survival time, Metric
Output: S'_f1 and S'_f2
Set Path = {}
Compute the Metric (Min, Max, Average … etc.) for each row, select the
smallest generated value and find the minimal element d_xy for this row
Path = {x,y}
Discard column x and column y
for i=1 to number of cities
    find the minimal element d_xa in row x
    find the minimal element d_yb in row y
    if (d_xa < d_yb) then
        insert a before x in the list Path
        x = a
    else
        insert b after y in the list Path
        y = b
    end
end
Compute S'_f1 and S'_f2 from Path
Return S'_f1 and S'_f2
```

Figure 3. The pseudo-code of the novel greedy DM-TSP1 method

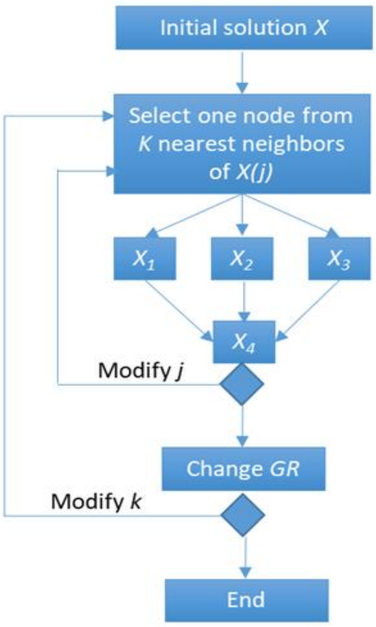

Figure 4. The flowchart of the FtN method [11]

4. EXPERIMENTAL RESULTS

The novel metaheuristic DM4 is applied to optimize the coverage repair policies for fourteen sensors using a moving actor with seven scenarios by changing the moving speed (*w*) from 0.4 to 1 (see Table 1). This is a standard instance originally taken from literature [37] where an Evolutionary Algorithm (EA) is performed in order to optimize the time and distance for the coverage repair strategy on behalf of the wireless network problem.

TABLE 1. The coordinates of 14 sensors with their residual survival times

Sensors	*X*	*Y*	Residual Survival Time (α_i)
1	16.47	96.10	39
2	16.47	94.44	27
3	20.09	92.54	36
4	22.39	93.37	23
5	25.23	97.24	39
6	22.00	96.05	37
7	20.47	97.02	35
8	17.20	96.29	37
9	16.30	97.38	39
10	14.05	98.12	35
11	16.53	97.38	36
12	21.52	95.59	33
13	19.41	97.13	23
14	20.09	94.55	24

No parameters are required for the metaheuristic DM4, just the stopping criterion which is fixed by no improvement of the current solution. Table 2 depicts the generated results and the performance of DM4 is computed for the two criteria using respectively Equation (3) (maximizing the number of active sensors) and Equation (4) (minimizing the total trajectory distance).

$$\%Perfomance_{f1} = \left(\frac{EA - DM4}{DM4} * 100 \right) \quad (3)$$

$$\%Perfomance_{f2} = \left(\frac{DM4 - EA}{EA} * 100 \right) \quad (4)$$

Obviously, DM4 generates four new better solutions than EA (respectively for instances with moving speed of 0.4, 0.5, 0.8 and 0.9) and finds the same results for the remaining three instances (thus, the improvement percentage is 19.96%). Besides, DM4 is developed under a Python programming language and a graphical representation of the generated solution are given.

Figure 5 illustrates the solution obtained by DM4 (after two seconds) with a moving speed varying from (*w*=0.4) to (*w*=1).

Figure 6 depicts the solutions generated by the two metaheuristics DM4 and EA for the two conflictual criteria. Obviously, DM4 outperforms EA on the first criterion (maximize f_1) for instances with speeds (*w*=0.4) and (w=0.8); concerning the second criterion (minimize f_2), DM4 outperforms EA especially for the instances with speeds (w=0.5) and (w=0.9).

TABLE 2. The generated results by DM4 and EA

W	The DM4 solutions	DM4		EA		% Performance	
		f_1	f_2	f_1	f_2	f_1	f_2
0.4	0-8-10-7-12-6-13-11-5-4-3-2-1-9-0	**10**	**33.4954**	9	31.2088	**10.00**	-
0.5	0-1-7-8-10-12-6-13-11-5-4-3-2-9-0	**11**	**36.2439**	11	36.4161	-	**0.47**
0.6	0-9-8-10-7-12-6-13-2-11-5-4-3-1-0	12	34.9211	12	34.9211	-	0.00
0.7	0-1-9-8-10-7-12-6-13-2-3-11-5-4-0	13	35.6519	13	35.6519	-	0.00
0.8	0-1-9-8-10-7-12-6-13-3-2-11-5-4-0	**14**	**37.2112**	13	30.8785	**7.14**	-
0.9	0-7-12-6-11-5-4-3-2-13-1-9-8-10-0	**14**	**31.2269**	14	31.9583	-	**2.34**
1.0	0-1-13-2-3-4-5-11-6-12-7-10-8-9-0	14	30.8785	14	30.8785	-	0.00

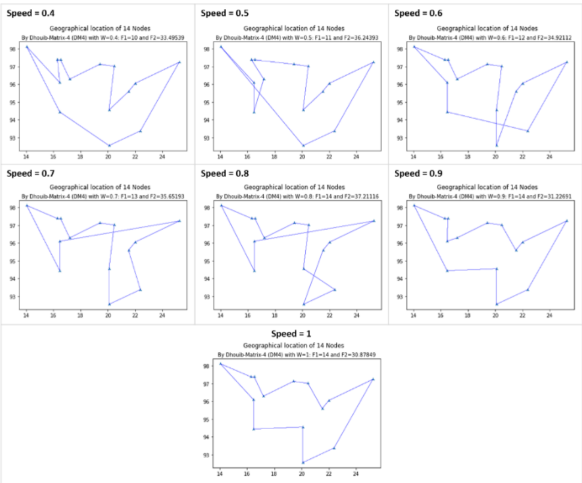

Figure 5. The solutions generated by DM4 with different moving speeds from (w=0.4) to (w=1)

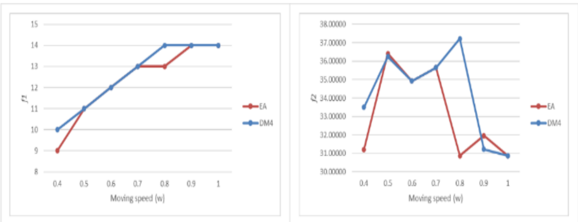

Figure 6. Comparing DM4 to EA with maximizing f_1 and minimizing f_2

Another example is considered from TSP-LIB entitled Berlin-52 where DM4 is applied to optimize the coverage repair policies for fifty one sensors using a moving actor with seven scenarios by changing the moving speed (*w*) from 0.4 to 1 (see Table 3).

Figure 7 illustrates the generated solutions by DM4 (after an average of 6 seconds) for Berlin-52 TSP-Lib instance with different moving speeds (from 0.4 to 1).

TABLE 3. The generated results by DM4 for Berlin-52 problem

W	The DM4 solutions	DM4	
		f_1	f_2
0.4	0-21-17-30-20-22-19-49-15-43-45-24-3-5-14-4-23-47-36-37-39-38-33-34-35-48-31-44-18-40-7-8-9-42-32-50-11-10-51-13-12-26-27-25-46-28-29-41-1-6-16-2-0	34	8104.01187
0.5	0-21-30-17-2-16-20-41-6-1-29-22-19-49-15-43-45-24-3-5-14-4-23-47-37-36-39-38-33-34-35-48-31-44-18-40-7-8-9-42-32-50-11-10-51-13-12-26-27-25-46-28-0	38	8070.62699
0.6	0-21-48-31-44-18-7-40-2-17-30-20-41-6-1-29-22-19-49-28-15-45-43-33-34-35-38-39-37-36-47-23-4-14-5-3-24-11-27-26-25-46-12-13-51-10-50-32-42-16-8-9-0	42	8948.94064
0.7	0-21-48-31-44-18-9-8-7-40-2-16-17-30-20-41-6-1-29-22-19-49-28-15-45-43-33-34-35-38-39-36-37-47-23-4-14-5-3-24-11-27-26-25-46-12-13-51-10-50-32-42-0	45	8105.87697
0.8	0-21-30-17-2-16-20-41-6-1-29-22-19-49-28-15-45-43-33-34-35-48-31-44-18-40-7-8-9-42-14-4-23-47-36-38-39-37-5-3-24-11-27-25-26-12-13-46-51-10-50-32-0	48	8654.12008
0.9	0-48-31-21-30-17-2-44-18-40-7-8-9-42-32-50-10-51-13-12-46-25-26-27-11-24-3-5-14-4-23-47-37-36-39-38-35-34-33-43-45-15-28-49-19-22-29-41-6-1-16-20-0	50	7863.03197
1.0	0-48-31-21-30-17-2-16-20-41-6-1-29-22-19-49-28-15-45-43-33-34-35-38-39-36-37-47-23-4-14-5-3-24-11-27-26-25-46-12-13-51-10-50-32-42-9-8-7-40-18-44-0	52	7684.23141

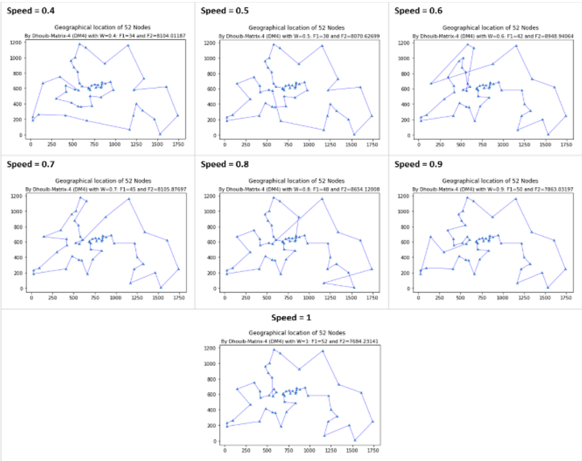

Figure 7. The solutions generated by DM4 for the Berlin-52 problem with different moving speeds from (w=0.4) to (w=1)

5. CONCLUSION

A Wireless Sensor Networks are mainly used to create a virtual layer from the physical world through exchanging information from a set of sensors. The purpose of the current study was to hierarchically optimize the coverage repair policies for wireless sensor networks using a mobile robot with different moving speeds by enhancing the novel Dhouib-Matrix-4 (DM4) metaheuristic. DM4 is improved to maximize at first the numbers of nodes to be visited in time and at second to minimize the trajectory distance.

This DM4 method is compared to the Evolutionary Algorithm on seven standard instances taken from the literature where the moving speed (w) of a mobile actor is varied from 0.4 to 1. The robustness of DM4 is proved by outperforming the Evolutionary Algorithm on four instances and finding the same results for the remaining three instances. Moreover, DM4 is simulated on other instances (dealing about 52 sensors) with diferent moving speeds.

As far as we know, no one in the literature generated the Pareto non dominated set solutions for the problem of coverage repair policies for wireless sensor networks using a mobile robot with different moving speeds. Despite this limitation, in future work we hope to use the proposed Dhouib-Matrix-4 metaheuristic to generate the Pareto non dominated set solutions for maximizing the numbers of nodes to be visited in time and in parallel (instead of hierarchical resolution) for minimizing the trajectory distance.

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Persian Abstract

چکیده

در این مقاله، فراابتکاری جدید Dhouib-Matrix-4 (DM4) برای بهینه‌سازی سیاست‌های تعمیر پوشش برای شبکه‌های حسگر بی‌سیم با استفاده از یک ربات متحرک با سرعت‌های متحرک متفاوت، بهبود می‌یابد. به صورت سلسله مراتبی، دو معیار متناقض در نظر گرفته می شود: ابتدا تعداد گره هایی که باید در زمان بازدید شوند به حداکثر می رسد، سپس در مرحله دوم، فاصله مسیر به حداقل می رسد. DM4 یک روش چند استارتی است که در هر شروع از اکتشافی حریصانه جدید Dhouib-Matrix-TSP1 استفاده می کند تا یک راه حل اولیه اولیه را ایجاد کند که توسط تکنیک جستجوی محلی جدید با عنوان Far-to-Near تشدید می شود. DM4 در هفت نمونه استاندارد از ادبیات استفاده می شود که در آن سرعت حرکت (w) یک بازیگر متحرک از ۰.٤ تا ۱ متغیر است. عملکرد DM4 با مقایسه نتایج آن با نتایج ایجاد شده توسط الگوریتم تکاملی (EA) که در آن DM4 عملکرد بهتری دارد اثبات می شود. EA در چهار نمونه و نتایج یکسانی را برای سه نمونه یادآوری می یابد. DM4 تحت زبان برنامه نویسی پایتون توسعه یافته است و یک نمایش گرافیکی از راه حل تولید شده نشان داده شده است.