A DSS based on Intelligent optimisation algorithms for solving the Postal Transportation Problem

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***Abstract*—The postal sector is essential in enhancing services for businesses and individuals by establishing a reliable communication network that ensures the efficient collection, transfer, and global delivery of mail, funds, and parcels. Consequently, optimizing routing and packing systems for the collection and transportation of letters and parcels is a critical component of an effective delivery management system. Traditionally, postal distribution challenges are modeled as Capacitated Vehicle Routing Problems (CVRP). To account for parcel dimensions, this paper introduces the Capacitated Vehicle Routing Problems with Two-Dimensional Loading Constraints (2L-CVRP). The problem involves designing routes that originate and terminate at a central depot, using a fleet of identical vehicles to meet demands at multiple locations. Furthermore, items transported in each vehicle must comply with two-dimensional orthogonal packing constraints, with the primary objective of minimizing total transportation costs. Given the NP-hard complexity of this problem, the paper proposes a hybrid metaheuristic that integrates Variable Neighborhood Search (VNS) with a Genetic Algorithm (GA) to improve GA's convergence toward high-quality solutions. This hybrid method capitalizes on GA's exploratory strengths and VNS's ability to effectively exploit the solution space. VNS is incorporated into GA's mutation operator, broadening and diversifying the solution space, thereby enabling the hybrid algorithm to explore new regions within the search space more effectively. We design a Decision Support System (DSS) that uses a hybrid HGA-VNS to fulfill customer needs and enhance the efficiency of vehicle routing. The proposed method is tested against both generated and existing approaches using benchmark instances. Empirical results on 210 benchmark instances demonstrate the competitiveness of the hybrid approach hybrid approach is highly competitive in terms of solution quality. Overall, the experiments highlight that the Hybrid GA-VNS provides an efficient solution for the 2L-CVRP, delivering results that are on par with state-of-the-art methods.**

***Index Terms*—CVRP with two-dimensional loading constraints, Variable Neighborhood Search (VNS), Genetic Algorithm (GA), Tunisian Post Office**

I. Introduction

The postal sector is vital in improving services for businesses and individuals, playing a key role in driving development and promoting economic, social, and financial inclusion. As such, optimizing the routing and packing systems for collecting and transporting letters and parcels is a critical aspect of an efficient delivery management system. Numerous studies have been conducted to address the challenge of finding optimal solutions for logistics distribution. One of the most widely researched problems in operations research and combinatorial optimization is the CVRP. This problem focuses on determining the most efficient routes for a fleet of vehicles to deliver goods or services to customers while respecting vehicle capacity limits and minimizing transportation costs or distances. A notable variant of CVRP is the 2L-CVRP, which incorporates two-dimensional loading constraints. This variant is based on the symmetric CVRP, where customer demands include items with weight and two-dimensional measurements. The primary objective is to minimize total transportation costs using a fleet of identical vehicles. This involves designing routes that start and end at a central depot while ensuring that items in each vehicle comply with two-dimensional orthogonal packing constraints. This problem, along with its variations, remains a significant area of research in academia. The integration of packing and routing tasks is essential for addressing optimization challenges in supply chain management. Efficiently organizing items into vehicles and planning delivery routes can lead to reduced logistics costs and faster delivery times. As a result, optimizing the interaction between these practical issues has garnered considerable attention and has become a central focus of recent research.

Given that the 2L-CVRP combines two NP-Hard problems, we propose a novel hybrid approach called HGA-VNS to tackle the 2L-CVRP. This innovative method combines GA and VNS. In HGA-VNS, a unique mutation operator inspired by VNS is applied to each individual in the population. This enables the hybrid GA to generate high-quality solutions, including optimal ones, while also exploring new regions of the search space.

To evaluate the performance of HGA-VNS, we conducted extensive experiments using various benchmark instances from existing literature, comparing it to well-established state-of-the-art algorithms. Optimizing the routing system for collecting and transporting letters and parcels is a crucial element of an efficient delivery management system. The transportation of goods is one of the most critical tasks in logistics, and a well-designed distribution strategy not only improves customer satisfaction but also reduces transportation costs. As a result, significant efforts have been made to develop effective solutions for optimizing logistics distribution planning in the postal sector. We successfully applied our approach to a real-world scenario involving the Tunisian Post Office (TPO), outperforming current methods in use. The proposed HGA-VNS approach delivered significantly improved solutions, highlighting its potential for practical applications in the field.

II. Related work

The 2L-CVRP problem was first introduced by Iori et al. (2007) [1], who used a Branch-and-Cut approach for the routing problem and a Branch-and-Bound method for the packing problem to solve small-scale instances. Since then, numerous metaheuristics have been developed to address the 2L-CVRP. State-of-the-art solutions include VNS [3], Simulated Annealing (SA) [4], and an adaptive GA [9]. Ferreira et al. [6] proposed a location-routing problem with two-dimensional loading constraints, combining Simulated Annealing with the Artificial Algae Algorithm. More recently, Soman and Patil (2023) [8] presented an integrated mathematical formulation to simultaneously model routing and loading requirements for small-scale instances, along with a scatter search-based heuristic for large-scale instances of the CVRP with release and due dates (VRPRDD) and two-dimensional unrestricted loading for oriented loading. Ji et al. (2023) [11] addressed the many-to-many heterogeneous vehicle routing problem with cross-docking and two-dimensional loading constraints (2L-MVRPCD) using a mixed integer linear programming model for small-scale instances. For large-scale problems, they proposed two hybrid heuristic approaches: an Adaptive Large Neighborhood Search (ALNS) algorithm with a new Best-Fit-Skyline (BFS) packing heuristic and a Tabu-based ALNS (ALNS/TS). Additionally, Zhang et al. (2023) [12] studied the two-dimensional loading-constrained vehicle routing problem with stochastic customers (2L-VRPSC) under various loading configurations, such as unrestricted oriented loading (2—UO—L), unrestricted rotated loading (2—UR—L), sequential oriented loading (2—SO—L), and sequential rotated loading (2—SR—L). They proposed an Enhanced Adaptive Tabu Search (EATS) algorithm incorporating the Multi-Order Bottom-Fill-Skyline (MOBFS) packing heuristic.

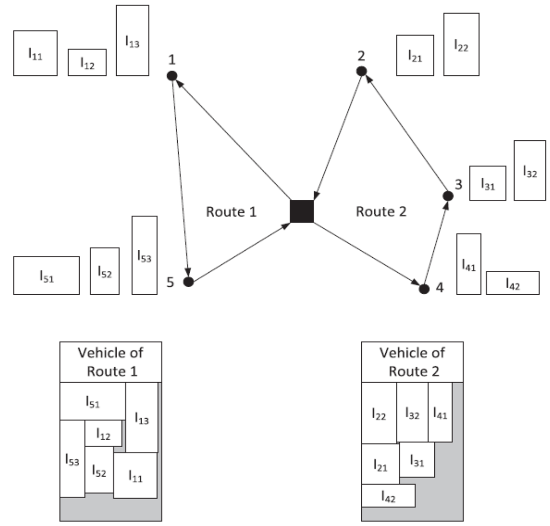

Fig. 1. 2L-CVRP solution

In the literature, various hybrid GA extensions have been proposed to tackle routing problems. Vidal (vidal2012hybrid) introduced the Unified Hybrid Genetic Search (UHGA), a Hybrid GA with Adaptive Diversity Control. UHGA integrates evolutionary search, local search, and advanced population management techniques to address challenges such as the multi-depot Vehicle Routing Problem (VRP), the periodic VRP, and the multi-depot periodic VRP. HGA-VNS has demonstrated its effectiveness in solving routing problems like the CVRP through numerical experiments [7].

In this study, we propose a hybrid approach to address the 2L-CVRP. This method combines GA and VNS, incorporating a specialized mutation operator based on VNS for each individual in the population. As a result, the hybrid GA can identify high-quality solutions, including optimal ones, while exploring previously uncharted regions of the search space.

III. Problem Definition

The 2L-CVRP is defined as a complete undirected graph $G = (V, E)$, where V represents the set of vertices and E consists a set of edges. Goods are transported using a set of K vehicles with a weight capacity Q and a loading surface with width W and length H. $h_{il} > 0$ and $w_{il} > 0$ are the length and width dimensions of customer's item. A nonnegative cost c_{ij} is associated with each edge. Figure 1 provides a 2L-CVRP solution with 5 customers and two distinct routes, illustrating the practical application of the problem

IV. Proposed HGA-VNS

As highlighted earlier, the main contribution of this paper is the integration of GA and VNS, termed HGA-VNS, to solve the 2L-CVRP. This hybrid approach leverages the exploration strengths of GA and the exploitation capabilities of VNS. In HGA-VNS, GA acts as the foundational algorithm, while VNS is employed as a mutation operator to improve individuals within the population, with a fixed mutation rate of 0.20. Each individual in the population contributes to generating new offspring solutions through genetic operators such as selection and crossover. Additionally, a specialized mutation operation, inspired by VNS, is applied to the path of each individual in the population. This dual mechanism enables the algorithm to effectively exploit existing solutions. This iterative process continues until a predefined maximum number of generations (iterations) is achieved, as detailed in Algorithm 1, which outlines the core steps of the HGA-VNS approach. We provide a more in-depth explanation of our proposed HGA-VNS methodology.

A. Genetic Algorithm

GA is widely recognized and utilized by researchers as a leading metaheuristic for solving VRP. In the standard GA framework, the process begins with the generation of an initial population of solutions. This is accomplished using a Greedy Randomized Adaptive Search Procedure (GRASP), which produces a set of feasible routes connecting different pairs of vertices. A more detailed discussion of GRASP will be provided. Once of routes is established, each individual solution is evaluated using a fitness function. Following this, a series of genetic operations—selection, crossover, and mutation—are applied to enhance the algorithm's ability to identify better solutions.

Further details regarding GA steps will be provided later in this article.

Algorithm 1 The HGA-VNS approach for the CVRP

```
Begin
Step 1: Generate the initial population : GRASP
Step 2: Evaluate each population: Fitness function
while  stopping criterion is not satisfied do
    Step 3: Apply Genetic operators
    Repeat
    Step 3.1: Select two parents from the current population: Tournament selection
    Step 3.2: Apply Crossover operator: PMX to generate new individuals (offspring)
    Step 3.3: Apply Mutation operator: (VNS): Perform VNS after each individual is selected in the population as a mutation operator
    Step 4: Replace the old population by the new one
end while
Step 5: Output the best founded solution: Individual with the best evaluation.
END =0
```

B. Variable Neighborhood Search: Mutation

the mutation operator consists of randomly changing the individual genes with a low probability. To improve the exploitation of the solution space, we integrate the Variable Neighborhood Search (VNS) procedure into the new population as a mutation operator. VNS employs four neighborhood structures, which are outlined below: **Intra-route moves** :

Insertion: Randomly selecting a customer and inserting them at a random position within the same route.

2-opt: Swapping pairs of links to optimize the route.

Inter-route moves :

Relocate: Moving a customer from one route to another in a random manner.

Exchange: Transferring a sequence of customers from one route (route1) to another (route2).

Parameters	Values
Population Size (N)	500
Selection	The tournament selection
Crossover rate	0,65
Mutation rate	0,20
VNS termination criteria	$kmax = 4$
Offspring	500
Maximum number of generations	1500

Fig. 2. HGA-VNS parameters

C. Stopping criteria

Evolutionary algorithms employ multiple stopping criteria, in our case, the algorithm runs until it reaches a predetermined limit of 1500 generations.

D. Two-dimensional packing problem

The NFDH (Next-Fit Decreasing Height) algorithm arranges items into horizontal levels, sorting them in decreasing order based on their length dimension and placing them in rows. Each row's base is called a level, with the two lines defining a level referred to as the ”floor” and ”ceiling” or the ”bottom” and ”top.” The first level aligns with the bottom of the bin, with its height determined by the first packed item of the last visited customer. Items are packed sequentially from left to right, aligning their bottoms with the current level until an item no longer fits. When this occurs, a new level is created with a height equal to the new item's dimension along the horizontal line, and the packing process resumes at this new level.

V. Experiments

A. Software-Hardware Implementation

Our proposed HGA-VNS algorithm was developed using Java Language version 7. All experiments were conducted on a PC with an 11th Gen Intel(R) Core(TM) i5-1135G7 CPU and 8 GB of RAM, running on Microsoft Windows 11 Pro. The stopping criterion for HGA-VNS involved running the algorithm 10 times for each instance.

B. Parameter settings

Figure 2 illustrates the used parameter settings.

C. Benchmarks

To assess the algorithm's performance, we created a collection of test instances for the 2L-CVRP by extending existing CVRP instances from literature sources, as described in Uchoa (uchoa2017new). These instances were obtained from the website http://vrp.atd-lab.inf.puc-rio.br/index.php/en/.

D. Computational results on 2L-CVRP benchmark instances

We present a comparative analysis of state-of-the-art algorithms using 2L-CVRP benchmark instances. The evaluated methods include the VNS by Wei et al. (2015) ([3]), the Simulated Annealing (SA) approach by Wei et al. (2017) ([4]), and the Parallel (PVNS) by Sbai et al. (2020) [10]. Table 1 provides a summary of the numerical results, highlighting the best solutions obtained and the computational time for Class 1. The first column lists the benchmark instances along with their Best Known Solution (BKS). For each algorithm, the columns labeled (Cost) present the best solutions found, while the (CPU) columns indicate the average computation time in seconds required to achieve these solutions. Additionally, the (%gap) columns display the percentage difference between the solutions generated by our HGA-VNS approach and the BKS, calculated using the following formula.

$$\%gap = 100((BKS - C_{HGA-VNS})/BKS)$$

E. Results for Class 1

In Table 1 it can be observed that the proposed HGA-VNS ranks first among all the algorithms, achieving the best results (BKS) for 28 out of the 36 tested instances, with a percentage optimality of 76%, outperforming SA.

In terms of the best-found solutions, Table 1 shows that HGA-VNS provides optimal solutions for 6 out of 36 instances, with an average percentage gap Avg_{gap} of 0.20% while HGA-VNS achieves an Avg_{gap} of 0.009%. These Avg_{gap} values demonstrate the effectiveness of HGA-VNS in obtaining high-quality solutions. Additionally, HGA-VNS delivers an average CPU time (Avg_{cpu} time) of 221.37 s seconds, which is faster than VNS, SA, and PVNS. Accordingly, it is evident that HGA-VNS is highly efficient for solving the addressed datasets. Specifically, it generates up to 75% of optimal solutions for a given dataset, with an Avg_{gap} that does not exceed 0.20%. These findings clearly highlight the effectiveness of the proposed approach.

VI. The TPO case study

For the fourth consecutive year, the Tunisian Post Office (TPO) has been recognized as the leading postal institution. TPO places a strong emphasis on e-commerce as part of its strategy to establish itself as a key player at the national, regional, and continental levels.

We examine the transportation of two-dimensional parcels across 29 post-parcel TPO agencies. We used the HGA-VNS to address the case of TPO, aiming to minimize the total transportation cost. The dataset includes over 356,000 parcels. TPO provides parcel delivery services to approximately 80,000 Tunisian customers engaged in e-commerce. The vehicle loading surface dimensions(length L, width$W$) is fixed to $(40,20)$ for all instances. To ensure the safe handling of parcels, the post-parcel agency offers various packaging options, including boxes of different sizes, designed to securely and effectively protect the contents. Each parcel is characterized by its two dimensions, height h and width w. Table 3 provides an example of a two-dimensional parcel packing (2DPP) scenario. The first column lists the pathways, the second column identifies the post-parcel agencies (PPA), columns 4 to 8 detail the number of parcels, and the last column presents the total weight in kilograms (Kg).

The results, as shown in Table 2, demonstrate that the HGA-VNS algorithm for the 2L-CVRP outperforms the existing HGA-VNS for CVRP proposed by [7]. Specifically, it reduces the total cost by up to 12% compared to the previous approach, achieving a total cost of 7134.808 DT over 10 days.

In summary, the application of the proposed HGA-VNS approach to the TPO case study has proven highly effective, significantly reducing fleet size requirements and travel costs compared to current scheduling practices. Additionally, the findings highlight that optimizing item arrangement within vehicles, considering both width and height constraints, along with strategic route planning, can lead to lower logistics costs and faster delivery times.

VII. A Decision Support System Architecture

We develop a Decision Support System (DSS) based on a HGA-VNS algorithm to meet all customer requirements and optimize vehicle routes (refer to Fig. 3). The first step involves inputting the problem parameters, such as the number of customers, vehicle capacity, and the number of available vehicles. In the second step, once the data is entered, geographic coordinates and customer demands are defined. The Genetic Algorithm then iteratively combines with VNS to diversify the exploration. After generating a numerical solution, the DSS proceeds to create a cartographic representation of the actual routes. In this context, it is crucial to take into account geographical landmarks that may impact distribution operations. For instance, an itinerary that passes by an educational facility, even if shorter, should be avoided during peak hours (8:00, 12:00, and 17:00). Finally, the vehicle pathways are highlighted.

TABLE I
COMPARATIVE RESULTS BETWEEN BKS, VNS, SA, PVNS, AND HGA-VNS FOR CLASS 1 INSTANCES

Instance	**BKS**	**VNS**			**SA**			**PVNS**			**HGA-VNS**		
		Cost	**CPU(s)**	**%gap**									
1.	278.73	278.73	0.0	0.00	278.73	0.9	0.00	278.73	0.0	0.0	278.73	0,20	0,00
2.	334.96	334.96	0.0	0.00	334.96	0.3	0.00	334.96	0.0	0.0	334.96	0,0	0,00
3.	358.40	358.40	0.1	0.00	358.40	1.0	0.00	358.40	0.1	0.0	358.40	0,1	0,00
4.	430.88	430.89	0.0	0.00	430.89	0.9	0.00	430.88	0.0	0.0	430.88	0,3	0,00
5.	375.28	375.28	0.0	0.00	375.28	0.0	0.00	375.28	0.0	0.0	375.28	0,0	0,00
6.	495.85	495.85	0.1	0.00	495.85	2.5	0.00	495.85	0.1	0.0	495.85	0,0	0,00
7.	568.56	568.56	0.0	0.00	568.56	0.0	0.00	568.56	0.0	0.0	568.56	0,1	0,00
8.	568.56	568.56	0.0	0.00	568.56	0.0	0.00	568.56	0.0	0.0	568.56	0,0	0,00
9.	607.65	607.65	0.1	0.00	607.65	1.1	0.00	607.65	0,2	0.0	607.65	0,0	0,00
10.	535.74	535.80	0.1	-0.01	535.80	5.8	-0.01	535.74	0,2	0.0	535.74	0,1	0,00
11.	505.01	505.01	0.0	0.00	505.01	0.6	0.00	505.01	0,1	0.0	505.01	0,1	0,00
12.	610.00	610.00	0.9	0.00	610.00	5.4	0.00	610.00	0,1	0.0	610.00	0,7	0,00
13.	2006.34	2006.34	0.1	0.00	2006.34	0.0	0.00	2006.37	0,2	-0.001	2006.37	0,0	-0,01
14.	837.67	837.67	0.1	0.00	837.67	0.0	0.00	837.67	0,2	0.0	837.67	0,1	0,00
15.	837.67	837.67	0.1	0.00	837.67	0.0	0.00	837.67	0,2	0.0	837.67	0,1	0,00
16.	698.61	698.61	1.1	0.00	698.61	4.0	0.00	698.61	1,2	0.0	698.61	1,0	0,00
17.	861.79	861.79	4.0	0.00	861.79	22.2	0.00	861.78	4,1	0.001	861.79	4,0	0,00
18.	723.54	723.54	1.4	0.00	723.54	6.7	0.00	723.54	1,5	0.0	723.54	4,1	0,00
19.	524.61	524.61	2.0	0.00	524.61	9.0	0.00	524.61	2,1	0.0	524.61	2,0	0,00
20.	241.97	241.97	3.5	0.00	241.97	14.6	0.00	241.97	3,6	0.0	241.97	5,2	0,00
21.	687.60	687.60	74.9	0.00	687.60	343.8	0.00	687.60	75	0.0	687.60	62,3	0,00
22.	740.66	740.66	21.2	0.00	740.66	101.1	0.00	740.66	21,3	0.0	740.66	32,1	0,00
23.	835.26	835.26	159.7	0.00	835.26	838.0	0.00	835.26	159,8	0.0	835.26	205,6	0,00
24.	1024.69	1024.69	175.9	0.00	1024.69	1250.2	0.00	1024.69	176	0.0	1024.69	183,4	0,00
25.	826.14	826.14	332.2	0.00	826.14	418.0	0.00	826.14	332,3	0.0	826.14	277,8	0,00
26.	819.56	819.56	1.7	0.00	819.56	1.6	0.00	819.53	1,8	0.003	819.56	2,9	0,00
27.	1082.65	1082.65	445.5	0.00	1082.65	1306.0	0.00	1082.65	445,6	0.0	**1081,43**	298,9	**0,11**
28.	1040.70	1042.12	1021.5	-0.14	1042.12	24.6	-0.14	1040.70	1021,6	0.0	1040.70	78,54	0,00
29.	1162.96	1162.96	172.9	0.00	1162.96	35.9	0.00	1162.96	173,0	0.0	**1162,37**	167,32	**0,05**
30.	1028.42	1028.42	1570.0	0.00	1029.79	1435.8	-0.13	1028.42	1570,1	0.0	1028.42	588,93	0,00
31.	1299.56	1302.48	1813.8	-0.22	1301.03	1884.0	-0.11	1299.48	1813,9	0.006	1299,97	920,57	-0,03
32.	1296.91	1300.22	1976.1	-0.26	1300.30	2006.9	-0.26	1296.91	1976,2	0.0	1296.91	917,83	0,00
33.	1298.02	1298.02	2204.1	0.12	1296.13	1884.2	0.15	1298.01	2204,2	0.118	**1294,28**	933,71	**0,29**
34.	708.39	708.39	2125.2	0.20	708.66	1658.3	-0.04	708.37	2125,3	0.204	**706,13**	1022,55	**0,32**
35.	865.39	865.39	2050.4	0.08	862.79	1611.0	0.30	866.06	2050,5	0.0	**862,78**	1137,43	**0,3**
36.	585.46	586.49	2420.2	-0.18	583.98	1276.3	0.25	585.45	2420,3	0.002	**581,93**	1121,27	**0,6**
Avg.	769.56	769.80	460.53	-0.02	769.62	448.64	-0.01	769.575	460.60	0.009	**769.18**	221.37	0.20

TABLE II
10-DAYS TPO EXISTING SOLUTIONS AND HGA-VNS SOLUTIONS

Instance	**TPO existing (DT)**	**HGA-VNS for CVRP [7](DT)**	**Difference-exit (DT)**	**Our HGA-VNS for 2L-CVRP (DT)**	**Difference-exit (DT)**	**Difference HGA-VNS (CVRP and 2L-CVRP)**
TPO1	5784	5212,85	571,15	4487,03	1296,97	725,82
TPO2	6886,88	6778,09	108,79	6145,65	741,23	632,44
TPO3	6461,18	6253,06	208,12	5785,68	675,5	467,38
TPO4	6267,25	6090,348	176,902	5879,87	387,38	210,478
TPO5	6737,412	6609,702	127,71	6175,44	561,97	434,26
TPO6	6693,896	6451,72	242,176	5285,21	1408,69	1166,51
TPO7	5335,44	5124,482	210,958	4596,41	739,03	528,07
TPO8	5675,054	5411,12	263,934	4298,28	1376,774	1112,84
TPO9	4947,58	4846,358	101,222	3278,94	1668,64	1567,418
TPO10	6175,488	5976,828	198,66	5687,24	488,25	289,59
AVG			2209,622		**9344,43**	**7134,808**

Difference-exit (DT): presents the difference cost in (DT) between the two problems and the existing TPO cost.

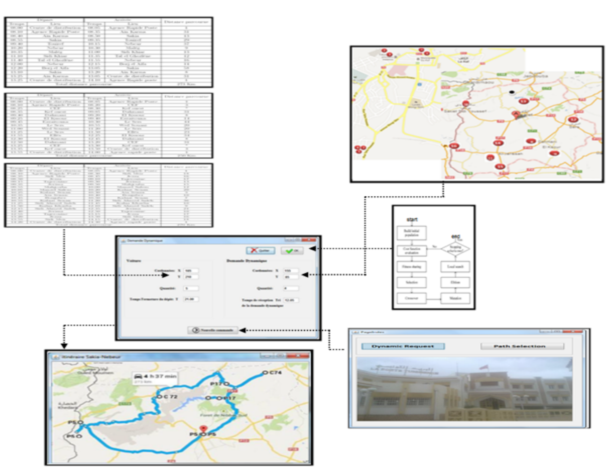

Figure 3: A post office DSS

VIII. CONCLUSION

This study delves into the Capacitated Vehicle Routing Problem with two-dimensional loading constraints (2L-CVRP) within the context of post distribution. Given its NP-Hardness, addressing the problem necessitates the application of approximate methods. Our proposed solution is a novel hybrid metaheuristic for 2L-CVRP named HGA-VNS. In the initial phase, we devised an advanced Genetic Algorithm (GA) that yields satisfactory results. To further enhance solution quality, we introduced a Variable

Neighborhood Search (VNS) mutation operator, significantly improving the intensification quality within the GA. This hybridization leverages the global search capability of GA and the local search proficiency of VNS, enhancing the overall search efficiency.

Through an extensive series of experiments encompassing 186 instances and 50 new generated instances, our algorithm consistently outperformed many state-of-the-art methods and the existing HGA-VNS for solving CVRP. Additionally, experiments conducted on a real case study involving the Tunisian Post Office affirmed that the HGA-VNS is an effective solution for CVRP, delivering superior results compared to existing methods and enhancing the company's service. In summary, we can conclude that efficiently organizing items into vehicles with considering width and height of items and planning delivery routes can result in reduced logistics costs and faster deliveries.

For future work, we extend the applicability of HGA-VNS to dynamic 2L-CVRP real-life scenarios where new customer requests emerge over time, disrupting the pre-designed routing schedule. This extension incorporates reparation routines to continuously adjust routes as the solution process evolves.

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