E-Commerce Delivery Optimization with Bicycle Deliveryman and Dual Autonomous Robots

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Abstract. The rapid growth of e-commerce has led to a surge in package deliveries, particularly during promotional events, resulting in increased workload for deliveryman. To address this challenge, this paper explores traveling salesman problem with bike and two autonomous delivery robots-referred to as 2TSPBR. The robots, each with three different-sized cargo compartments, are responsible for delivering packages of varying sizes. When their inventory is low, they restock from the bicycle’s service points. The Variable Neighborhood Search (VNS) algorithm is employed to generate and optimize delivery routes for the bicycle and robots. The results indicate that the VNS algorithm significantly outperforms the CPLEX solver in terms of computational time, providing rapid convergence to near-optimal solutions. This study demonstrates the efficiency and effectiveness of the proposed VNS algorithm in delivering accurate solutions for the integrated delivery system.

Keywords: last-mile delivery; delivery robot; VNS.

1. Introduction

The exponential growth in online shopping has sparked a dramatic upsurge in the number of packages requiring delivery, a trend that is most pronounced during peak shopping seasons, thereby substantially increasing the burden on couriers. As online sales are expected to constitute a quarter of global retail by 2027 [1], the logistics sector is under pressure to evolve. Srinivas et al. (2022) [2] highlighted that autonomous delivery robots offer a viable solution, enhancing efficiency, cutting costs, and promoting sustainability. They can work alongside deliveryman, lightening their load and offering an eco-friendly delivery option. Our paper investigates the use of two such robots to aid a bicycle deliveryman in handling the varied demands of e-commerce deliveries. These robots, equipped with compartments of varying sizes, complement the deliveryman 's task by carrying different package sizes and refilling at the deliveryman 's service point to maintain uninterrupted service. This integrated system aims to maximize efficiency, ease the deliveryman's burden, and adaptably address the challenges of the e-commerce delivery boom.

The existing literature on robot delivery systems has explored various strategies to optimize delivery efficiency. Chen et al. (2021) [3] and Yu et al. (2022) [4] have investigated the use of Adaptive Large Neighborhood Search (ALNS) algorithms to coordinate robot and vehicle movements, considering robot capacity constraints. Heimfarth et al. (2022) [5] and Ostermeier et al. (2023) [6] have expanded on this by integrating dedicated release points, robot depots, and multi-vehicle deliveries into their improved Variable Neighborhood Search (VNS) algorithms. Zhao et al. (2023) [7] have addressed the Traveling Salesman Problem with Bike and Robot, presenting mixed-integer linear programming models, valid inequalities, and a genetic algorithm with dynamic programming.

The remainder of the paper is structured as follows: Section 2 constructs an integer programming model for the problem, introduces the VNS heuristic algorithm for solving; Section 4 presents two related numerical experiments; Finally, Section 4 concludes the paper.

2. Problem modeling and Algorithm design

2.1 Formulation of 2TSPBR

2.1.1 Problem description

At the outset of the delivery process, two robots depart fully loaded with packages, each equipped with three distinct cargo compartments to accommodate the varying sizes of customer packages. The bicycle, unconstrained by capacity limitations, supports the robots in their mission. As the robots complete their deliveries and deplete their stock, they will go to the customer served by bicycle to replenish supply. This restocking ensures that robots can continue their delivery duties without interruption. While the two autonomous robots and a bicycle deliveryman collaborate to fulfill delivery tasks, the primary objective is to minimize the number of customers served by the bicycle due to its higher cost of service compared to the robot. As depicted in Figure 1, the black line represents the bicycle's delivery route: 0-5-1-2-0. The blue line indicates the path of the first robot: 0-4-5-6-0. The robot replenishes its inventory at customer 5. The red line represents the path of the second robot: 0-3-2-7-0. The second robot replenishes its inventory at customer 2.

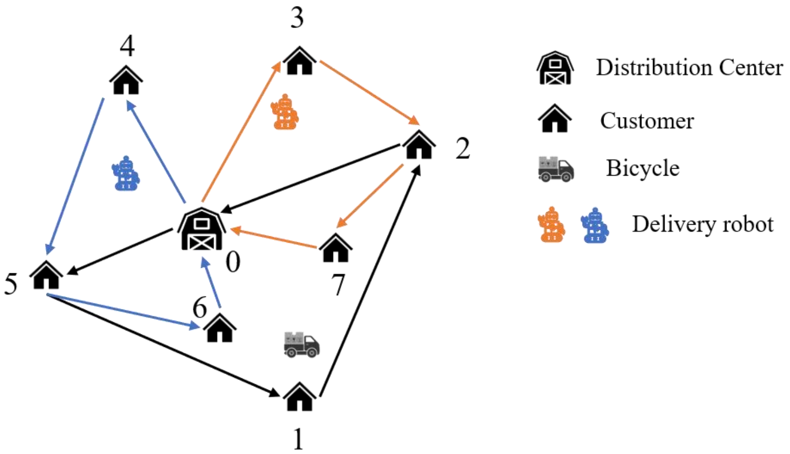

Figure1 Example of 2TSPBR (with a feasible solution)

2.1.2 Model formulation

The 2TSPBR is defined on the graph $\mathrm{G} = (\mathrm{V}, \mathrm{A})$, where V represents the set of nodes involved in the model and $\mathrm{A} = \{(\mathrm{i},\mathrm{j})|\mathrm{i},\mathrm{j} \in \mathrm{V}, \mathrm{i} \neq \mathrm{j}\}$ represents the set of arcs. The node set $\mathrm{V}_0 = \mathrm{V}_{\mathrm{n}+1}$ consists of the distribution center and $\mathrm{V}_1 = \mathrm{V}_0 + \mathrm{C}$, $\mathrm{V}_2 = \mathrm{C} + \mathrm{V}_{\mathrm{n}+1}$, the set of customers C, which include the bicycle serve only points C_b and the remain customers C_r.The fleet conducting the delivery tasks K consists of bicycle B, and two robots R. The service time for customer i is set to s_i. In order to prevent one of the vehicles serving too many customer points, resulting in a longer completion time, a parameter ς for the maximum working time is set, which is taken from the maximum working time when only bicycle serve all customers. The parameter information is presented in Table 1.

Table 1 Notation and definitions of the 2TSPBR model.

$Q_k^l\ Q_k^m\ Q_k^s$: The number of large, medium, and small cargo compartments in the k-th vehicle	d_i: =1,if only one robot replenishes at customer point i; else 0
$q_{ki}^l\ q_{ki}^m\ q_{ki}^s$: When vehicle k reaches the node, the remaining number of packages in the large, medium, and small cargo warehouses (not yet served)	$c_i^l\ c_i^m\ c_i^s$: =1, if customer point i is suitable for large, medium, and small warehouses of robots, it is 1; else 0
$t_{ij}^b\ t_{ij}^r$: The time bicycle and robot takes to travel along arc (i,j).	h_{ki}: The time when vehicle k arrives at the point i
z_{ki}: =1,if vehicle k serves customer i; else 0	x_{kij}: =1,if the vehicle passes through arc(i,j),else 0
y_i^b: =1, if customer point i is serviced by bicycles but	y_{ki}^m: =1,if two robots restocking at customer point i at

no restocking behavior occurs; else 0	the same time, including robot k; else 0;
p: Single replenishment time	y_i^r: =1, if customer point i is served by robot; else 0
y_i^s: =1, if customer point i is serviced by bicycles and replenishment occurs, it is 1; else 0	y_i^n: =1, if there are two robots restocking at customer point i;else 0
M: Big-M value for vehicle synchronization constraints	a_{ki} b_{ki}: =1, if two robots replenish goods at customer point i at the same time, and vehicle k replenishes goods first/later at point i,else 0

We introduce the model's formulation, detailing the objective and constraints that shape the problem's structure, facilitating its analysis through translation into a mathematical construct.

$$\text{Min } \sum_{i \in C} z_{ki} \qquad k \in B$$

$$z_{k0} = z_{kn+1} = 1 \qquad k \in K \quad (1)$$

$$\sum_{i \in V_1} x_{kil} = \sum_{j \in V_2} x_{klj} \qquad l \in C, k \in K, i \neq l, j \neq l \quad (2)$$

$$\sum_{i \in V_1} x_{kij} = z_{kj} \qquad j \in V_2, k \in K, i \neq j \quad (3)$$

$$q_{ki}^l \leq Q_k^l \qquad q_{ki}^m \leq Q_k^m \qquad q_{ki}^s \leq Q_k^s \qquad i \in V, k \in R \quad (4)$$

$$q_{kj}^l + c_i^l z_i^l \leq q_{ki}^l + M(2 - x_{kij} - y_i^r) \qquad q_{kj}^m + c_i^m z_i^m \leq q_{ki}^m + M(2 - x_{kij} - y_i^r)$$

$$q_{kj}^s + c_i^s z_i^s \leq q_{ki}^s + M(2 - x_{kij} - y_i^r) \qquad i \in C_r, j \in V_2, k \in R, i \neq j \quad (5)$$

$$c_i^l z_i^l + c_i^m z_i^m + c_i^s z_i^s = y_i^r \qquad i \in C_r \quad (6)$$

$$z_{kj} = 1 \qquad y_i^b = 1 \qquad i \in C_b, k \in B \quad (7)$$

$$y_i^b + y_i^s + y_i^r = 1 \qquad i \in C \quad (8)$$

$$y_i^b + y_i^s = z_{ki} \qquad i \in C, k \in B \quad (9)$$

$$\sum_{j \in C} x_{kji} \geq y_i^s + y_i^r \qquad i \in C_r, k \in R, i \neq j \quad (10)$$

$$\sum_{k \in R} z_{ki} \geq y_i^s \qquad i \in C_r \quad (11)$$

$$2(a_{ki} + b_{ki}) = y_{ki}^m \qquad i \in C_r, k \in R \quad (12)$$

$$a_{ki} + b_{ki} \leq 1 \qquad i \in C_r, k \in R \quad (13)$$

$$2y_i^n = \sum_{k \in R} y_{ki}^m \qquad i \in C_r \quad (14)$$

$$y_i^s = y_i^n + d_i \qquad i \in C_r \quad (15)$$

$$h_{ki} + t_{ij}^r x_{kij} + pd_i + pa_{ki} + 2pb_{ki} + s_i y_i^r \leq h_{kj} + M(1 - x_{kij}) \qquad i \in V_1, j \in V_2, k \in R \quad (16)$$

$$h_{ki} + t_{ij}^b x_{kij} + pd_i + 2py_i^n + s_i(y_i^b + y_i^s) \leq h_{kj} + M(1 - x_{kij}) \qquad i \in V_1, j \in V_2, k \in B \quad (17)$$

$$\sum_{i \in V_1} \sum_{j \in V_2} (\mathrm{s}_i + t_{ij}^r) x_{kij} + \sum_{i \in V_1} \left[p(a_{ki} + d_i) + 2pb_{ki} \right] \leq \varsigma \qquad k \in R, i \neq j \quad (18)$$

$$\sum_{i \in V_1} \sum_{j \in V_2} (\mathrm{s}_i y_i^b + t_{ij}^b x_{kij}) + \sum_{i \in V_1} (pd_i + 2py_i^n) \leq \varsigma \qquad k \in B, i \neq j \quad (19)$$

The objective of our model is to minimize the number of customers served by the bicycle, thereby reducing delivery costs, subject to the following constraints: Constraints 1 and 2 ensure that all vehicles start and end at the distribution center, maintaining node flow balance throughout the process. Constraints 3 and 4 relate node visitation to arc traversal, determining vehicle paths, and limit the use of robot cargo compartments to their maximum capacities. Constraint 5 records the capacity changes of different sized cargo compartments between nodes. Constraint 6 ensures that packages from robot-served customers are placed in a single compartment size and served once. Constraint 7 prevents robots from serving locations exclusive to the bicycle only nodes. Constraints 8, 9, 10, and 11 categorize customers and restrict which vehicles can serve them. Constraint 12 illustrates the replenishment frequency of replenishment points. Constraints 13, 14, and 15 manage restocking sequence. Constraints 16 and 17 represent the time relationship between nodes changes of robots and the bicycle, respectively. Constraints 18 and 19 restrict the robots and bicycle from completing the entire delivery within the specified maximum working time.

2.2 Heuristic Solutions for the 2TSPBR

2.2.1 Generation of solution

First, the necessary minimum number of restocking points is established, and an initial TSP route is created as a starting sequence. The bicycle route is then formed by selecting customers to be served by the bicycle, including the required restocking points. The first robot's route is built by removing the bicycle-served customers from the total set and assigning the rest using the TSP route, with a subset of restocking points selected from the bicycle route. The route is ordered based on the initial TSP sequence, with restocking points inserted as needed. The process is repeated for the second robot, determining the necessary restocking points and inserting them into the route which is generated from the remaining points to create the second robot's delivery route.

2.2.2 VNS for 2TSPBR with Cross-Sectional Variations

In the application of the VNS method for solving the problem, we initially generate routes for the bicycle and the two robots. Once these routes are established, we apply a series of cross-sectional variations to create new solutions. These variations include shuffling the order of customer visits within the same robot's route, swapping customers between different vehicles, and changing the order of customer segments between two restocking points for the same robot. The VNS algorithm specifically targets the TSP paths within the routes, applying cross-sectional variations to these paths to explore neighboring solutions. By doing so, VNS aims to escape local optima and search for a better global solution.

3. Numerical experiments

A comparison is made between the results obtained using the VNS algorithm described in Section 2.2 and those obtained using the commercial solver CPLEX. The CPLEX experiments in this study were conducted on Windows 10 using Python 3.7 and CPLEX 12.10 solver. The VNS experiments were implemented on Windows using PyCharm 2022.3.2 and executed on a laptop equipped with an i5-1035G1 CPU @ 1.00GHz and 16.0GB of memory.

Table 2. Comparison between CPLEX and VNS

Instance_num	CPLEX		VNS	
Inst.	Obj	Time(s)	Obj	Time(s)
10	2	0.13	2	0.03
15	4	118.48	4	0.042
20	4	0.13	4	0.108
30	6	15.14	6	0.023
40	-	-	9	0.059
50	-	-	11	0.18
60	-	-	13	0.107

The results presented in Table 2 reveal that, when the CPLEX solver is able to find a solution, the objective function values for both CPLEX and VNS remain consistent. However, a notable difference is observed in the runtime for each method. Across all instances where a solution was found, VNS consistently outperformed CPLEX in terms of computational speed. Specifically, when the number of customers increased to 40, CPLEX failed to converge to a solution within the 7200-second time limit, whereas VNS was able to produce a solution in less than one second. This demonstrates that the VNS algorithm developed for this study is not only efficient in terms of computational time but also effective in delivering accurate solutions. VNS quickly found near optimal solutions, even in instances where CPLEX struggles, highlights the utility and robustness of our approach.

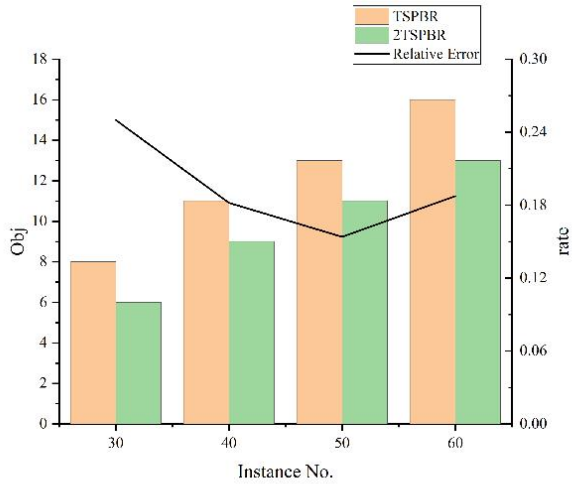

Figure2 Comparison Analysis between Single and Dual Robot Delivery Systems

To assess the economic benefits of dual-robot systems in practical applications, we designed an experiment to comparatively analyze the cost-effectiveness of using a single robot versus two robots in executing delivery tasks. From the Figure 2, it can be observed that employing a collaborative working model with two robots, as opposed to a single robot, can achieve a decrease of approximately 18% in the overall objective. This significant number reduction is primarily attributed to the advantages of dual-robot systems in task allocation, route optimization, and load balancing, which collectively enhance delivery efficiency and reduce the time and resources required to complete tasks.

4. Summary

The integration of two autonomous delivery robots with a bicycle deliveryman offers a promising solution to the challenges posed by the increasing demand for package deliveries in the e-commerce industry. By leveraging the strengths of both deliveryman and robotic assistance, the proposed system aims to minimize delivery costs while ensuring efficient and timely deliveries. The VNS algorithm developed in this study has shown remarkable performance, outpacing the CPLEX solver in terms of computational speed and delivering accurate solutions. The ability of the VNS algorithm to quickly converge to near-optimal solutions, even for larger instances, highlights its potential for real-world application. The findings of this study contribute to the ongoing research in optimizing delivery processes in the face of the growing e-commerce industry, paving the way for more efficient and sustainable delivery systems.

Acknowledgements

This research work is supported by the National Natural Science Foundation of China (No.71801018) and BUPT innovation and entrepreneurship support program (NO.2024-YC-A161).

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