BRANCH AND BOUND SOLUTION OF ROUTING PROBLEMS FOR DRONE-BASED SUPPLY

Ádám FRANCUZ[1] and Tamás BÁNYAI[2]
[1] University of Miskolc, Institute of Logistics, Miskolc-Egyetemváros, 3515, Hungary
E-mail: francuzadam13@gmail.com
[2] University of Miskolc, Institute of Logistics, Miskolc-Egyetemváros, 3515, Hungary
E-mail: alttamas@uni-miskolc.hu

ABSTRACT*: The economical implementation of transportation and other logistics operations lead to increased challenges in the package delivery sector. The dynamically changing demands of customers has a great impact on the efficiency, reliability, quality and availability of these services. To this end, the development of supply chains is increasingly driven by the emergence and diffusion of advanced technologies in the fourth industrial revolution, not only in manufacturing but also in services. One of the most controversial of these technologies is drones. In this paper, the authors show how drone-based material handling can be integrated into a conventional truck-based package delivery process and how the branch and bound methodology can be applied to the optimal design of drone delivery tasks*
KEYWORDS*: branch and bound, optimization, heuristics, drone-based transportation*

1 INTRODUCTION

The ever-evolving and diversifying customer demands are completely transforming the way of different logistics services, including last-mile logistics processes. In the era of e-commerce and online shopping, the development and optimisation of home delivery logistics processes is becoming increasingly important. In global commerce, there are many competing companies offering better and better options that can respond flexibly to the constant changes in customer demands. Within the frame of the fourth industrial revolution, the application of drone-based service in the field of package delivery systems become more and more important. Years ago, this type of solution would have been a distant idea, but nowadays, several transport companies have official licenses to parcel delivery by drones. Drone delivery can also offer a solution to environmental issues and even to labour shortages.

In this scientific paper, we will examine the different drone-based last-mile logistics solutions, their various advantages and conditions, and we will discuss the implementation of drone-based transportation as a routing problem. The routing problem is implemented using the Branch & Bound algorithm, which is often used in logistics optimization. The results of the optimization are compared to point-to-point transportation, which highlights the importance of addressing this discipline and finding solutions to implement them.

2 DRONE-BASED SUPPLY

Unlike road transport, drones can fly in the air, allowing them to avoid traffic and complicated navigation routes. When choosing a mode of transport, speed is an important consideration for buyers. Statistical studies found that 79% of shoppers would prefer to choose drone delivery if they could have their parcel delivered in a shorter time (Walker, 2016). Moreover, faster delivery times could potentially reduce delivery costs for shoppers, which in turn could lead to increased sales for retailers. Furthermore, it is important to highlight that this technology could work in cooperation with existing delivery methods to facilitate faster and more cost-effective fulfilment of goods (Delivery, 2021).

In addition to the many economic benefits, there are also environmental benefits of using drones. Delivering a package by road results 1000 g greenhouse gas emission. A study published in Nature Communications in 2018 showed that using small drones instead of diesel delivery trucks can reduce climate change by decreasing energy consumption and greenhouse gas emission (Nature, 2018). Drone delivery also has drawbacks: it can endanger the safety of other flying objects, it requires a lot of practice to handle drones professionally, and insurance problems.

There is a wide range of application of drone-based delivery services in the world. The ongoing COVID-19 pandemic situation and the governmental restriction restrictions have forced restaurants to look for new opportunities for delivery (Figure 1). However, the partnering with delivery services is a conventional way to widen service area (Uber Eats, DoorDash, Postmates, Seamless, Goldbelly, etc.). but restaurants seeking to capitalize on new technologies (Reynolds, 2020).

Fig. 1 Drone-based pizza delivery (Reynolds, 2020)

The big package delivery services are also invested in up-to-date technologies to improve their services. For example, DHL Express operates with EHang a fully automated smart drone (Figure 2) that undertake last-mile delivery in urban areas of China (DHL, 2019).

Fig. 2 Drone-based package delivery by DHL (DHL, 2019)

There are different application fields of drone-based technologies. In the civilian era the most important applications are focusing on photography, construction, agriculture, logistics, surveillance and disaster management. In the environment sector soil monitoring, water and under water surveillance, mountain inspection are the most important applications, while in the defence we can identify different applications regarding spying, missile launching, surveillance or medical supply in warzones (Macrina, 2020).

3 literature review

The emergence of drone-based delivery is driven by dynamically changing demand of customer and their increasing expectations through e-commerce. To achieve this, companies are looking for cost-effective and faster delivery operations. The integration of autonomous vehicles, including drones, to perform last-mile logistics tasks can provide a significant competitive advantage over rival companies (Salama, 2020), thus the operational design of drone-based logistics models has seen significant growth in recent years (Moshref-Javadi, 2021). Industry 4.0 will enable the operation of new logistics equipment and new logistics solutions based on cyber-physical systems.

The design of drone-based transportation can be traced back to the well-known Travelling Salesman Problem (TSP) in the literature, and is thus referred to in many articles as "TSP-D" (Drone based Travelling Salesman Problem), which aims to minimize the overall delivery time. Since most variants of the problem are NP-hard, a metaheuristic-based approach is used to find an optimal solution, for which several algorithms are available.

Metaheuristics-based algorithms are adaptive and intelligent algorithms that have proven their success on many similar problems. Among the constructive algorithms, the nearest neighbour algorithm can be highlighted, while among the corrective algorithms, the genetic algorithm can be mentioned (Agárdi, 2020). As a randomized adaptive search procedure, the brute force algorithm selects the optimal result using local search alternatives (Almuhaideb, 2021). The problem can be extended to the Vehicle Routing Problem (VRP), which, in addition to minimizing the transport route, also addresses the optimization of the transport schedule. The results obtained by different algorithms can be compared according to the route and cost parameters (Yadav, 2018).

4 MODEL OF DRONE-BASED ROUTING

Transport by drones can be considered as a cruise operation. Two important elements of a round trip task are that the point of origin and the point of arrival must coincide and that the stations that make up the route must be part of the route only once. The problem can be interpreted mathematically in many different ways and many solution methods have been developed to optimize the routes. The routing problem can be defined as a complete weighted graph (G), where the vertices of the graph are the delivery addresses (A, B, C, ...) and the edges are the lengths of the routes between delivery addresses. This special graph is called a Hamiltonian graph. If the graph of a Hamiltonian path is extended by the parameter that the starting and ending points coincide, we can define a Hamiltonian cycle (Figure 3).

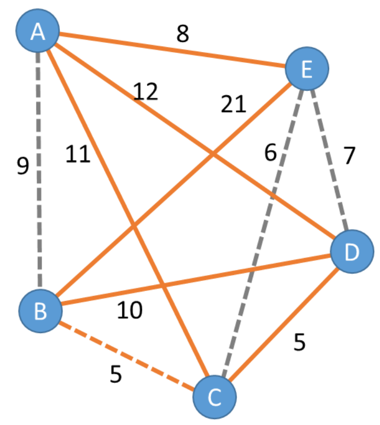

Fig. 3 Hamiltonian cycle (own edition)

The traveling salesman problem can be defined as an integer linear programming problem. The cities are labelled from 1 to n. The parameter x_{ij} is a binary value, specifying whether there is an existing route between delivery point i and j. $x_{ij} = 1$ if the road segment between i and j is in the Hamiltonian cycle, and $x_{ij} = 0$ if the road segment between i and j is not in the Hamiltonian cycle.

The parameter D_{ij} defines the length of the route segment between i and j. The objective function of the problem can be written with these parameters:

$$\sum_{i=0}^{n}\sum_{j=0}^{n} D_{ij} * x_{ij} \rightarrow min \qquad (1)$$

The objective function summarizes the distances that are included in the Hamiltonian cycle. The objective of the task is to optimize this sum. The constraints of the optimization problem are the followings:

- We leave every delivery point once:

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad (2)$$

- We arrive in every delivery point once:

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad (3)$$

- The starting point and the arrival point ("k" point) are the same:

$$\sum_{j=0}^{n} x_{0j} = \sum_{i=0}^{n} x_{i0} = k \qquad (4)$$

Within the frame of the drone-based routing problems, not only these basic constraints, but also other time- and capacity related constraints can be defined. The time-based constraints can define the lower and upper limit of delivery services (delivery time window). The capacity-related constraints can focus on the loading capacity and battery capacity of the drones, which defines the maximum flight distance depending on the weight of the package to be delivered.

The time-related constraints, regarding package delivery time to the customer can be defined as follows:

$$\tau_i^{min} \leq \sum_{j=1}^{i} t_{\alpha\beta} \leq \tau_i^{max} \qquad (5)$$

where τ_i^{min} is the lower time limit of the package delivery service to the customer i, τ_i^{max} is the upper time limit of the package delivery service to the customer i, $t_{\alpha\beta}$ is the flight time between two predecessor delivery address of parcel delivery task i.

In the same way, we can define the capacity-related constraints for the drone, which defines, that it is not allowed to exceed the upper limit of the loading capacity of the drone within one route flight:

$$\sum_{j=1}^{i} q_{\delta} \leq q^{max} \qquad (6)$$

where q^{max} is the loading capacity of the drones and q_{δ} is the weight of packages to be delivered to the predecessor delivery addresses.

5 POTENTIAL SOLUTION METHODS

There are several methods to solve the TSP problem. It is an NP-hard problem, so it is not practical to consider the full solution space. A traditional solution is the brute force algorithm, which is a nested linear search, but it can only be applied to a limited number of stations. Other algorithms based on random choice include the evolutionary (genetic) algorithm, the ant colony algorithm, tabu search or the simulated annealing.

One of the most commonly used solution methods for combinatorial optimization problems is the branch & bound algorithm. Within the frame of this work we will apply this methodology to the implementation of routing. There are (n-1)! solutions for n package delivery point. It is not possible to consider all the potential solutions, because for example, for 10 stations, there are 9!=362.880 ways to make a route. The method aims to break down the whole solution set into different subtasks and tries to block as many solution directions as possible, thus reducing the number of possible solutions. The possible solutions can be demonstrated in a tree structure (Figure 4).

The term "branch” refers to the fact that an integer programming problem is decomposed into subtasks such that their objective function is the same as the objective function of the programming problem and the set of potential solutions is a subset of the solution set of the problem. The term “bound” means that constraints are defined for the optimal objective function values of the subtasks, which makes it possible to exclude a number of subtasks.

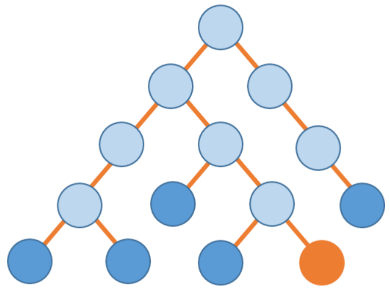

Fig. 4 Tree structure of the branch and bound algorithm (own edition)

We can use different queue data structures for the branch and bound algorithm. This FIFO queue-based implementation yields a breadth-first search, while the LIFO queue will yield a depth-first algorithm (Mehlhorn, 2008). Pereira and Vila proposed a general structure for branch and bound optimisation (Figure 5), where each step can be executed in parallel by each thread (Pereira, 2015).

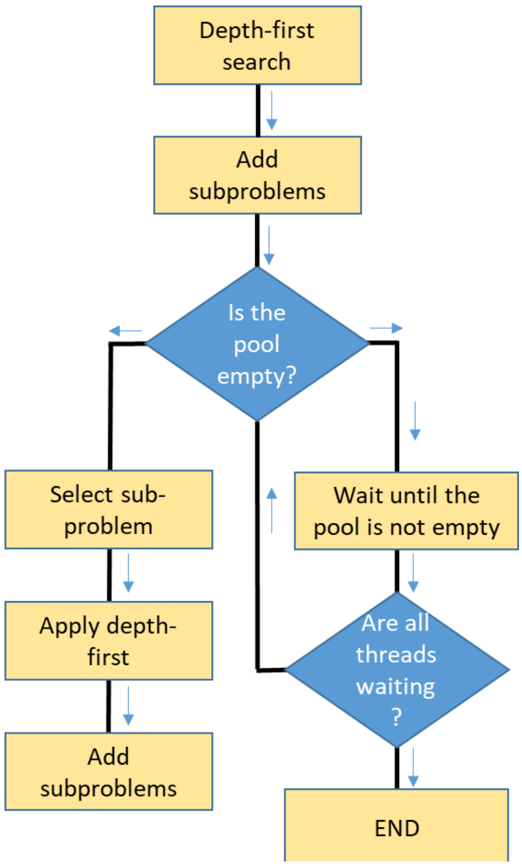

Fig. 5 Flowchart of branch and bound optimization (Pereira, 2015)

6 BRANCH AND BOUND SOLUTION

The initial data for the scenario is a package delivery program with 10 delivery addresses, where the distances between delivery points are defined in a route matrix. The objective of the optimization problem is to find a route that starts and stops at station 1, visiting each station exactly once during the round route (Figure 6).

	A	B	C	D	E	F	G	H	I	J	K
1	R	1	2	3	4	5	6	7	8	9	10
2	1	x	11	12	15	18	11	12	6	10	1
3	2	14	x	8	14	1	5	11	7	16	8
4	3	20	6	x	10	4	10	5	11	14	10
5	4	19	10	18	x	5	10	7	2	11	8
6	5	8	18	16	9	x	6	3	5	11	2
7	6	19	9	18	1	7	x	17	11	13	20
8	7	12	15	16	4	20	16	x	4	18	18
9	8	11	8	6	17	18	8	8	x	19	19
10	9	3	9	19	7	18	15	12	19	x	20
11	10	1	12	5	16	4	13	6	18	3	x

Fig. 6 Initial route matrix (own edition)

The first step of the optimization algorithm is to compute the reduced route matrix (Figure 7). The reduced matrix is a matrix obtained from the initial route matrix with at least one 0 value in each row and column, obtained by subtracting the minimum value of each row and column from the values in the same row or column. The sum of these minimum values is important for further calculations.

R	1	2	3	4	5	6	7	8	9	10
1	x	8	11	14	17	8	10	5	7	0
2	13	x	7	13	0	2	9	6	13	7
3	16	0	x	6	0	4	0	7	8	6
4	17	6	16	x	3	6	4	0	7	6
5	6	14	14	7	x	2	0	3	7	0
6	18	6	17	0	6	x	15	10	10	19
7	8	9	12	0	16	10	x	0	12	14
8	5	0	0	11	12	0	1	x	11	13
9	0	4	16	4	15	10	8	16	x	17
10	0	9	4	15	3	10	4	17	0	x

Fig. 7 Reduced route matrix (own edition)

To determine a given station on the minimized route, another reduced value must be determined. This value differs from the previous one in that each route segment has a different value. For example, when examining the route segment 1→2, all elements of the first row and second column must be excluded: if the starting station is 1, the other values of that row are negligible. By the same operation, if the station of arrival is 2, the other values in that column are also negligible. In addition, due to short-circuiting, the 2→1 section must also be excluded. After the exclusions, the matrix is reduced again, which gives a different result than the primary reduced sum value due to these operations.

We can assign to each stage a cost value, which can be calculated using the formula below:

$$Cost(x,y) = R(x,y) + \gamma + \hat{\gamma}(x,y) \qquad (1)$$

where $Cost(x, y)$ is the cost between station x and y, $R(x, y)$ is the length of the route between station x and y, γ: value of the first reduced matrix, $\hat{\gamma}(x, y)$: value of the second reduced matrix defined for the route segment between station x and y.

When determining the second station, the starting station "x" will always be station "1" and all possible cases will be examined (Figure 8).

	A	B
2	Cost(1,2)	47
3	Cost(1,3)	47
4	Cost(1,4)	59
5	Cost(1,5)	57
6	Cost(1,6)	47
7	Cost(1,7)	49
8	Cost(1,8)	47
9	Cost(1,9)	50
10	Cost(1,10)	39

Fig. 8 Cost analysis for the definition of the second station of the route (own edition)

To create an optimized route, the route segment with the lowest cost must be selected for a given station, so in this case the second station will be station 10. By repeating the previous process, the complete optimized round route can be determined. When calculating the cost value, the given route segment is continuously variable, the value of the first reduced matrix is a constant value independently from the route segment. However, for the value of the second reduced matrix, the exclusions must be continuously monitored. In addition to the exclusion of the total row value of the starting point, the total column value of the arrival point, the row and column values associated with the previously used stations shall also be excluded. For example, when defining the third station, the full row and column values of stations 1 and 10 must be excluded, as no more segments can leave or arrive from this station (except for the last value when defining the arrival point as station 1 due to the round route condition). The round route generated by the branch & bound algorithm can be defined as shown in Table 1.

Table 1. The optimized round route of the drone-based delivery (own edition)

Route	Cost(min)	L(min)
1		
10	39	1
3	43	5
2	45	6
5	50	1
7	54	3
8	63	4
6	78	8
4	102	1
9	122	11
1		3

7 RESULTS

As a result of the optimization, the round route computed by the branch & bound algorithm can be completed in 43 route units (Figure 9). However, if this round route is not feasible, the destinations must be visited as shuttle trips, which, in addition to the significantly more travel time required, also increases the time required for loading and unloading significantly (Figure 10).

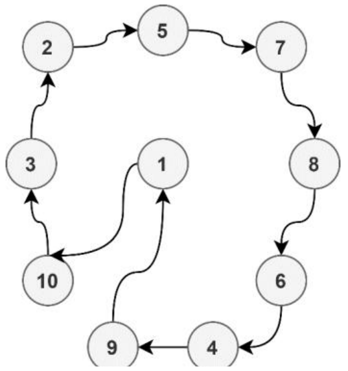

Fig. 9 The optimized round route of the drone-based package delivery (own edition)

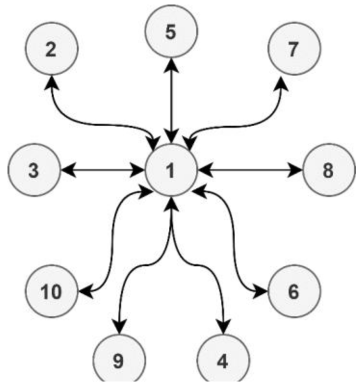

Fig. 10 The shuttle route-based solution (own edition)

To determine the shuttle route length, the route lengths from the first station of the initial path matrix to all stations and from all stations to the first station are added together:

$$L_{inga} = \sum_{n=1}^{9} L(1,n) + \sum_{n=1}^{9} L(n,1) = 203 \quad (7)$$

The final results show that the length of the round route is almost a quarter of the length of the shuttle route, which illustrates the importance of the research area and the potential for future improvements to save travel time and associated time.

8 CONCLUDING REMARKS

In About 73% of customers said, that they would pay about 10 USD for a drone delivery service. This fact proves that drone delivery would be very popular with customers (Urban Hub, 2021). The drone-based material handling is becoming increasingly important today, as advances in technology and increasingly sophisticated regulation allow drone transport to be put into practice in more and more areas. The deployment of drone systems requires the implementation of a number of design tasks that require rethinking logistics tasks such as route planning, scheduling, resource allocation. In this paper, the authors present an example of planning for drone-based parcel delivery through the method of branch and bound optimization. The presented planning method is not only applicable to drone delivery, but can also be applied to hybrid solutions where drone delivery complements a conventional transport sector, for example as a combination of truck delivery and drone delivery (Figure 11).

Fig. 11 Hybrid delivery solution integrating truck-based and drone-based delivery (Urban, 2021)

Our future research plans include extending the method to the investigation of hybrid systems with time and capacity constraints for multiple trips.

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