Tabu Search for Multi-Objective Hub Location Planning: A Case Study of the Northern Rail Line, Thailand

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Abstract. Rail transport system is considered as one of the most sustainable transportation modes with low carbon emissions per kilometer and unit transported. However, investing in rail infrastructure comes with significant construction costs. Therefore, the design of a rail transport system must be carefully planned, taking into account many relevant factors. In this research, we determine the optimal location of transportation hubs in the rail transport network using a multi-objective mathematical model with objectives of minimizing the total cost of transportation and minimizing the maximum passenger travel time in transportation network. The model is tested and applied to a real-world case study in the rail transport system of Thailand. Because the complexity of the multi-objective mathematical model and the large-scale of real case study, we develop a metaheuristics algorithm to efficiently solve this problem. The algorithm is based on the Tabu Search method and is designed to explore non-dominated neighborhoods. This approach allows the model to handle large-scale problems within a reasonable time frame while generating Pareto fronts. The results demonstrate the effectiveness of multi-objective optimization in supporting rail hub location planning.

1 Introduction

Public transportation planning is critically important, since it impacts on both industry development and population growth. Rail transport is an efficient public transportation system, capable of moving large numbers of people and goods at lower costs. It also benefits the environment by producing less carbon. In many countries, rail systems serve as the backbone of transportation networks. However, designing and implementing a rail transport network is a complex and costly task, as it involves numerous factors. The rail transport network must be integrated with the existing transportation systems and be easily accessible to the surrounding population. If a train station is located far from residential areas, it can create inconvenience in using the service, leading to longer travel times between passengers' starting points and the train stations. In this study, we focus on designing a rail transportation hub location network with consideration of passenger travel time from their origin to destination.

Hub Location Problem (HLP) involves locating hub facilities and allocating demand nodes to hubs in order to route the traffic between origin–destination (OD) pairs, which have been used in many applications, such as airline systems, telecommunication network systems, delivery systems, and transportation network systems [1-5]. A transport hub is a place in the transportation network that facilitates the transfer of passengers or cargo between different transportation modes. It functions as a central point where passengers can easily

transit between routes and types of public transport. Public transport hubs include railway stations, airports, bus stops, and ferry docks. In transportation hub network, the high volume of flows can transport between hub to hub. The objective of hub location planning is to find a place to locate a facility in order to minimize the total setup cost and the total cost of transportation between clients and facilities. The HLPs are classified in many categories as the following:

- Solution space: continuous (the domain of hub is a plane) or discrete (the domain of hub is at a particular node in a network).
- Objective function: minisum (minimizing the total cost of locating hub and allocation of nodes to hub nodes) or minimax (minimizing the maximum transportation cost from origin nodes to destination nodes).
- Hub capacity: uncapacitated (hub can serve unlimited passengers) or capacited (hub can serve limited passengers).
- The number of hubs: known (number of hub is given at p) or unknown (number of hub is needed to find).

First significant HLP mathematical model was introduced by O'Kelly [6] in a quadratic integer programing formulation, which was called the single allocation p-HLP. It was the classical HLP model, where a node was allowed to connect with one hub. The objective was minimizing total transportation cost that transferring flows from origins to destinations, the number of hub was given at p, and hub has unlimited capacity. The fixed facility hub cost was later included in the single allocation p-HLP model by O'Kelly [7].

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Later, Campbell [8] introduced linear integer programming formulation for HLPs, included single allocation and multiple allocation with a constraint for considering the capacity of hubs, which limited the volume of flows in a network. The models were broadly applied to solve many transportation network problems. For comprehensive details about hub location models, see [9-10].

Based on previous studies, most of the HLP models focus on determining the optimal location of hubs by minimizing the total transportation cost. However, this objective may result in a solution that efficient for the provider but for not the customers, as fewer hubs tend to be opened and potentially neglecting some passengers in the system in favour of optimizing overall system performance.
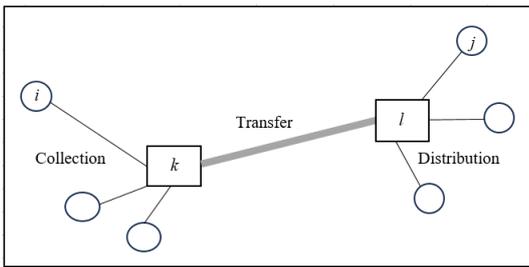
Fig. 1. The structure of hub location model.

In this study, we consider a bi-objective hub location model with consideration of transportation cost and passenger travel time, where the solution space is in a network, the hub capacity is unlimited, and the number of hub is known. The structure of hub location network can be represented in Fig. 1, where we transfer a flow from node i to node j via hubs k and l. The objectives are to minimize the total transportation cost and the maximum passenger travel time.

2 Mathematical model

In this section, we describe the detail of a bi-objective hub location model with objectives of minimizing total transportation cost and minimizing maximum passenger travel time. The goal is to find the optimal location of hubs in existing rail transportation network and allocate each node to their closest available hubs. Note that the model is adjusted from the previous work in [5], but the number of hubs in this case is predetermined and the establishing hub cost is not included. The details of the bi-objective hub location model are described as the following.

Notations and parameters are defined as follow: n denote number of stations; $i,j,k,l = 1,2,\dots, n$, where i and j represent nodes, and k and l represent hubs; C_{ij} = transportation cost from node i to node j; W_{ij} = amount of flow from node i to node j; O_i = total flow originating at node i; D_j = total flow to node j. To differentiate between different modes of transportation, the discount factors are applied into the model. χ = discount factor for collection cost; δ = discount factor for distribution cost; α = discount factor for transhipment cost between hubs; β = discount factor for traveling time between hubs; t_{ij} = traveling time from node i to node j; s_k = delay

time at hub k; Decision variables are defined as follow: $X_{ik} = 1$ if node i is allocated to hub at node k, $= 0$ otherwise; $X_{kk} = 1$ if node k is selected to be hub, $= 0$ otherwise; Y^i_{kl} = total amount of flow that is directed from node i via hubs k and l. Note that the decision variable X_{kk} is equal to 1 if node k is chosen to become hub, where the X_{ik} is a transportation route that assign node i to hub k with among of the flow Y^i_{kl}.

Mathematical Model
Minimize

$$Z_1 = \sum_{i=1}^{n}\sum_{k=1}^{n} C_{ik}X_{ik}(\chi O_i + \delta D_i) + \sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n}\alpha C_{kl}Y^i_{kl} \quad (1)$$

$$Z_2 = \max_{i,j,k,l}\{t_{ik}X_{ik} + t_{lj}X_{lj} + (s_k + \beta t_{kl} + s_j)Y^i_{kl}\} \quad (2)$$

Subject to

$$\sum_{k=1}^{n} X_{ik} = 1 \qquad\qquad \forall i \qquad\qquad (3)$$

$$X_{ik} \leq X_{kk} \qquad\qquad \forall i,k \qquad\qquad (4)$$

$$\sum_{l=1}^{n} Y^i_{kl} - \sum_{l=1}^{n} Y^i_{lk} = O_i X_{ik} - \sum_{j=1}^{n} W_{ij}X_{jk} \quad \forall i,k \qquad (5)$$

$$\sum_{k=1}^{n} X_{kk} = p \qquad\qquad\qquad (6)$$

$$Y^i_{kl} \geq 0 \qquad\qquad \forall i,k,l \qquad (7)$$

$$X_{ik} \in \{0,1\} \qquad\qquad \forall i,k \qquad (8)$$

The objectives are minimizing total transportation cost (Eq. (1)), and minimizing maximum passenger travel time (Eq. (2)). The cost consists of three parts: collection cost (χ), distribution cost (δ), and transfer cost between hub arcs (α). The passenger travel time consists of four parts: traveling time from origin node to hub, hub to hub, hub to destination node, and delay time at the hubs. Eq. (3) allows allocation of one node to exactly one hub. Eq. (4) ensures that flow is only assigned to a hub that has been selected. Eq. (5) represents the flow balancing at hubs. Eq. (6) limits the number of hubs. Eq. (7) and Eq. (8) enforces the signs of decision variables.

3 Multi-Objective Tabu Search

To solve the bi-objective hub location problem, we developed the Multi-Objective Tabu Search (MOTS). The first objective, which is minimizing total transportation cost is generally handled with the exact methods. However, the second objective, which is minimizing maximum passenger travel time is nonlinear, making the whole problem hard to solve. In this case, we need an efficient metaheuristics method.

Tabu Search (TS) is a metaheuristic optimization algorithm designed to solve combinatorial optimization problems where the solution space is large and complex. It enhances the performance of local search methods by employing memory structures that prevent the algorithm from revisiting previously explored solutions, for a certain number of iterations. This memory-based approach allows the algorithm to escape local optima and explore the solution space more effectively. In this

study, we develop the MOTS, which is able to classify solutions into dominated and non-dominated groups, then only non-dominated solution will be kept in the next iteration.

MOTS Steps are as follow:
- Step 1: Initial Solution

MOTS starts with an initial solution and iteratively explores its neighbourhoods to find an improved solution. We create our first solution based on the solution representation as in Fig. 2. The solution represents a solution of the problem with 10 nodes and 2 hubs (n=10, p=2), where hubs are located at nodes 4 and 7, then nodes 1, 2, and 3 are connected with hub 4 and nodes 5, 6, 8, 9, and 10 are connected with hub 7, respectively.

The first solution is chosen from the p out of n nodes that has the highest total weight in and out to become a hub. Then, allocate all nodes to their nearest hubs.
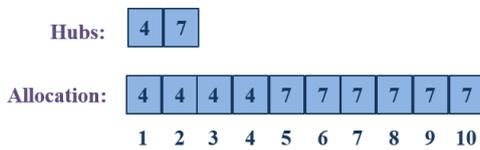

Fig. 2. Solution representation of MOTS.

- Step 2: Evaluation

The solution has been evaluated by calculating the objectives, which are the total transportation cost and maximum passenger travel time. In this step, three parameters are recorded, which are solutions (hub and node allocation) and objectives (total cost and maximum travel time). Then add a solution to the Pareto List

- Step 3: Neighbourhood Search

To improve a solution, we search the new solution on the neighbourhoods of the existing solution. Note that one solution leads to many neighbourhood solutions. For example, at the current solution of [4,7] in 10 node problem, we have a set of hub {4, 7} and a set of non-hub node {1, 2, 3, 5, 6, 8, 9, 10}. A new neighbourhood is generated by randomly selecting a new hub on a non-hub node set.

- Step 4: Non-dominated Check

The neighbourhood solutions that we created in previous step have to check for dominance. If a solution is dominated by other solutions, then we remove it from the Pareto list, if not we keep it in the Pareto List.

- Step 5: Update the Tabu List

TS has a short-term memory structure that records recently visited solutions or certain attributes of those solutions, preventing the algorithm from returning to them for a fixed number of iterations.

- Step 6: Aspiration criteria

The MOTS is performed iteratively until we reach the stopping criteria, which can be the optimal solution reaching or the maximum number of iterations. If we reach the aspiration criteria, then stop, otherwise go to Step 3.
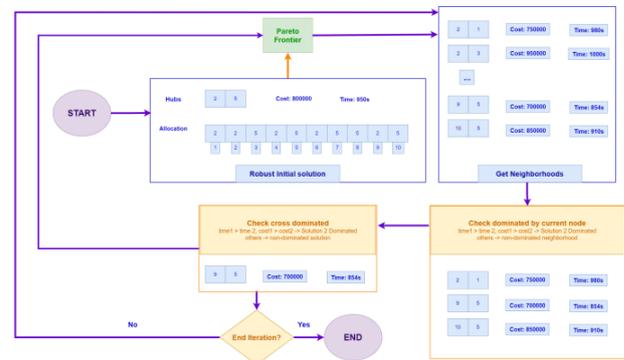
The framework of MOTS is shown in Fig. 3.

Fig. 3. The framework of MOTS.

4 Computational results

4.1 Computational Experiment

The proposed MOTS algorithm was implemented and coded in python. The experiments were conducted and run on the computer with specifications of an Intel Core i7-12700K processor running at 3.6 GHz, 32 GB of DDR4 RAM, and a 1 TB NVMe SSD for storage.

4.2 AP data set

To test the performance of the proposed algorithm, we examine the MOTS with the standard dataset. The Australia Postal (AP) dataset was employed to address the Uncapacitated Single Allocation p-Hub Location Problem (USApHLP) with the aim of minimizing the total cost. The AP dataset serves as a recognized benchmark for hub location problems, offering valuable insights into logistics and transportation challenges. This dataset comprises two components:
- Coordinates: The dataset includes longitude and latitude coordinates for each postal location across Australia.
- Weights: The weights in the dataset denote the volume of mail or goods transported between different postal locations.

The MOTS is able to find the optimal solutions for the AP dataset in reasonable time.

4.3 A case study of railway station planning

In this section, we applied the hub location problem model to solve a real-world case study in railway station planning. The aim is to determine the optimal location of railway transit hubs in the transportation network, where nodes represent existing train stations that have the potential to be selected as hub candidates.

The case study is taken from the northern rail line from Bangkok to Chiang Mai, Thailand. To see and understand the result, we test and solve the proposed model in both cases, small and medium. The small

dataset is the line from Bangkok to Ayutthaya, which includes 10 existing stations ($n = 10$). The medium dataset is the line from Bangkok to Chiang Mai, which includes 54 existing stations ($n = 54$).

The experiments are conducted for 3 cases. First, we solve the problem with small dataset and limit the number of hub at 2. The results show in Fig. 4, where the Y-axis represents the first objective; the sum of travel cost (baht) and the X-axis represents the second objective; the max travel time (min.) Based on these results, if we focus on the minimum transportation cost, hubs 1 and 7 should be opened. On the opposite side, if we focus on the passenger travel time, hubs 8 and 4 should be opened. The decision-makers also have alternatives when objectives are compromised. In many cases the solutions in between are more practical. In this case, solution [8,2] is reasonably to be selected, since it has the lower travel time compared to solution [1,7] and also lower cost compared to solution [8,4]. For the small dataset, MOTS find the all solution points in 0.02 sec. Next, we solve the problem with medium dataset and limit the number of hub at 4 and 8. The results show in Figs. 5-6, respectively. For the medium dataset, MOTS find the all solution points in 48 and 114 sec., respectively. With single-objective, we only get one optimal solution. However, with bi-objective, we can see from the graphs that we get all the solution points. These solution points provide valuable alternatives to decision-makers.
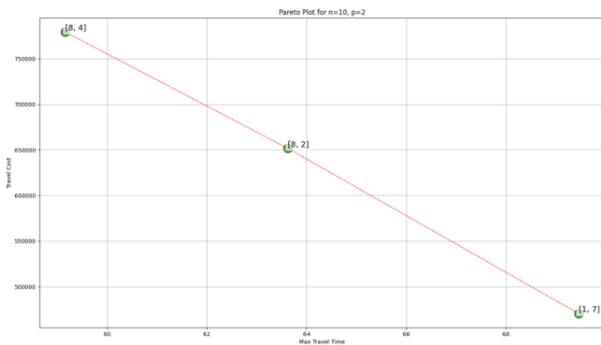
Fig. 4. Solution points from a small dataset (*n*=10, *p*=2).
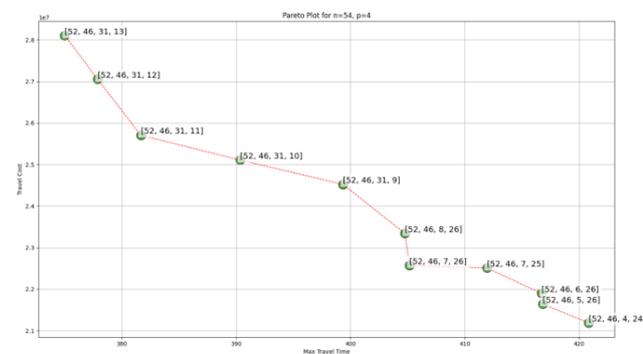
Fig. 5. Solution points from a medium dataset (*n*=54, *p*=4).
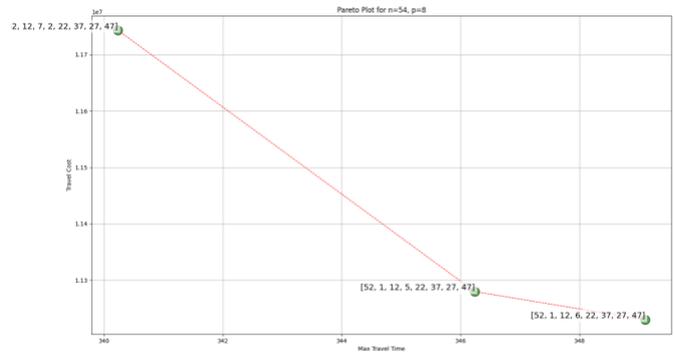
Fig. 6. Solution points from a medium dataset (*n*=54, *p*=8).

5 Conclusion

We present the Multi-Objective Tabu Search for solving hub location problem in railway transportation planning. Since the problem is complexed, it is formulated as a bi-objective hub location model for determining optimal transportation hub in railway network. Two objectives are considered with minimizing total transportation cost and minimizing maximum passenger travel time. The transportation cost consists of traveling cost from origin to destination via hubs. The travel time consists of traveling time from origin to destination via hubs and delay time at hubs. We applied the model for solving a case study in rail transportation network. The Multi-Objective Tabu Search is developed to find all of solution points. The results show that the proposed algorithm finds non-dominated solutions in a few seconds. The Pareto frontier results offer valuable insights for decision-makers in transportation planning.

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