Model for route planning of freight buses

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Abstract. This paper introduces freight buses as a novel solution for city logistics, aiming to replace other freighters currently operated by various private logistics firms within city centers. The focus lies on investigating the route planning challenge associated with integrating freight buses into an city distribution framework. Each freight bus follows a predefined route, repeatedly traversing from a distribution center to multiple depots before returning to the distribution center. All depots are serviced by multiple freight buses on a consistent basis. This route planning problem presents a fresh iteration of the periodic vehicle routing problem. To tackle this challenge, the paper proposes a Mixed-Integer Linear Programming model, serving as a fundamental framework for future research endeavors concerning freight buses.

1. Introduction

As the e-commerce sector continues to flourish, the streets of urban areas are witnessing a notable surge in the presence of freight vehicles. This proliferation can be attributed to the escalating demand for efficient delivery services driven by the ever-expanding online marketplace. However, this growth not only brings about serious traffic congestion but also contributes significantly to environmental pollution.[1][2][3](Chong-wen, 2013; Baldoquin and Martínez, 2020; Kaspi and Raviv, 2022). To alleviate traffic congestion and enhance efficiency, increased collaboration among logistics companies is essential.

The joint delivery is considered an effective method for saving logistics costs and improving delivery efficiency. Shi and Chen (2020) introduces a joint distribution system that uses digital connectivity to share logistics resources and solve capacity imbalances for O2O deliverymen during peak and off-peak hours.[4] Wang and Chen (2021) discusses joint distribution models, proposing three optimization models and using Chaopi Trading Co., Ltd. as a case study.[8] Zhang and Huang (2023) discusses the optimization of logistics paths through a two-stage planning model. This model seeks to minimize delivery time and transportation costs by integrating improved K-Means ++ clustering and a multi-chromosome genetic algorithm.[10] The study demonstrates significant savings in time and cost through this optimized collaborative delivery system, showcasing the effectiveness of combining vehicle and UAV distribution.[5][6]

Motivated by joint distribution, in this paper, this paper proposes a novel concept: running freight buses in cities. This concept aims to centralize the delivery of parcels onto a bus, thus achieving shared delivery of goods, reducing the number of freight vehicles, and alleviating urban traffic congestion. Furthermore, the operation of freight buses will provide faster delivery times for parcels, thereby enhancing the efficiency of urban logistics. This paper aims to explore the concept of freight buses and their application in urban logistics, while proposing corresponding route planning models to guide the planning of freight bus routes and achieve optimal cargo distribution.

In a macroscopic perspective, the routing problem of freight bus belongs to the category of periodic routing problems (PVRP). Rothenbacher (2019) reviews the literature on vehicle routing problems over time, focusing on periodic, inventory, release date, and multi-trip problems.[13] Shi-Yi Tan (2021) provides a detailed analysis of the latest literature on VRP published between 2019 and 2021, using a classification framework.[11] In the typical PVRP, each customer must be visited on one or more times within a planning periods, with each customer having a range of feasible visit options.[7][9][15](Vidal and Laporte,2019; Wang and Cai， 2020). Freight bus route planning differs from standard periodic vehicle routing problems because freight buses operate on fixed routes, visiting various customers or sites at the same frequency each day. Additionally, due to vehicle capacity constraints, certain customers may not be fully serviced during specific time windows, resulting in delayed deliveries and penalties.[12][14] Therefore, freight bus route planning needs to consider these unique circumstances to ensure the fulfillment of each customer's demand while minimizing the adverse effects of delivery delays.

2. The advantages of freight buses

Figures 1 and 2 compare the freight bus system with the traditional urban freight system. Freight buses present numerous advantages over conventional urban freight vehicles.

Firstly, similar to city passenger buses, freight buses operate on fixed routes and schedules, enhancing transport efficiency and predictability. Secondly, freight buses are

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typically larger than traditional freight vehicles, allowing for bulk distribution and high-volume transport, thus playing a crucial role in urban logistics. Additionally, freight buses enjoy the privilege of using dedicated lanes, further boosting their transport efficiency by avoiding traffic congestion. Lastly, freight bus systems are often centrally managed by the government, ensuring smooth operation and safety standards. Government involvement facilitates coordination among stakeholders and promotes the development and enhancement of the freight bus system.

In essence, freight buses not only enhance logistical operations but also contribute significantly to fostering sustainable urban environments and improving the quality of life for city residents.

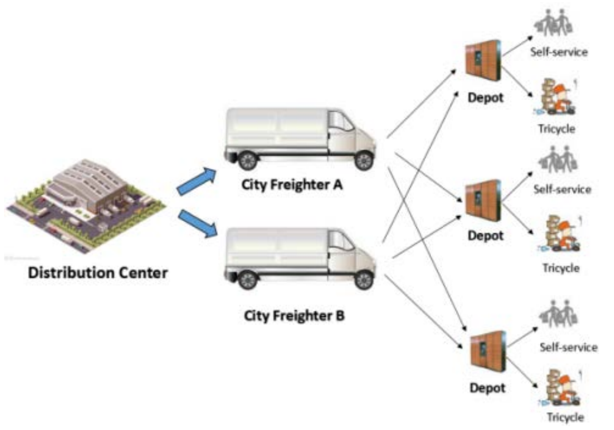

Fig. 1. City freighters system

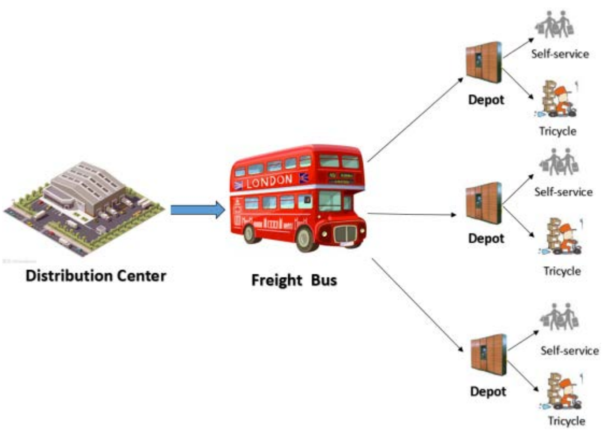

Fig. 2. Freight buses system

3. Mathematic Model for Freight Buses Routing

In addition to proposing the concept of freight buses, we also investigated how to operate freight buses more efficiently in urban areas. Through the preceding analysis, we know that the routing problem is a specialized periodic routing problem.

As an initial study, we begin by developing a Mixed-Integer Linear Programming model to address the route planning challenge for freight buses.

3.1 The description of the problem

As shown in Figure 3, we assume that all freight buses depart from a freight center, follow fixed routes to visit several stops, and then return to the freight center. Each freight bus may operate multiple times per day, with only one bus visiting each stop, and the demand at each bus stop must be fully satisfied by the end of each day. It should be noted that, in line with the actual process of express delivery, the demand at each stop can only be met on time or delayed, but it cannot be fulfilled ahead of schedule. Additionally, delayed fulfillment incurs a linear delay penalty.

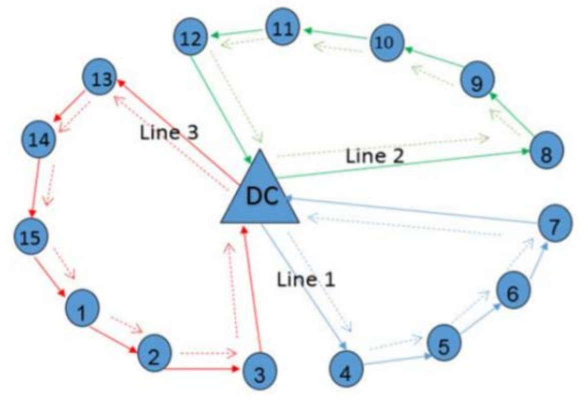

Fig.3. An example of route planning

We have the following elements defined:

- o *Distribution center.*
- V Fleet of freight buses.
- G Depots.
- U Capacity of each freight bus.
- C_{ij} Operating cost for each freight bus when traveling between nodes ij $(i, j \in \{s\} \cup G)$.
- M Number of time periods considered.
- $d_i(k)$ Demand of depot i during the k-th period, $i \in G, k \in \{1,2 \ldots M\}$.
- P Penalty coefficient P per period and per unit of demand.

Our task involves strategizing the route for each freight bus and determining the amount of delivery for each freight bus at each depot during specific time intervals. The primary goal is to reduce the overall operational expenses of all freight buses while also minimizing the costs incurred due to delayed deliveries across the defined time periods (M periods).

3.2 Mathematical model

Here's the comprehensive mathematical model for planning the routes of freight buses:

Decision Variables

- x_{ij}^{v} This refers to a binary variable denoted as x_{ij}^{v}, which takes the value of 1 if freight bus v *travels* from node i to j ; 0 otherwise.
- y_{i}^{v} This refers to a binary variable denoted as x_{ij}^{v}, which takes the value of 1 if and only if the depot i is served by the freighter bus v; 0 otherwise.

- $d_i^v(k)$ The unloaded quantity of the freighter bus *v* at the depot *i* on the *k*-th visit; 0 otherwise.
- $Q_i^v(k)$ The load of the freighter bus *v* when it just arrives at node *i* during the *k-th* visit.

The target Function

The objective is to minimize the total costs over the M periods, encompassing both the operational route expenses of freight buses and the penalties incurred for late deliveries.

MinimizeZ=

$$M \ * \ \sum_{i\in\{o\}\cup G}\sum_{j\in\{0\}\cup G}\sum_{v\in V} c_{ij}x_{ij}^v \ +$$

$$\text{P*} \ \sum_{i\in G}\sum_{n=1}^{M}\sum_{k=1}^{n}(\, d_i(k) - \sum_{v\epsilon V} d_i^v(k))$$

Constraints

$$\sum_{j\in G} x_{oj}^v = \ \sum_{j\in G} x_{jo}^v \qquad \forall v \in V \qquad (1)$$

$$\sum_{i\in\{o\}\cup G} x_{ij}^v = \ \sum_{i\in\{0\}\cup G} x_{ji}^v$$

$$\forall j \in G, \forall v \in V \qquad (2)$$

$$\sum_{i\in\{o\}\cup G} x_{ij}^v = y_j^v$$

$$\forall j \in G, \ \forall v \in V \qquad (3)$$

$$\sum_{v\in V} y_j^v = 1 \qquad \forall j \in G \qquad (4)$$

$$Q_j^v(k) >= Q_i^v(k) + d_j^v(k) - U(1 - x_{ij}^v)$$

$$\forall i \in G, \forall j \in \{o\} \cup G, \forall v \in V, \ \forall k \in \{1,2 \dots M\} \qquad (5)$$

$$Q_o^v(k) = 0 \quad \forall v \in V, \ \ \forall k \in \{1,2 \dots M\} \qquad (6)$$

$$0 <= Q_i^v(k) <= U \qquad \forall i \in G, \forall v \in V \qquad (7)$$

$$\sum_{k=1}^{M} d_i^v(k) = \ d_i * y_i^v \ \ \forall i \in G, \forall v \in V \qquad (8)$$

$$\sum_{k=1}^{n} d_i^v(k) <= \ \sum_{k=1}^{n} d_i(k) \ \ * y_i^v$$

$$\forall i \in G, \ \forall v \in V, \forall n \in \{1,2 \dots M\} \qquad (9)$$

$$x_{ij}^v \in \{0,1\} \qquad y_i^v \in \{0,1\}$$

$$\forall i \in \{o\} \cup G, \ \ \forall j \in \{o\} \cup G, \ \ \forall v \in V \qquad (10)$$

Constraints (1) ensure that each freight bus begins and ends its route at the DC. Constraints (2) mandate that a freight bus departing from a depot must also leave that depot. Constraints (3) and (4) ensure that every depot is serviced and that each depot is serviced by at most one freight bus. (5), (6), and (7) establish constraints on vehicle capacities. Constraints (8) ensure that all demands must be fulfilled within the specified M periods. Constraints (9) dictate that, the delivery made by freight bus at each depot can only satisfy the demand for that period or earlier periods, but not for later periods. Lastly, constraints (10) specify the feasible ranges for all decision variables.

4 Conclusions

In this paper, we introduced the concept of freight buses as a promising solution for urban logistics, presenting an innovative approach to address the challenges posed by city freight transportation. Our research focused on the critical aspect of route planning for freight buses within an urban distribution system. The primary objective was to explore the feasibility and efficiency of integrating freight buses into city logistics networks. We established that freight buses, with their fixed routes and repeated tours from distribution centers to depots and back, offer a viable alternative with the potential for improved operational efficiency and reduced environmental impact.

By framing the route planning of freight buses within the context of a periodic vehicle routing problem, we highlighted the unique characteristics and challenges associated with this novel transportation mode. We elucidated the necessity of devising effective route planning strategies to optimize resource utilization and meet delivery demands within specified timeframes. To address this challenge, we formulated a MILP model, providing a systematic and mathematical approach to route planning for freight buses. This model serves as a foundational framework for future research endeavors, offering a basis for the development of advanced optimization algorithms and decision support systems tailored to the needs of urban freight transportation. In the future, we will validate the model further by incorporating real or simulated operational data and conduct more quantitative analyses on freight buses.

In conclusion, our research on the concept of freight buses and the development of a route planning model represent significant contributions to the field of urban logistics. We envision that further research and implementation of freight bus systems will continue to enhance the efficiency and sustainability of city freight transportation, paving the way for a more interconnected and resilient urban logistics network.

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References

1. Baldoquin, M., Martínez, J., & Díaz-Ramírez, J. (2020). A unified model framework for the multi-attribute consistent periodic vehicle routing problem. PLoS ONE, 15.
2. Chong-wen, Z. (2013). The Development Trend of Modern Logistics Industry. Journal of Inner Mongolia University for Nationalities.
3. Kaspi, M., Raviv, T., & Ulmer, M. (2022). Directions for future research on urban mobility and city logistics. Networks, 79, 253 - 263.
4. Shi, Y., Chen, M., Ting, Q., Liu, W., & Cai, Y. (2020). Digital connectivity in an innovative joint distribution system with real-time demand update. Comput. Ind., 123, 103275.
5. Tan,S.-Y.;Yeh,W.-C.(2021)The Vehicle Routing Problem: State-of-the-Art Classification and Review. *Appl. Sci.* 11(21), 10295.

6. Tavakkoli-Moghaddam, R., Saremi, A.R., & Ziaee, M.S. (2006). A memetic algorithm for a vehicle routing problem with backhauls. *Applied Mathematics and Computation, 181*(2), 1049-1060.
7. Vidal, T., Laporte, G., & Matl, P. (2019). A concise guide to existing and emerging vehicle routing problem variants. Eur. J. Oper. Res., 286, 401-416.
8. Wang, L., Chen, X., & Zhang, H. (2021). Joint distribution models in fast-moving consumer goods wholesale enterprise: Comparative analysis and a case study. Advances in Production Engineering & Management.
9. Wang, Y., Wang, L., Chen, G., Cai, Z., Zhou, Y., & Xing, L. (2020). An Improved Ant Colony Optimization algorithm to the Periodic Vehicle Routing Problem with Time Window and Service Choice. Swarm Evol. Comput., 55, 100675.
10. Zhang, Q.; Huang, X.; Zhang, H.; He, C.(2023) Research on Logistics Path Optimization for a Two-Stage Collaborative Delivery System Using Vehicles and UAVs. *Sustainability*,15(17), 13235.
11. Tan, S.-Y.; Yeh, W.-C. (2021) Vehicle Routing Problem: Latest Classification and Review. applied Science. 11 (21),10295.
12. Trentini, A., Campi, A., Malhene, N., & Boscacci, F. (2011). City passenger and cargo sharing Transport solutions: new ideas for Milan in international comparison. Territory, 59, 38-44.
13. Rothenbacher, A. (2019). Branch pricing cutting method for periodic vehicle routing problems with flexible timetable structures. Transp. Sci., 53, 850-866.
14. Martín, I., SALAZAR-GONZÁLEZ, J., & Yaman, H. (2019). Periodic vehicle routing problem with driver consistency. Eur. J. Oper. Res., 273, 575-584.
15. Dayarian, I., Crainic, TG, Gendreau, M., and Rei, W. (2015). A branching and pricing approach to the multi-period vehicle routing problem. Computers and Operations Research , 55, 167-184 .