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Scheduled Transport Service Design for Cross-Border Logistics in Airport Cluster

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Abstract. The airport cluster plays a pivotal role in the highly-growing market of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) through achieving bundling of cargo flows via multimodal transport and higher connectivity to the rest of the world via frequent transport services. Due to the uncertainties of cross-border logistics, as well as limited and expensive space at the airport cluster, it is increasingly popular to build cross-border logistics parks in the Pearl River Delta region for cargo consolidation and storage, where customs clearance, security screening, and other services for exports could be completed before transporting cargoes to the airport cluster by sea for air transshipment to worldwide destinations, and vice versa. This paper studies the design of cross-border scheduled transport service by barge between a logistics park and multiple airports in the airport cluster for both imports and exports. The barge service is operated by a third-party logistics company who visits multiple airports to pick up and drop off cargoes in milk-run mode. In addition to the barge service, the operator offers the more expensive truck service for supplementary and expediate transport. We model this scheduled transport service design problem with the objective of minimizing the total operating cost considering transport cost, flight schedules, and capacity limits. A series of numerical experiments are conducted to illustrate the effectiveness of the scheduled transport service and generate managerial guidelines for the GBA multimodal transport development.

Keywords. Scheduled transport service, multimodal transport, barge transport, cross-border logistics, airport cluster

Introduction

Cross-border cargo transshipment demand is experiencing a rapid increase because of the highly-growing international trade. The demand increase is even greater in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) where a large number of manufacturing plants are located and many cargoes from other regions are also imported and exported through it. To satisfy these demands, the airport cluster in the GBA plays a vital role because of its frequent transport services and high connectivity to the rest of the world. The airport cluster includes Hong Kong International Airport (HKG), Macao

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International Airport (MFM), Shenzhen Baoan International Airport (SZX), Guangzhou Baiyun International Airport (CAN), and Zhuhai Jinwan Airport (ZUH) [1]. Among them, HKG is an international shipping center and aviation hub, and it has been the main gateway for air cargo going into and out of the GBA [2].

Facing the increasing demands, the land of HKG available to accommodate the cargoes for export and import is scarce and land reclamation from the sea is extremely expensive [3]. Besides, there are high operation uncertainties in cross-border logistics during the customs clearance, security screening, etc. [4], which would reduce the operation efficiency and incur extra costs [5].

To address the problems of limited and expensive space and operation uncertainties, the Airport Authority Hong Kong and Dongguan Government co-operate to develop the sea-air multimodal cross-border cargo transshipment mode between the two cities by setting up an upstream logistics park in Dongguan and a new airside multimodal cargo pier at HKG, which is expected to reduce cost by 50% and the handling time of cargoes by approximately one third [6]. The security screening and custom clearance for export cargoes from mainland China could be completed in advance at the upstream logistics park in Dongguan, which could hedge against the above operation uncertainties, then the exports will be transported seamlessly to HKG for direct air transshipment to overseas destinations. Similarly, imports may also be transported to mainland China via HKG and the logistics park through reverse procedures. Here, barge transport is recommended for transshipping cargoes between the logistics park and HKG since it can handle relatively large volumes of cargo with lower costs and carbon emissions [7][8]. Extending this mode to airport cluster in the GBA may bring more benefits, as has been studied in many other supply chain and logistics systems, such as the hinterland transport system [9][10].

However, to realize cost-effective operations and sustainable development, there are still some problems to be solved: (1) How to design the barge service mode connecting the logistics park and airports in the scenario of cross-border logistics? (2) What is the optimal service frequency and barge capacity considering transport and inventory cost? (3) How do the transshipment demands, transport costs, and holding costs at the logistics park and airports affect the optimal decision of barge service?

To answer these questions, this paper proposes a scheduled barge service for cargo transshipment in the cross-border logistics system of airport cluster. Specifically, the milk-run mode [11][12][13][14][15] is adopted for the barge service, in which the barge will visit all airports with predefined schedule in one route. Meanwhile, expediate truck service is provided as a supplement to the barge service. Then the model for scheduled barge milk-run service is developed to minimize the total cost, based on which the barge service in scenarios with different transport cost and holding cost is designed.

This work will contribute to smart and sustainable operations for global supply chain and logistics management with improved cross-border handling efficiency and reduced transport costs. Specifically, this work designs a new and easy-to-adopt mode for cargo transshipment in airport cluster and develops important managerial insights on designing barge's milk-run frequency with different holding costs at logistics park and airports. New insights are developed for the cooperation of cities in urban agglomerations to further improve their attractiveness and influence in global supply chain system by interdisciplinary application of economic and logistical research methods.

The rest of this paper is organized as follows. Section 1 introduces the problem based on the case in the GBA and Section 2 presents the mathematical model. Numerical studies and managerial implications are given in Section 3. Section 4 concludes the whole paper and points out the future works.

1. Problem description

This problem considers a logistics park and several airports in airport cluster, which can be connected by barges, as illustrated in Figure 1. The barges depart from the logistics park, visit all these airports, then return to the logistics park, where the customs clearance, security screening, and other compulsory procedures for exports and imports can be completed. Cargoes can be transported and received worldwide by flights.

The transport service between the logistics park and airports is designed to be a scheduled milk-run service by barge, that is, all the airports in this scenario will be visited in each milk-run at a fixed frequency. Without loss of generality, the transshipment demand is considered with rate D_i for airport i. The cargoes will only be transshipped between the logistics park and the airports, while the transshipment between different airports will not be considered here. A homogeneous fleet of barges is available with the largest capacity Q. The transport cost of one milk-run by barge is denoted by C_m. The barges will be dispatched at a fixed frequency and route within the planning horizon to pick up and deliver cargoes, and the unsatisfied demand will be fulfilled by trucks with extra cost C_r per unit. The holding cost of cargoes at airports and logistics park are H_a and H_l per unit per time, respectively. In this scenario, the optimal barges' milk-run frequency and barge load will be found to minimize the total cost of this scheduled service while satisfying the demand.

Table 1 summarizes the notations adopted in this paper.

Table 1. Notations.

Indices:	
i	Index of airport ($i = 1,2 \dots, n$)
Parameters:	
T_c	Length of the planning horizon
D_i	Transshipment demand at airport i (unit/time)
C_m	Barge's transport cost ($/milk-run)
C_r	Truck's transport cost ($/unit) ($C_m < C_r Q$)
H_a	Holding cost at airports ($/unit/time) ($H_a > H_l$)
H_l	Holding cost at logistics park ($/unit/time)
ΔH	Holding cost differential $\Delta H = H_a - H_l$
Q	Barge's largest capacity (units)
Decision Variables:	
x	Barges' milk-run frequency within a planning horizon
v	Barge load for one milk-run

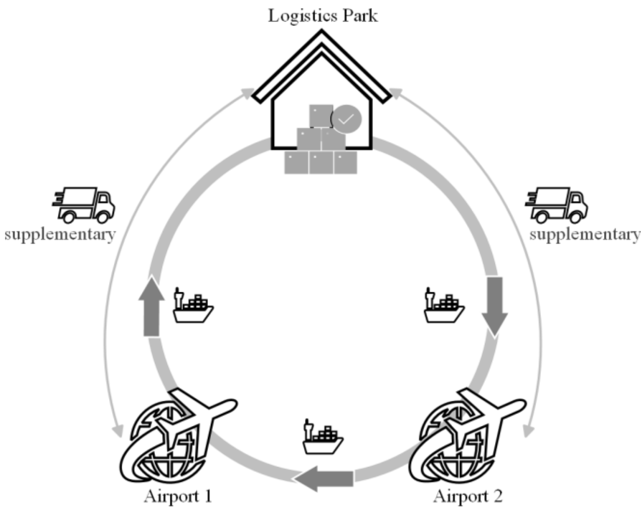


Figure 1. Scenario description.

2. Mathematical model

The objective of the scheduled barge transport service is to minimize the total transport and holding costs while satisfying the transshipment demands, as shown below:

$$\boldsymbol{Min}\ \ C(x,v) = C_m x + xv\frac{v}{2\sum_i^n D_i}\Delta H + C_r(T_c \sum_i^n D_i - xv) \tag{1}$$

subject to

$$xv \leq T_c \sum_i^n D_i \tag{2}$$

$$0 \leq v \leq Q \tag{3}$$

$$0 \leq x \tag{4}$$

where $C_m x$ in Equation (1) is barges' total transport cost with x times of milk-run within the planning horizon T_c, and $(xv^2 \Delta H/2\sum_i^n D_i)$ is xv units of cargoes' holding cost differential between the logistics park and the airport with average storage duration $(v/2\sum_i^n D_i)$ earlier than the air freight cut-off time. The last part of Equation (1), $C_r(T_c \sum_i^n D_i - xv)$, is total cost incurred in transshipping $(T_c \sum_i^n D_i - xv)$ units of cargoes by truck.

The above model is a mixed integer programing model. To find the approximately optimal solution, the integer condition is relaxed first. Then x^* will be rounded up and down to the nearest integers. By choosing the lower-cost solution between these two nearest integers, the integer optimal solution will be found.

The Lagrangian and Karush-Kuhn-Tucker (KKT) conditions are used here, which provide an efficient solution approach to this optimization problem with inequality constraints. The Lagrangian of this problem is constructed as

$$\boldsymbol{Min}\ L(x,v) = C_m x + xv\frac{v}{2\sum_i^n D_i}\Delta H + C_r\left(T_c\sum_i^n D_i - xv\right) + \lambda_1(-x) + \lambda_2(-v) + \lambda_3(v-Q) + \lambda_4\left(xv - T_c\sum_i^n D_i\right) \quad (5)$$

where the Lagrange multipliers are $\lambda_j \geq 0\ (j = 1,2,3,4)$. Furthermore, the KKT conditions are conducted as

$$\begin{cases} C_m + v\frac{v}{2\sum_i^n D_i}\Delta H - C_r v - \lambda_1 + \lambda_4 v = 0 \\ \frac{xv}{\sum_i^n D_i}\Delta H - C_r x - \lambda_2 + \lambda_3 + \lambda_4 x = 0 \\ \lambda_1(-x) = 0 \\ \lambda_2(-v) = 0 \\ \lambda_3(v-Q) = 0 \\ \lambda_4\left(xv - T_c\sum_i^n D_i\right) = 0 \end{cases} \quad (6)$$

Proposition 1. The optimal solutions for barge's milk-run frequency x and barge's load v are characterized by the following equation:

$$(x^*, v^*) = \begin{cases} (0\,, 0) & Condition\ I: \pi = C_r T_c \sum_i^n D_i \\ \left(\frac{T_c\sum_i^n D_i}{Q}, Q\right) & Condition\ II: \pi = T_c\left(\frac{C_m\sum_i^n D_i}{Q} + \frac{Q\Delta H}{4}\right) \\ \left(T_c\sqrt{\frac{\sum_i^n D_i \Delta H}{2C_m}}, \sqrt{\frac{2C_m\sum_i^n D_i}{\Delta H}}\right) & Condition\ III: \pi = T_c\sqrt{C_m\sum_i^n D_i\Delta H} \end{cases} \quad (7)$$

Note: $\pi = \min\left[C_r T_c \sum_i^n D_i, T_c\left(\frac{C_m\sum_i^n D_i}{Q} + \frac{Q\Delta H}{4}\right), T_c\sqrt{C_m\sum_i^n D_i\Delta H}\right]$

Condition *I* means that when truck's unit transport cost is less than the barge cost per unit plus the holding cost differential per unit, that is $C_r < C_m\sqrt{C_m\Delta H/2\sum_i^n D_i} + \sqrt{\Delta H/2C_m\sum_i^n D_i}$, then the optimal decision is dispatching trucks only to transship cargoes expeditiously near the cut-off time.

Condition *II* means that when dispatching trucks is not relatively beneficial and the holding cost differential is low, that is, $C_r > C_m\sqrt{C_m\Delta H/2\sum_i^n D_i} + \sqrt{\Delta H/2C_m\sum_i^n D_i}$ and $\Delta H < 4C_m\sum_i^n D_i/Q^2$, then the optimal decision is filling each barge to its largest capacity with a lower barge's milk-run frequency.

Condition *III* means that when $C_r > C_m\sqrt{C_m\Delta H/2\sum_i^n D_i} + \sqrt{\Delta H/2C_m\sum_i^n D_i}$ and $\Delta H > 4C_m\sum_i^n D_i/Q^2$, the optimal decision is increasing barge's milk-run frequency to reduce cargoes' storage time at the airports until the cost minimization is reached.

To imply this model and solutions into real cases, we must round the results of x^* to the nearest two integers. Rounding down x^* implies that a small number of cargoes will be transshipped by trucks. And the optimal x^* will be found by comparing the corresponding total costs.

3. Numerical study

In this part, a numerical study is provided to validate the proposed model. In addition, the impact of key parameters on the optimal decisions and the total costs are evaluated.

3.1. Parameter settings and basic case

Taking the airport cluster in the GBA as a case, we consider one upstream logistics park and two airports with large transshipment demands of cargoes. The barges transship cargoes from the logistics park (i.e., Dongguan logistics park) to airports (i.e., HKG and MFM).

Our parameter settings are based on realistic parameter values from the above case and the money is in US dollar. The milk-run distance is set as 200 km in this case while the average road transport distance is 100km. The planning horizon is set as 7 days, and the time unit is set as one hour. The transshipment demands D_i with airport i are derived from the list of cargo flights on HKG website and we set D_i as 300 tons per hour. The one milk-run transport cost C_m is \$3000, and the road transport cost is C_r \$10 per ton. The holding cost at the logistics park and airport is \$0.5 and \$2 per ton per hour, respectively. The largest capacity of a barge Q is set as 1000 tons. According to our barge service design model presented in Section 2, the optimal decision for this case can be generated and is shown in Figure 2. In this case, the optimal barges' milk-run frequency is 101 and the barge load is 998 tons.

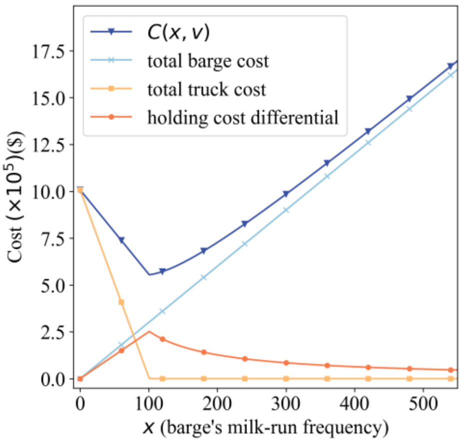


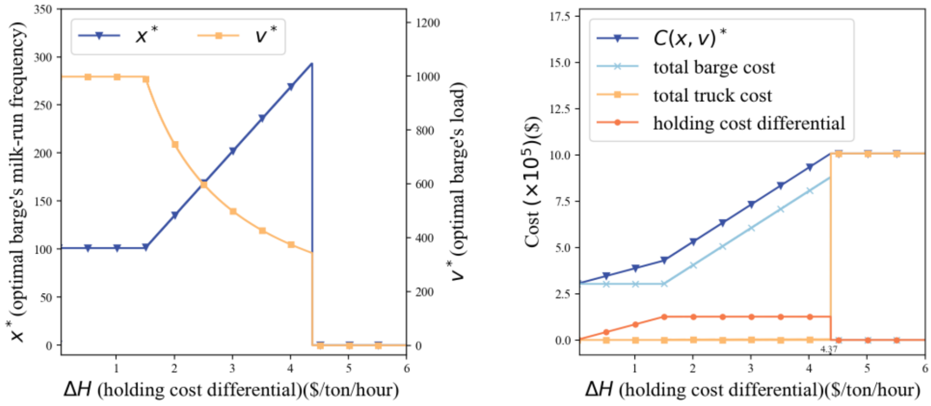
Figure 2. Solutions for basic case.

3.2. Sensitivity analysis

3.2.1. Impact of holding cost differential

To analyze the impact of holding cost differential $\Delta H = H_a - H_l$ on optimal decisions and costs, we set ΔH to range from \$0.01 to \$6 per ton per hour and other parameters remain the same. Figure 3 summarizes the results. As can be seen from Figure 3(a), when ΔH is small enough, that is, less than \$1.5, the optimal barge's load v^* is the largest capacity, and this is because more storage time in the logistics park will not bring more benefits. A lower frequency x^* means some cargoes' storage time at the airport is longer.

And when ΔH is between \$1.5 and \$4.37, the optimal barge's milk-run frequency x^* tends to increase as ΔH increases, and the optimal barge's load v^* tends to decrease as ΔH increases. It is worth noting that when ΔH is more than \$4.37, there is no additional revenue generated by barge's milk-run service compared with truck transport. And the best decision is to use trucks only for expediate transshipments to airports near the cut-off time.

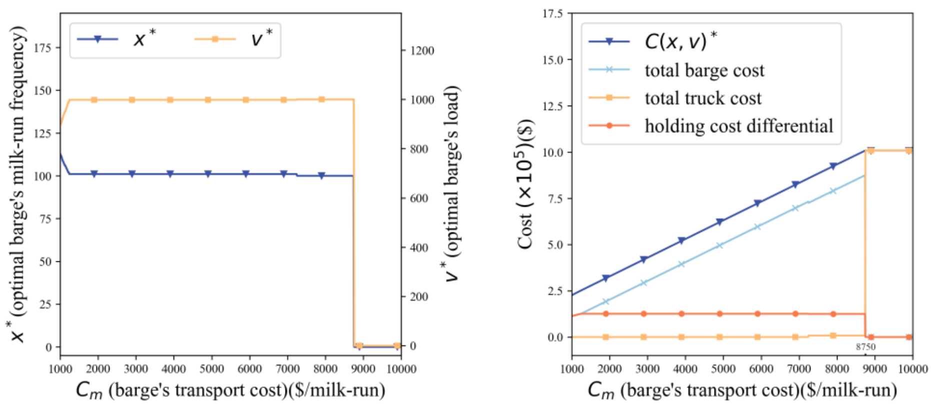


(a) (b)

Figure 3. The impact of holding cost differential ΔH.

3.2.2. Impact of barge's transport cost

To analyze the impact of barges' transport cost for one milk-run C_m on optimal decisions and costs, we set C_m to range from \$1000 to \$9000 and other parameters remain the same. Figure 4 summarizes the results. As can be seen from Figure 4(a), when C_m is less than \$1232, x^* tends to decrease as C_m increases, and the optimal barge load v^* tends to increase as C_m increases. The optimal decision $x^*$and v^* remain the same when C_m is between \$1233 and \$7250. And when C_m is between \$7250 and \$8750, the optimal decision x^* and v^* is 100 and 1000, respectively. Once C_m is above \$8750, the optimal decision is using trucks only to tranship the cargoes according to Figure 4(b).



(a) (b)

Figure 4. The impact of barge's transport cost C_m.

3.2.3. Impact of demand

To analyze the impact of transshipment demand D_i on optimal decisions and costs, we set D_i to range from 100 to 500 tons per hour and other parameters remain the same. Figure 5 summarizes the results. As can be seen from Figure 5(a), when D_i is less than 100 tons, the optimal decision is using trucks to transship cargoes since barge's milk-run service will cost more than truck, and the total cost per unit is equal to truck's transport cost per unit according to Figure 5(a). When D_i is between 100 tons and 300 tons, the optimal barge load v^* tends to increase up to the largest capacity as D_i increases and x^* is around 101. It is worth noting that when D_i is above 300 tons, the holding cost differential per unit decreases due to economies of scale.

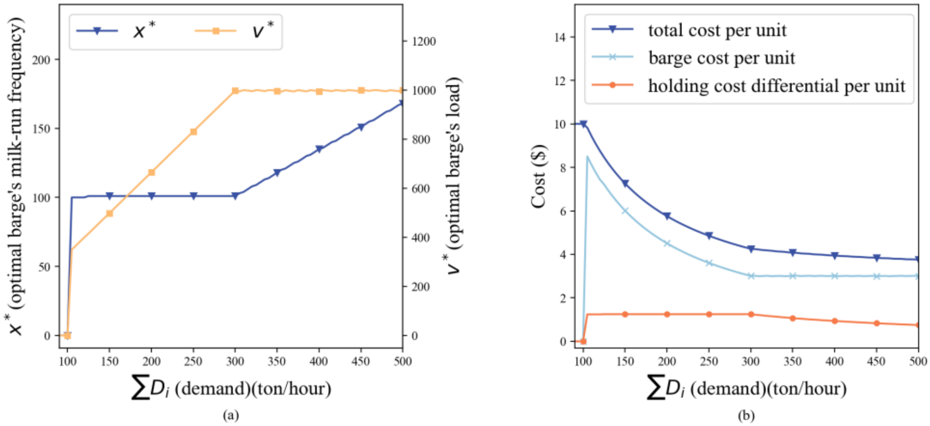


Figure 5. The impact of transshipment demand.

3.3. Managerial implications

The numerical results offer some important managerial implications.

First, it is beneficial for the operators to increase barge's milk-run frequency when the holding cost differential between the logistics park and airports are high. Through increasing the frequency, cargoes would have more opportunities to be transported to the airport near the flight time, so as to save the storage cost at airport.

Second, it is important to find the threshold value of ΔH and C_m above, that is under which conditions there will be no benefit to using barge's milk-run service.

Third, there are economies of scale in GBA case. That means, it is beneficial for the operator to take on more transshipment orders within the constraints of barge amounts and inventory capacity of the logistics park, and more airports in the airport cluster using this milk-run service will further improve the overall benefits.

4. Conclusion

This paper studies the design of scheduled barge transport service between a logistics park and multiple airports in the airport cluster for imports and exports. The barge service is operated by a third-party logistics company who visits multiple airports to pick up and drop off cargoes in one milk-run route. The operator also offers the more expensive truck service for supplementary transportation. We model this scheduled transport service design problem to minimize the total transport and inventory cost considering the barge capacity and demands. The KKT conditions are adopted to derive the optimal decisions. A series of numerical experiments are conducted to validate the proposed model and find the optimal solutions for the case in the GBA. The impact of key parameters on optimal decisions and total costs are evaluated. It is found that the holding cost differential and barge's transport cost have significant impacts on the decision, and more airports in the airport cluster using this milk-run service will further improve the overall benefits.

The proposed approach also has some limitations. In this work, we only consider the barge and truck service with the same capacity for transshipment in airport cluster, and in the experiments, only two airports are considered. Future research could be carried out in the following avenues. It would be interesting to design the cross-border scheduled transport service in different modes and settings with dynamic demands. And further study could consider simultaneous pickup and delivery which will further reduce the operation costs. Besides, considering market competition and applying cost-benefit analysis with a multi-scope assessment, such as the impact on environment, will further facilitate the implementation of the proposed scheduled transport service.

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