Hub Location in Intermodal Distribution Networks with Economies of Scale and Service-Level Constraints

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Abstract. Hub location problems have been widely studied with the intent of developing an efficient solution for real-world problems. However, most contributions make simplistic assumptions, and as a result, they fall short of dealing adequately with characteristics of real operational problems. Consequently, a decision maker probably works with results based on limited variables. This study considers multiple hub types, multiple vehicle types, service levels, delivery schedules, delivery lead time, and real hub operating and transportation cost structures. Hence, strategic, tactical, and operational decision problems under demand uncertainty are integrated. We propose a multi-period, multi-allocation capacitated hub location problem with intermodal transportation. To solve this problem, a stochastic mixed-integer linear program (MILP) with chance constraints is formulated. A data set from a third-party logistics service provider (3PL) is investigated. Our results confirm that the intermodal hub distribution network offers significant cost savings to the 3PL. A change of service levels affects cost, inventory and throughput at hubs, fleet size, and delivery schedule, yet it hardly affects the number of opened hubs and locations.

1 Introduction

The hub, or facility, location problem plays a critical role in strategic supply network design. It has been investigated from various angles to acquire efficient solutions for real-world problems [1]. Nevertheless, most contributions fall short of dealing adequately with the characteristics of real operational problems. For example, economies of scale in the classical location literature have been assumed to occur on hub arcs with a constant discount factor, see [1]. Although employing multiple vehicle types has been applied to inter-hub connections [2], applying it to the whole network has been inadequately studied. Consequently, a decision maker probably works with an inadequate hub network, vehicle type, and cost assessment.

To efficiently determine solutions that could support the decision maker, we integrated strategic, tactical, and operational problems. Furthermore, we took into account the service level of demand satisfaction under time restrictions. Additionally, multiple hub types, multiple vehicle types, delivery schedules, delivery lead time, and real hub operating cost and transportation cost structures were included to answer the following research question: how to design the intermodal hub distribution network with economies of scale under demand uncertainty in order to satisfy demand at a high service level but at minimum total cost?

2 Literature review

Because the location problem is an NP-hard problem [1], many researchers have developed heuristic methods that solved the problem in less time, while some have investigated the problem for applications of 3PLs' operations, such as [3].

Moreover, attempts to improve solutions by considering characteristics of real operational problems are found in several articles. For example, [4] introduced a modal connectivity cost that was part of the intermodal hub set-up cost, and [5] claimed that economies of scale not only occur in inter-hub connections but also in others. Furthermore, [6] took service level into consideration and solved their problems by employing chance constraints. Considering delivery scheduling, [7] took different shipping frequencies into account but those were exogenous schedules, so an optimal schedule was not reported from their model.

3 Problem description

We analysed the problem from a 3PL's perspective and proposed a multi-period, multi-allocation capacitated hub location with intermodal transportation under demand uncertainty. We conducted both hub network delivery and direct delivery options, employed multiple vehicle types for both road and rail transportation, and took vehicle capacity restrictions into account. To satisfy customers under time restrictions, delivery services should achieve the service level that was defined as the probability of demand satisfaction and a cyclic planning approach was included for managing inventory.

Apart from the above operational assumptions, costs were a key component of the problem and we categorised them into three main groups. The first group was hub costs, consisting of hub set-up, modal connectivity, and operating costs. The second was transportation costs, and the third was inventory costs, consisting of inventory holding and in-transit inventory costs.

4 Model formulation

We formulated a MILP with chance constraints and proposed a deterministically equivalent form for solving the problem. All of the notations, equations and descriptions were explained in [8].

5 Numerical study and results

We investigated the data set from a 3PL in Thailand, where two warehouses distributed beverage products to 25 aggregated demand nodes across the country. In this study, we defined the demand nodes as potential hubs, considered a single product type (pallet), and deployed four truck types for road transportation and three container types for rail transportation. Additionally, Table1 shows other parameters that we employed. Lastly, we considered that the strategic decisions were fixed for a year, while the operational decisions were determined on a weekly basis.

Table 1. Input parameters.

Parameter	Value
Service level	**99%**, 97%, 95%, 90%, 80%
Delivery schedule	**Exogenous schedule (everyday),** Endogenous schedule
Hub capacity	**1000** pallets
Modal connectivity cost	**20%** of total hub costs

Remark: Bold letters are set as based case's parameters.

Results

Twelve different scenarios were examined, in which a network without hub and a hub network with 99% service level were defined as an as-is scenario and a base case, respectively. The problems were solved on an Intel® Core™ i7-4770 CPU @3.40GHz, with 32 GB of RAM. The MILP was implemented in Xpress IVE version 7.9 and solved by Xpress Optimizer. The terminating criterion was set at a 3% optimality gap.

It is obvious from Figure 1 that the base case decreased its total costs by 54% compared to the as-is scenario because intermodal transportation could be used and many larger vehicles were employed for long-haul transportation after establishing the hubs.

Investigating the results in more detail, the transportation costs of the base case declined considerably by 61%, while its fleet size was larger (see Figure 3) because unit transportation cost per kilometre for a longer trip was cheaper than for the shorter one. Consequently, economies of scale took place in the hub network and the transportation costs reduced. Nonetheless, establishing the hubs slightly increased the fixed set-up costs by 0.7%.

Considering the results from the service level angle, Figures 1-3 clarify that the total costs, inventory levels, throughput, fleet size, and total vehicle distance decreased when the service level decreased. Nevertheless, the number of opened hubs and locations were the same over all scenarios, except for the case of 80% of the service level. Thus, the benefits of lower service levels were in the reduction of the hub operating costs, transportation costs, and inventory holding and in-transit inventory costs.

Moreover, we compared different exogenous and endogenous delivery schedules. Figures 1-3 demonstrate that all of the outcomes from the endogenous scheduling cases were lower than those from the exogenous cases.

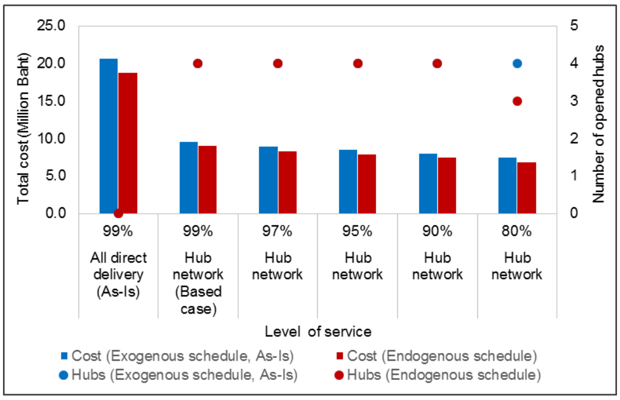

Figure 1. Total cost and number of opened hubs.

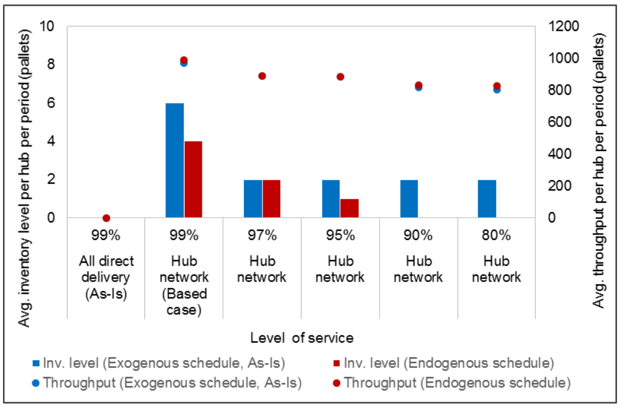

Figure 2. Average inventory level and average throughput at opened hubs (pallets per hub per period).

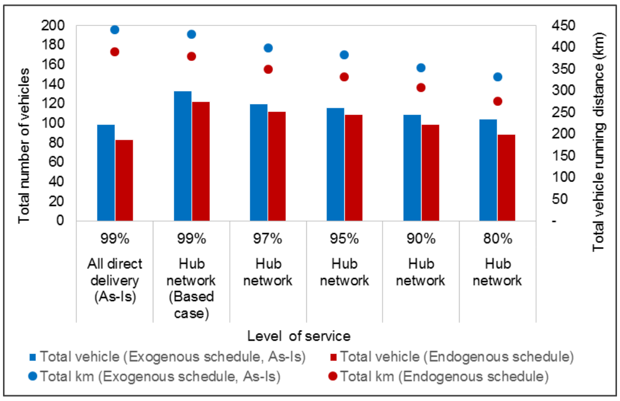

Figure 3. Total number of vehicles and total vehicle distances.

6 Conclusion

We propose a mixed-integer linear program in order to solve a combination of hub location, transportation, and inventory problems. Moreover, we integrate real-world operating characteristics and apply a real data set provided by a 3PL to the model. Regarding the numerical results, it was certain that conducting the integrated problems offers a large amount of cost savings to the 3PL. Furthermore, including an endogenous delivery schedule slightly increased the cost savings. Considering a change of service levels, we found this hardly affected the number of opened hubs and locations while it impacted cost, inventory, fleet size, and delivery schedule.

This research aims to improve and provide solutions to the decision maker that does not only help to evaluate the budget (total cost), but also provide information for the investment plan (hub locations and vehicles) and the operational plan (delivery schedule).

This extended abstract is part of the working paper in [8]. In the paper, the reader can find the model formulation, including other scenarios and further sensitivity analyses.

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