A stochastic facility location model for intermodal freight hubs

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Abstract: This article proposes a stochastic model for assessing the location of facilities for logistics terminals, modelled as freight transfer hubs to optimise the physical distribution of foreign trade products from the production centres to seaports and vice versa. The objective function minimises social costs, including private logistics costs (fares, travel times, transhipment) and external costs. In addition, the proposed approach uses a multinomial logit model as a demand function to incorporate consumer stochastic behaviour when choosing a route and location. The model was applied to the multimodal Colombian freight network. Results show that the social costs of logistics networks are reduced by including terminals that encourage intermodality. Network structure and economies of scale affect terminals selection.

Keywords: facility location; logistics terminals; intermodality; intermodal hub location problem.

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1 Introduction

Intermodal transport has emerged as an efficient and effective logistics strategy to combine the benefits of different transport modes. It offers a feasible option to distribute shipments at a competitive cost and time compared to the traditional unimodal networks. The integration of transport modes allows cargo shipment between origins and destinations which are economically and operationally viable (Arnold et al., 2001). Likewise, intermodality is crucial to enhancing efficiency and competitiveness in supply chain management. Usually, cargo is transported in a high-capacity mode such as rail or inland waterway for long distances (benefiting from economies of scale). In contrast, low-capacity modes (i.e. lorries) are used as feeders. In addition to economic benefits, intermodal transport mitigates environmental impacts.

Lorries are the main generator of negative externalities (i.e. pollution, congestion, noise, and traffic crashes) associated with freight transport. Inland waterways and rail have lower social costs than road transport. Márquez and Cantillo (2013) show that the external costs of road transport in Colombia are about 37 times higher than those of river transport and three times those of rail transport. Therefore, intermodal solutions which replace the road transport mode with alternatives that consume fewer resources would reduce the congestion, safety, and environmental problems caused by unimodal transport networks (Arnold et al., 2004; Yamada et al., 2009).

In Colombia, road transport is, by far, the predominant mode within the total cargo movement, with 84.4% participation; followed by the railway mode, with 11.9%; inland waterways with 1.5%; cabotage with 2.7%, and air mode with 0.04% (Ministry of Transport, 2020). It should be noted that, when coal and oil are excluded from the modal matrix, the following distribution is presented: the road transport mode mobilizes 97.0%, cabotage 1.9%, inland waterways 0.9%, air 0.1%, and railways mobilize 0.1%. On the other hand, according to the Global Competitiveness Report (World Economic Forum, 2019), Colombian transport infrastructure ranks 92 out of 141 studied countries. The lack of appropriate connections and intermodal facilities is one of the causes of the country's lag in this regard.

The panorama shows that the country does not take full advantage of the potential offered by intermodality for cost reduction but instead maintains a huge dependence on roads for freight transport, even over long distances. Facilitating intermodality requires, among other policies, designing appropriate logistics networks enabling intermodal exchange and connectivity. This article proposes a model that facilitates and promotes multimodality by designing a robust intermodal transport network to optimise the physical distribution of foreign trade products from the production centres to seaports and vice versa.

Various studies have shown the environmental benefits of intermodality, but these impacts have been less considered in hub location problems. The model framework presented in this paper includes external costs associated with each transport mode in the social cost minimisation objective function. The model is tested in a real-application case study in the regional intermodal network in Colombia, connected through a sparse network of road, rail, and inland waterways links. The resulting nonlinear integer programming problem was linearised and solved by CPLEX. Also, the optimal solution was confirmed by solving the problem again through an exhaustive enumeration algorithm.

This work contributes to logistics terminal location modelling in several ways. First, the proposed approach includes integrated decisions regarding terminal location and routes based on the p-hub median model, involving two levels of decisions (consolidation and distribution terminals), using social costs minimisation (private logistics cost plus externalities) in an intermodal context. Second, using a multinomial logit model (MNL) such as a demand function (location and route) allows incorporating consumer stochastic behaviour. Utility functions are assumed to be random variables, thus considering the agents' idiosyncratic nature. Finally, applying the model to the Colombian context leads to managerial insights where the expected impacts on the current national transport network were assessed.

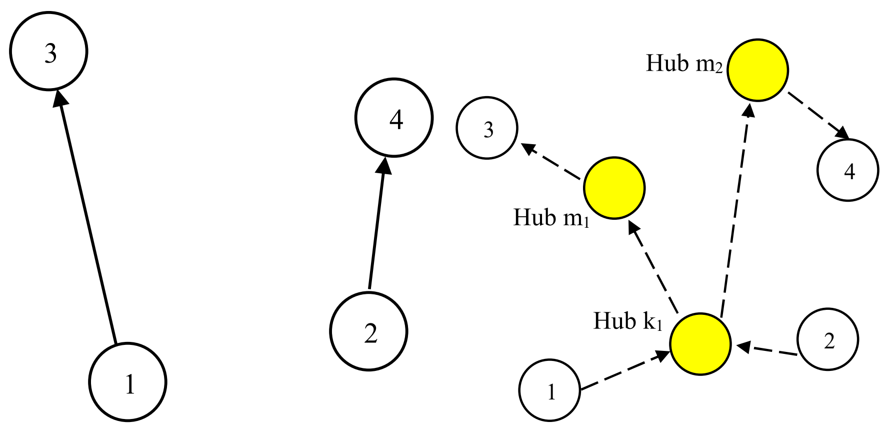
The rest of this document is organised as follows: Section 2 presents the literature review related to IHLP, emphasising the stochastic transport mode choice problem and considering externalities in the cost minimisation function. Section 3 describes the model and its mathematical formulation. Section 4 addresses the case study to which the model was applied. Section 5 present the results and their managerial implications to the Colombian context. Finally, Section 6 concludes.

2 Literature review

Hub location problems (HLPs) have been studied extensively in the literature. Goldman (1971) introduced the hub concept in transport networks as a particular facility designed as a switching or transhipment point. O'Kelly (1986) presented the first mathematical formulation and solution method where hubs connect a set of interacting nodes. Then, O'Kelly (1987) used a quadratic mathematical formulation to solve the single allocation p-hub median problem. Next, Campbell (1994) developed a formulation for four types of discrete hub location problems: the p-hub median problem, the uncapacitated hub location problem, the p-hub centre problem, and the hub-covering problem; according to the author, the hub location problems can be classified by how demand points are assigned or allocated to single or multiple allocations.

Several studies, especially the works carried out by Alumur and Kara (2008) and Farahani (2013), exposed extensive literature reviews about HLP in which models, methodologies, and hub facilities location applications are explored. The reviews are related to solving big-size problems, alternative network topologies, integration of cost and service, dynamic models, competition, and models with stochastic elements and reliability considerations.

Figure 1 Flows through hubs and traditional direct flows, (a) direct flows (b) flows through hubs (see online version for colours)



(a) (b)

Source: Vidovi and Ze (2011)

Critical elements of an intermodal transport network are the intermodal terminals (IMTs). IMTs are hubs that serve as a point for transhipment, consolidation, classification operations, and an intermodal transfer node of the system. Thus, IMTs must be located at strategic points that allow modal interchanges and intermediate reloading. This way, they could help make the process more profitable and increase its value. Likewise, the locations of the IMTs need to attract a minimum amount of cargo to benefit from economies of scale and cover high setup costs to make them viable (Lagoudis et al., 2017). The IMTs location problem can be approached as a hub and spoke network. It consists of locating a certain number of hubs from a set of potential IMTs and cargo assignments served by each hub with a minimum total cost (Crainic and Kim, 2007; Vidovi and Ze, 2011). This problem in the literature is called the intermodal hub location problem (IHLP).

Figure 1 illustrates an IHLP. Nodes 1 and 2 represent demands from origins (i.e., production/consumption centres) and nodes 3 and 4 destinations (i.e., seaports). Low volume demands are transported by road to an intermodal terminal (IMT) or a hub [node k1 in Figure 1(b)]. Cargo consolidation at the hubs allows for taking advantage of economies of scale. At a hub, traffic is consolidated into larger flows by high-capacity rail or river services that are routed to other hubs [nodes in m1 and m2 in Figure 1(b)], where traffic is deconsolidated and then moved again by road to destinations (Vidovi and Ze, 2011).

The first IHLP research specifically focused on locating IMTs is accredited to Arnold et al. (2001). Using mixed-integer linear programming (MILP), they studied regional intermodal transport systems where transfer costs using road-rail modes are minimised. The number of hubs was fixed at two IMTs. Due to a large number of decision variables and constraints in their previous work, Arnold et al. (2004) reformulated a solution to the binary linear program by a heuristic approach, resulting in a significant reduction of the complexity for large-scale problems. After that, Racunica and Wynter (2005) introduced economies of scale in unimodal rail networks. They included nonlinear and concave transport cost functions to capture economy of scale effects, and a linearisation algorithm was proposed for reducing the nonlinear problem. Then, Limbourg and Jourquin (2009) introduced the modal connectivity cost or transhipment costs defined as variable costs of handling flows at the hubs, and transport costs. The solution of the model was approached by repeatedly solving the p-median problem for each update in modal connectivity cost on the design of a road-rail intermodal network. The research conducted by Ishfaq and Sox (2010) proposed a p-hub median model for the hub allocation-location interaction in an interregional multimodal logistics network operated by a logistics service provider. This model included different shipment types, several modes of transport, transhipment costs, economies of scale, and service times. The research conducted by Ishfaq and Sox (2011) discussed a model to solve the issue of the p-hub median with multiple assignments that grant connections between different modes of transport. The proposed model included transport costs, modal connectivity costs, fixed installation costs, and limitations of service times in a multimodal network (railroad). Meng and Wang (2011) developed a new network design model with multiple modes to grant the flow of various types of containers, including different interest groups, different types of containers, and transfer processes in each hub. On the other hand, Ishfaq and Sox (2012) explored the effect of limited resources and the variability of modal transit times in the design of hub networks considering the limitations of service times. For such purpose, they designed a multiple allocation p-hub median model integrated into a system of queues with different products and deterministic routes, which allowed traffic rates and variabilities to be obtained in average waiting shipping times in the logistics network.

Almost without exception, the mixed-integer linear programming (MILP) technique and a deterministic mode choice modelling approach have been used to locate IMTs in most previous research of IHLPs described in the previous paragraphs (see Table 1). These approaches conduct to 'all-or-nothing' assignment of flows between competing modes. Teye et al. (2017) demonstrated that the solution to MILP models is corners to the simplex formed by the constraints, and this forces the allocation part of the problem to assign all to the minimum cost mode. This method is helpful under non-competitive situations in which a single shipper or firm decides how to combine the transport modes and routes at minimum cost and where to allocate the IMTs. Sasaki and Fukushima (2001) modelled a hub location through the Stackelberg game, showing the significance of rival companies when locating and designing hubs. They used a logit function to determine the assignment of customers to available services to capture stochastic choice preferences.