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MILP model for designing the intermodal inland terminals and seaports network: a case study

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Abstract This paper aims to propose a Mixed Integer Linear Programming (MILP) model based on the typical hub location problem, which has been designed and used to propose an analysis for the intermodal inland terminals network design considering container seaports, their traffic and limited allocations. The main container freight flows from/to selected seaports and distances between provinces (with the support of a Geographic Information System) are considered. Estimated functions for road and railway transport costs are included, these being the required inputs to solve the problem. The model's main objective is to reduce total transport costs through the optimal location of a set of inland terminals connected to seaports by railway. The problem has been successfully solved by using the Gurobi software, which allows an interesting analysis of inland terminals location and their area of influence.

Keywords: MILP, Network Design, Hub location, Case Study, Intermodal terminal

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1.1 Introduction

Globalization, increase in maritime container traffic and environmental concerns are some of the trends that make designing the logistics chains of containers transport a complex task. Nowadays, logistics platforms play an important role as key instruments for territorial balance and for the development of a more sustainable transport model by bundling volumes, rationalizing traffics and fostering intermodal transport.

For years, the container shipping business has focused on reducing maritime transport costs through economies of scale. This has led to a high level of concentration in the industry, the use of increasingly large container ships and the development of new hub-and-spoke systems where a few hub ports concentrate the cargo. The ever-increasing difference between high volumes concentration on the seaside and landside atomization has led to different kinds of problems such as terminals congestion and road congestion at seaport accesses.

In this context, shipping companies, terminal operators and port authorities now also focus on inland transport, port-hinterland connections and integral door-to-door services. Competition no longer lies between ports, but between complex logistics networks which integrate ports, inland intermodal terminals, as well as logistics and distribution centers.

In Spain, many logistic nodal infrastructures have been road-oriented and planned from a regional or local point of view, which is not always aligned with the European and Spanish general transport policy where substantial efforts are being made to foster alternative and more efficient transport modes like rail.

The literature about hub location is extensive. An interesting review is proposed by Alumur and Kara (2008), Campbel (1994) and Gelareh and Nickel (2011). Nevertheless to the best of our knowledge, an MILP model for designing intermodal terminals and seaports network which considers the non linear discount factor has not yet been proposed.

Section 2 introduces a brief problem description. Section 3 proposes the MILP model by considering non linear scale-reduced factors. Section 4 presents the results, and the last section proposes a conclusion.

1.2 Problem definition

The network hub location problem has been vastly analyzed by presenting different formulations as well as heuristics proposals to solve it. Alumur and Kara (2008) provide a detailed review of the different approaches available in the literature. Single and multiple allocation problems, fixed costs of opening hub facilities, cost functions, discount factors and optimization methods have been studied. Hubs are facilities which bundle volumes and concentrate flows in order to reduce transport costs through economies of scale. In the literature, a discount factor is considered, but it is a fixed parameter. Given the origin/destination matrix of traffic flows in a many-to-many distribution system, the hub location problem deals with the hub facilities location and the demand nodes allocation to hubs in order to route the traffic flows between origin-destination pairs so that total costs are minimized. In the single allocation problem, each demand node is assigned to a unique hub so that all the incoming and outgoing traffic of this node is routed through this hub, while each demand node can be assigned to more than one hub in multiple allocation problems (Figure 1.1).

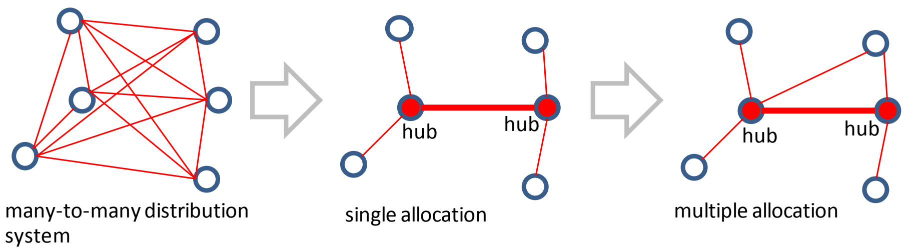

Fig. 1.1 The hub location problem

This case study analyzes the specific problem, which presents the following particularities:

- The flow origin/destination matrix has been developed at the province (NUTS-3) level. A total of 47 Spanish provinces has been considered as freight flows origin/destination (Islands have not been considered in the study).
- Only container seaport-hinterland traffic flows from and to the four main Spanish container seaports (Valencia, Algeciras, Barcelona and Bilbao) have been considered.
- The provinces of the four main Spanish container seaports are already considered to be hub nodes.
- Any transport between hub nodes is done by rail (all hubs are connected to each other by rail), while truck transport is used to connect the rest of the nodes with their respective hubs.
- Transport costs are estimated.
- Fixed costs for opening hub facilities are not considered.
- Each province (demand node) can be assigned to a maximum number of hubs (multiple allocations).
- The objective of the model is to determine an additional hubs location, a hubs allocation, in order to minimize total costs.

1.3 MILP model formulation

The model described below is a mixed integer mathematical programming model. Because of the length constraint, all the constraints are not introduced. The omitted constraints are present in (Ernst and Krishnamoorthy 1998).

Table 1.1 contains the notations for the sets and indices used for the formulation.

Table 1.1 Sets and Indices

N	Province set
P	Seaport set $(\subseteq N)$
Π	Discount factor set
$p \in P$	Seaport index
$i, j, k \in N$	Province index
$r \in \Pi$	Discount factor index

Table 1.2 contains the parameter notations.

Table 1.2 Parameter notations

C_{ij}	Cost of transporting one container unit by truck from province *i* to province *j*
I_{pj}	Importation of total flow, whose origin is seaport *p* and destination is province *j*
E_{jp}	Exportation of total flow, whose origin is province *j* and destination is seaport *p*
$H^{\max}$	Maximum number of hubs desired
K_j	Maximum allocation number for province *j*
$O_p^P = \sum_{j \in N} I_{pj}$	Amount of containers whose origin is seaport *p*
$O_j^J = \sum_{p \in P} E_{jp}$	Amount of containers whose origin is province *j*
$D_p^P = \sum_{j \in N} E_{jp}$	Amount of containers whose destination is seaport *p*
$D_j^J = \sum_{p \in P} I_{pj}$	Amount of containers whose destination is province *j*
$A_r \in [0,1]$	Discount factor for reduction *r*
$\overline{M} \geq 1 + \sum_{p \in P} \sum_{j \in N} \left(I_{pj} + E_{jp} \right)$	A sufficiently positive large number

$\Delta_r^{I+} / \Delta_r^{I-}$	Maximum/Minimum flow of importation containers that consider reduction *r*
$\Delta_r^{E+} / \Delta_r^{E-}$	Maximum/Minimum flow of exportation containers that consider reduction *r*

Table 1.3 contains the variable notations

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Z_{ij}	1 if province *j* is allocated to province *i* (0 otherwise)
Y_{kij}	Fraction of the container flow from province *k* to province *j* which is routed via the hubs in province *i*
V_{ij}	Fraction of the container flow from province *i* to province *j*
ϕ_{rpi}	1 if reduction *r* is applied between seaport *p* and province *i* (0 otherwise)
$\alpha_{pi} = f\left(V_{pi} + V_{ip}\right)$	Discount factor applied between seaport *p* and province *i*. It is volume-dependent.

The model can be formulated as shown below:

$Minimise[z]$

$$z = \sum_{i \in N} \sum_{j \in N} C_{ij} \cdot \sum_{p \in P} \left(Y_{pij} + Y_{jip}\right) + \sum_{p \in P} \sum_{i \in N} \alpha_{pi} \cdot C_{pi} \cdot \left(V_{pi} + V_{ip}\right) \tag{1.1}$$

$$z = \sum_{i \in N} \sum_{j \in N} C_{ij} \sum_{p \in P} \left(Y_{pij} + Y_{jip}\right) + \sum_{p \in P} \sum_{i \in N} C_{pi} \sum_{r \in \Pi} A_{rpi} \cdot \phi_{rpi} \cdot \left(\Delta_r^{E+} + \Delta_r^{I+}\right) / 2 \tag{1.2}$$

Subject to:

$$\sum_{r \in \Pi} \phi_{rpi} \leq 1 \quad \forall p \in P, i \in N \tag{1.3}$$

$$\sum_{r \in \Pi} \phi_{rpi} \geq Z_{ii} \quad \forall p \in P, i \in N \tag{1.4}$$

$$V_{pi} - \overline{M} \cdot \phi_{rpi} \leq -\overline{M} + \Delta_r^{I+} \quad \forall r \in \Pi, p \in P, i \in N \tag{1.5}$$

$$V_{pi} - \overline{M} \cdot \phi_{rpi} \geq -\overline{M} + \Delta_r^{I-} \quad \forall r \in \Pi, p \in P, i \in N \tag{1.6}$$

$$V_{ip} - \overline{M} \cdot \phi_{rpi} \leq -\overline{M} + \Delta_r^{E+} \quad \forall r \in \Pi, p \in P, i \in N \tag{1.7}$$

$$V_{ip} - \overline{M} \cdot \phi_{rpi} \geq -\overline{M} + \Delta_r^{E-} \quad \forall r \in \Pi, p \in P, i \in N \tag{1.8}$$

$$\phi_{rpi} \in \{0,1\} \quad \forall r \in \Pi, p \in P, i \in N \tag{1.9}$$

Objective (1.1) consists in minimizing total transport cost, which include the sum of transport costs by road and transport costs by railway between each province and seaport. The discount factor is flow volume-dependent (it depends on the traffic between provinces), so it is variable and Objective (1.1) is non linear.

As Objective (1.1) is non linear, an alternative linear form is proposed in (1.2). This objective function has been linearized using the Special Set Orders 1 variables. In this case, transport costs are penalized in accordance with the superior limit of the flow range values.

(1.3) forced the model to consider just one discount factor, which is active between seaport p and province i.

(1.4) implies considering one discount factor between seaport p and province i if i is a hub.

Constraints (1.5)-(1.8) force the container flow value between seaport p and province i to be inferior and superior to the limits for flow value when a discount factor r is active.

(1.9) defines the domains of the considered variables.

1.4 Results

1.4.1 Considered scenarios

Different scenarios have been developed for the analysis when considering different:

- Discount factors for railway transport
- Intra-province road transport cost estimation at hubs
- Maximum number of hubs
- Maximum number of allocations

1.4.2 Experimental results

The following figure presents some results obtained when solving the problem for the different scenarios. As observed, the total transport cost of the optimal solution, the selected inland hub nodes for this solution, a visual illustration of the transport flows between nodes, nodes allocation to hubs, are used to evaluate the solution (Figure 1.2).

	scenario nº 13	scenario nº 14	scenario nº 15
total transport cost	436.897.683,00	382.288.172,60	432.951.562,60
selected inland hubs	N3 (Alicante)	N19 (Guadalajara)	N3 (Alicante)
	N19 (Guadalajara)	N22 (Huesca)	N14 (Córdoba)
	N22 (Huesca)	N24 (León)	N19 (Guadalajara)
	N24 (León)	N30 (Murcia)	N22 (Huesca)

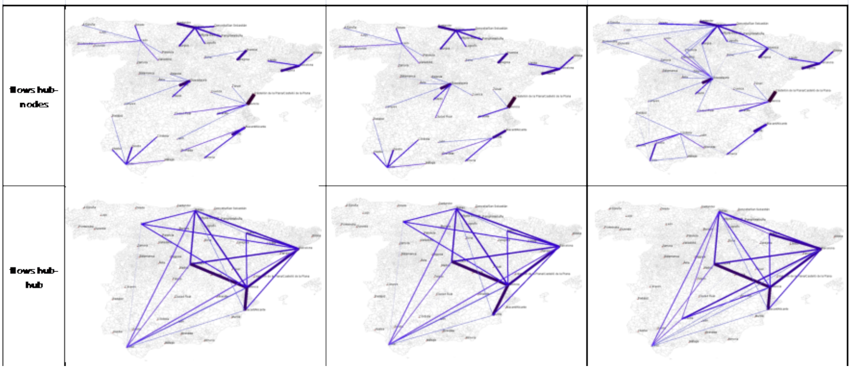

Fig. 1.2 Optimal solution for the different scenarios

The results analysis allows us to identify key inland hub nodes, such as Alicante, Madrid and Zaragoza, in almost all the scenarios for the optimal solution. It can be observed than when intra-province road transport costs increase, hub nodes like Madrid or Zaragoza shift to alternative locations in the surrounding provinces or nodes, such as Guadalajara or Huesca, respectively (for example, see Scenarios 13, 14 and 15). This is due to the fact that an increase in intra-province road transport costs can make this even bigger than an alternative road transport from/to a neighboring province. This effect can be compared to the effect of including additional costs relating to the establishment of hubs in places like Madrid due to high land and real-estate prices.

Other additional hubs which appear as part of the solution in some of the scenarios are Seville and Castellón, and León but to a lesser extent. The Castellón hub appears in the optimal solution in the scenarios where savings through railway transport are significant. This is because of its intense traffic with the Port of Valencia hub, but Castellón does not really act as a hub and no other nodes are allocated to the Castellón hub.

Finally, and as expected, we observe that better results are obtained with the multiple allocation problem (that is, total transport costs are reduced). Nonetheless, there are no significant changes in the identification or selection of the inland hubs between the single allocation and the multiple allocation (double allocation in this case) scenarios.

1.5 Conclusion

As a general conclusion of this research work, a new MILP model formulation is proposed in this paper that considers different discount factors which are volume-dependent. Moreover, it can be stated that the application of this MILP model to different scenarios and the analysis of the results can prove most useful for policy makers and for logistic and transport operators to design and plan an efficient intermodal network that connects ports with its hinterland. As observed, this kind of analysis with a scientific approach provides interesting inputs to make strategic decisions at the infrastructure planning level, which are also very sensible from the territorial, social and political points of view.

Further research has been identified throughout this work, as follows: (i) designing specific heuristics for the problem considered herein; (ii) solving the problem in a distributed manner; and (iii) incorporating variants such as uncertainty (it may be stochastic or uses fuzzy methods) is another future research line.

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