Netw Spat Econ (2011) 11:295–314
DOI 10.1007/s11067-009-9126-7

The p-hub Model with Hub-catchment Areas, Existing Hubs, and Simulation: A Case Study of Serbian Intermodal Terminals

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Published online: 9 February 2010

Abstract This paper addresses the problem of optimally locating intermodal freight terminals in Serbia. To solve this problem and determine the effects of the resulting scenarios, two modeling approaches were combined. The first approach is based on multiple-assignment hub-network design, and the second is based on simulation. The multiple-assignment p-hub network location model was used to determine the optimal location of intermodal terminals. Simulation was used as a tool to estimate intermodal transport flow volumes, due to the unreliability and unavailability of specific statistical data, and as a method for quantitatively analyzing the economic, time, and environmental effects of different scenarios of intermodal terminal development. The results presented here represent a summary, with some extension, of the research realized in the IMOD-X project (Intermodal Solutions for Competitive Transport in Serbia).

Keywords Intermodal freight terminals location · p-hub location model · Simulation · Case study

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1 Introduction

Acordingly to statistical data (2009), the volume of freight transport in Europe (EU-27) has increased 40% in the last decade alone, mostly through increases in road transport, which has significant environmental and economic consequences. Road transport has negative impacts: noise, pollution, traffic accidents, congestion, costs, etc. (Nijkamp 1994). One possible solution for a more environmentally friendly transportation system is the integration of different modes of transport within the framework of intermodal transport.

The development of intermodal solutions would reduce the negative impact of road transport by replacing it with less resource-consuming transport modes (Arnold et al. 2004). These intermodal solutions will enable future growth in transport demand to be partially absorbed by non-road alternatives.

Intermodal transport is defined by the European Conference of Ministers of Transport (ECMT 2001) as “movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes of transport without handling the goods themselves in changing modes”. Also, the term intermodality has been used to describe a system of transport whereby two or more modes of transport are used to transport the same loading unit or truck in an integrated manner, without loading or unloading, in a door-to-door transport chain. This loading unit can be a container, swap body, or semi-trailer: the usual term representing all these units is ITU (intermodal transport unit).

The major part of the cargo’s journey is performed by rail, inland waterway or sea, while the initial and/or final legs are typically carried out by road. The main idea behind intermodal transportation is to combine the advantages of different transport modes: sea, rail, or inland waterway transport for long distances and/or large quantities; road transport for short or medium distances and/or smaller quantities.

The most important elements of an intermodal transport network are the terminals, i.e., intermodal nodes, which are locations that connect two or more transport modes. Therefore, the main objective of this paper is to determine optimal intermodal terminal locations. Solving these strategic-level problems is particularly important for regions and countries with a low level of intermodalism, of which Serbia could be considered a typical example.

Intermodal terminals may be designed to handle different ITUs and to serve different transportation modes (e.g. rail-road, river-road, river-rail-road) depending on the configuration of the transport network, node locations, accessibility from different transport modes, demand characteristics, transport flow volumes, and so on. Due to the geographical position of Serbia and the existing transport network characteristics, the term “intermodal terminal” includes rail-road and rail-river-road terminals in this research.

The approach used here to optimally position intermodal terminals is based on hub network design models, since such models can easily be extended to the location of intermodal terminals (Arnold et al. 2004). Namely, rail-road as well as rail-river-road intermodal transportation systems are organized as so-called hub-and-spoke networks, illustrated in Fig. 1. To take advantage of economies of scale, low-volume demands from origins (nodes 1, and 2 in Fig. 1(b)) are moved by road to an intermediate point—a intermodal terminal or a hub (node HUB a in Fig. 1(b)). At a hub, traffic is consolidated into larger flows by high-capacity rail or river services that are routed to other hubs (nodes HUB b,c in Fig. 1(b)), where traffic is deconsolidated and then moved again by road to destinations (nodes 3, and 4 in Fig. 1(b)).

Because intermodal transportation systems introduce not only economic, but also environmental benefits, our proposed solution method was based on two approaches: multiple assignment p-hub network IP location model, and simulation. The deterministic p-hub location model is used to choose intermodal terminal locations from the set of possible candidate locations, while simulation evaluated each set of chosen locations quantitatively analyzing the economic, time, and environmental effects of intermodal terminal development. Also, simulation has been proved as a supporting technique in the process of input data estimation, used as a tool for origin-destination (O/D) matrix determination and for estimation of future demand between O/D pairs.

While this paper is concerned with the problem of locating intermodal freight terminals in Serbia, the proposed approaches offer some more general innovations in this field. Firstly, the p-hub network location model, used to find optimal locations, is extended to introduce terminal catchment areas. Secondly, the proposed solution methodology based on simulation allows for estimation of costs, time, and environmental performance. The idea of the catchment area is introduced in order to correctly model the influence of distance between users and terminals on realized intermodal service. Namely, in real intermodal networks, customers at origins and destinations use intermodal service only when they are within a certain resonable distance from a terminal (usually about 100 km,). Therefore, catchment area denotes the area within the circle of certain predefined radius from the intermodal terminal location. That is, any arbitrary customer can be allocated to the terminal only if it is located within the terminal catchment area. Although imposition of catchment area requirements is a common feature of intermodal networks in the real world, to the best of authors' knowledge this characteristic has not received attention in previous research. However, some practical recommendations about the distance between users and terminals can be found in different Internet sources and studies (see for example report Regional Intermodal Terminals (2004) or Network Rail (2009) web page). In this study, the radius of the catchment area was varied in order to analyze its impact on the intermodal network configuration.

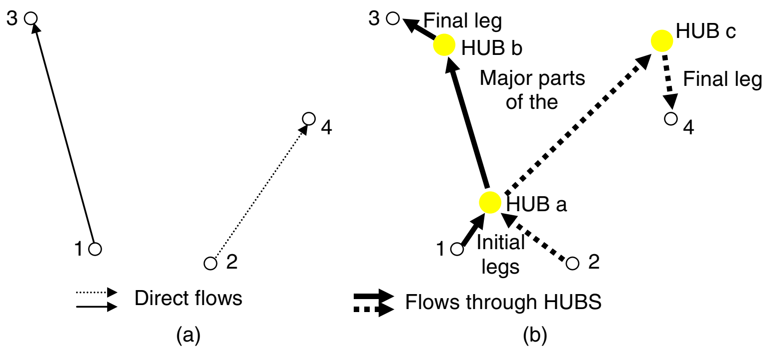

Fig. 1 Flows through hubs and traditional direct flows

Similarly, most studies dealing with intermodalism pointed out its positive impact to the environment, but those effects usually are not estimated. Our proposed methodology, which gives estimates of costs, time, and environmental performance, tries to fill this gap, offering more parameters to decision maker. Therefore, in this case study the process of intermodal transport network design is based on two main steps:

- Application of mixed-integer deterministic multiple assignment p-hub network location model to minimize transportation costs
- Application of simulation to estimate savings in transport costs, transport time, and environmental effects

The remainder of this paper is organized as follows. Section 2 presents a short literature overview of the field of intermodal terminal location problems. The solution approach based on the multiple assignment hub-network design approach is described in Section 3. In Section 4, the main concept of the simulation modeling approach is described. A brief description of the approach to input data estimation, as well as some of the inputs, are presented in Section 5. Section 6 presents computational results, and Section 7 gives some concluding remarks.

2 Literature overview

P-hub location formulations appear in many application areas and in the literature one may find several variants. The basic model (O'Kelly 1987) assumes that all traffic passes through two hubs on its route from its origin to its destination, no hub capacities, no direct transport between nonhub terminals, and no fixed costs for establishing a link between a regional and a consolidation terminal.

The main idea on the efficiency of hub networks is based on the assumption that interhub transportation is more efficient due to the concentration of flows, which means that transportation between hubs has a lower unit cost than the other movements in the system (Crainic and Kim 2007).

The first hub location model was defined as a quadratic integer program, and was presented by O'Kelly (1987). This formulation referred to the single allocation p-hub median problem, and later Klincewicz (1991) developed an exchange heuristic for this problem type. Since then, a substantial number of papers devoted to hub location has appeared, dealing with different problem types, its variants, and formulations (single and multiple allocation p-hub median problems with or without the fixed costs of opening facilities,…). As hub location problems have been studied so extensively, numerous linear formulations and algorithms, particularly for the class of p-hub median problems, have been proposed. For example, O'Kelly et al. (1995) presented a lower bound based on a linearization of the hub location, where distances satisfy the triangle inequality. Skorin-Kapov et al. (1996) developed mixed integer linear formulations with tight linear programming relaxations. Klincewicz (1996) proposed the dual-ascent technique for the uncapacitated hub location problem using the solution to a transportation problem to determine feasible dual values. Ernst and Krishnamoorthy (1998) presented MILP formulations for the multiple allocation p-hub median problem. Sohn and Park (2000) proposed a mixed integer programming formulation for the single allocation problem in the three-hub system, and Hamacher et al. (2000) examined the feasibility polyhedron of the uncapacitated hub location problem with multiple allocation. Most recently, Alumur and Kara (2008) included some recent trends of hub-location models, and provided a synthesis of the literature in this area, citing more than 100 papers related to hub location problems.

The problem of optimal hub location in a network has received attention over the past decade due to its importance in air passenger and cargo transportation, telecommunication and postal delivery services, as well as in intermodal freight transportation. To optimally locate rail/road terminals for freight transportation in the Iberian Peninsula, Arnold et al. (2004) formulated a solution to the binary linear program by a heuristic approach. Groothedde et al. (2005) presented the results of design and implementation of a collaborative hub network for the distribution of fast-moving consumer goods using a combination of trucking and inland barges. Racunica and Wynter (2005) devised a model for an innovative hub-and-spoke network for intermodal freight transport on dedicated or semi-dedicated freight rail lines, which could make use of shuttle trains between hubs. Initial results for an agent-based model for the evaluation of road-rail intermodal freight hub location decisions was given by Sirikijpanichkul et al. (2007). Janic (2007) proposed a model for calculating comparable, combined internal and external costs of intermodal and road freight transport networks. For a more details on intermodal transportation, see the recent book chapter in Crainic and Kim (2007).

3 Multiple assignment p-hub network location model

Because of the nature of intermodal services, where the major part of the cargo's journey usually occurs by rail, inland waterways or sea, and where initial and final legs are often carried out by road transport, the problem of locating intermodal terminals may be described as a hub location problem, as previously shown in Fig. 1(b).

To be more clear, let us consider the set of origin and destination nodes on a freight transportation network, and assume that some of these nodes are going to be transformed into intermodal freight terminals or hubs. Then, the problem of locating intermodal freight terminals is equal to the problem of finding the subset of nodes to be transformed into terminals, and determining terminals to be used in the route associated with each origin–destination pair in such a way that the total cost is minimized, while each route from the origin to the destinion node should pass through two terminals.

In this paper, a model for locating intermodal terminals is based on the multiple assignment hub-network design approach described in O'Kelly et al. (1996). This approach assumes symmetric flow data, further reducing the size of the problem, while the reduced formulation is able to find integer solutions to the LP relaxation most of the time. The assumption about symmetric flow data in this study can be easily accepted, as intermodal traffic tends to be organized in this way, equalizing transport flows between O/D pairs in both directions.

The original model is modified according to additional requirements regarding catchment areas and the existence of intermodal terminals abroad, whose locations are not subject to optimization. The catchment area restriction ensures that transport flows in rail-road intermodal transportation networks are routed through two terminals, where the first is close to the origin and the second is close to the destination node. Since the objective here was to find the optimal locations of intermodal terminals in Serbia, while locations of terminals abroad were known, it was necessary to reformulate the problem according to this network configuration. This reformulation further reduced the size of the problem, because the four index variable X_{ijkm} which denotes fraction of flow from origin i to destination j routed through the hubs k and m, can be transformed into a three index variable X_{ijk}. Assumption of the known location of intermodal terminals abroad was introduced through the costs calculation. Intermodal transport costs C_{kj} were calculated as costs between hub k and the terminal abroad close to the destination j, while C_j comprised intermodal transport costs from a terminal near the destination j to destination j. That is, for terminals abroad whose locations were not subject to location analysis, single allocation of each destination j to the intermodal terminal of known closest location implicitly assumed.

Furthermore, we sought to analyze the impact of intermodal terminal catchment areas on the terminals' location. Consider two origin nodes i', and i", inside and outside of the terminal k catchment area, defined by the circle of radius R_k (Fig. 2).

The catchment area models the influence of distance between users and terminals, in the sense that for all origin and destination nodes, intermodal service may exist only when they are within the certain (resonable) distance from a terminal. The size of the catchments area could be calculated as the origins/destinations within reach for distribution during one normal working day, e.g. within 2–3 h driving time (truck on road), which leaves 2–3 h for handling and service time. Depending on the average driving speed, the area will be then within a radius of 100–200 km. From Fig. 2, it is obvious that $(d_{i'k} - R_k) < 0$, and $(d_{i''k} - R_k) > 0$. From there, inequality $(d_{ik} - R_k) \cdot X_{ijk} \leq 0$ can be used to prevent any fraction of flow $X_{ijk} > 0$ from origin i to destination j to be routed through the hub k, when origin i is outside of its catchment area.

The model was reformulated as shown below.

Minimize

$$Z = \sum_{i \in O} \sum_{j \in D} \sum_{k \in H} W_{ij} \left(C_{ik} + C_{kj} + C_j \right) \cdot X_{ijk} \tag{1}$$

subject to

$$\sum_{k \in H} X_{ijk} = 1 \quad \forall i \in O \quad \forall j \in D \tag{2}$$

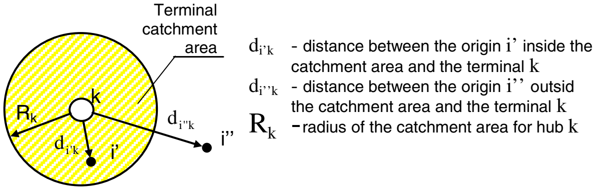

Fig. 2 Terminal catchment area

$$X_{ijk} - Y_k \leq 0 \quad \forall i \in O \quad \forall j \in D \quad \forall k \in H \tag{3}$$

$$\sum_{k \in H} Y_k = p \quad Y_k \in \{0\,,1\} \quad \forall k \tag{4}$$

where

- p number of hubs to be opened
- W_{ij} flow from origin i to destination j
- C_{ik} transport costs of the first leg per unit of flow (from origin i to hub k)
- C_{kj} intermodal transport costs per unit of flow (between hub k and the terminal close to the destination j)
- C_j transport costs of the second leg per unit of flow (from terminal near the destination j to destination j)
- X_{ijk} fraction of flow from origin i to destination j routed through the hub k
- Y_k binary variable, Y_k=1 if hub k is opened, otherwise $Y_k = 0$

Constraints (2) ensure that the flow between every origin-destination pair (i,j) is routed via some hub. Constraints (3) ensure that the O-D flows are only routed via locations that are hubs. Finally, constraint (4) specifies the number of hubs to be opened.

Equations (1, 2, 3 and 4) formulate the multiple-assignment p-hub network location model without terminal catchment areas. To make the problem much closer to reality by including terminal catchment areas, the previous formulation was modified by adding one more group of constraints and by changing constraint (4) to (6). Hence, the multiple-assignment p-hub network location model that includes terminal catchment areas of radii R_k can be formulated by using terms (1, 2 and 3) and adding the following two constraints, given by (5) and (6).

$$(d_{ik} - R_k) \cdot X_{ijk} \leq 0 \quad \forall i \in O \quad \forall j \in D \quad \forall k \in H \tag{5}$$

$$\sum_{k \in H \cup \{D\}} Y_k = p + 1 \quad Y_k \in \{0\,,1\} \quad \forall k \tag{6}$$

where

- D dummy node
- d_{ik} distance between the origin i to hub k, ($d_{iD} \approx 0$)
- R_k radius of the catchment area for hub k

A dummy node was included to collect transport flows from districts with a distance greater than R_k from any opened hub (terminal node). In this way, it was possible to ensure that the flow between every origin-destination pair (i,j) was routed via some hub, as stated by constraint (2). Transport costs via the dummy node were chosen to be large enough to prevent directing flows through this hub, except in the case when there is no other node to be used, as defined by constraint (5). Note that in the real intermodal system, flows routed through the dummy node are not carried by intermodal transport technology, but by direct road tansport.

Because the objective was to find the optimal locations of intermodal terminals in Serbia only (only element of the set O), sets O and D can be considered as disjoint $O \cap D = \emptyset$, while $H \subseteq O$. If m,n and p are number of origins, destinations and potential terminal locations respectively, because of symmetric flow data, the total number of variables in the formulation given by (1–4) is $p(1 + m \cdot n)$, of which p variables are binary. The total number of linear constraints is $m \cdot n\ (1 + p)$. When the model includes terminal catchment areas, the number of constraints increases to $m \cdot n\ (3 + 2p)$. In this case study, the intermodal network had 31 origins, 17 destinations and 14 potential terminal locations, and the total number of variables was 7,392, with 16,337 linear constraints when the model respects terminal catchment areas.

The multiple-assignment p-hub network location model was solved using LPsolve IDE v5.5.

4 Simulation modeling approach

The general concept of the simulation model used in this case study resulted from two main objectives that should be realized:

- using simulation as a supporting technique in the process of input data estimation, as a tool for origin-destination (O/D) matrix determination and for estimation of future demand between O/D pairs
- evaluating sets of locations chosen by p-hub location model, quantitatively analyzing the economic, time, and environmental effects of intermodal terminal development

The main idea implemented in the module where simulation is used as a supporting technique in the process of input data estimation was in creating randomly generated instances of expected flows from all origins $i \in O$ to all destinations $j \in D$ (from/to matrix of W_{ij} values) that could be used together with the cost, time and environmental impact parameters, in optimally locating intermodal freight terminals in Serbia.

Creating randomly generated instances of expected flows was realized in two phases. In the first phase, based on rules described in the Section 5.3, to each destination $j \in D$ abroad is assigned its participation $0 \leq \gamma_j \leq 1$ in total flows, where $\sum_{j \in D} \gamma_j = 1$. In the second phase, based on rules described in the Section 5.4, simulation is used to calculate number q_i of ITUs generated in each origin $i \in O$, where $\sum_{i \in O} q_i = Q$, and Q denotes total intermodal transport flow volume, described in the Section 5.2. Based on those two values it was possible then to create one instance of the from/to matrix of W_{ij} values, making product $W_{ij} = q_i \cdot \gamma_j$. The averaged value of all expected flows obtained in different replictions is used in linear programming model.

In this way aforementioned problems of unreliabile statistical data, uncertainties in future flow prediction, and unpredictable socio-economic development of specific regions are avoided to a certain extent, as well as the problem of current state replication, since flow intensities and distance patterns are not in fixed proportion, but defined by ranges of stochastic variable parameters.

The next step in the simulation model application was the module that calculated the economic, time, and environmental effects of applying both traditional and intermodal transportation chains. For each pair of source-destination points, and each randomly generated instance of expected flows between them, six performance factors were calculated: costs of road and intermodal transportation, transit times of road and intermodal chains, and pollutant emissions for each transport chain realization. These performances were calculated for some terminal location scenarios determined by the p-hub location model. Finally, because simulation provided huge amount of outputs, collected through multiple replications, it was possible to present all those performances as ranges of output values, as shown in Section 6.

The simulation model was implemented in VBasic 6 and MS Excel software for the analysis of different transport volumes tariffs, and input parameters.

5 Input data determination

Determining the optimal solution for terminal locations in a real network required a tremendous amount of input data related to candidate terminal locations, origin-destination flows matrices, and estimated future demand intensities.

Due to the unreliability of statistical data, uncertainties in future flow prediction, unpredictable socio-economic development of specific regions during the IMOD X project realization (IMOD X 2006), input data were based on different data sources, expert estimates, and simulation for origin-destination (O/D) matrices determination and estimation of future freight volume intensities between O/D pairs.

Inputs used in the intermodal network modeling process are the following:

- Candidate locations for intermodal freight terminals
- Total intermodal transport flow volumes in Serbia in 2015
- Distribution of flows between import/export origins/destinations
- Distribution of flows between districts in Serbia
- Demand elasticity and terminal catchment areas
- Transport costs and operation times in the transportation process
- Data regarding the environmental impact of the transport system

5.1 Candidate locations of intermodal transport terminals

Candidate locations were based on the spatial plan of the Republic of Serbia (Strategy of Economic Development 2002). There were 14 candidate locations, as shown in Fig. 3.

5.2 Intermodal transport flow volumes in Serbia in 2015

Development of intermodal transport in Serbia depends on several direct and indirect factors. However, the impact of some factors is very difficult to analyze, particularly in the case of their future behavior. Additionally, numerous obstacles arise from the fact that statistical data from the previous periods are not reliable or relevant. Because of these factors, and because of the limited availability of relevant data

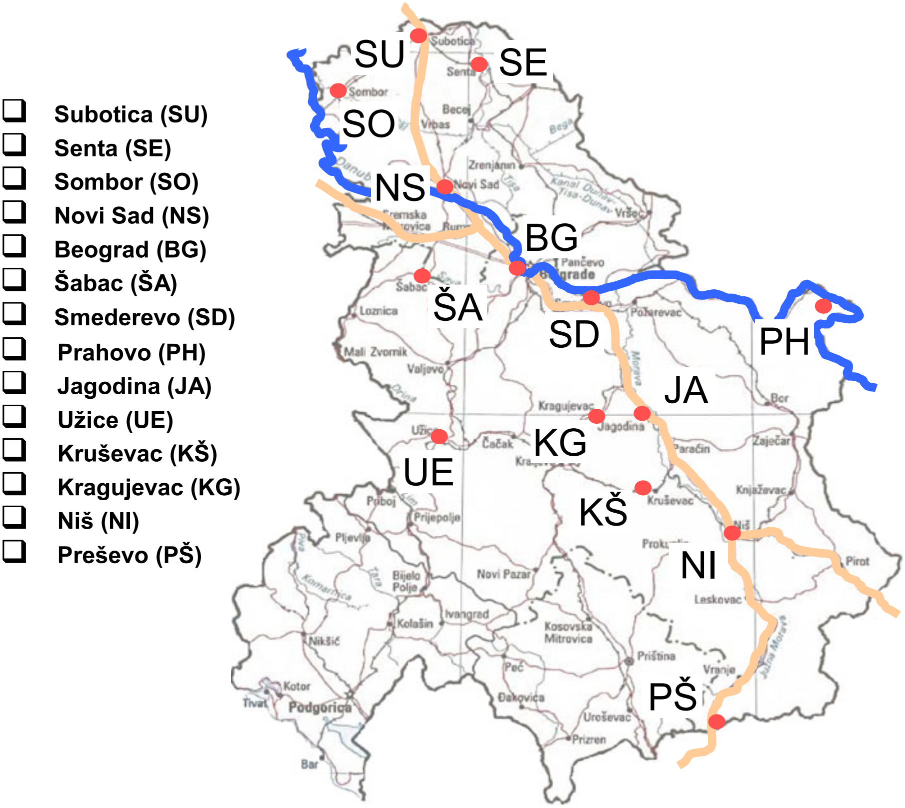

Fig. 3 Candidate locations of intermodal terminals in Serbia

(especially those related to intermodal transport flows), intermodal transport volumes were estimated based on the expected economic development of Serbia for 2015.

The analysis presented in IMOD X (2006) resulted in 57 different possible volumes for the total intermodal transport flows, ranging from 58,490 to 264,891 ITU. This study presents results for the scenario with a total intermodal transport flow volume of 120,000 ITU, as the most possible total volume expected, while effects of intermodal network development, determined by simulation, are presented as unit values per one ITU.

5.3 Distribution of flows across inbound/outbound directions

All of the source/destination countries were divided into four groups, based on their percentage of the total flows and distances. The first group consists of two countries (Italy and Germany), the second group includes the former Yugoslavia (ex YU) countries, the third group consists of overseas destinations (Canada, USA, Africa, Asia, Australia), and all other are in the fourth group. Groups contribution to the total flows was described by uniform distributions for each group:

– Participation of the first group was estimated to be uniformly distributed between 10 and 20% of the total import–export flows

– Participation of the second group was estimated to be uniformly distributed between 5 and 30% of the total import–export flows
– Participation of the third group was estimated to be uniformly distributed between 8 and 12% of the total import–export flows
– Participation of the fourth group was a complement of the 100%, which gives 38–77% of the total import–export flows

Participation of flows within the second and third group is divided equally among group members. In the first group, the participation of Italy was assumed to follow a uniform distribution between 44 and 66% and the remaining participation was attributed to Germany.

The second group represents all countries that arose from the former Yugoslavia, without further separation of flows.

The third group covers overseas destinations, and has Port Koper as a source/destination point. Flow intensities in different directions within the same group were assumed to be shared equally.

The fourth group has five distance classes: countries within 400 km, 600 km, 900 km, 1,500 km, and 2,000 km.

Participation of countries within different distance classes was assumed to follow a uniform distribution with left boundary between 1 and 8%, proportionaly to the participation of the fourth group, and the right boundary assumed to be one fifth of the participation of fourth group.

The specific origin/destinations within the defined groups were not considered individually. Rather, they were represented as centers of larger zones, served by a particular intermodal terminal (Fig. 4). Depending on the source/destination country, the zone's radius was between 50 and 300 km, depending on the density of the intermodal terminal network. In total, in all of four groups of countries there were 17 zones, considered in the model as source/destination nodes.

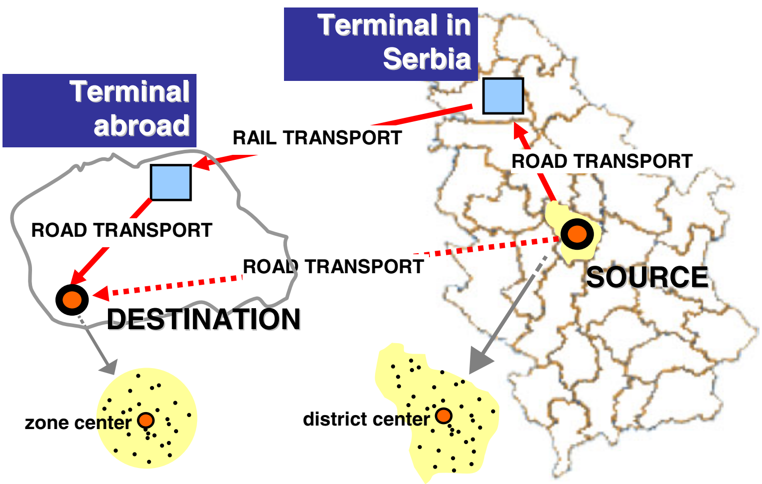

Fig. 4 Concept used for definition of source/destination nodes

5.4 Distribution of flows across districts in Serbia

Similar to the introduction of uncertainty in the distribution of import–export flows over destinations abroad, the flows among Serbian districts was also considered as a stochastic variable.

Based on this analysis and similar studies, districts in Serbia were clustered into four groups according to their size, GDP, degree of development, and so on. Thus, the first group consists of the Belgrade district. The second group consists of less-developed districts in Vojvodina and the district of Nis. The third group consists of even less-developed districts, and the fourth group consists of underdeveloped districts.

In the simulation, the starting assumption was that the district of Belgrade will retain the leadership position between now and 2015; however, changes in the relative degree of development among the remaining districts are possible. Hence, it was assumed that districts from group II can move to group III with a certain probability, and vice versa. It was also assumed that changes in the relative degrees of development among districts in groups II, III, and IV are also possible.

The simulation of the distribution of flows across districts was performed in two phases. In the first phase, the change of group composition was simulated, and in the second phase, the relative share of each specific district was simulated.

The probability of a district to move from group III to group II was fixed at 35%, and the probability that two districts will change status in the given period (until 2015) was fixed at 5%. In this way, the internal distribution of flows over distances and quantities was also taken into account, and an additional step was made to avoid mirroring existing relationships into the future.

Sources and delivery points inside Serbian districts were not considered individually (Fig. 4). Rather, they were represented by the district centers. In this way, the average distance inside each district was used to measure the “first leg” transportation costs realized by road transportation, and intermodal flow volumes were related to the district as a whole. In this study 31 district centers were considered as source/delivery nodes.

5.5 Demand elasticity and terminal catchment areas

Although similar studies typically assume a small increase in flow volumes when the number of terminals increases (for example, see Arnold et al. 2004), the impact of the number of terminals on the increase in demand for intermodal transport is not considered in this research. The reason for this is in the relatively small territory of Serbia where the average initial leg and final leg are relatively short even in the case of existence of only a few terminals. However, the impact of increases in flow volumes is partially considered by introducing terminal catchment areas.

The radius of the catchment area is based on the assumption of an average driving time (truck on road) of 2–3 h. Hence, in this study, three catchment area radiuses were analyzed: 100 km, 150 km, and 200 km. In one scenario, the terminal network was analyzed without the impact of terminal catchment areas, meaning that the estimated intermodal transport flows are realized independently from the distances between the source/destination nodes and terminals.

In the modeling process, the district allocation to terminals was determined based on the minimal distance, restraining flows from distances longer than the catchment area radius.

5.6 Transport costs and transport operation times

The transport costs and operational times used in this study were based on real market prices, tariffs of transport service providers, and realistic estimates of operation times. A detailed structure of costs and operational times are given in the IMOD-X (2006).

In this analysis, the ratio of the costs of road and railway transport was varied. The analysis was run based on the current cost ratio for road to railway transport and for two alternatives in which the railway costs were decreased by 20% and 30%.

5.7 Data related to the environmental impact of the transport system

The data required and the related methodology were adopted from the PORTAL transport teaching material (2003).

In general terms, estimation of the transport-related emissions included emission produced when the engine is hot, when the engine is cold, and emission by evaporation (only for VOC).

6 Computational results

This paper gives the main results that illustrate the solution approaches that were applied. The results show the optimal locations for the cases when up to five terminals are opened.

6.1 Results obtained by p-hub modeling approach

Results of the analysis using the p-hub network location model are presented in Table 1, and show the optimal locations for the cases where $p \leq 5$ terminals,

Table 1 Results of the p-hub network location model

p-hub model results	Number of terminals to be opened				
	1	2	3	4	5
Without terminal catchment areas	BG	BG,NI	BG,NI,NS	BG,NI,NS,UE	BG,NI,NS,UE,SD
With terminal catchment areas of 100 km radius	NS	NS,BG	NS,BG,KŠ	NS,BG,KŠ,PŠ	NS,BG,KŠ,PŠ,PH
With terminal catchment areas of 150 km radius	NS	NS,JA	BG,NS,PŠ	BG,NS,JA,PŠ	BG,NS,NI,JA,PŠ
With terminal catchment areas of 200 km radius	BG	BG,NI	BG,JA,PŠ	BG,NS,JA,PŠ	BG,NS,SD,JA,PŠ

according to the concept of analyzing intermodal freight transport with a small number of intermodal terminals.

This approach also analyses the percentage of flows that could be captured by hubs when catchment areas are considered. Additionally, inbound/outbound flows to/from districts that are not allocated to any of opened terminals must be realized by direct road transportation, which will increase transportation costs. Results of the analysis are shown in Tables 2, 3, 4 and 5.

It should be noted that, in the case in which the radius of terminal catchment areas is 200 km, it is possible to serve 98% of the estimated demand through terminals even when only three terminals are opened. The results above show that the costs of intermodal transport increases with increasing catchment areas, while direct road transportation costs decreases, as a result of wider catchment areas, which collect a larger portion of flows realized through terminals. In the same time total costs decrease slowly and when three or more terminals are opened remain almost constant.

In this case study it is obvious that intermodal transportation is not competitive compared with road transportation, as a result of the high tariffs incurred when transporting ITU by rail. Specifically, because of the current proportion of rail and road transportation tariffs, road transport is always favorable, with the total costs for the scenario of 120,000 ITU being 71.15 mil. EUR and 69.36 mil. EUR when 98% of the estimated demand is served. It is interesting that in the case of catchment areas of 150 and 200 km, total costs are permanently decreasing from 1 to 5 hubs, which indicates that further increasing the number of hubs to 6, 7, 8 or more would be even more expensive. However, this decrease has only theoretical importance because of decreasing flows' intensity in terminals, which may have implications for the adequacy of building terminals of low capacity.

Although it seems to be surprising, these results are a logical consequence of the current proportion of rail and road transportation tariffs, where the rail transport and terminal transhipment costs make up 0.7 and 0.82 of the total intermodal costs, respectively on distances of 500 km and 1,000 km. From this perspective, the results are consistent with those from previous research (see Arnold et al. 2004) where it is found that the market shares of rail and combined transport are reduced and tend to be insignificant when the relative cost of rail is greater than 0.80, and that the rail and combined transport could be considered as optimal choice only when the relative cost of rail is lesser than 0.60. As Arnold et al. (2004) stated, this perfectly illustrates the fact that, when no environmental bonus is granted, the economic competitiveness of rail (and transhipping operations) is a determining factor in the

Table 2 Costs of intermodal transport without terminal catchment areas

No. of hubs	Intermodal costs [mil. EUR]
1	82.63
2	76.13
3	73.33
4	72.16
5	71.35

Table 3 Impacts of terminal catchment areas of 100 km

No. of hubs	Intermodal costs [mil. EUR]	Percentage of flows realized through terminals [%]	Costs of direct road transportation [mil. EUR]	Total costs of road and intermodal transportation [mil. EUR]
1	38.92	53.66	35.16	74.08
2	52.25	77.83	18.44	70.69
3	57.82	84.93	13.09	70.91
4	60.17	87.75	10.63	70.80
5	62.03	89.95	8.87	70.90

choice of transportation variation in the market shares of the different modes or combination of modes.

Thus, increases in the intermodal share, and the benefits gained from using energetically and ecologically favorable transport modes, require lower tariffs on rail transportation.

An important consideration is also the accuracy of the assumed terminal catchment areas, since the decision of intermodal terminal locations is sensitive to the value of this parameter, as can be seen in tables Tables 3–5.

It is also interesting to evaluate the expected percentage of total flow volume through terminals in different location scenarios and for different terminal catchment areas. These outputs are shown in Table 6.

The overall conclusion that can be drawn from this analysis is verification that Belgrade (BG) and Novi Sad (NS) should be considered as the most important intermodal network nodes, since they are optimal in almost all scenarios and accommodate a significant portion of total freight flow volumes. Additionally, Niš (NI), as a large city and regional center together with Preševo (PŠ), and Jagodina (JA), particularly Preševo, could play important roles in scenarios with larger numbers of terminals.

The computational performance achieved for the p-hub network location model, solved by LPsolve IDE v5.5, 32-bit Windows version, on an AMD Turion X2 Dual-

Table 4 Impacts of terminal catchment areas of 150 km

No. of hubs	Intermodal costs [mil. EUR]	Percentage of flows realized through terminals considered [%]	Costs of direct road transportation [mil. EUR]	Total costs of road and intermodal transportation [mil. EUR]
1	44.42	60.43	30.17	74.59
2	61.34	81.75	14.95	76.29
3	63.17	90.06	8.25	71.32
4	66.67	95.10	4.33	71.00
5	66.69	95.57	3.93	70.59

Table 5 Impacts of terminal catchment areas of 200 km

No. of hubs	Intermodal costs [mil. EUR]	Percentage of flows realized through terminals [%]	Costs of direct road transportation [mil. EUR]	Total costs of road and intermodal transportation [mil. EUR]
1	60.78	84.16	13.71	74.49
2	70.88	96.00	3.61	74.49
3	72.41	98.00	1.79	74.20
4	69.61	98.00	1.79	71.40
5	68.90	98.00	1.79	70.69

Core Mobile RM-70 2.0 GHz, was very good. All optimization problems were solved in less then 15 sec.

6.2 Results obtained by simulation model

After various sets of locations were determined by the p-hub network location model, simulation was performed to estimate the expected savings resulting from intermodal terminal development, compared with direct road transportation (cost savings, transport time savings, and environmental effects: carbon monoxide—CO, volatile organic compounds—VOC, mono-nitrogen oxides, NO and NO_2—known as NOx emission) for some of the most preferable terminal location scenarios.

Table 6 Expected freight flow volumes through terminals

Catchment areas	Terminals in solution	Percentage of freight flows through the terminal [%]								
		BG	NS	NI	UE	SD	KŠ	PŠ	PH	JA
100 km radius	two	73.4	26.6	–	–	–	–	–	–	–
	three	67.2	24.4	–	–	–	8.4	–	–	–
	four	65.0	23.6	–	–	–	8.0	3.4	–	–
	five	63.4	23.0				7.9	3.3	2.4	
150 km radius	two	–	73.2	–	–	–	–	–	–	26.8
	three	67.0	23.0	–	–	–	–	10.0	–	–
	four	58.2	21.8	–	–	–	–	8.0	–	12.0
	five	57.9	21.7	5.5	–	–	–	5.2	–	8.6
200 km radius	two	85.3	14.7	–	–	–	–	–	–	–
	three	79.0	–	–	–	–	–	9.3	–	11.7
	four	57.8	21.1	–	–	–	–	9.3	–	11.8
	five	57.9	21.8	4.3	–	–	–	6.2	–	9.8
Without terminal catchment areas	two	83.5	–	16.5	–	–	–	–	–	–
	three	62.8	20.6	16.6	–	–	–	–	–	–
	four	59.3	20.7	15.8	4.2	–	–	–	–	–
	five	47.6	20.7	14.4	4.2	13.1	–	–	–	–

Following the premise of the projects' terms of reference under which the analysis should be directed to the effects of intermodal terminal development "in bigger cities and/or cargo-intensive regions in Serbia" (IMOD-X 2006), and keeping in mind the results from the p-hub network location model, this section presents the expected economic, time, and environmental effects as determined by simulation.

The effects of developing the given intermodal terminals were calculated by the simulation model for transport flow volumes in 2015 with 120,000 ITU. The results are presented in the form of unit effects (i.e., total effects divided by the total volume of goods) as shown in Table 7. Note that the nominal economic effect can be simply calculated from the given unit effects, as the product of the flow volume, and the unit effect.

The simulation model results show that the best economic effects are achieved by developing terminals in Belgrade (BG), Novi Sad (NS) and Nis (NI). However, closer analysis of these results reveals high sensitivity of the outputs to the selection of input values.

From these results, it is obvious that the development of intermodal transport, given the current ratio of costs for road and railway transport, is not justifiable from an economic point of view, as was also concluded from the p-hub model results. However, it can be seen that development of intermodal transport becomes economically justifiable with a decrease in the railway transport costs of 20% or more (for terminals located in BG-NI, or BG-NS-NI). The simulation shows that, in addition to the rail tariffs, there is another barrier to intermodal application—rail transport transit time. Specifically, transit times observed on the real system are too long compared with those for the road transportation system. Hence, increasing the intermodal share and benefiting from the use of energetically and ecologically favorable transport modes requires lower tariffs for use of the rail transportation and decreases in the time of rail transport operations.

Finally, it is worth mentioning that a greater number of terminals require a greater initial infrastructure investment. If the necessary investments are provided from the state and taxpayers (state budget), the size of the infrastructure investment needs to be considered as an additional criterion in the process of selection the best location scenario. On the other hand, if the results of this analysis are to be understood as a basis for creation of necessary conditions (e.g., legal, urban, and so on) for the development of terminals at specific locations, then infrastructure investments of potential logistics providers cannot be taken as an additional criterion in the process of selecting the best location scenario.

7 Conclusions

A two-part modeling approach for solving the intermodal terminal location problem was developed and applied to a real intermodal system. The results show that the two approaches can be used together as tools for determining the locations of terminals. The main considerations used in the process of input data estimation are also presented, which was likely the most complex part of the research conducted during the IMOD X project realization.

Table 7 Effects of implementation of intermodal transportation—simulation model outputs

Terminal locations	Costs savings (Eur/ITU)									Time savings (h/ITU)			Savings in polutants emission (g/ITU)								
	Current road and rail tariffs			Rail tariffs decreased 20%			Rail tariffs decreased 30%						CO			NOx			VOC		
	min	average	max	min	average	max	min	average	max	min	average	max	min	average	max	min	average	max	min	average	max
BG	−180	−80	14	−149	−55	63	−150	−46	56	−61.6	−58.79	−55.6	605	937	1280	335	491	650	1572	2455	3382
BG, NS	−166	−61	37	−135	−37	77	−122	−27	68	−61.3	−58.53	−55.4	642	969	1301	355	507	661	1677	2545	3440
BG, NI	−98	−2	96	−76	22	113	−72	31	135	−61.6	−58.50	−55.3	719	1064	1402	392	556	710	1893	2813	3718
BG, NS, NI	−91	17	108	−51	41	128	−35	50	144	−61.1	−58.24	−55.2	745	1096	1421	408	572	718	1966	2902	3768

The optimization model based on a p-hub model formulation is extended to introduce terminal catchment areas in order to correctly model the influence of distance between users and terminals on realized intermodal service. It is shown that the proposed formulation gives very good results in a short computational time and can therefore be used for comprehensive analysis.

The simulation model calculates three performance factors for defined location scenarios: costs, time, and pollution effects incurred by realization of both traditional and intermodal transport chains.

Although the results obtained give some answers related to the optimal location of intermodal terminals, there are several possible directions for further research. Further analysis is required regarding demand. Additionally, possible improvements in the modeling approaches should be considered, including multicriteria analysis, particularly because of the multifaceted nature of logistics performance factors that are used for the evaluation of different scenarios and solutions.

Acknowledgements The authors gratefully acknowledge the insightful comments of NETS Location Area Editor, and two anonymous reviewers which significantly improved the paper. This research was conducted as part of a one and a half year project (2005–2006): Intermodal Solutions for Competitive Transport in Serbia (IMOD-X), created to evaluate the possibilities of organizing a competitive intermodal transport services in Serbia. The project was a part of the bilateral assistance program between Norway and Serbia and was fully financed by the Norwegian Government.

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