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DYMEMULP – Dynamic Model of Process Optimisation in Regional Logistics

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ABSTRACT

The expansion of logistics requirements, limited space and strict requirements of generators of logistics requests (GLR) in terms of service quality complicate the supply of the region, resulting in the necessity to improve logistics models (MoL). Proximity to water, the presence of ports and piers along the coast, new eco vehicles and the development of cooperation between land and water transport are elements for improving the existing MoLs in an economically and environmentally acceptable way. Research on the development of an improved multi-echelon logistics network with variable terminals including the coordination and cooperation of a heterogeneous group of transport agencies for the realisation of goods flows represents an innovation in regional logistics (RL). This article presents an integrated MoL development process using dynamic optimisation with a focus on spatial, temporal, transport, economic and environmental components.

KEYWORDS

regional logistics; logistics model; optimisation; coordination and cooperation.

1. INTRODUCTION

The "regional metabolism" trend represented in terms of [1–4] (1) larger numbers of inhabitants and GLRs, (2) existence of different supply chains (SC) in a limited area, (3) change in the type and structure of logistical requirements, (4) limitations in the realisation of physical distribution of goods, (5) limited space for system development, (6) increased requirements for the preservation of the environment and historical components, requires the improvement of the existing MoL in order to provide a quality response to new logistical needs. The resulting changes in the SC structure, which are reflected in the specialisation, professionalisation and integration of certain logistics systems (LS) and processes, as well as the greater volume of commodity exchange, affect the implementation of the reengineering process of the existing MoL in the domain of systemic, technological and organisational improvements with an emphasis on optimisation, in order to develop a higher level of logistics. It is required that a new MoL integrates several regional functions [2], i.e. housing, tourism, transit and city logistics, into one functional model, which relies on a new paradigm of logistics. The focus is on [1] the total integration of the system, the efficient and economical operation of the RL system, the development of solutions with minimal spatial interventions and the application of technologies that have a small negative impact on the environment.

Ports today have the characteristics of modern logistics centres (LC) [1]. From a strategic point of view, an important systemic solution is the connection of a large port as a p-Hub with several smaller regional ports and wharves along the entire coast of the region [2], which can exist as a network of city distribution centres (CDC). Piers along the coast represent the basis for the development of a network of cross docking terminals (CDT), with the aim of realising the physical distribution of goods (*Figure 1*).

The creation of a new MoL is the result of the need for optimal, efficient, high-quality and ecologically acceptable supply to the region.

The focus on “port-oriented logistics chains” aims to [2]: include the port in RL as an integrum system of the regional importance, enable the transfer of part of the transport to the water side and the goal of reducing the number of trucks on the streets.

The new logistics needs of the region initiate the improvement of the existing MoL with a focus on: (1) the new logistics network in which the p-Hub port is located, (2) the application of eco-vehicles in the process of distribution of goods, (3) the establishment of cooperation and coordination processes and (4) digitisation of all systems and processes. The key optimisation elements go in the direction of [2] coordination on the road–sea route and cooperation on the truck–eco distribution vehicle (cargobike, cargo hopper) route. The development of a CDT network in the form of flow terminals along the coast for receiving solar-electric powered distribution boats carrying delivery containers is an essential technological component of coordination. By connecting CDT and distribution zones on the mainland with eco vehicles that distribute goods to GLR, a naturally paired and improved technological solution can be provided.

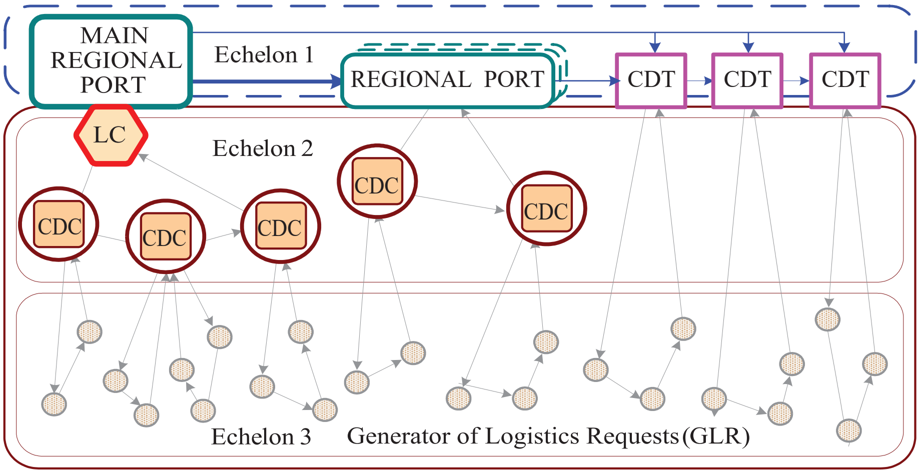

Figure 1 – Presentation of the improved logistics network of the region [2]

This article aims to present the original optimisation procedure DYMEMULP in the reengineering of the regional MoL, which contains a multi-echelon logistics network with variable CDTs, multiple unified sets of vehicles and various forms of coordination and cooperation in the transport process.

2. PROBLEM DEFINITION AND METHODOLOGY FORMULATION

The reengineering of the regional MoL in this article is focused on the relation [2]: geographic space → logistics profile → clustering → location-allocation problem → system solution → supply optimisation. The development of new MoLs requires comprehensiveness [5]: (1) strategic planning of the logistics network, (2) concentration of logistics flows within the LC, (3) development of CDTs in the function of rapid transfer of goods flows from the water side, (4) representation of the process of cooperation of modes of transport, (5) process coordination in road transport, (6) process management according to the core supply chain management model (7) representation of the new logistics paradigm, (8) integration of several regional functions into one model, (9) digitalisation of processes. The MoL must meet a number of objectives: (1) elimination of delays in the realisation of goods flows, (2) reduction of freight transport in urban and tourist areas, (3) elimination of duplication of capacity with the aim of greater spatial availability, (4) lower costs of operating the system, (5) ensured expected level of supply and quality of logistics service etc.

The MoL development process has 4 phases [2]: (1) determination of the logistics needs of the region, (2) planning of a possible logistics network, which can meet the identified needs, (3) identification of a new MoL based on the DYMEMULP optimisation and (4) comparison of the proposed solution to some other techniques. In the first phase, the border of the region and the number, spatial arrangement of GLRs and their qualitative and quantitative logistical needs are determined. The established logistics profile of the region generates a possible multi-echelon logistics network that can meet the needs. The identified possible network and the transport processes in it need to be optimised. Finally, the new and previous MoLs should be compared based on the criteria.

DYMEMULP is a mathematical model [6–21] for MoL development, which finds the answer to the question of what is the optimal logistics network for a region with a certain number of service zones $J(j) = \{1, 2, 3, ..., p\}$ with a defined potential number and spatial arrangement of LCs as p-Hub (P_h), number and spatial arrangement of fixed CLCs $I(i) = \{1, 2, 3, ..., m\}$ and variable CDT satellites $L(l)=\{1, 2, 3, ..., n\}$, with different forms of cooperation and coordination in transport.

The problem of determining the optimal location of potential CDCs and CDTs [9, 19–21] can be solved by general optimisation, heuristics and metaheuristics. For the purposes of the research presented in this article, the methods of the gravity model are used.

3. MATHEMATICAL FORMULATION OF THE DYMEMULP MODEL

One region constitutes a set of clusters $\varepsilon=\{e\}$, divided into zones j, $j \in J$. Within the zones there are GLRs z, $z \in Z$, which generate flows of goods.

Each zone is represented by essential attributes:

A) *number of objects* No_z, with a defined probability of belonging by zone:

$$P(No)=\begin{Bmatrix} j_1 & j_2 & \cdots & j_z \cdots & j_m \\ p_{n1} & p_{n2} & \cdots & p_{nz} \cdots p_{nm} \end{Bmatrix}, p_{nj}=\frac{N_{oj}}{\sum_{j=1}^{m} N_{oj}}=\frac{N_{oj}}{N_o} \tag{1}$$

B) *average number of deliveries* $\overline{f}$ during the day $No_z \cdot \overline{\lambda}_{jt}$,

$$P(\bar{f})=\begin{Bmatrix} j_1 & j_2 & \cdots & j_z \cdots & j_m \\ p_{f1} & p_{f2} & \cdots & p_{fz} \cdots p_{fm} \end{Bmatrix}, p_{fj}=\frac{N_{oj} \cdot \lambda_j}{\sum_{j=1}^{m} (N_{oj} \cdot \overline{\lambda}_j)}=\frac{f_j}{\overline{f}} \tag{2}$$

C) *average daily quantity of delivered goods* $\overline{q}$, $No_z \cdot \overline{\lambda}_{jt} \cdot \overline{q}_{jt}$, by zones:

$$P(\bar{q})=\begin{Bmatrix} j_1 & j_2 & \cdots & j_z \cdots & j_m \\ p_{q1} & p_{q2} & \cdots & p_{qz} \cdots p_{qm} \end{Bmatrix}, p_{qj}=\frac{N_{oj} \cdot \lambda_j \cdot q_j}{\sum_{j=1}^{m} (N_{oj} \cdot \lambda_j \cdot \vec{q})}=\frac{q_j}{\vec{q}} \tag{3}$$

Each GLR from the set $Z=\{z\}$ has attributes $D=\{d_z\}$: GIS position (x, y), quantity of goods $q(d_z)$, requested in the period $t(d_z)$ within the zone $j(d_z)$, which should be delivered in the interval $[t_1(d_z)$, to $t_m(d_z)]$. Delivery frequency $W(d_z)$, quantity of one delivery $Vis(d_z)$ and required delivery time $Zvi(d_z)$ are also attributes. The values of $q(d_z)$ and $W(d_z)$ are defined by the quantitative O-D matrix.

All GLRs from the set $Z=\{z\}$, according to logistic requirements (type of goods etc.), are divided into five groups:

$$G=\{1, \ldots, 5\}\text{: } RG_e^s=\begin{Bmatrix} G_1 & G_2 & G_3 & G_4 & G_5 \\ p_1 & p_2 & p_3 & p_4 & p_5 \end{Bmatrix}, \quad \sum_{t=1}^{5} p_t=1 \tag{4}$$

A “day before” delivery strategy was defined for GLRs.

Each cluster e has a defined graph $A=B \cdot V$ of the transport network consisting of: (1) class of nodes $B=\{1, ..., n\}$ and (2) class of links $V=B \cdot B$.

The regional p-Hub (P_h) is located within the port (*Figure 2*) and has a given location due to the location of the port itself. Fixed satellites P_h, in the form of CDCs, $I=\{i\}$, are in operation throughout the year. Their potential location is determined based on preferential supply zones. Every satellite $i \in I$ has a defined capacity and set of vehicles k. In period t_2, when the demand for goods increases $h(q_j+q^*_j) \in H$, a set of variable satellites is introduced into the logistics network $L=\{l\}$. These are flow-through CDTs, partially technologically developed. Their potential location is determined by the location of boat docks along the coast of the region. The indicator δ_{lt} is defined as the opening of CDT l only in period t_2, $\delta_{lt}=\{0,1\}$. CDT satellites are supplied with goods from Ph, CDC, or both, as economics dictate.

After defining the potential locations of satellites i, $i \in I$ and l, $l \in L$, it is necessary to determine the distances d, so the following notation is introduced:

d_{ikt} – distance from P_h to CDC i if using vehicle types k in the period t;
d_{lkt} – distance from P_h to CDT l if using vehicle types k in the period t;
d_{ijkt} – distance from CDC i to zone j, if using vehicle types k in the period t;
d_{ljkt} – distance from CDT l to zone j, if using vehicle types k in the period t;
d_{ilkt} – distance from CDC i to CDT l if using vehicle types k in the period t.

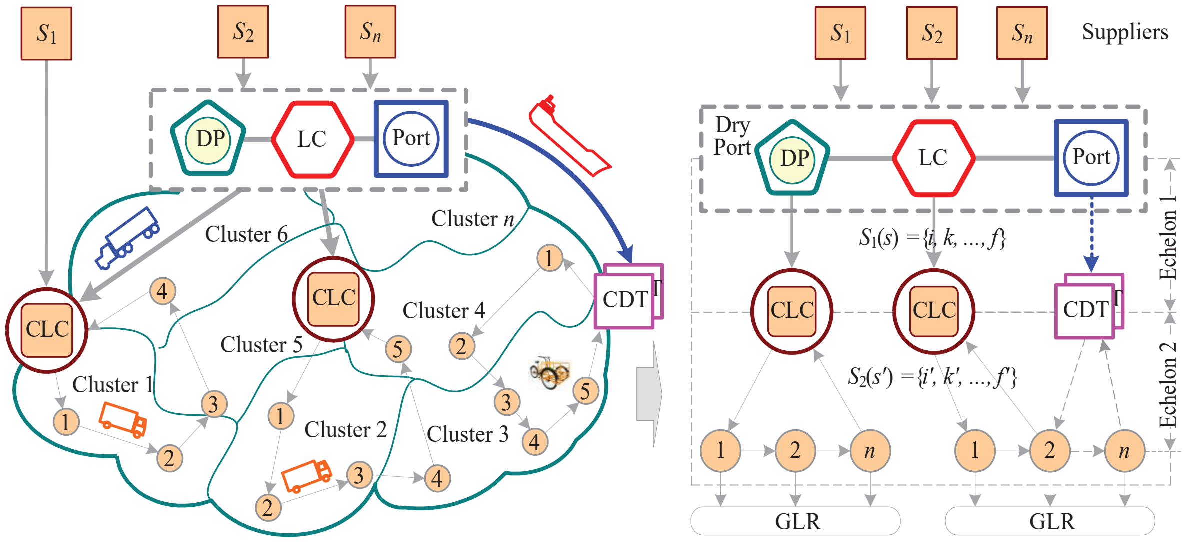

Figure 2 – Multi-echelon logistics network of the region

Logistics providers $\Psi(\psi)=(1, 2, ..., n)$ in P_h and CDCs, define the needs for goods by zones of the region within the quantitative O-D matrix (t, m^3).

Every P_h, CDC and CDT owns a set of vehicles k, $k\in K$. Vehicle type set $K=5$:

- $k=1$, truck, load capacity $g_1=5$ t and load factor $\eta_1=0.9$,
- $k=2$, cargohopper, load capacity $g_2=5$ t and load factor $\eta_2=0.9$
- $k=3$, cargo bike, load capacity $g_3=0.5$ t and load factor $\eta_3=0.9$,
- $k=4$, eco boat, load capacity $g_4=20$ t and load factor $\eta_4=0.9$,
- $k=5$, tow truck, load capacity $g_5=26$ t and load factor $\eta_5=0.9$.

Vehicles from the set K perform transport processes in the time interval T, where $T=365$ days. The time interval T may contain an arbitrary number of time periods t, $t\in T$ stationary demand, length n_t, where $\sum_{t\in T} n_t = 365$. It is accepted that there are two periods: tourist season ($n_1=120$ days) and the offseason ($n_2=245$ days).
The transport process is presented as a vector of transport activity. Total transport activity represents the sum of individual transport processes between echelons:

$$U^{TR} = \sum_{t\in T}\sum_{i\in I}\sum_{k\in K} q_{it}\cdot d_{ikt}^{P-CDC} + \sum_{t\in T}\sum_{l\in L}\sum_{k\in K} q_{lt}\cdot d_{lkt}^{P-CDT} + \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} q_{ijt}\cdot d_{ijkt}^{CDC-Z}$$
$$+\sum_{t\in T}\sum_{i\in I}\sum_{l\in L}\sum_{k\in K} q_{ilt}\cdot d_{ilkt}^{CDC-CDT} + \sum_{t\in T}\sum_{l\in L}\sum_{j\in J}\sum_{k\in K} q_{ljt}\cdot d_{ljkt}^{CDT-Z} + \sum_{t\in T}\sum_{l\in L}\sum_{k\in K} q_{lt}\cdot \bar{d}_{lkt}^{\,routa-Z} \quad (5)$$

where q_{et} represents quantity of goods and d_{et} is a distance between echelons e in period t.

Capacities $S_p=\{g_r\}$ within P_h and CDC meet storage needs in the period T, $S_p \geq \left(\sum_{j=1} q_{rj} \sum_{j=1} W\right) T$, where $\sum_{i=1} q_{rj}$ is the total demand GLR, and $\sum_{j=1} W$ the total frequency of deliveries. Sum capacity P_h and CDC must be $\geq q_{jt}$ from the demand of the zones j.

The consolidated supply process is realised by vehicles of the types k_4 and k_5, transporting the aggregate quantity goods $q\in Q$ from P_h to one or more satellites from the set I or L.

Distribution of goods is realised from satellites i, $i\in I$ or l, $l\in L$, vehicle types k_1, k_2, k_3 *and* k_4; so that the total amount of goods $q\in Q$ points to the GLR for the defined zone j, $j\in J$.

Vehicles k have defined movement routes r_{kt}, in period t. Each route is defined based on: total demand $\sum_{i=1} q_{jt}$ GLR z in the zone j in the period t, vehicle load capacity g_k and satellite locations i and j. Each zone j has a defined mean route length $\bar{d}_{jkt}$ which is realised by vehicle k in the period t.

If the number of routes is r_{jkt}, and their length is $d_{(rjkt)}$, then $\bar{d}_{jkt} = \frac{\sum_{e=1}^{r_{jkt}} d(e)}{r_{jkt}}$, and:

- k_5, $k_5 \in K$ moves along a defined route r_{Pik_5t} transporting a quantity of goods q_{jt} from P_h to the satellite and returning to P_h $\phi(k_5) = \{P_h, i = 1,...,|\phi(k_5)|\}$;
- k_4, $k_4 \in K$, moves along defined routes $r_{P_hik_4t}, r_{P_hlk_4t}$ i r_{ljk_4t} by water. Boat k_4 delivers goods q_{jt} in period t_2 from P_h to satellite *i* or *l* or directly to zone *j*, returning after unloading to satellite P_h $\phi(k_4) = \{P_h, i = 1,...,|\phi(k_4)|\}$;
- k_2, $k_2 \in K$, moves along a defined route r_{ljk_2t} from satellite *l* to zone *j* distributing goods q_{jt}, and returns after realisation $\phi(k_2) = \{l \in L, i = 1,...,|\phi(k_2)|\}$. The location of the satellite *l* determines the affiliation of the routes r_{ljk_2t} with zones of preference *l* in period t_2;
- k_3, $k_3 \in K$, moves along a defined route r_{ljk_3t}, from satellite *l* to zone *j*, distributing goods q_{jt}, and returns after realisation $\phi(k_3) = \{l \in L, i = 1,...,|\phi(k_3)|\}$. Transport means k_2 and k_3 are coordinated with means k_1 (*truck – eco vehicle)*.

The use of a particular vehicle type *k* is defined through the following indicators:

δ_{jkt} – indicator of the use of vehicles of type *k* for the supply of zone *j* in period *t*, $\delta_{jkt}=\{0,1\}$;
δ_{lkt} – indicator of the use of vehicles of type *k* for supplying satellites *l* in period *t*, $\delta_{lkt}=\{0,1\}$.

Defined distances between LCs require unit costs to be defined as ξ_k with respect to using type *k* vehicles for transporting goods at a distance of 1 km:

C_{ijkt}^{CDC-Z} – the cost of one tour of a type *k* vehicle from CDC to zone *j* and within it, $C_{ijkt}^{CDC-Z} = (d_{ijkt} + \bar{d}_{jkt})\xi_k$;
C_{ljkt}^{CDT-Z} – the cost of one tour of a type *k* vehicle from CDT to zone *j* and within it $C_{ljkt}^{CDT-Z} = (d_{ljkt} + \bar{d}_{jkt})\xi_k$;
$C_{ikt}^{P_h-CDC}$ – the cost of one tour of a type *k* vehicle from P_h to CDC, $C_{ikt}^{P_h-CDC} = d_{ikt}\xi_k$;
$C_{lkt}^{P_h-CDT}$ – the cost of one tour of a type *k* vehicle from P_h to CDT, $C_{lkt}^{P_h-CDT} = d_{lkt}\xi_k$;
$C_{ilkt}^{CDC-CDT}$ – the cost of one tour of a type *k* vehicle from CDC to CDT, $C_{ilkt}^{CDC-CDT} = d_{ilkt}\xi_k$;
F_i^{CDC} – CDC opening costs reduced to interval *T* (annual level);
F_l^{CDT} – CDT opening costs reduced to interval *T* (annual level);
X_{ijkt}^{CDC-Z} – total number of tours in period *t* from satellite *i* to zone *j*;
X_{ljkt}^{CDT-Z} – total number of tours in period *t* from satellite *l* to zone *j*;
$X_{ikt}^{P_h-CDC}$ – total number of tours in period *t* from P_h to satellite *i*;
$X_{lkt}^{P_h-CDT}$ – total number of tours in period *t* from P_h to satellite *l*;
$X_{ilkt}^{CDC-CDT}$ – total number of tours in period *t* from satellite *i* to satellite *l*;
Y_i^{CDC} – binary variable = 1 if opening CDC and 0 otherwise;
Y_l^{CDT} – binary variable = 1 if opening CDT and 0 otherwise;
M_t – Large enough positive number to linearise the constraint, $M_t = \sum_{j \in J} q_{jt}$.

The mathematical formulation of the DYMEMULP model is:

$$\begin{aligned} \min & \sum_{t \in T}\sum_{i \in I}\sum_{j \in J}\sum_{k \in K} C_{ijkt}^{CDC-Z} X_{ijkt}^{CDC-Z} + \sum_{t \in T}\sum_{l \in L}\sum_{j \in J}\sum_{k \in K} C_{ljkt}^{CDT-Z} X_{ljkt}^{CDT-Z} + \sum_{t \in T}\sum_{i \in I}\sum_{l \in L}\sum_{k \in K} C_{ilkt}^{CDC-CDT} X_{ilkt}^{CDC-CDT} \\ & + \sum_{t \in T}\sum_{l \in L}\sum_{k \in K} C_{lkt}^{P_h-CDT} X_{lkt}^{P_h-CDT} + \sum_{t \in T}\sum_{i \in I}\sum_{k \in K} C_{ikt}^{P_h-CDC} X_{ikt}^{P_h-CDC} + \sum_{i \in I} F_i^{CDC} Y_i^{CDC} + \sum_{t \in T}\sum_{l \in L} F_{lt}^{CDT} Y_{lt}^{CDT} \end{aligned} \tag{6}$$

with the following restrictions:

$$\sum_{i \in I}\sum_{k \in K} g_k \eta_k X_{ijkt}^{CDC-Z} + \sum_{l \in L}\sum_{k \in K} g_k \eta_k X_{ljkt}^{CDT-Z} \geq q_{jt} \quad \forall t \in T \; \forall j \in J \tag{7}$$

$$\sum_{k \in K} g_k \eta_k X_{lkt}^{P_h-CDT} + \sum_{i \in I}\sum_{k \in K} g_k \eta_k X_{ilkt}^{CDC-CDT} - \sum_{j \in J}\sum_{k \in K} g_k \eta_k X_{ljkt}^{CDT-Z} \geq 0 \quad \forall t \in T \; \forall l \in L \tag{8}$$

$$\sum_{k \in K} g_k \eta_k X_{ikt}^{P_h-CDC} - \sum_{l \in L}\sum_{k \in K} g_k \eta_k X_{ilkt}^{CDC-CDT} - \sum_{j \in J}\sum_{k \in K} g_k \eta_k X_{ijkt}^{CDC-Z} \geq 0 \quad \forall t \in T \; \forall i \in I \tag{9}$$

$$X_{ikt}^{P_h-CDC} \leq M_t Y_i^{CDC} \quad \forall i \in I \; \forall k \in K \; \forall t \in T \tag{10}$$

$$X_{lkt}^{P_h-CDT} \leq M_t \delta_{lkt} Y_{lkt}^{CDT} \quad \forall l \in L \; \forall k \in K \; \forall t \in T \tag{11}$$

$$X_{ilkt}^{CDC-CDT} \le M_t \delta_{lkt} Y_{lt}^{CDT} \quad \forall i \in I\ \forall l \in L\ \forall k \in K\ \forall t \in T \tag{12}$$

$$X_{ilkt}^{CDC-CDT} \le M_t Y_i^{CDC} \quad \forall i \in I\ \forall l \in L\ \forall k \in K\ \forall t \in T \tag{13}$$

$$X_{ijkt}^{CDC-Z} \le M_t \delta_{jkt} Y_i^{CDC} \quad \forall i \in I\ \forall j \in J\ \forall k \in K\ \forall t \in T \tag{14}$$

$$X_{ljkt}^{CDT-Z} \le M_t \delta_{jkt} Y_{lt}^{CDT} \quad \forall l \in L\ \forall j \in J\ \forall k \in K\ \forall t \in T \tag{15}$$

$$X_{ikt}^{P_h-CDC}, X_{lkt}^{P_h-CDT}, X_{ilkt}^{DC-DT}, X_{ijkt}^{CDC-Z}, X_{ljkt}^{CDT-Z} \in N \cup \{0\} \tag{16}$$

$$Y_i^{CDC}, Y_l^{CDT} \in \{0,1\} \tag{17}$$

Function *6* minimises the costs of supplying the zones of the region by choosing the most convenient CDTs and CDT locations, the opening of which is associated with fixed costs, as well as by using the most convenient transport chains. Constraint *7* ensures that the quantity of goods required in each of the observed periods is delivered to the zones of the region. Constraint sets *8 and 9* represent typical flow conservation constraints, while constraints *10–15* ensure that the supply flow can be realised only if the source and destination nodes, CDC and CDT are open, Constraints *16 and 17* define the domains of the variables.

4. TEST EXAMPLES AND RESULTS

4.1 General test example

For a general example, two sets of randomly generated problem instances were determined (*Table 1*): instances of medium dimensions (Ω=50) and instances of large dimensions (Λ=50).

Table 1 - Input data for examples of type Ω and type Λ

Parameter description	Parameter input value		
F_i^{CDC} (€/year)	[698,460.80 - 713,449.48]		
F_i^{CDT} (€/year)	$type_1$=2,023	$type_2$=7,612	$type_3$=8,637
Quantity of goods q_{jt}	Ω=U~(10, 4,600) Ω=U~(10, 5,200) Ω=U~(10, 4,600)	Λ=U~(10, 4,200) Λ=U~(10, 4,400) Λ=U~(10, 4,600)	
Time horizon	365 days		
Time period	t_1=245 days,	t_2=120 days	
Number of supply zones	Ω=U~(40, 100)	Λ=U~(100, 180)	
Number of potential locations CDC	Ω=U~(4, 15)	Λ=U~(16, 45)	
Number of potential locations CDT	Ω=U~(16, 50)	Λ=U~(50, 100)	
Distance P-CDC [km]	d_{ikt}=U~(1, 200)		
Distance P-CDT [km]	d_{lkt}=U~(1, 150)		
Distance CDC - CDT [km]	d_{ilkt}=U~(1, 140)		
Distance CDC-Z	d_{ijkt}=U~(1, 200)		
Distance CDT-Z	d_{ljk2t}=U~(1, 20), d_{ljk3t}=U~(1, 2),		
Average route length within the zone Z (K, km)	d_{jk1t}=U~(1, 20), d_{jk2t}=U~(1, 15), d_{jk3t}=U~(1, 2)		
Unit cost of the vehicle (K, €/km)	(k_1, 0.69), (k_2, 0.22), (k_3, 0.13), (k_4, 0.35), (k_5, 0.99)		
Vehicle load capacity (K, tons)	(k_1, 5), (k_2, 5), (k_3, 0.5), (k_4, 20), (k_5, 26)		
The average degree of utilisation of the vehicle's carrying capacity	η_k=0.9		

The concept of generating instances included: (1) different number of randomly generated zones *j*, (2) randomly generated quantities of goods for distribution q_{jt}, whereby the growth of future demand was varied $R^{*q}_d, \forall d \in D$ from +100% to +400% compared to current demand, (3) randomly generated number and spatial arrangement of satellites *i*, $i \in I$ and *l*, $l \in L$, (4) randomly generated distances between network nodes d_{ikt}, d_{lkt}, d_{ijkt}, d_{ljkt}, d_{ilkt}, *i* (5) different opening costs satellites F_i^{CDC} and F_l^{CDT}.

Table 2 – Test results for test cases type Ω and type Λ

Instance	CDC	CDT	Zone	q_{jt1}	q_{jt2}	Solution speed [s]
Ω1	3	22	66	142,566.3	171,079.6	1.01
Ω2	7	43	54	152,335.3	182,802.3	3.53
Ω3	8	23	59	130,008.8	156,010.5	1.97
Ω4	5	46	69	166,692.4	208,365.5	3.00
Ω5	9	35	48	129,914.4	155,897.3	2.90
Ω6	11	39	71	167,423.4	209,279.3	2.73
Ω7	4	46	81	189,303.6	236,629.4	2.62
Ω8	10	30	64	148,259.7	177,911.6	1.64
Ω9	8	28	88	207,522.2	259,402.8	2.32
Ω10	10	48	95	217,477.4	271,846.7	3.68
Ω11	6	29	64	155,618.6	186,742.4	1.45
Ω12	14	30	78	203,761.1	254,701.3	3.28
Ω13	3	24	72	190,381.6	237,977.0	1.04
Ω14	12	43	62	135,595.7	162,714.9	4.21
Ω15	14	30	66	141,480.5	169,776.6	10.17
Ω16	5	50	96	225,613.8	282,017.3	3.60
Ω17	8	42	71	172,288.8	215,361.0	4.03
Ω18	11	41	64	154,886.2	185,863.4	4.59
Ω19	11	19	41	106,416.1	127,699.3	0.97
Ω20	14	33	43	120,072.9	144,087.4	1.64
Ω21	12	44	82	218,887.9	273,609.9	18.64
Ω22	4	24	100	221,265.8	265,519.0	2.31
Ω23	11	43	67	147,839.2	177,407.0	15.83
Ω24	10	31	43	103,939.2	124,727.0	1.36
Ω25	8	43	72	192,302.2	240,377.7	3.71
Ω26	2	23	90	192,379.3	240,474.1	1.29
Ω27	14	24	58	115,428.9	138,514.6	10.13
Ω28	13	23	70	176,249.4	220,311.8	3.92
Ω29	12	50	63	148,910.4	178,692.4	4.10
Ω30	8	33	95	204,769.2	255,961.4	2.59
Ω31	11	46	54	146,054.0	175,264.8	3.89
Ω32	10	25	76	204,967.9	247,018.6	2.15
Ω33	14	28	74	166,256.5	207,820.7	1.83
Ω34	13	35	51	153,002.1	183,602.5	12.04
Ω35	8	50	85	181,887.1	227,359.0	2.50
Ω36	9	37	88	199,872.9	249,841.1	5.69
Ω37	14	46	95	216,223.9	270,279.9	54.36
Ω38	14	38	89	174,606.3	218,257.9	7.25
Ω39	9	44	87	208,963.1	261,203.9	4.60
Ω40	10	31	62	136,212.1	163,454.6	1.89
Ω41	8	39	54	152,155.9	182,587.1	2.29
Ω42	4	19	94	249,844.2	312,305.2	1.65
Ω43	15	50	100	277,956.2	333,547.4	5.71
Ω44	6	31	77	201,512.7	251,890.9	14.01
Ω45	9	35	65	142,418.1	170,901.8	3.60
Ω46	6	41	94	235,121.3	293,901.6	4.29
Ω47	9	24	66	160,094.5	192,113.3	2.15
Ω48	7	25	98	270,468.6	324,562.4	4.85
Ω49	12	18	84	204,078.3	255,097.9	6.55
Ω50	9	35	97	279,453.5	335,344.2	9.44
Λ51	17	72	146	377,940.4	453,528.5	165.36
Λ52	30	75	160	377,334.5	452,801.4	130.14
Λ53	24	65	113	264,910.7	317,892.9	123.16
Λ54	18	62	128	304,401.6	365,281.9	49.72
Λ55	18	56	117	255,448.4	306,538.1	335.39
Λ56	18	72	152	358,912.5	430,695.0	23.00
Λ57	29	69	122	235,159.0	282,190.8	62.60
Λ58	18	65	154	364,151.4	436,981.7	75.25
Λ59	29	59	120	262,066.5	314,479.8	39.87
Λ60	28	63	150	386,017.1	463,220.5	22.51
Λ61	26	62	139	287,081.9	344,498.3	16.46
Λ62	27	55	136	308,859.7	370,631.7	129.37
Λ63	26	56	117	255,448.4	306,538.1	71.54
Λ64	19	64	154	348,173.3	417,807.9	983.76
Λ65	20	56	133	301,198.2	361,437.9	1,101.88
Λ66	19	58	132	299,911.5	359,893.8	159.98
Λ67	30	68	106	246,223.0	295,467.6	220.37
Λ68	22	61	126	300,166.4	360,199.7	161.07
Λ69	18	53	144	280,253.0	336,303.6	805.85
Λ70	30	70	101	235,504.6	282,605.5	752.39
Λ71	26	60	143	296,190.7	355,428.8	45.32
Λ72	21	70	103	239,987.3	287,984.7	57.35
Λ73	20	68	156	333,148.5	399,778.2	29.89
Λ74	30	59	133	301,198.2	361,437.9	116.08
Λ75	27	60	125	255,521.9	306,626.2	214.60
Λ76	22	62	145	283,562.9	340,275.4	177.26
Λ77	21	74	113	268,193.1	321,831.7	74.36
Λ78	19	72	150	304,306.7	365,168.1	1,691.71
Λ79	28	66	105	230,974.7	277,169.6	226.54
Λ80	30	68	139	299,448.1	359,337.7	887.15
Λ81	25	58	148	308,881.0	370,657.2	39.53
Λ82	27	68	110	233,685.0	280,422.0	90.33
Λ83	16	52	152	396,142.3	475,370.8	40.20
Λ84	40	90	180	409,460.4	491,352.5	0.00
Λ85	25	53	101	242,643.9	291,172.7	45.10
Λ86	19	60	157	410,144.7	492,173.6	546.75
Λ87	26	69	143	326,795.0	392,154.0	1,135.03
Λ88	22	66	108	237,927.8	285,513.4	57.59
Λ89	18	65	111	253,322.5	303,987.0	12.92
Λ90	45	90	180	458,195.4	549,834.4	0.00
Λ91	17	53	135	288,596.3	346,315.6	16.69
Λ92	19	57	122	263,202.1	315,842.5	19.63
Λ93	28	65	118	263,973.4	316,768.1	26.83
Λ94	27	61	137	301,503.0	361,803.6	15.62
Λ95	23	64	157	328,372.9	394,047.5	209.56
Λ96	29	62	119	278,353.6	334,024.3	3,249.53
Λ97	30	75	150	374,064.0	448,876.8	228.79
Λ98	29	53	124	270,244.9	324,293.9	333.34
Λ99	19	53	145	321,799.8	386,159.8	76.85
Λ100	31	81	163	465,740.4	558,888.5	0.00

The defined set of test instances (*Table 2*) was solved by applying the *DYMEMULP* model, using the CPLEX 12.2 program on a computer with an Intel i3-540 processor at 3.07 GHz, 4 GB of RAM memory. The analysis was realised with a limited problem solving time of 3600 seconds. Input data processing was implemented in the C++ programming language.

The program varies 12 types of data in an acceptable time and can provide optimal solutions to instances of type Ω and type Λ for regions up to level: I=30CDC, L=75CDT, J=160 supply zones, K=5 sets of vehicles, T=1 time interval with two periods observed.

4.2 Case study

The proposed DYMEMULP optimisation was tested on the Montenegrin coast region. Empirical data were collected and systematically processed. The traffic network of the region was created using the GPS system in the WGS84 coordinate system. For easier processing, i.e. to calculate the distance of points in a plane and not on an ellipsoid, all data from WGS84 were transferred to the UTM34 coordinate system, namely to ESRI Shape – UTM34 standard GIS format, which is supported by every GIS program. The projection of all data was done in Google Earth and transferred to the QGIS program (version 2.2).

It was established that there were 1456 GLRs in the winter period and 2365 GLRs during the tourist season in the region. K-means clustering determined 21 clusters and 37 supply zones. For each zone $j, j \in J$ the centre of the network was determined, using the program Python ver. 2.7.8. The defined centre of the zone (*Table 3*) was the basis for defining the routes within those zones. All defined routes are constant and do not change during time periods t_1 and t_2. Defined routes in *DYMEMULP* are treated as a cost incurred by the vehicle during the distribution of goods.

In order to define the cost of construction, the author made conceptual solutions of CDCs and CDTs in AutoCAD. The construction costs are: (1) CDC1 – Bar €698,460.80, (2) CDC2 – Verige €713,449.48, (3) CDC3

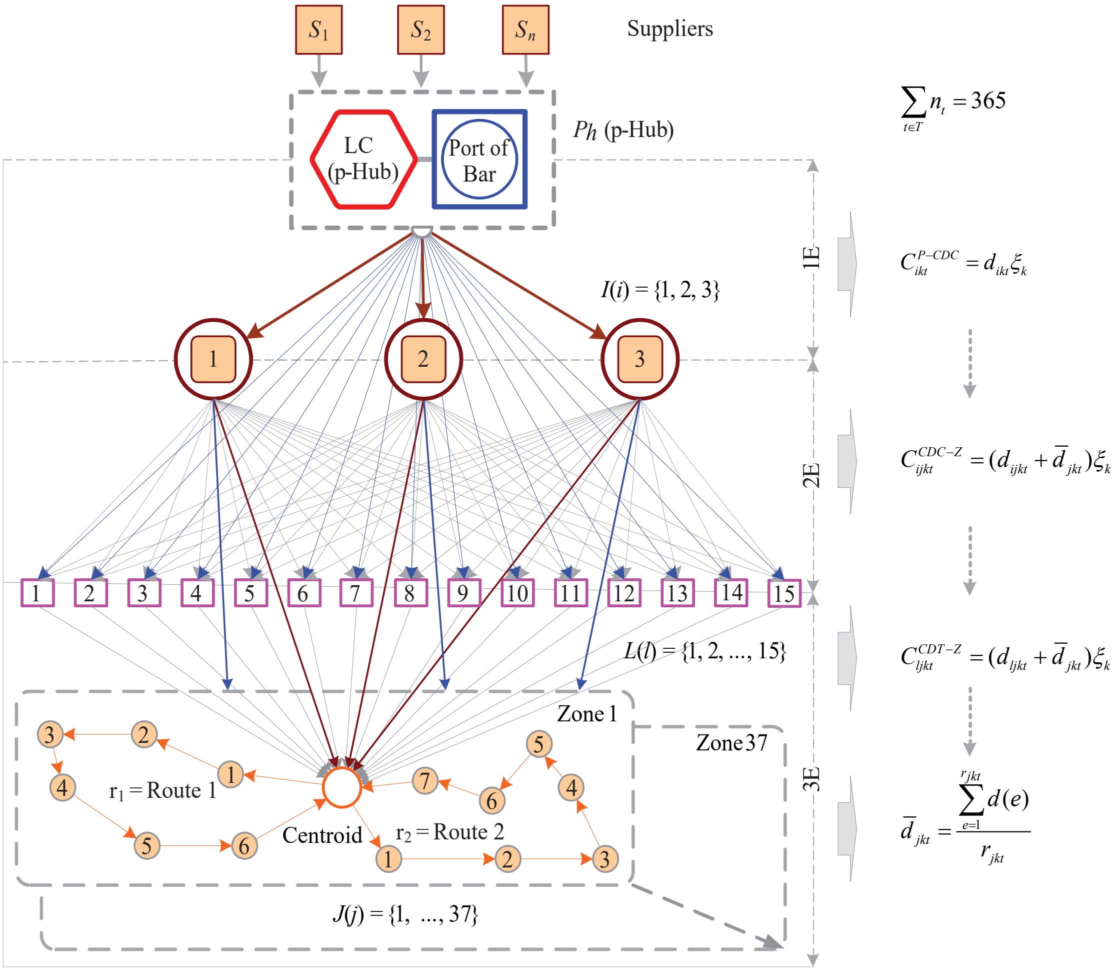

Figure 3 – Potential logistics network of the region

Table 3 – List of defined zones of the Montenegrin littoral region

Zones				Quantity of goods [t]		Route [km]			
No	Coordinates of the centre		Name	t_1 (245 days)	t_2 (120 days)	Route 1	Route 2	Route 3	Route 4
1	41.90366	19.30238	Ulcinj 1	3,479.0	5,331.6	9.70	38.80	11.20	
2	41.92446	19.20389	Ulcinj 2 coast	4,625.6	5,502.0	3.43	13.72	3.44	1.70
3	41.93088	19.20890	Ulcinj 2 ground	5,740.4	4,956.0	11.64	46.56	12.84	
4	42.01074	19.15131	Utjeha coast	210.7	1,530.0	1.46	5.84	0.75	
5	42.00226	19.15009	Utjeha ground	889.4	825.6	8.62	34.48	4.70	
6	42.03487	19.14284	V. Pijesak coast	200.9	1,615.2	1.50	6.00	0.70	
7	42.03104	19.14835	V. Pijesak ground	1,180.9	902.4	2.52	10.08	1.50	
8	42.08588	19.12449	Bar Jug	7,274.1	4,150.8	12.90	51.60	32.25	
9	42.09894	19.09848	Bar Centar	12,669.0	6,661.2	4.40	17.60	8.80	
10	42.11309	19.09005	Bar Sjever	2,682.8	1,776.0	14.62	58.48	29.24	
11	42.13570	19.05846	Sutomore coast	948.2	4,047.6	2.40	9.60	4.80	
12	42.14239	19.04604	Sutomore ground	2,871.4	1,771.2	12.60	50.40	25.20	
13	42.15984	19.00254	Canj	298.9	2,386.8	3.60	14.40	2.40	
14	42.19520	18.96362	Buljarica	210.7	2,151.6	7.96	31.84	1.80	
15	42.20648	18.94352	Petrovac	2,033.5	4,812.0	2.37	9.48	4.74	3.80
16	42.25659	18.89279	Rezevici-Przno coast	343.0	1,711.2	3.23	12.92	2.20	
17	42.25608	18.89779	Rezevici-Przno ground	722.8	1,413.6	6.62	26.48	13.24	
18	42.28141	18.87562	Becici	1,038.8	5,386.8	4.21	22.80	11.40	
19	42.27811	18.83799	Budva old city	1,016.8	2,874.0	1.50	15.00	1.14	
20	42.28441	18.83831	Budva 1	3,153.2	7,856.4	3.32	16.88	8.44	
21	42.29033	18.84173	Budva 2	4,838.8	6,808.8	4.90	20.12	10.06	3.40
22	42.35625	18.70447	Lastva coast	107.8	871.2	37.00	148.00	22.00	
23	42.36039	18.76014	Lastva ground	2,021.3	1,422.0	29.80	125.60	31.40	
24	42.41391	18.63647	Krtole coast	999.6	1,545.6	9.60	40.80	9.40	
25	42.39643	18.67185	Krtole ground	1,675.8	1,204.8	13.30	54.80	13.70	
26	42.41613	18.71773	Kukoljina	1,185.8	1,288.8	8.65	34.60	8.65	
27	42.42930	18.69728	Tivat	5,889.8	5,822.4	4.57	23.04	11.52	2.76
28	42.42474	18.77017	Kotor old city	3,540.3	2,142.0	0.90	5.40	0.42	
29	42.44896	18.76556	Kotor coast	3,782.8	3,841.2	8.07	33.20	16.20	8.10
30	42.44899	18.76616	Kotor ground	5,105.8	3,312.0	4.70	21.60	10.80	
31	42.48991	18.69327	Orahovac-Kamenari	1,151.5	1,573.2	22.32	89.28	19.40	
32	42.44003	18.62599	Kamenari-Zelenika coast	3,155.6	6,566.4	11.76	47.04	23.52	11.92
33	42.44189	18.62523	Kamenari-Zelenika ground	2,393.7	2,468.4	17.89	71.56	35.78	
34	42.45301	18.57246	Zelenika-Meljine	2,374.1	1,662.0	3.65	15.80	7.90	
35	42.44996	18.53552	H. Novi coast	3,104.2	5,064.0	28.40	14.20	6.05	
36	42.45303	18.53758	H. Novi ground	4,804.5	4,650.0	5.62	26.80	13.40	
37	42.45862	18.51501	Igalo	5,620.3	5,719.2	6.58	32.80	16.40	
			TOTAL	103,341.0	123,624.0				

– Zelenika €702,460.80, (4) CDTs for cargobike €2,023.45, (5) CDTs for cargohopper €7,612.45, and (6) CDT solutions for the use of cargobike and cargohopper €8,637.81.

The potential network structure (*Figure 3*) consists of: Ph in Bar, three CDCs – Bar, Verige and Zelenika, 15 CDTs that are interactively connected with the Ph and CDCs and supply 37 zones.

Transport processes are realised by five unified sets of vehicles *k*, $k \in K$: (1) tow truck with a capacity of 26 t, (2) a boat with a capacity of 20 t, (3) a diesel truck with a capacity of 5 t, (4) a cargohopper with a capacity of 5 t, and (5) a cargobike with a capacity of 0.5 t. It was determined that there are 6 types of transport chains: (1) tow truck – truck, (2) boat – cargohopper, (3) boat – cargobike, (4) tow truck – boat – cargohopper, (5) tow truck – boat – cargobike, (6) tugboat – boat. By changing the transport chain, the unit cost changes ξ_k for vehicle *k*, $k \in K$.

The optimisation results are as follows:

```
Established CDCs:
CDC1=Bar                          Costs=698,460.80
CDC3=Zelenika                     Costs=702,460.80

Established CDTs:
Int2=Summer CDT2=Ulcinj porat     Costs=8,637.81
Int2=Summer CDT3=Utjeha           Costs=2,023.45
Int2=Summer CDT4=V.Pijesak        Costs=2,023.45
Int2=Summer CDT5=Sutomore         Costs=8,905.31
Int2=Summer CDT6=Canj             Costs=2,269.84
Int2=Summer CDT7=Buljarica        Costs=2,269.84
Int2=Summer CDT8=Petrovac         Costs=8,637.81
Int2=Summer CDT9=Sv.Stefan        Costs=2,269.84
Int2=Summer CDT10=Becici          Costs=7,612.45
Int2=Summer CDT11=Budva porat     Costs=8,637.81
Int2=Summer CDT12=Tivat porat     Costs=8,637.81
Int2=Summer CDT13=Kotor porat     Costs=8,637.81
Int2=Summer CDT15=Igalo           Costs=8,637.81

CDC-Z:
Int1=Winter CDC1=Bar Zone1   Vehicle1=truck          Tours=   774 Costs= 60.31   Total= 46,676.84
Int1=Winter CDC1=Bar Zone2   Vehicle1=truck          Tours= 1,028 Costs= 44.20   Total= 45,439.04
Int1=Winter CDC1=Bar Zone3   Vehicle1=truck          Tours= 1,276 Costs= 52.77   Total= 67,336.05
Int1=Winter CDC1=Bar Zone4   Vehicle1=truck          Tours=    47 Costs= 22.58   Total=  1,061.11
Int1=Winter CDC1=Bar Zone5   Vehicle1=truck          Tours=   198 Costs= 33.15   Total=  6,563.22
Int1=Winter CDC1=Bar Zone6   Vehicle1=truck          Tours=    45 Costs= 18.22   Total=    819.72
Int1=Winter CDC1=Bar Zone7   Vehicle1=truck          Tours=   263 Costs= 18.66   Total=  4,906.95
Int1=Winter CDC1=Bar Zone8   Vehicle1=truck          Tours= 1,617 Costs= 22.49   Total=    372.80
Int1=Winter CDC1=Bar Zone9   Vehicle1=truck          Tours= 2,816 Costs= 10.76   Total= 30 311.42
Int1=Winter CDC1=Bar Zone10 Vehicle1=truck           Tours=   597 Costs= 24.45   Total= 14,598.80
Int1=Winter CDC1=Bar Zone11 Vehicle1=truck           Tours=   211 Costs= 12.83   Total=  2,707.97
Int1=Winter CDC1=Bar Zone12 Vehicle1=truck           Tours=   639 Costs= 29.12   Total= 18,606.40
Int1=Winter CDC1=Bar Zone13 Vehicle1=truck           Tours=    67 Costs= 24.29   Total=  1,627.30
Int1=Winter CDC1=Bar Zone14 Vehicle1=truck           Tours=    47 Costs= 38.17   Total=  1,794.03
Int1=Winter CDC1=Bar Zone15 Vehicle1=truck           Tours=   452 Costs= 32.94   Total= 14,889.15
Int1=Winter CDC1=Bar Zone16 Vehicle1=truck           Tours=    77 Costs= 47.93   Total=  3,690.41
Int1=Winter CDC1=Bar Zone17 Vehicle1=truck           Tours=   161 Costs= 50.81   Total=  8,180.67
Int1=Winter CDC1=Bar Zone18 Vehicle1=truck           Tours=   231 Costs= 54.25   Total= 12,531.24
Int1=Winter CDC1=Bar Zone19 Vehicle1=truck           Tours=   226 Costs= 58.65   Total= 13,254.90
Int1=Winter CDC1=Bar Zone20 Vehicle1=truck           Tours=   701 Costs= 58.26   Total= 40,842.78
Int1=Winter CDC1=Bar Zone21 Vehicle1=truck           Tours= 1,076 Costs= 60.58   Total= 65,186.23
Int1=Winter CDC3=Zelenika Zone22 Vehicle1=truck      Tours=    24 Costs= 95.63   Total=  2,295.22
Int1=Winter CDC3=Zelenika Zone23 Vehicle1=truck      Tours=   450 Costs= 77.00   Total= 34,651.80
Int1=Winter CDC3=Zelenika Zone24 Vehicle1=truck      Tours=   223 Costs= 56.86   Total= 12,678.89
Int1=Winter CDC3=Zelenika Zone25 Vehicle1=truck      Tours=   373 Costs= 58.10   Total= 21,670.55
Int1=Winter CDC3=Zelenika Zone26 Vehicle1=truck      Tours=   264 Costs= 37.88   Total= 10,000.58
Int1=Winter CDC3=Zelenika Zone27 Vehicle1=truck      Tours= 1,309 Costs= 30.04   Total= 39,325.76
Int1=Winter CDC3=Zelenika Zone28 Vehicle1=truck      Tours=   787 Costs= 38.23   Total= 30,083.86
Int1=Winter CDC3=Zelenika Zone29 Vehicle1=truck      Tours=   841 Costs= 52.81   Total= 44,415.40
Int1=Winter CDC3=Zelenika Zone30 Vehicle1=truck      Tours= 1,135 Costs= 48.30   Total= 54,820.50
Int1=Winter CDC3=Zelenika Zone31 Vehicle1=truck      Tours=   256 Costs= 65.16   Total= 16,681.88
Int1=Winter CDC3=Zelenika Zone32 Vehicle1=truck      Tours=   702 Costs= 23.82   Total= 16,720.80
Int1=Winter CDC3=Zelenika Zone33  Vehicle1=truck     Tours=   532 Costs= 31.73   Total= 16,878.34
Int1=Winter CDC3=Zelenika Zone34  Vehicle1=truck     Tours=   528 Costs=  6.14   Total=  3,242.45
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Int1=Winter CDC3=Zelenika Zone35 Vehicle1=truck                Tours=   690 Costs=  18.17   Total= 12,540.47
Int1=Winter CDC3=Zelenika Zone36 Vehicle1=truck                Tours= 1,068 Costs=  12.45   Total= 13,294.04
Int1=Winter CDC3=Zelenika Zone37 Vehicle1=truck                Tours= 1,249 Costs=  18.19   Total= 22,717.31
Int2=Summer CDC1=Bar Zone8 Vehicle2=cargohopper                Tours=   923 Costs=  14.65   Total= 13,523.80
Int2=Summer CDC1=Bar Zone9 Vehicle2=cargohopper                Tours= 1,481 Costs=   5.90   Total=  8,731.98
Int2=Summer CDC1=Bar Zone10 Vehicle2=cargohopper               Tours=   395 Costs=  14.62   Total=  5,773.64
Int2=Summer CDC1=Bar Zone22 Vehicle4=boat                      Tours=    49 Costs=  28.26   Total=  1,384.69
Int2=Summer CDC3=Zelenika Zone24 Vehicle4=boat                 Tours=    86 Costs=  11.48   Total=    987.28
Int2=Summer CDC3=Zelenika Zone29 Vehicle4=boat                 Tours=   213 Costs=  21.23   Total=  4,521.46
Int2=Summer CDC3=Zelenika Zone31 Vehicle4=boat                 Tours=    87 Costs=  23.38   Total=  2,034.06
Int2=Summer CDC3=Zelenika Zone32 Vehicle4=boat                 Tours=   365 Costs=  12.12   Total=  4,425.26
Int2=Summer CDC3=Zelenika Zone33 Vehicle2=cargohopper          Tours=   549 Costs=  22.39   Total= 12,292.99
Int2=Summer CDC3=Zelenika Zone34 Vehicle2=cargohopper          Tours=   370 Costs=   3.85   Total=  1,424.50
Int2=Summer CDC3=Zelenika Zone35 Vehicle4=boat                 Tours=   282 Costs=   5.99   Total=  1,687.77
Int2=Summer CDC3=Zelenika Zone36 Vehicle2=cargohopper          Tours=     1 Costs=  11.92   Total=     11.92

CDT-Z:
Int2=Summer CDT2=Ulcinj porat Zone1 Vehicle2=cargohopper       Tours= 1,185 Costs=   9.86   Total= 11,679.36
Int2=Summer CDT2=Ulcinj porat Zone2 Vehicle2=cargohopper       Tours= 1,223 Costs=   1.60   Total=  1,958.76
Int2=Summer CDT2=Ulcinj porat Zone3 Vehicle2=cargohopper       Tours= 1,102 Costs=   6.62   Total=  7,292.60
Int2=Summer CDT3=Utjeha Zone4 Vehicle3=cargobike               Tours= 3,400 Costs=   0.22   Total=    751.40
Int2=Summer CDT3=Utjeha Zone5 Vehicle3=cargobike               Tours= 1,835 Costs=   1.51   Total=  2,767.18
Int2=Summer CDT4=V.Pijesak Zone6 Vehicle3=cargobike            Tours= 3,590 Costs=   0.23   Total=    840.06
Int2=Summer CDT4=V.Pijesak Zone7 Vehicle3=cargobike            Tours= 2,006 Costs=   0.52   Total=  1,043.12
Int2=Summer CDT5=Sutomore Zone11 Vehicle2=cargohopper          Tours=   900 Costs=   1.50   Total=  1,346.40
Int2=Summer CDT5=Sutomore Zone12 Vehicle2=cargohopper          Tours=   394 Costs=   5.79   Total=  2,279.68
Int2=Summer CDT6=Canj Zone13 Vehicle3=cargobike                Tours= 5,304 Costs=   0.51   Total=  2,689.13
Int2=Summer CDT7=Buljarica Zone14 Vehicle3=cargobike           Tours= 4,782 Costs=   0.62   Total=  2,983.97
Int2=Summer CDT8=Petrovac Zone15 Vehicle2=cargohopper          Tours= 1,070 Costs=   1.37   Total=  1,468.90
Int2=Summer CDT9=Sv.Stefan Zone16 Vehicle3=cargobike           Tours= 3,803 Costs=   0.88   Total=  3,361.85
Int2=Summer CDT9=Sv.Stefan Zone17 Vehicle3=cargobike           Tours= 3,142 Costs=   2.19   Total=  6,878.47
Int2=Summer CDT10=Becici Zone18 Vehicle2=cargohopper           Tours= 1,197 Costs=   3.26   Total=  3,897.43
Int2=Summer CDT10=Becici Zone18 Vehicle3=cargobike             Tours=     1 Costs=   1.14   Total=      1.14
Int2=Summer CDT11=Budva porat Zone19 Vehicle3=cargobike        Tours= 6,387 Costs=   0.20   Total=  1,278.68
Int2=Summer CDT11=Budva porat Zone20 Vehicle2=cargohopper      Tours= 1,746 Costs=   2.43   Total=  4,240.68
Int2=Summer CDT11=Budva porat Zone21 Vehicle2=cargohopper      Tours= 1,513 Costs=   2.96   Total=  4,480.30
Int2=Summer CDT11=Budva porat Zone21 Vehicle3=cargobike        Tours=     1 Costs=   1.33   Total=      1.33
Int2=Summer CDT12=Tivat porat Zone23 Vehicle2=cargohopper      Tours=   316 Costs=  18.26   Total=  5,770.16
Int2=Summer CDT12=Tivat porat Zone25 Vehicle2=cargohopper      Tours=   268 Costs=  11.75   Total=  3,148.46
Int2=Summer CDT12=Tivat porat Zone26 Vehicle2=cargohopper      Tours=   287 Costs=   5.08   Total=  1,458.53
Int2=Summer CDT12=Tivat porat Zone27 Vehicle2=cargohopper      Tours= 1,294 Costs=   2.60   Total=  3,364.92
Int2=Summer CDT13=Kotor porat Zone28 Vehicle3=cargobike        Tours= 4,760 Costs=   0.19   Total=    891.07
Int2=Summer CDT13=Kotor porat Zone29 Vehicle2=cargohopper      Tours=     2 Costs=   4.84   Total=      9.68
Int2=Summer CDT13=Kotor porat Zone30 Vehicle2=cargohopper      Tours=   736 Costs=   3.65   Total=  2,687.87
Int2=Summer CDT13=Kotor porat Zone31i Vehicle2=cargohopper     Tours=     2 Costs=  16.06   Total=     32.12
Int2=Summer CDT15=Igalo Zone36 Vehicle2=cargohopper            Tours= 1,033 Costs=   4.88   Total=  5,045.17
Int2=Summer CDT15=Igalo Zone37 Vehicle2=cargohopper            Tours= 1,271 Costs=   3.83   Total=  4,865.39

P-CDC:
Int1=Winter CDC1=Bar Vehicle5=tow truck                        Tours= 2,414 Costs=   1.98   Total=  4,779.72
Int1=Winter CDC3=Zelenika Vehicle5=tow truck                   Tours= 2,006 Costs=154.84   Total=310,601.02
Int2=Summer CDC1=Bar Vehicle5=tow truck                        Tours= 1,436 Costs=   1.98   Total=  2,843.28
Int2=Summer CDC3=Zelenika Vehicle4=boat                        Tours= 1,567 Costs=  44.08   Total= 69,071.79

P-CDT:
Int2=Summer CDT2=Ulcinj porat Vehicle4=boat                    Tours=   878 Costs=  17.36   Total=  5,242.08
Int2=Summer CDT3=Utjeha Vehicle4=boat                          Tours=   131 Costs=   9.03   Total=  1,182.93
Int2=Summer CDT4=V.Pijesak Vehicle4=boat                       Tours=   140 Costs=   6.72   Total=    940.80
Int2=Summer CDT5=Sutomore Vehicle4=boat                        Tours=   324 Costs=   4.27   Total=  1,383.48
Int2=Summer CDT6=Canj Vehicle4=boat                            Tours=   133 Costs=   8.19   Total=  1,089.27
Int2=Summer CDT7=Buljarica Vehicle4=boat                       Tours=   120 Costs=  10.36   Total=  1,243.20
Int2=Summer CDT8=Petrovac Vehicle4=boat                        Tours=   268 Costs=  11.73   Total=  3,142.30
Int2=Summer CDT9=Sv.Stefan Vehicle4=boat                       Tours=   174 Costs=  19.46   Total=  3,386.04
Int2=Summer CDT10=Becici Vehicle4=boat                         Tours=   300 Costs=  21.98   Total=  6,594.00
Int2=Summer CDT11=Budva porat Vehicle4=boat                    Tours=   975 Costs=  24.43   Total= 23,819.25

CDC-CDT:
Int2=Summer CDC1=Bar CDT12=Tivat porat Vehicle4=boat           Tours=   542 Costs=  50.26   Total= 27,240.92
Int2=Summer CDC1=Bar CDT15=Igalo Vehicle4=boat                 Tours=   576 Costs=  39.55   Total= 22,780.80
Int2=Summer CDC3=Zelenika CDT13=Kotor porat Vehicle4=boat      Tours=   304 Costs=  15.56   Total=  4,729.48
```

Table 4 – Effects of the developed MoL for the region

Zone	Time effects $\sum_j V_j^p - V_j^{it}$		Economic effects $\sum_j C_j^p - C_j^{it}$		Transport effects $\sum_j T_j^p - T_j^{it}$		Ecological effects $\sum_j E_j^p - E_j^{it}$	
	t_1	t_2 (%)	t_1	t_2 (%)	t_1	t_2 (%)	t_1	t_2 (%)
1	0	- 35.1	0	+ 33.35	0	- 19.31	0	+ 87.75
2	0	- 37.2	0	+ 35.34	0	- 20.46	0	+ 93.00
3	0	- 36.3	0	+ 34.49	0	- 19.97	0	+ 90.75
4	0	- 33.7	0	+ 32.02	0	- 18.54	0	+ 84.25
5	0	- 32.8	0	+ 31.16	0	- 18.04	0	+ 82.00
6	0	- 28.7	0	+ 27.27	0	- 15.79	0	+ 71.75
7	0	- 29.2	0	+ 27.74	0	- 16.06	0	+ 73.00
8	0	- 25.5	0	+ 24.23	0	- 14.03	0	+ 63.75
9	0	- 18.8	0	+ 17.86	0	- 10.34	0	+ 47.00
10	0	- 22.3	0	+ 21.19	0	- 12.27	0	+ 55.75
11	0	- 23.4	0	+ 22.23	0	- 12.87	0	+ 58.50
12	0	- 25.4	0	+ 24.13	0	- 13.97	0	+ 63.50
13	0	- 27.6	0	+ 26.22	0	- 15.18	0	+ 69.00
14	0	- 28.2	0	+ 26.79	0	- 15.51	0	+ 70.50
15	0	- 31.3	0	+ 29.74	0	- 17.22	0	+ 78.25
16	0	- 33.7	0	+ 32.02	0	- 18.54	0	+ 84.25
17	0	- 33.2	0	+ 31.54	0	- 18.26	0	+ 83.00
18	0	- 34.6	0	+ 32.87	0	- 19.03	0	+ 86.50
19	0	- 35.1	0	+ 33.35	0	- 19.31	0	+ 87.75
20	0	- 27.3	0	+ 25.94	0	- 15.02	0	+ 68.25
21	0	- 26.5	0	+ 25.18	0	- 14.58	0	+ 66.25
22	0	- 28.9	0	+ 27.46	0	- 15.90	0	+ 72.25
23	0	- 29.8	0	+ 28.31	0	- 16.39	0	+ 74.50
24	0	- 27.4	0	+ 26.03	0	- 15.07	0	+ 68.50
25	0	- 31.3	0	+ 29.74	0	- 17.22	0	+ 78.25
26	0	- 32.5	0	+ 30.88	0	- 17.88	0	+ 81.25
27	0	- 35.7	0	+ 33.92	0	- 19.64	0	+ 89.25
28	0	- 32.5	0	+ 30.88	0	- 17.88	0	+ 81.25
29	0	- 34.8	0	+ 33.06	0	- 19.14	0	+ 87.00
30	0	- 31.3	0	+ 29.74	0	- 17.22	0	+ 78.25
31	0	- 33.3	0	+ 31.64	0	- 18.32	0	+ 83.25
32	0	- 29.7	0	+ 28.22	0	- 16.34	0	+ 74.25
33	0	- 26.5	0	+ 25.18	0	- 14.58	0	+ 66.25
34	0	- 29.7	0	+ 28.22	0	- 16.34	0	+ 74.25
35	0	- 27.3	0	+ 25.94	0	- 15.02	0	+ 68.25
36	0	- 28.5	0	+ 27.08	0	- 15.68	0	+ 71.25
37	0	- 24.7	0	+ 23.47	0	- 13.59	0	+ 61.75

Based on the results of the optimisation process, it is concluded that an optimal multi-echelon regional network has been established, consisting of: 1 p-Hub, 2 CDCs (Bar and Zelenika), as well as 13 CDTs, which function in the period t_2.

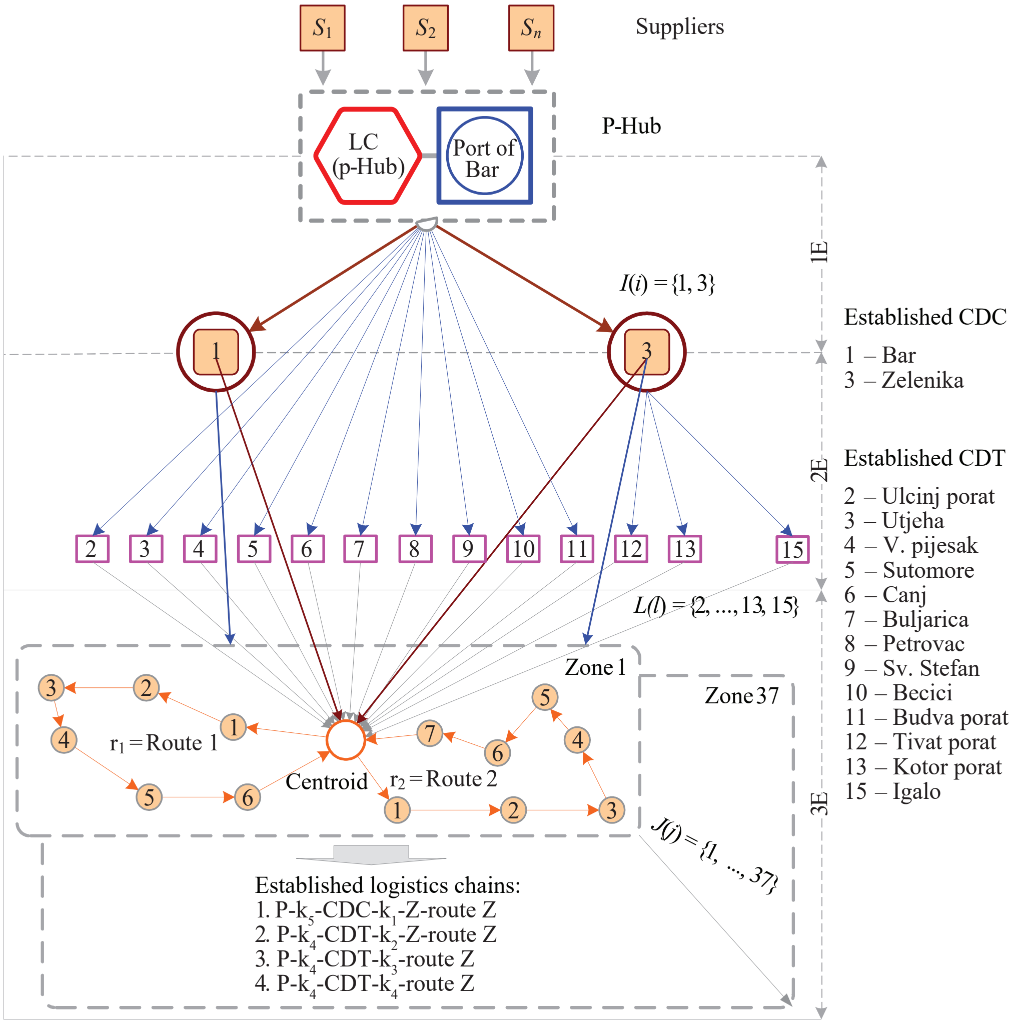

Figure 4 – Establishment of logistics network after DYMEMULP optimisation

The effects of applying the optimisation process are shown in *Table 4*.

5. DISCUSSION

Economies of regions depend more and more on LSs and their degree of operability. Greater intensity of freight transport in regions initiates the application of new technological solutions, organisational forms, forms of cooperation and management methods in order to reduce their negative impact on space, systems, processes and the environment. The main goals of logistics today are [1−5] process optimisation, system integration, space rationalisation and digitisation. The application of simple solutions in the function of complex optimisation is the task of strategic logistics planning. By initiating new strategic approaches, it should enable the integration and rationalisation of the usage of various micro, meta and macro networks and LSs in a region with the aim of its optimal supply. Reengineering MoLs goes into the direction of seeking a minimum balance between needs, wishes and possibilities in a region, applying postulates, economics, logistics, management and ecology. Because SCs have the character of a bridge in connecting micro, meta and macro LSs [2], the new logistics paradigm emphasises the optimisation of all its links. The application of optimisation in the development process of regional MoLs represents an approach to defining the cargo balance, selection of logistics networks and services and the design of an improved logistics service. It supports making strategic decisions in the function of realising operational processes.

In the expansion of logistics activities in the regions, and the increasing spatial limitation within them, the creation of a cooperative distribution model is one of the possible sustainable solutions. Distribution solutions based on the cooperation of road and water transport systems, as well as those solutions that enable coordination in road traffic, can influence the creation of a series of positive effects: reduction of total logistics costs, increase in flexibility, reliability and quality in supply, reduction of traffic congestion, reduction of environmental pollution, creation of a higher quality tourist service, increase in the level of safety etc.

The results obtained by testing the DYMEMULP optimisation procedure indicate:

1) Justification of its application in solving real problems in regional logistics;
2) The possibility of monitoring 4 components: time, transport, economic and environmental;
3) The possibility of iterative action, changing the input data in the instance if the optimal solution is not found;
4) The possibility of parallel optimisation of a large number of SCs with the quantification of effects for each SC separately;
5) Openness of the model for adding restrictions, related to the capacity of the LC, management of stock of goods in the LC, definition of optimal routes in order to monitor the operation of the entire system;
6) That a program that varies 12 types of data in acceptable time can offer optimal solutions of instances of type Ω and type Λ for regions of size up to level I=30 CDC, L=75 CDT, J=160 supply zones, K=5 sets of vehicles in time interval with two periods observed;
7) Efficiency in solving a concrete example for the Montenegrin littoral region where a case of cooperation and coordination was observed by valorising the port and CDTs. It was shown that the new MoL solution for the Montenegrin coastal region has an average of +30% time savings in transport, +28.49% economic profit, and 16.5% less transport work compared to the current solution;
8) A high level of environmental acceptability of the new MoL for the Montenegrin littoral region due to the application of technologies with a low negative impact on the environment. The average achieved positive environmental effects amount to +74.99%, which is a significant level of acceptability.

6. CONCLUSION

The goal of the research presented in this article was to develop an MoL based on a system analysis using the original DYMEMULP optimisation procedure as a quality basis for the development of strategic solutions for an optimal multi-echelon logistics network and the process of dynamic routing of a heterogeneous group of vehicles, which will be able to contribute to: a higher level of operability of RL, reducing the total costs of logistics, reducing the time of order realisation in conditions of uncertainty, achieving greater spatial and ecological effects, reducing traffic jams by using the sea as a road and preserving the natural and historical heritage by using eco vehicles.

The obtained results provide a direct answer to the question of which system structure is justified to establish, which transport chains are acceptable, and which model of cooperation and coordination is acceptable, which essentially represents a gradual approach to total logistics integration. The work contributes to the field of logistics theory in the area of strategic planning due to finding new forms of cooperation and transport coordination. It contributes to optimisation theory as it shows the development of a new original, universal and flexible optimisation model open to innovation, where after minor adjustments it can be applied to solve capacitive routing problems in general optimisation or heuristics and metaheuristics.

The practical implications of addressing the logistical issues in this article are in providing guidance for policy makers and decision makers in regional entities when defining new integrated MoLs. An additional practical implication is the developed model that provides a simple but effective tool for decision makers in solving all kinds of practical multi-criteria problems in RL. Its practicality is also reflected in the fact that it enables investigating the additional application of existing, and especially new, rapidly emerging transport technology solutions, and using the possibility of evaluating and selecting new solutions.

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Željko Ivanović

DYMEMULP – Dinamički model optimizacije procesa u regionalnoj logistici

Sažetak

Ekspanzija logističkih zahtjeva, ograničeni prostor i strogi zahtjevi generatora logističkih zahtjeva (GLZ) po pitanju kvaliteta usluge usložnjavaju snabdijevanje regiona, pa je potrebno unaprijediti modele logistike (MoL). Blizina vode, prisustvo luka i pristaništa duž obale, nova eko vozila i razvoj kooperacije između *kopnenog* i *vodnog* vida transporta su elementi za unapređenje postojećih MoL na ekonomsko i ekološki prihvatljiv način. Istraživanje razvoja unapređene multiešalonske logističke mreže sa varijabilnim terminalima uključujući koordinaciju i kooperaciju heterogene grupe transportnih sredstava za realizaciju robnih tokova, predstavlja inovativnost istraživanja u regionalnoj logistici (RL). U ovom radu je prezentovan integrisani proces razvoja MoL primjenom dinamičke optimizacije sa fokusom na prostornu, vremensku, transportnu, ekonomsku i ekološku komponentu.

Ključne riječi
regionalna logistika, model logistike, optimizacija, koordinacija i kooperacija.