Modeling of Transport and Logistical Processes at the Local Level: The Case of Tatarstan

R. S. Nikolaev and D. O. Egorov

Abstract Transport flows at the local level (within the boundaries close to counties) are the basic links (elementary units), from which the formation of more powerful flows begins. This is one of the most complicated links of the logistics chain, which is the primary element of the "hinterland" formation for the transport and logistics nodes. The potential of the transport and logistics hub and the choice of mechanisms for optimizing transport and logistics processes at more global levels (meso- and macro-levels) will depend on the flows efficiency in the hinterland area. The work presents approaches to the study and modeling of transport-logistical processes at the local level, as well as the mechanisms for identifying the most acceptable space-time organization variants of transport and logistics processes. Modeling was carried out by the example of Yelabuga municipal district in the Republic of Tatarstan (Russia).

1 Introduction

Transport and logistics processes are typical for all levels of the territorial hierarchy. In any case, the territories that do not generate commodity flows consume the product and require certain transportation expenditures. The spatial distribution and commodity specialization of physical flows in relation to the local environment where they take place remain largely unexplored (Ducruet and Itoh 2016).

There are three main levels of transport and logistics systems: local, regional, and global (Rodrigue et al. 2017; Ortiz-Astorquizaa et al. 2018; Sheu and Lin 2012). The local level is a part of the regional one. Local transport-logistics processes arise in the counties (municipalities), as well as inside and between the settlements that make up its structure. A distinctive feature of this level is the low-flow intensity. As a rule, transport and logistics operations at this level are carried out directly by economic entities without the involvement of specialized transport and logistics agents. While

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this level is often ignored, it can lead to appearance of social and economic isolation (Egorov and Nikolaev 2016), increasing inequality and violating the principles of sustainable development.

One should note several properties of the local level, which makes it important in the analysis of transport and logistics processes:

- The local level actively participates in the formation of gravity zones, attraction areas, and hinterlands for larger nodes;
- The local level is the "last mile" logistics, considered as one of the most complicated (Aized and Srai 2013);
- Single expenditures at the local level are almost invisible in the final value of goods, but due to multiplicity they are significant;
- The local-level logistics is socially oriented and solves the problems of rural settlements and small towns, creating favorable conditions for their sustainable development. Transportation and mobility are central to sustainable development; they are means to improve social equity, health, resilience of cities, urban–rural linkages, and productivity of rural areas (Makarova et al. 2017; Cetinkaya et al. 2011; Gudmundsson et al. 2016; Litman 2014; McKinnon et al. 2015).

Transport and logistics processes are operations in the field of movement, accumulation, (de)consolidation and distribution of goods, services, finance, information, and people. It covers the whole transport chain from production to consumption and includes inbound, outbound, internal, and external movements (Huber et al. 2015).

Optimization measures at the local level are rather limited. Basic solutions for this level are multimodal terminals and operations, autonomous vehicles, an intelligent transportation system (ITS), infrastructure usage, economies of scale, and behavior/educational issues (Engström 2016).

2 Methodology

The research is based on the microsimulation of economic agents' behavior in the sale and supply. Multi-agent systems allow for the modeling of the local interactions of these actors (Ben-Akiva et al. 2013; Liedtke 2009). Having a microscopic modeling base for the transport of goods would be a significant improvement for transport forecasts and the assessment of policy measures (Liedtke and Schepperle 2004). Integrating the decisions and the behavior of logistics service providers into freight transport models is essential for accurate describing of future developments in freight transport systems (Rolko and Friedrich 2017).

The basic model of economic agents' behavior is the direction of sales flows to the nearest consumer able to use them (consume or transform). Business entities transport products to points with the greatest consumer potential and least transportation costs. For local territorial systems, the sales in the nearest zone are typical, but if there are necessary productions or transport-logistics infrastructure.

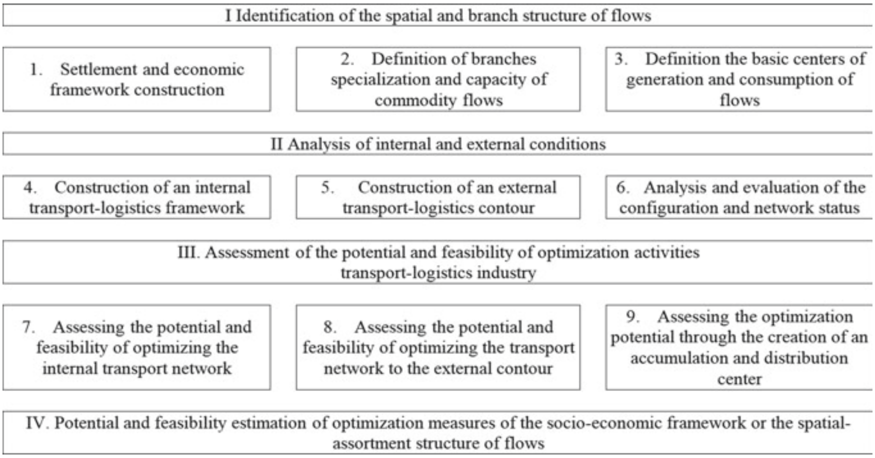


Fig. 1 Determining of the transport and logistics optimization appropriateness at the local level

Road transport is the most important for the "last mile" logistics. It is necessary to identify the hierarchical structure within the logistics buyer–supplier network and the distribution within the modal interaction of different territorial systems (Beckers et al. 2017). At the local level, as centers of attraction and distribution, it is advisable to consider nodes that meet criteria: population more than 5 thousand people; multimodality and (or) intermodality; availability of warehouse infrastructure.

The study of transport and logistics processes at the local level and the definition of opportunities for their optimization are carried out in several stages (Fig. 1).

Estimation of the generation and consumption potential of commodity flows was established through statistical and financial indicators that greatest extent tied to the territory: population; taxable incomes and social payments of the population; proceed from the activities of economic entities (taking into account the location of employees and the value of fixed assets); production and sale in physical terms; the number and carrying capacity of trucks.

The volume of existing commodity flows was identified through generation and absorption capacity analysis.

3 Results and Discussion

Approbation of the model was carried out by the example of Yelabuga County (municipal district) in the Republic of Tatarstan, which includes one city district and 16 rural settlements. The population of the county is 85.6 thousand people. The branches of specialization are agro-industrial production, manufacturing, and mining. Here is a special economic zone "Alabuga."

The external infrastructure of transport logistics is characterized by the access to the nodes. Logistics hubs hold a significant role today and this significance—especially regarding management and handling—is still increasing (Hesse and Rodrigue 2004). The external transport and logistics contour of the county is represented by six nodes—Naberezhnye Chelny, Mendeleevsk, Sosnovka, Mamadysh, Kizner, and Yelabuga (Fig. 2). At present, there are five automobile and two railways “inputs,” three monomodal, and two multimodal border connections.

The internal transport-logistic framework is represented mainly by monomodal elements (Fig. 3). The only multimodal node in the county is Yelabuga city. The main frame-forming element is the M-7 highway, which determined the typological

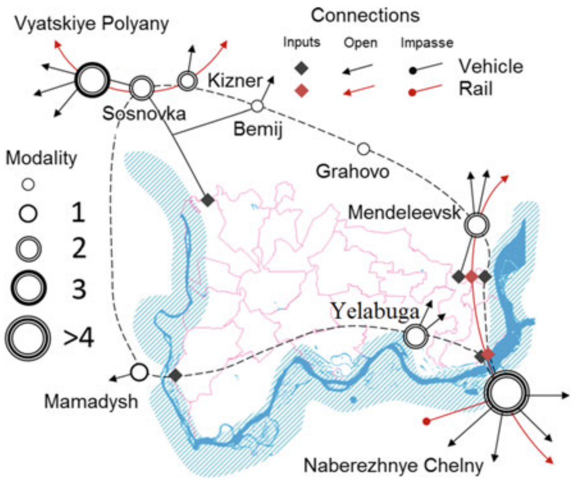


Fig. 2 External transport-logistic contour (framework)

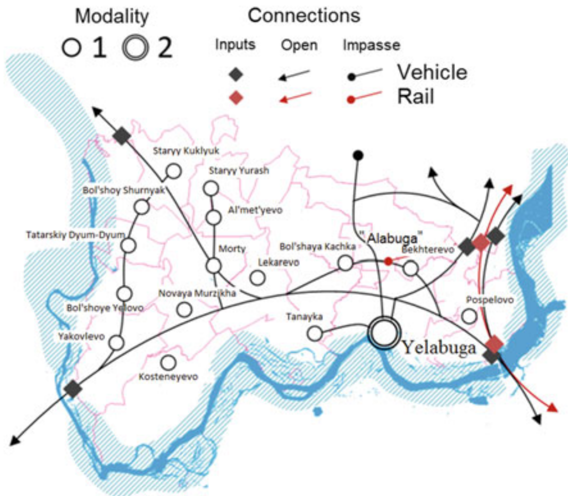


Fig. 3 Internal transport-logistics network (framework)

features of the county's transport system. The main flows pass along the multimodal meridional trunk (eastern part of the district) and the southern latitudinal corridor. Both of them have an extremely important transit position.

For unimodal territorial systems, the availability of external transport-logistic nodes is important. These nodes have a greater degree of valence (counts of the transport direction), modality, and logistization, and provide a possibility to accumulate, consolidate, transship, and distribute different flows. More developed transportation and logistics nodes form a "hinterland" (a zone of "gravitation" or "attraction") (Hoggart 2016). The attraction strength depends on: node power, degree of valence and modality, the level of development and configuration of the transport network in the hinterland zone, the availability of alternative nodes and transport options.

Despite the proximity of the Mamadysh to the western part of the county, the greater capacity and modality of Yelabuga allow one to include all the district territories into the zone of its hinterland.

3.1 Transportation Volumes

The pattern of freight flows at the local level is hierarchical and varies depending upon whether the flows are generated by wholesale trade activities or by manufacturing (Guerrero and Proulhac 2014). The potential of goods flow generated by settlement (Q_{gen}) is distributed through proportion of the property of economic entities and their revenues:

$$Q_{\text{gen}} = Q_{\text{GEN}} \cdot d_{\text{f}} \cdot k_{\text{r}} \tag{1}$$

Q_{GEN}—volume of the goods flow in the county; d_{f}—share of productive assets in settlement i from all funds in the region; k_{r}—correction coefficient for the volume of financial and economic activity.

Absorption of the commodity flow (Q_{abs}) is carried out in the process of both final consumption by population and intermediate consumption by economic entities. The consumption volume by population was estimated through data on taxable incomes with calculation of social payments. Tonnage was calculated through the total weight of the annual commodity bundle consumed in the settlement. The fixed cost of the commodity bundle was adjusted for self-sufficiency of households. The volume of consumption by business entities was estimated through data of goods flow generating the intensity adjusted for the resource of the industry:

$$Q_{\text{abs}} = \left(Q_{\text{gen}} \cdot k_{\text{abs}}\right) + ((P \cdot I) \cdot k_{\text{w}}) \tag{2}$$

k_{abs}—coefficient of resource intensity; P—population in the settlement i; I—average income per person in the settlement i; k_{w}—weight coefficient (tons per unit of consumption expenditure).

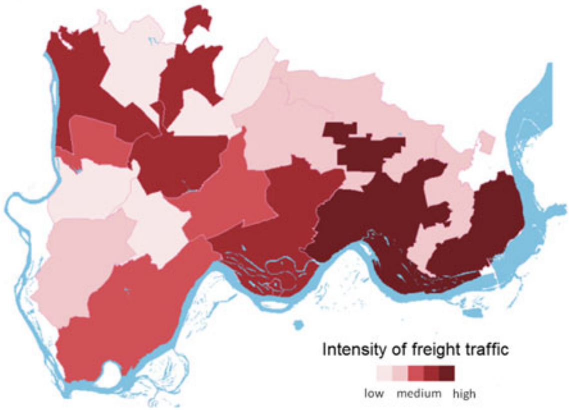


Fig. 4 Settlements of Yelabuga County by potential of commodity flows, Initial data: Rosstat Database Indicators of municipalities; Federal Tax Service Reporting

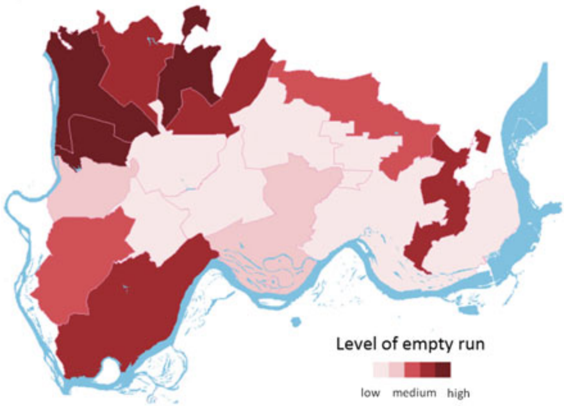


Fig. 5 Settlements of Yelabuga County by level of empty run

The volume of freight traffic (Q_{crg}) is formed by summing up the data on the generation (Q_{gen}) and absorption (Q_{abs}) of commodity flows. The potential volume of generated commodity flows in Yelabuga County is identified mainly through the agricultural complex. Among the rural settlements, the most intensive turnover is observed in Bol. Shurniak, St. Yurash, Morty, and Tanaika (Fig. 4).

In the county, there are settlements that consume significantly more than they can offer for shipment that is reflected in the high degree of empty run of vehicles (Fig. 5). Also, some of the settlements in front generate more goods than they consume.

3.2 *Internal Framework Optimization*

The linkage of settlements within the hinterland determines its stability, efficiency of the production, and inner transport. Accessibility is an important determinant of the attractiveness of counties for logistics activities (Van den Heuvel et al. 2014). The distortion of transport networks is influenced by such factors as: natural physical and geographical barriers, administrative boundaries, features of the settlement system and major highways.

The distortion degree of the transport network for a certain point (C_{tln}) was calculated as the ratio of integrated real transport accessibility and integrated physical accessibility to all settlements. It is actually reflects the percentage of distances elongation due to network underdevelopment or the presence of any barriers in the settlement system:

$$C_{\text{tln}} = \left(\sum D_{\text{r}} - \sum D_{\text{p}}\right) \Big/ \sum D_{\text{p}} \tag{3}$$

$\sum D_{\text{r}}$—total minimum distance to all points in the network along the roads; $\sum D_{\text{p}}$—total minimum physical distance to all points in the network.

The level of braking in the internal network (B_{tln}) was calculated through the ratio of the existing and ideal (with a speed of 70–90 km/h) integrated time availability. It actually reflects the amount of lost time because of the inadequate state of roads and congestion on the roads per unit of distance (minutes per 100 km):

$$B_{\text{tln}} = \left(\frac{\sum T_{\text{r}} - \sum T_{\text{i}}}{\sum D_{\text{r}}}\right) * 100 \tag{4}$$

$\sum T_{\text{r}}$—total minimum time to reach all points in the network on existing roads; $\sum T_{i}$—total time to reach all points in the network along the roads provided that the speed regime is 70–90 km/h.

The ratio of the two indicators allowed identifying four groups of settlements (Fig. 6). The first group (I) includes settlements with minimal distortion of the transport network and the level of inhibition in it. For the second group (II), a high degree of network distortion is typical, but the speed mode is quite favorable. The third group (III) is characterized by an average degree of distortion of the network, but by lower speeds in it. For the fourth group (IV), transport and temporary availability should be improved.

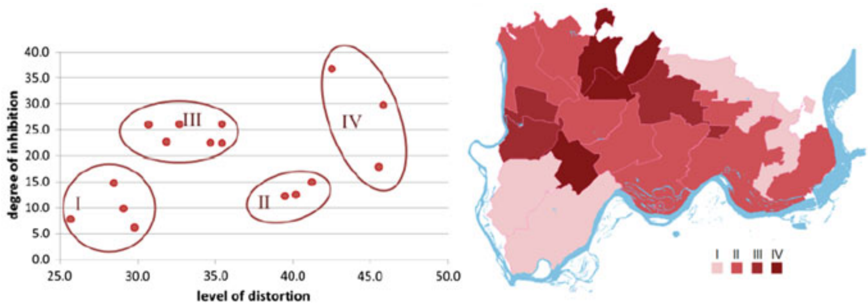


Fig. 6 Settlements by the level of distortion and the level of braking in the internal transport network (Initial data: Yandex.Maps—physical distance and road distance, https://yandex.ru/maps)

3.3 External Framework Optimization

Interaction with the external framework reflects intramodal processes in which flows of one level move to another level through production or logistic operations.

In the course of processing, the product is transformed. Then, it is distributed further or consumed. During logistic processing, the product is (de)consolidated, accumulated, and redistributed at the following levels. Thus, the external transport-logistics contour provides either consumption (processing) of the primary product, or its distribution through the network. In addition, there are vertical movements of the flows in the opposite direction: from the higher to lower levels (i.e., from the external to internal networks).

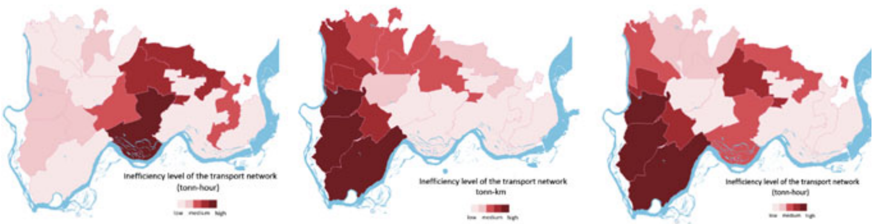
Optimization is the same as for the internal framework, but relatively individual elements of the external structure are capable of absorbing and processing commodity flows. Optimization of the external framework is possible with respect to individual objects (the base or nearest element) or in combination with all contour elements (integral accessibility). Integral accessibility characterizes degree of alternative distribution and possible risks in the system.

It is possible to reveal the volumetric level of inefficiencies of freight traffic (I_e) relative to the nearest distribution element in the external framework (Fig. 7). It actually reflects the proportion of the overloaded cargo turnover or loss of time to the nearest element in the external contour due to the high degree of network distortion.

$$I_e = \big((D_r \cdot q_c) - \big(D_p \cdot q_c\big)\big)/(D_r \cdot q_c) \cdot 100; \tag{5}$$

q_c—volume of cargo transportation; D_p, D_r—physical and real distances.

The main opportunities for optimization are associated with a reduction in transportation costs (Fig. 8). The "input–output" tables and the structure of gross output demonstrate that the main directions of rationalization and optimization are associated with a reduction in fuel costs (23%) and labor intensity (24%).



(a) *Temporal* (b) *Spatial* (c) *Spatial-temporal*

Fig. 7 Settlements by the inefficiency level of the transport network relative to the nearest element in the external contour

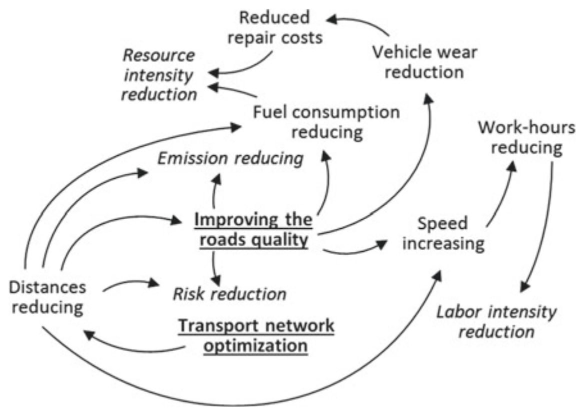


Fig. 8 Cognitive map of the impact of transport network optimization and improving the roads quality

Reducing costs along with increasing the average speed in the area (Δ_s) is estimated by the following model:

$$\Delta_s = \left(\left(t_r - \acute{t}\right) \cdot n\right) + \left((d \cdot f) - \left(d \cdot \acute{f}\right)\right) \cdot p_f; \quad (6)$$

t_r, $\acute{t}$—time of transportation at the existing (real) and normative speed mode; n—wage rate; d—distance of carriage; f, $\acute{f}$—fuel consumption at existing and normative speed mode; p_f—fuel price.

Calculations for the Yelabuga County showed the possibility of reducing costs through improving the speed limit by about 0.75 million rubles per year in prices of 2018 (12 thousand US dollars at the average annual exchange rate). Speed optimization allows reducing up to 10% of costs.

The reduction of costs in the optimization of the transport network (Δ_t) is estimated according to the following model:

$$\Delta_t = \left(\left(d_r \cdot f \cdot p_f - d_{p*c} \cdot \acute{f} \cdot p_f\right) + (m \cdot t_r \cdot n - m \cdot t_i \cdot n)\right) \cdot k_a \quad (7)$$

d_r, d_{p*c}—distance of the existing road and the physical distance with the curvature; m—number of trips; k_a—coefficient of unaccounted expenses (depreciation, repairs, maintenance).

It is quite clear that the restructuring of the entire network configuration in a short time is impossible and requires large investments, while in the long term the economic framework can significantly transform.

Creating an ideal network model with minimum costs for the basic distribution center will save up to 4.5 million rubles (71.8 thousand US dollars) or about 40% of costs under current conditions for fuel, labor, and other expenses. The maximum saving potential from the transportation of 1 ton of cargo is characteristic of the northwestern part of the region (from 60 to 85 rubles per ton, which is equivalent to 1.0–1.5 US dollars per ton) (Fig. 9). But even this is a small amount. Savings from the

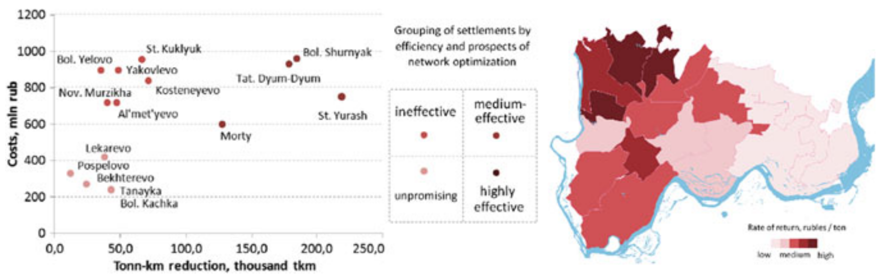


Fig. 9 Settlements grouping by perspectives of network optimization

creation and operation of new routes with current costs for the roads construction and maintenance in Russia (from 10 to 50 million rubles (0.2–0.8 million US dollars) per 1 km of one lane[1]) make it profitable to optimize the network only on high-intensity routes with large traffic and cargo turnover. At the local level, other priorities are singled out: social problems, socioeconomic exclusion, and improvement of transport access.

According to the simulation, savings (over 10 years) due to optimizing the most intensive freight routes only through local freight turnover can cover not more than 5% of building and operating costs.

At the same time, there are a number of external and internal factors:

– additional economy during empty run;
– the population's gain (temporary and cost);
– savings on intra-settlement transportation of goods (including technological);
– increasing production capacity and investment attractiveness;
– one separate optimized segment of the local level can become a transit element for more powerful directions (e.g., between large cities) (Fig. 10).

So, through optimizing the flows of meso- and macro-levels (regional, interregional, and federal), the payback of each particular element of the new network will be acceptable.

3.4 Distribution Center

Distribution centers are the one of the most effective mechanisms for optimizing transport flows. At low hierarchical levels, it is also possible to create local accumulation and distribution points (LADP). The concept of "local logistics center" is rather vague. There are approaches when local logistics centers embrace 5–8 km and have limited logistics infrastructure (Grabara et al. 2012). If the existing network is unchanged, LADP placement must meet next criteria of minimizing distance: to the

[1]Report on the cost of construction, reconstruction, overhaul, repair and maintenance of 1 km of public roads of the Russian Federation. The Ministry of Transport of the Russian Federation.

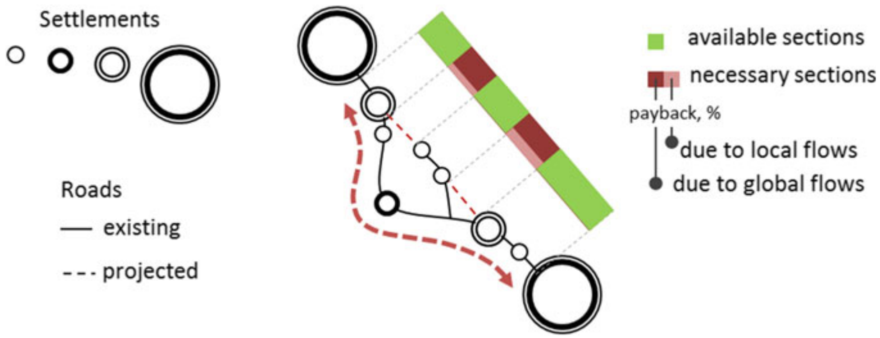


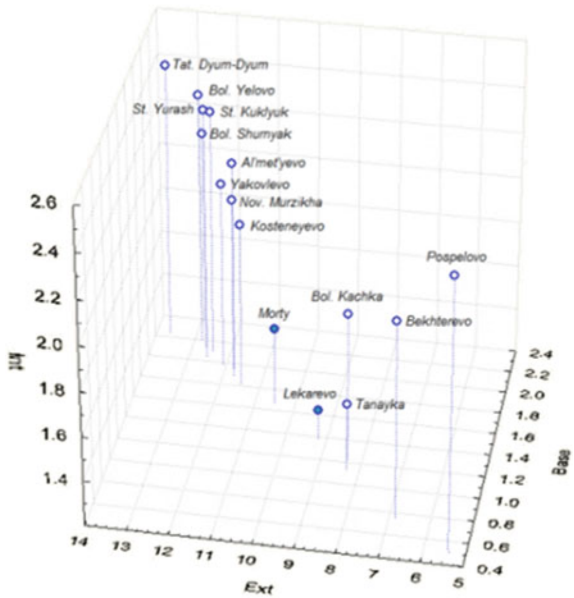
Fig. 10 Interaction of different levels of transport and logistics systems in support of the rationale for optimizing solutions in the transport network

basic node in the external framework (*Base*), to all elements in external (*Ext*) and internal (*Int*) frameworks (with weighing) (Fig. 11).

The existing network limits the distribution to all potential points. It is necessary to additionally determine the points suitable for inclusion in the system of local accumulation and distribution, in accordance with the condition:

$$\left(d_{\mathrm{b/l}} + d_{\mathrm{l/f}}\right) \geq d_{\mathrm{b/f}}, \quad (8)$$

Fig. 11 Model for LADP choosing



$d_{b/l}$—distance from the basic distribution center (BLDC) to the LADP; $d_{l/f}$—distance from the LADP to the final destination point (FDP); $d_{b/f}$—distance from the BLDC to the FDP.

$$\Delta_d = \left(\sum C_{b/f} + \sum E_{b/f}\right) - \left(\sum C_{b/l} + \sum C_{l/f} + \sum E_{b/l} + \sum E_{l/f}\right) \quad (9)$$

Total costs for moving the flow of goods:

$\sum C_{b/f}$ from BLDC to FDP by low-tonnage transport fleet.
$\sum C_{b/l}$ from BLDC to LADP by medium-tonnage transport fleet.
$\sum C_{l/f}$ from LADP to FDP by low-tonnage transport fleet.

Losses from empty run:

$\sum E_{b/f}$ from BLDC to FDP by low-tonnage transport fleet.
$\sum E_{b/l}$ from BLDC to LADP by medium-tonnage transport fleet.
$\sum E_{l/f}$ from LADP to FDP by low-tonnage transport fleet.

Modeling showed that with the existing network configuration, creating of the LADP in Yelabuga County (Fig. 12) will reduce the costs in the covered network by 25–30%, mainly by reducing the empty traffic.

Consolidation and deconsolidation of cargo flows in the LADP allow using the vehicles with different carrying capacity. Accordingly, in the consolidated area it is more efficient to use vehicles with greater load-carrying capacity. Such differentiated approach allows a more rational distribution of fuel and labor costs.

The large investment capacity of transport network transformation is reflected in the inertness of this process. It forces economic agents to use the existing (not always effective) transport network, or to seek other options for reducing transport costs. At present, there is a lack of interest in optimizing transport and logistics processes at the local level.

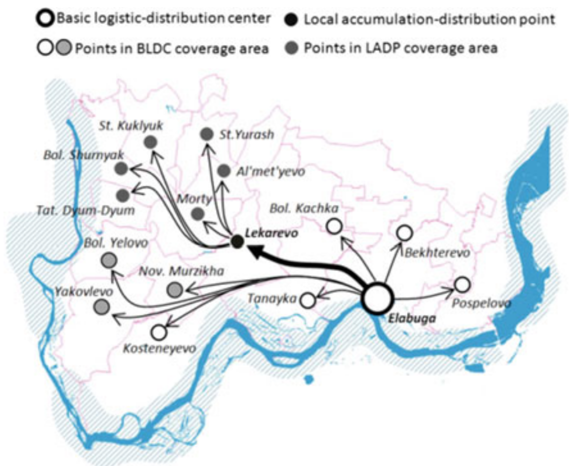


Fig. 12 Functioning scheme of LADP

Another approach to optimizing transport and logistics processes at the local level is the spatial and sectoral transformation of the economic framework, the shifting of the main production elements toward more successfully located zones in the transport network. In the Yelabuga County, there are also physical transformations of the economic framework.

4 Conclusions

Transport-logistics processes at the local level have a number of distinctive features that limit the interest in them, both from logistics agents and from researchers. At the same time, processes at the lowest hierarchical levels are the basic elements that allow evaluating the potential of more global transport and logistics nodes, determining the effectiveness of their functioning and developing directions (mechanisms) for their optimization.

The local level is distinguished by small volumes of cargo transportation. There is orientation to the external contour of economic centers and transport-logistics nodes, which provide consumption or processing of freight flows. In addition, at the local level there are quite intensive transport processes of intra-system significance. For systems more involved into the territorial division of labor, supply, and marketing, a higher degree of accessibility and development of the transport and logistics infrastructure should be envisaged.

The main optimization directions of transport and logistics processes at the local level are the transport network transformation, rationalization of the transport fleet, and the creation of a storage or distribution infrastructure. Another rather extreme measure is the economic framework transformation. Usually, such transformation occurs naturally, but it lasts long enough.

In addition, the recoupment and appropriateness of capital-intensive optimization measures cannot always be fully assessed through a system of cost indicators. Transport and logistics optimization allows reducing the social and economic exclusion, resources intensity, and pressure on the environment. All these aspects are in the plane of "sustainable development" and should be evaluated using other approaches.

The algorithm for identifying the feasibility of optimization measures at the local level can consist of four major stages:

(1) Analysis of the settlement and economic frameworks, identification of the spatial and branch structure of the flows.
(2) Analysis of the existing transport and logistics complex (definition of nodes, networks and frameworks, gravitational fields).
(3) Potential and feasibility assessment of the transport and logistics infrastructure optimizing:
   - transport network transformation;
   - transportation fleet modernization;
   - logistics elements creating.

(4) Potential and feasibility assessment of optimization measures with the settlement and economic frameworks and (or) the spatial-assortment structure of flows.

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