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From Linear to Nodal Transport Infrastructure. Case Study: Maramureş County. Romania

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A B S T R A C T

The concept of linearity geometrically individualizes itself as the simplest form of representing the space. It developed, therefore influencing the communication and transport networks even from the beginning, until the end of the 19th century. Conceptually, linearity in transport and communication infrastructure has developed as excessively long networks, without too many nodes, all established on the idea of avoiding areas affected by geomorphologic risks. This manner of developing networks has determined a certain potential of communication exceeding in some areas, while other areas lacking or even becoming isolated. In the 21st century, when technology is able to fight all limits of accessibility, imposed by relief, for the development of infrastructure by constructing tunnels, bridges, a new approach has been established, that of nodal networks. The concept of nodal network in the development of transport and communication provides certain advantages, such as: the assimilation of several linear networks and their connection through nodes, therefore providing access in the territory through a node towards several directions, by using the same type of network or by using other types of infrastructures. Our case study underlines accurately the benefits brought up by passing from the linear to nodal infrastructure and new opportunities for development as its direct result.

1. INTRODUCTION

The issue of transport networks in spatial planning has been and still remains relevant because territorial development depends on the characteristics of their technical and spatial distribution. Transport network represents the "channels of territory" through which all other anthropogenic systems are connected and cooperate for well-functioning and development. On the other hand, natural geographical systems use specific transport and communication networks, some of which are also used in the anthropogenic systems (e.g. streams, river basins).

The characteristics of the spatial distribution of transport networks are integrated in spatial planning, and once properly resolved, they allow the implementation of technical characteristics.

The characteristics of spatial distribution of transport networks include the following:

- the network type (linear, circular, nodal);
- the network density (km/sq km);
- the number of arcs and nodes a network includes;
- the network arcs length (km);
- the number of node connections;
- the service capacity of arcs and transit capacity of nodes [vehicles per day].

If these spatial characteristics of networks are adequately designed, they generate favourable conditions for the implementation of technical features that should support and facilitate the traffic.

The main feature of the spatial distribution of networks is *the type of existing (current) network* that influences and determine the other technical characteristics. From the conceptual perspective, we can reveal three types of networks: linear, circular and nodal, plus the multimodal in case of the highly developed networks (fig. 1).

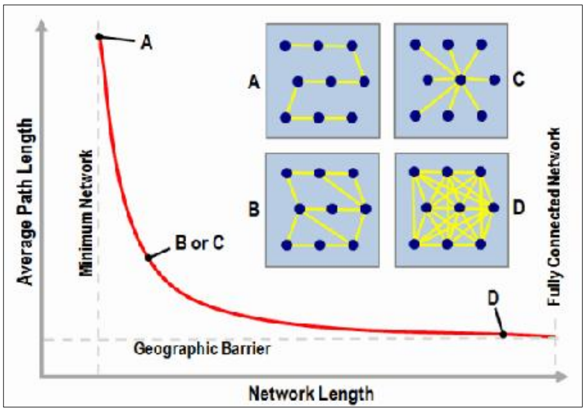


Fig. 1. The development stages of transport networks [1].

The type of network established in a territory depends on its level of development.

Thus, in the peripheral or underdeveloped areas we notice only linear networks or just their ends whereas in the developed or central areas the nodal and multi-modal networks are often designed. From this axiom we can infer that, for developing a transport network in a territory, we have to go through a *series* of phases:

- phase I – the connection of a territory to the economic and social circuit. This is achieved through any linear network and its endings (fig. 1 A, C);

- phase II – the appearance of early development poles; including the already connected area into wider development areas and building a circular network by closing the linear network's ends (fig. 1 B);

- phase III – the growth of the development poles ranks; territorial development through economic diversification and building the nodal transport network (fig. 1 D);

- phase IV – transforming the peripheral area into central as result of all geopolitical and macro-territorial economic changes and building the multimodal network.

In case of the transport network development in a territory, we have to go through all four phases with their specific organizational problems and features, reliability and usage.

In areas not subject to these conscious planning actions, the network develops in accordance with "natural patterns", step by step, as determined by the current local development needs (fig. 2).

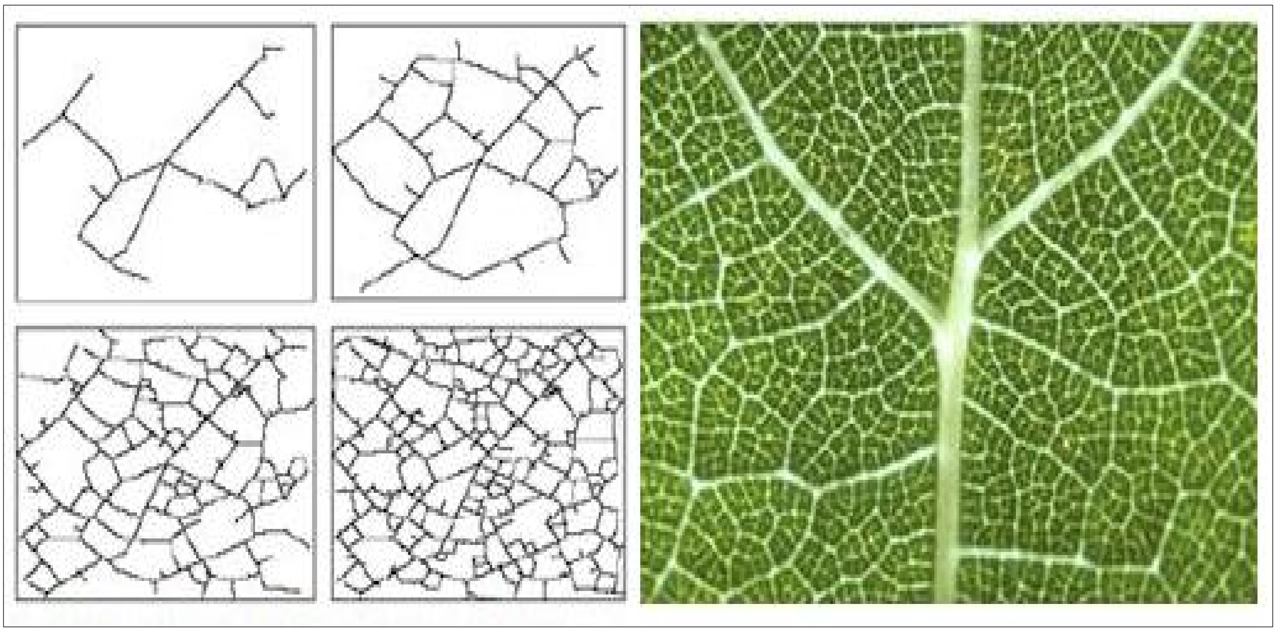


Fig. 2. The association of a designed network with a natural one [9].

Relying on such an approach for network development proves to be valid up to a certain level (the maximum level of economic autarchy), after which, the inclusion of territory into the economic circuit involves other parameters of development and design, such as: cost, efficiency, effectiveness, implementation time, access time, impact minimization, development support, etc.

In spatial planning, the evaluation of the characteristics of transport network begins with establishing its development phase and its type, whereas the development strategy provides, among other things, the next stage of network development.

In case of Maramureş County transport network, when updating the County Spatial Plan (PATJ) (2008-2009), it had to be reassessed in terms of typology, stage of development; therefore, new proposals were made for its future development in accordance with the theoretical premises presented below.

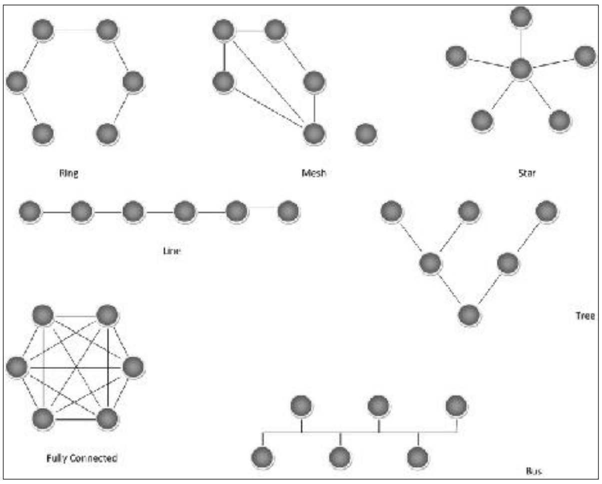


Fig. 3. Types of transport networks [11].

2. TRANSPORT NETWORK - CONCEPT

Transport network represents all settlements (nodes) and connecting routes (arcs) between them and it can be visualized by a finite graph, undirected or partially oriented, simple or connected.

Connection routes (arcs) consist of public roads, railways, electricity grids, pipelines etc.

They form the arcs of network, oriented or undirected and they can be included into several categories: simple arcs; double arcs; loop arcs.

The network nodes are differentiated by:

- *sources*: settlements in which the product is available to be transported to other places;

- *destinations*: locations where the product is required for consumption, the demand could not be covered by the local production;

- *intermediate centres (transit)*: settlements in which the product is found only in transit, therefore the consumption being provided by local production.

Trying to explain the structure of a transport network, we will use some elements of the graph theory [12].

A graph is a structure G = (V, E) that consists of a set V, whose elements are called vertices or nodes and a set E of elements, called edges, and each edge $e \in E$ is associated with two nodes x, $y \in V$, not necessarily distinct, called ends of edge e. A sub-graph of the graph G = (V, E) is a graph G' = (V', E') in which $V' \subseteq V$ V, $E' \subseteq E$ and any edge $e \in E'$ has the same both ends in G' as in G.

As it can be seen, the general definition does not exclude the existence of edges with only one end (these edges are called loops), nor the existence of more edges with the same ends (fig. 4 a).

Therefore, G will be called simple graph if it has no loops and any two nodes represent ends for at least an edge.

We say that G is finite if its vertices and edges are finite in number (fig. 4 b).

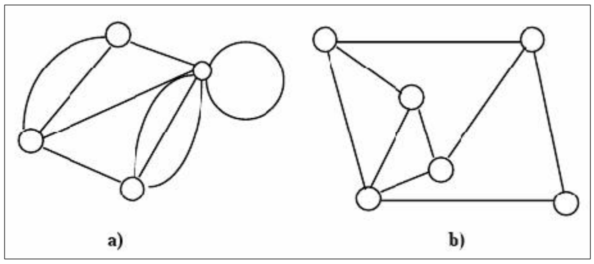


Fig. 4. The general structure of a network graph [12].

2.1. Transport networks – logistic support for transport

Transport creates practical links between regions and economic activities, holding multiple meanings such as: historical, social, political, economic and environmental. Many of the transport systems have universal access so that it is not suitable for some users to be favoured when in competition with others. For example, everyone has access on a public road, either by using an individual means of transport, either means of public transport, or on foot. This way, access is uniform everywhere, with locations and rules specific to transport system and which allows individuals to enter or exit anytime. Therefore, access is uniform whereas the accessibility is not [8].

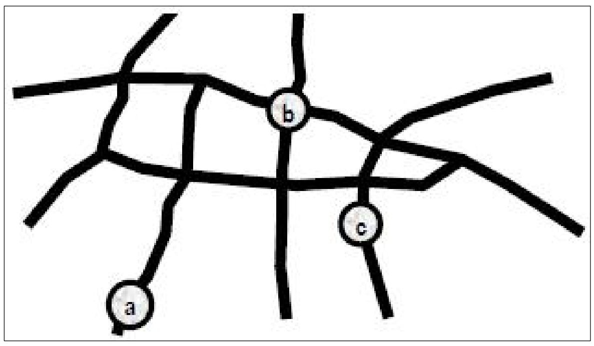


Fig. 5. Access and accessibility in transport networks [8].

The concept of *accessibility* is relative. If we look at transport network (fig. 5) with three nodes (a, b and c) we note that access to the system is allowed through all of them. However, if we compare them, point *b* is "more accessible" as compared to points *a* and *c*. We can conclude that accessibility depends on network configuration, whilst access to the network does not. This is of great interest logistically, in case of programming and optimization of routes [8].

The phrase "*distance is not time*" expresses a general truth. There is a tendency to transform distance in time in case it is necessary to drive it and to measure the performance of transportation system, which is a conceptual mistake. As long as distance is constant, time in which it is crossed depends on transport technology or on flow congestion.

In case of transport network the length of each segment is calculated in kilometres. In case of a particular itinerary the geographical length can be calculated exactly. Yet, the time required for travelling cannot be precisely estimated. Thus, in case of another route of the same length within the network, the time required to cross it will be different even if the same transport technology is used.

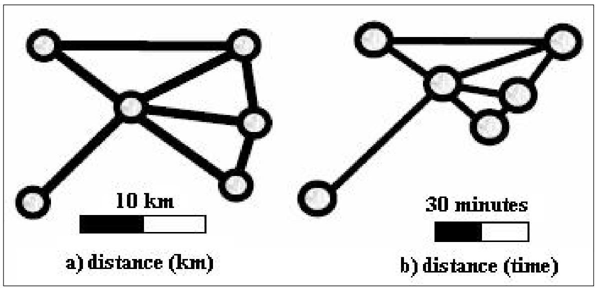


Fig. 6. The relativity of perceiving distance within the same transport network [8].

Practice often describes distance as the time required to drive a certain route. This way of expressing is rather based on supposition, but because it is often practiced, we illustrate it in fig. 6. The same network can be designed as the representation of absolute distance in kilometres (fig. 6a), or as representation of distance in time, case in which it is deformed, as shown in fig. 6b. Figure 6b reflects the level of accessibility in terms of duration and not in terms of length. From a logistical perspective this type of perception is useful for route optimization.

2.2. Spatial continuity of transport networks

Besides means of transport, the basic components of transport systems include: networks, nodes and transport demand. Transport networks have specific patterns in case of any form of transport (rail, road, air, river, sea, and pipeline).

So as to achieve continuity of transport between the starting point and destination, sometimes, different transport networks must be used.

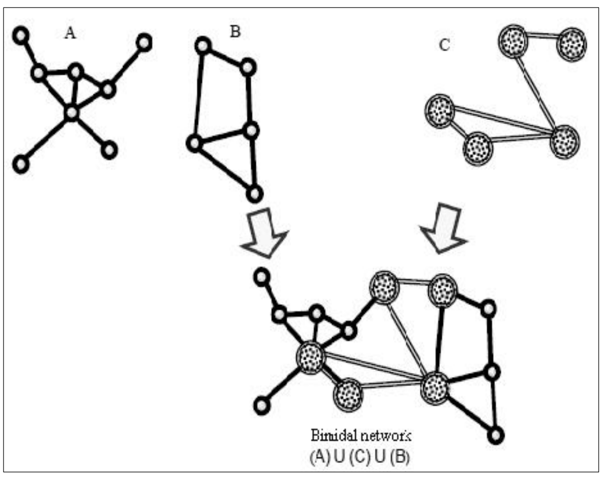


Fig. 7. Multimodal transport networks [8].

Figure 7 shows the principle of using transport modes' networks to ensure spatial continuity of transportation.

Networks A and B are of the same type in case of transport mode and they provide accessibility for the same area, but there is a discontinuity between them (mountain range, water surface, stream). Network C is a different kind of network regarding the transport mode but it has common nodes with each of the other two. So as to provide transportation from a node of network A to any node of network B, we have to also use network C, by using several nodes it shares with each of networks A and B.

The graphical representation of a transport network through the network graph allows us to assign nodes and arcs/edges different meanings, such as [8]:

For nodes:

- transit capacity [vehicles per day];
- simultaneous parking capacity [number of vehicles];
- individual costs of transit;
- individual time of transit;
- average time of parking;
- arcs of entry and exit.

For arcs/edges:

- entry and exit nodes;
- technical and commercial average speed;
- traffic capacity [vehicles per day];
- individual cost of transit;
- individual energy consumption [kWh/vehicle km];
- individual indicators of pollution [noxious waste/vehicle or dB /vehicle].

If we want to drive a route from the start node to the destination node, it is allowed, at least theoretically, to choose a corridor in the network graph out of the multitude of possible roads linking the two nodes. Basically, we can find as many possible routes, as one can identify in the road network graph. It is, however, necessary for each route to be known: the intermediate nodes, the capacity, as well as the individual cost of transit.

Common network nodes, with different transport modes are considered "intermodal nodes", whereas transport activities that use various modes of transport, generally called "multimodal transport", determine a structure with certain logistical aspects.

In terms of logistics, multimodal transport activities should be approached in a distinctive way. The usage of intermodal nodes (commonly referred to as terminals) involves a complex system of integrated logistics. Conceptually, the transport system is structured by a set of relationships and constraints between nodes, networks and demand. It cannot be made the separation between transport networks, transport demand and transport flow as they closely interact.

2.3. Reliability and vulnerability of transport networks

The concepts of reliability and vulnerability are extremely important when assessing the capacity of transport networks to ensure continuity in use. Natural disasters that have occurred in recent years (earthquakes, floods, fires), crimes (terrorism, sabotages, wars), especially the spread of human settlements and the expansion of urban areas generate a particular interest for research conducted on transport network reliability and vulnerability [2].

The impact the failure of network nodes or links can have, it is impressive. Policy makers, local authorities, planners and traffic engineers require methods and tools to evaluate network reliability and achieve a functional analysis of the consequences determined by the withdrawal of certain components. The possibility to evaluate, manage and minimize the effects of transport network functional degradation generates various economic, social and environmental benefits. In urban areas, thereby, it determines the reduction of travel costs for users; it reduces congestion and negative externalities, as well as it provides continuity for social and trade activities.

The reliability of transport network elements expresses the capacity of well functioning during a given period, under specified conditions of use. If certain elements of the transport network fail, the network can remain functional even though with lower performance.

There are three forms of network reliability [3, 4]:

- *reliability in relation to network connectivity* - the probability that two nodes in the network remain connected;
- *reliability in relation to journey duration* - the probability of travelling between two nodes to be completed in a given time; duration is affected by the awareness of the drivers and changes in the traffic flow;
- *reliability in relation to the capacity of arcs* - the probability of a network to satisfy a given level of transport demand; the capacity reserve takes some of the loss determined by the degradation of other network elements. The vulnerability of networks is expressed by the consequences of network elements failure, without taking into account the probability of failure. It is possible that the failure of some network elements has a low probability, but when the event occurs, the social, economic and environmental impact can have such intensity as to represent a major problem. The analysis of vulnerability highlights the structural defects in the network topology. Taylor and D' Este [3] ascertain two forms of transportation networks vulnerability:

- *vulnerability in relation to the cost of journey* - if the degradation of one or more connections of a route linking two nodes leads to substantial increase in the general travel cost, then the connection between these nodes is vulnerable;
- *vulnerability in relation to accessibility* - a node is vulnerable if the failure of a small number of links in the network results in a significant decrease in the accessibility of the node.

2.4. Networks accessibility index

Taylor and D' Este [2] use the Hansen accessibility index when they characterize the vulnerability of transport networks.

Accessibility for a node *i* is:

$$A_i = \sum_{j \neq i} B_j f(c_{ij})$$

where:

Bj – the attraction exerted by node *j*;

cij – the generalized cost of traveling between nodes *i* and *j*;

f(*cij*) – the impedance function of journey.

Usually, the impedance function[1] is expressed as the inverse generalized cost or as a negative exponential function.

$$(f(c_{ij}) = e^{-\beta c_{ij}}$$

where β is a calibration parameter.

The nodal accessibility index results from the following relation:

$$HA_i = \frac{\sum_{j \neq i} B_j f(c_{ij})}{\sum_{j \neq i} B_j}$$

and the accessibility index for the entire transport network:

$$TA = \sum_i HA_i$$

A disturbing event occurred in the network, with consequences for the functioning of the arc k, leads to a decrease in the values of accessibility indices:

$$\Delta HA_i = HA_i^{(0)} - HA_i^{(k)},$$
$$\Delta TA = TA^{(0)} - TA^{(k)}.$$

where index (0) refers to the original network, and index (*k*) to the network where link *k* is inoperative.

1 Impedance - the variable that characterizes a system, in certain circumstances, to prevent the normal development of a process that takes place in a system.

2.5. Transport cost within networks

Jenelius E. et al. [5] proposed the variation of the generalized cost of performing transportation, as a measure of the decrease in network performance.

If the arc k belongs to the set of arcs whose non-functionality does not isolate parts of the network, then the importance of this link for the whole network is:

$$\Omega(k)=\frac{\sum_i\sum_{j\neq i}\phi_{ij}\,(c_{ij}^{(k)}-c_{ij}^{(0)})}{\sum_i\sum_{j\neq i}\phi_{ij}c_{ij}^{(0)}},$$

where:

$c_{ij}^{(0)}$ - the generalized cost of travelling from node *i* to node *j* in the initial network

$c_{ij}^{(k)}$ - the specific cost for the network in which arc k is inoperative.

In addition, the inoperability of one link, results in the exposure of nodes. The vulnerability of a node *i* is determined by:

$$\Phi(i)=\max_{k\in L^{n-c}}\frac{\sum_{j\neq i}\phi_{ij}\,(c_{ij}^{(k)}-c_{ij}^{(0)})}{\sum_{j\neq i}\phi_{ij}c_{ij}^{(0)}}$$

where: L^{n-c} denotes the set of arcs whose inoperability does not isolate parts of the network.

2.6. The evaluation of transport reliability in relation to network connectivity

The probability that two network nodes remain connected depends on the probability of functioning of the routes linking the two nodes [3, 5, 6]. The probability of functioning P (**X**ij) of a set of arcs **X**ij = (*ik, kl... sj*) connecting two nodes *i* and *j*, is:

$$P(\mathbf{X}_{ij})=\prod_{kl\in\mathbf{X}_{ij}}p_{kl}$$

where *pkl* is the probability of optimum functioning of the link (*kl)*.

It is considered that reliability of transit nodes equals 1. Any malfunctions experienced by the node can be transferred to the probabilities of proper functioning of adjacent arcs.

Each transport network consists of a set of minimal roads and minimum cuts.

The minimum path between two nodes represents any sequence of arcs, in which any arc fault leads to the refusal of the link. Any minimum path *Aij* that connects the network nodes *i* and *j* has an associated logic function α (*Aij)*, which equals 1 if the link is operational and equals 0 if not:

$$\alpha(A_{ij})=\bigcap_{kl\in A_{ij}}x_{kl}$$

where *xkl* = 1 if arc (*kl*) is operational and 0 if not functional.

The minimum section represents a set of arcs in which to restore the functionality the arc means to restore the connection between the two nodes. Each minimum section *Bij* corresponding to the pair of nodes *i* and *j* has an associated logic function β (*Bij)*, which has the value 0 if all consisting arcs are broken and 1 if at least one of them is operational:

$$\beta(B_{ij})=\bigcup_{kl\in B_{ij}}x_{kl}$$

Structurally, the transport network can be represented by the set of minimum paths arranged in parallel or by the set of minimum cuts arranged in series. It appears that the formal representation of transport networks supposes that an arc can belong to different paths and minimum sections.

Consequently, network reliability cannot be assessed based on a mathematical model designed on the assumption of independence of elements, but it is possible to estimate the maximum and minimum limits of probability to achieve connection between two nodes:

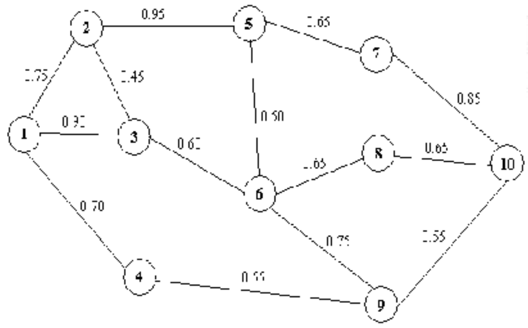
$$\prod_{s=1}^{S}\left[1-\prod_{kl\in B_{ij}^{s}}\left(1-p_{kl}\right)\right]\leq P(\mathbf{X}_{ij})\leq 1-\prod_{q=1}^{Q}\left(1-\prod_{kl\in A_{ij}^{q}}p_{kl}\right)$$

where:

S – the number of minimum cuts;

Q – the number of minimum paths connecting the pair of nodes (*i, j*).

In case of the large networks is difficult to identify all the minimal paths and minimum cuts. Figure 8 illustrates the undirected graph associated with a network and the probabilities to achieve connection between any two nodes.



$P[X_{ij}]x10^2$	1	2	3	4	5	6	7	8	9	10
1	-	95,97	97,19	84,27	95,65	93,75	94,06	85,53	90,75	97,62
2		-	91,27	79,87	98,62	90,83	92,03	82,48	86,65	94,08
3			-	81,85	93,49	92,98	91,65	83,61	88,79	95,42
4				-	79,22	80,56	78,86	72,91	81,82	82,32
5					-	89,99	91,99	82,18	86,22	93,86
6						-	87,45	85,63	91,16	92,38
7							-	76,99	78,71	92,74
8								-	76,38	84,57
9									-	89,04

Fig. 8. Probabilities of connection between nodes [4].

3. MARAMUREŞ COUNTY TRANSPORT NETWORK

At the update of Maramureş County Spatial Plan (PATJ) (2008), when analyzing the current situation and the proposals for the future development of transport network, in addition to its quantitative and qualitative assessment, great attention was paid to the spatial reconfiguration of the network. Firstly, road and rail transport networks were brought into attention, as they have the greatest impact on spatial development, and then the other types of technical networks (electricity, gas, water) with smaller effects.

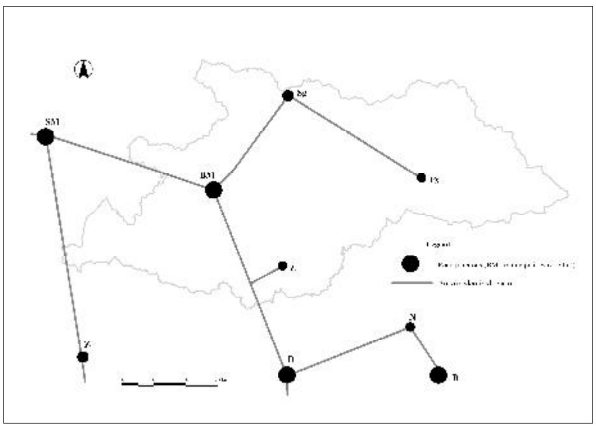


Fig. 9. Major road network configuration of Maramureş County during 1918 – 1944.

Maramureş County, by its peripheral location within the country, developed its transport network rather late, as compared to other areas. This was also determined by its membership to other regional structures (i.e. the historical Maramureş, as a whole functional territorial unit before 1918). From this perspective we can identify several stages of setting up the transport network:

a) the phase until 1918, when Maramureş was part of Transylvania, under the rule of the Habsburg Empire. The transport network was rather poor, represented by inefficient roads, most of them being earth roads with some paved sections. It had a linear-tree character, using natural corridors (valleys, river basins) as routes. The railway network was only at the beginning of its development.

b) the phase 1918 - 1944, when Maramureş county becomes part of Greater Romania, and subsequently, by the Vienna Dictate (1940), part of Hungary for a short period of time (1940-1944). During this phase, transport network develops substantially; the first connecting routes occur in the linear network; all along, the main roads are modernized and widened, later on being called “country roads”. The railway network is finally designed, presently remaining unchanged. During the same period the first nodes within the network are outlined (fig. 9).

The main nodes were represented by Baia Mare, which made the connection to the southern part of the county, and Sighetu Marmaţiei to northern part.

c) the phase 1944 - 1989, during which the country's political orientation switches from capitalism to socialism and there is an increasing development through industrialization, fact that stimulates the development of road network. New routes are established and the linear network closes, therefore becoming circular. All along, the number of nodes increases, whereas the main roads are upgraded by widening and asphalting. Thus, the communication potential increases substantially as the duration of access decreases (fig. 10).

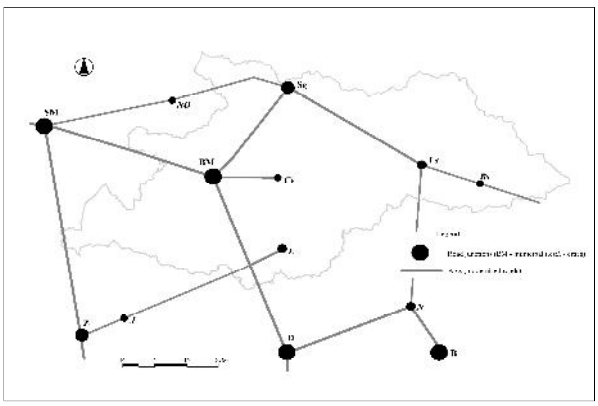


Fig. 10. Major road network configuration of Maramureş County during 1944 - 1989.

The other roads of the network are less efficient, still carrying the technical features from the previous period. Despite all the efforts of modernizing the network this could not meet the current development needs.

d) the phase 1989 up to present, has resulted in numerous attempts to add up new elements to the network to develop a nodal network. Nevertheless, the network remained incomplete, lacking in high level routes (highways, express roads) which would undertake a rapid transfer of the flows to the distribution nodes (fig. 11).

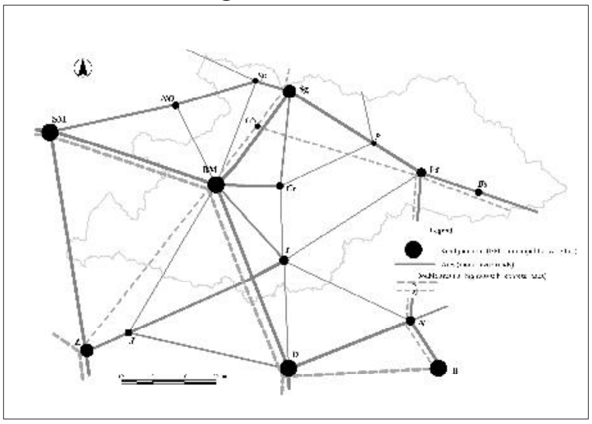


Fig. 11. Major road network configuration of Maramureş County from 1989 to present.

Still, there is low density of the nodal type network, frequently, the lower class roads (county and local) with low degree of modernization being predominant (fig. 12).

This fact greatly distorts the network the duration of access, turning unviable from this perspective.

This reflects on the accessibility of the area and the emergence of non-compliant probability of accessing some routes, which ultimately lead to their overcrowding.

The presence of the natural barrier in the middle sector of the county still determines a high level of traffic linearity within the county even if the nodal network is already established.

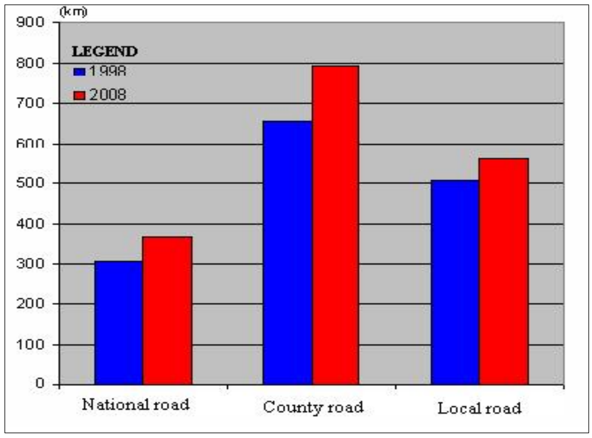


Fig. 12. The structure of public road network in Maramureş County.

Network viability is another major factor in reducing the functionality of road transport network. Despite the fact that the road network has a quite complex and completely nodal character, the reduced level of using certain routes (arcs) is determined by the road condition.

Therefore, routes that have a rudimentary road infrastructure, of earth or gravel, are impractical during the cold season of the year and partially practicable for the rest (fig. 13).

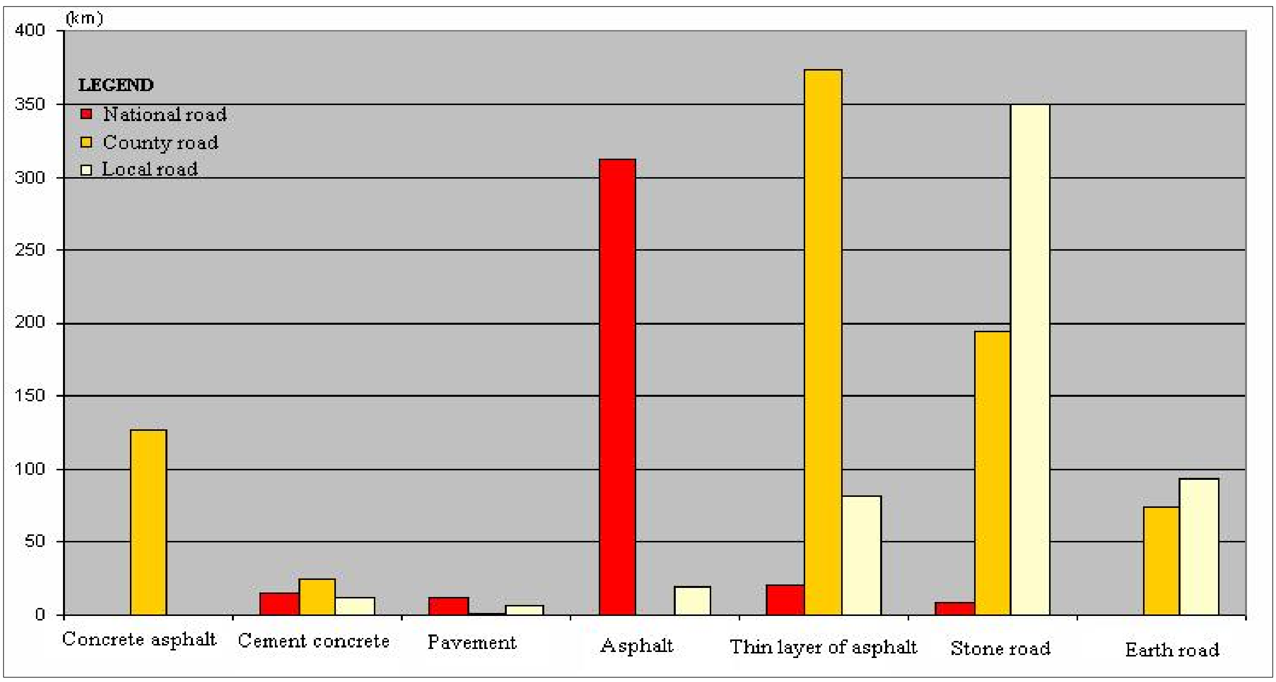


Fig. 13. The structure of public road network by type of pavement in Maramureş County (2008).

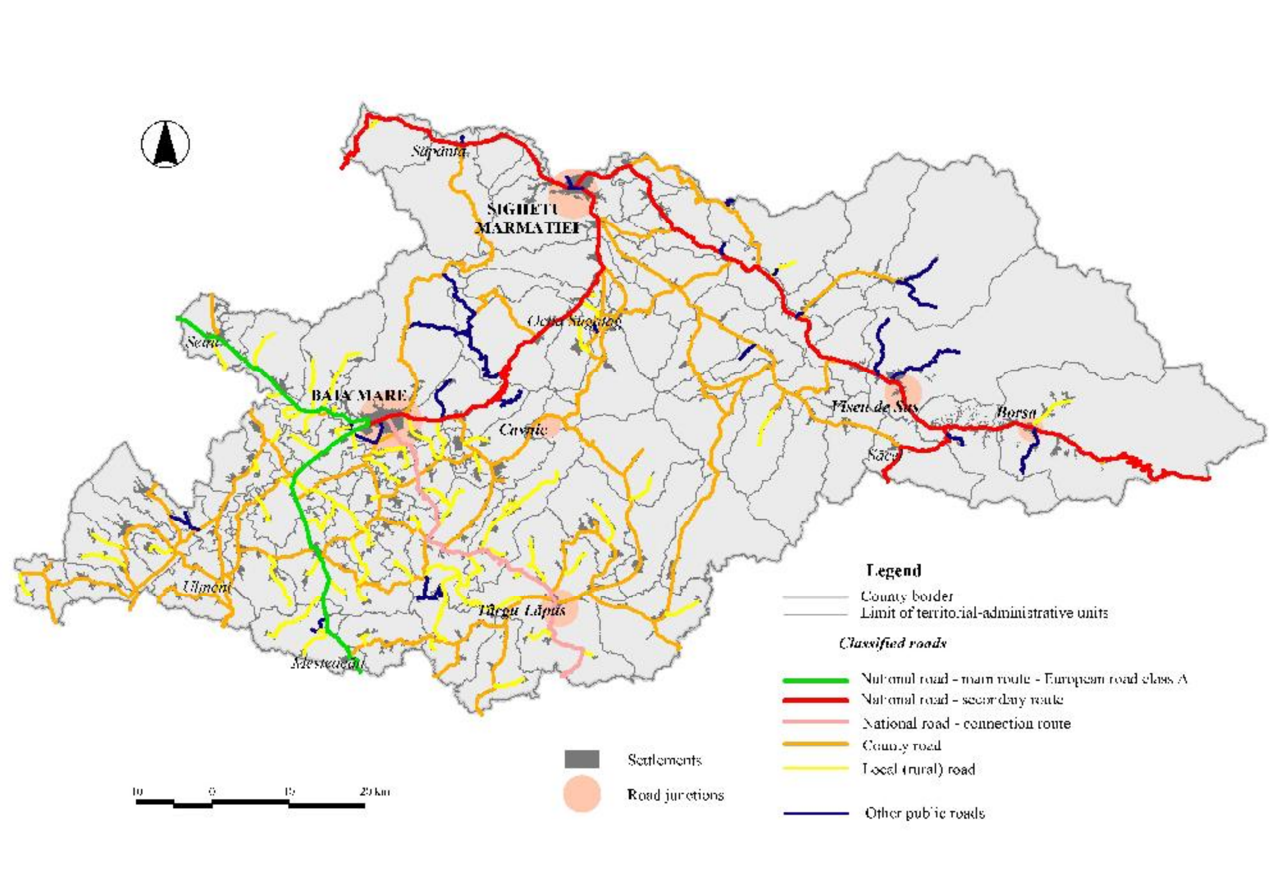


Fig. 14. The current transport network Maramureş County (2008).

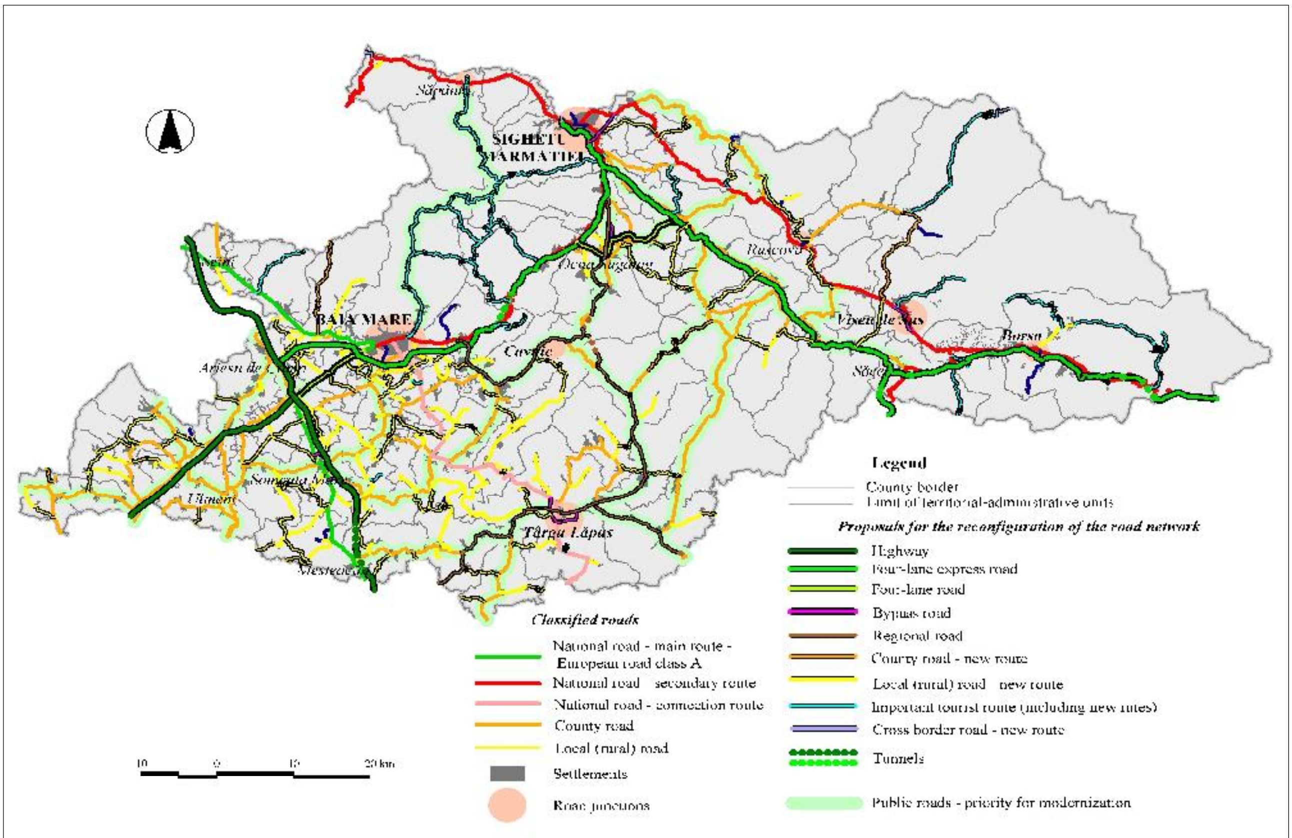


Fig. 15. Proposals for better functioning and modernization of road network in Maramureş County. Modernization and construction of a new network of four-lane roads.

This way, the nodal network of the county area remains actually the same, with a high degree of linearity in some areas and circular as a whole, which is determined exclusively by the optimal functionality of national roads and of some local roads.

In order to implement a functional nodal network in Maramureş County, based on the theoretical aspects and the information in the territory, we made a series of proposals for its optimization.

The first step proposed for the modernization of existing routes within the network was to restore the network functionality by using the current structural pattern.

4. CONCLUSION

This study presents a practical approach, which can be applied to solve the transport network development issues in spatial planning.

The development of transport networks cannot be accomplished only intuitively, but based on expert analyses and quantitative indicators that highlight the dysfunctions and indicate the appropriate solutions to be followed.

On the other hand, it highlights the mutations that occurred in the network over time (in this case, the road network of Maramureş County, Romania) and the spatial configuration at this moment - now considered t_0 in addition to which the network reconfiguration was designed for this to become functional and holding a nodal character – the basic assertion for its transformation into a multi-modal network.

Solving the transmission network represents the fundamental premise for the harmonious development of the entire territory.

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