Modelling the Road Network as an Expression of Historical Spatial System Change in the Klaipeda Region (Lithuania)

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Abstract: Since the 20th century, the Klaipėda region (Lithuania) has undergone significant political, economic, social, and cultural changes related to the disappearance of Prussia (1923), the Soviet occupation (1944) and the restoration of independence (1991). This has led to radical transformations in the spatial system, of which the road network is a key component. Networks could be analysed using space syntax methods by assimilating them to a mathematical graph model, for which quantitative indexes based on topology can be applied to assess their spatial configurations. The 'Generic City' approach, by simulating foreground and background urban networks, can be modified innovatively on a territorial scale. Based on historical cartographies and open geographic databases, indexes characterising both networks are derived to describe the length, angularity or accessibility of the pre-Soviet, Soviet and post-Soviet networks. The analysis identified four main spatial structures associated with the network by combining the indexes in a K-means machine learning algorithm. They highlight the spatial impacts of collectivisation, industrialisation, and tertiarisation of the economy, post-World Wars and post-Cold War geopolitical events, and their consequences as drivers of the territorial organisation and dynamics such as the metropolisation or peri-urbanisation.

1 INTRODUCTION

Since the 20th century, the coastal region of Klaipėda in Lithuania has undergone significant and rapid transformations. These changes were initially political, with the territory being divided between the Kingdom of Prussia and the Russian Empire, experiencing a brief period of independence during the interwar years, being incorporated into the Union of Soviet Socialist Republics (USSR) in 1944, and finally seeing the restoration of independence in 1991 (Plakans, 2011). These geopolitical shifts have been accompanied by economic, social, cultural, and societal changes, including agrarian reforms such as agrarian capitalism and collectivisation (Jespen et al., 2015), urban expansion, particularly suburban sprawl (Cirtautas, 2015), Soviet industrialisation, and the subsequent deindustrialisation and tertiarisation after the Soviet era (Idzelis, 1984; Köll, 2024), alongside recent trends of population decline and migration (Ubarevičienė and Van Ham, 2017), throughout the 20th and early 21st centuries.

The organisation of geographic space is significantly influenced by societal changes, whether directly or indirectly. The analysis of these territorial transformations is rooted in the concept of spatial systems, which refers to the distribution (structures) of geographical entities — such as built environments, road networks, land use, land cover, and land parcels — in space according to either spontaneous or regulated logics (Archaeomedes, 1998; Allain, 2004; Ellisalde, 2004).

The objective of this research is to examine the evolution of the spatial system in the Klaipėda region

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(Lithuania) since the 20th century. To achieve this objective, the road network has been modelled using space syntax methods, with a particular focus on the 'Generic City' concept.

The analysis of spatial systems involves examining their structural complexity, which includes the participation of multiple agents; spatial complexity characterised by various geographical scales; and temporal complexity marked by non-linear evolutions (Badariotti, 2005). Spatial analysis and modelling offer methodologies for comprehending the intricacies of spatial systems by translating geographical reality into mathematical forms (Georges and Verger, 2013). This methodological approach has been employed to describe "[…] the distribution, configuration and covariation" of geographical objects in space" (Voiron-Canicio, 1995).

In complex spatial systems, networks facilitate the relationships between various points of attraction and diffusion, such as urban centres (Georges and Verger, 2013). The mathematical graph model serves as the theoretical basis for space syntax, wherein networks are represented by nodes corresponding to the network segments and links connecting these nodes. This theoretical framework enables the simulation of interrelationships between spatial configurations and their associated urban functions (Laouar and Manzouz, 2017; Abida, 2018). Syntactic indexes based on the topology of network segments are utilised to examine how spatial structure influences human behaviour through simulated movement.

This research focuses on the Klaipėda region, where spatial changes are particularly pronounced compared to the rest of Lithuania. The unique environment of this coastal area is attributable to its position as a maritime interface. During the Soviet era, the port of Klaipėda emerged as a pivotal facilitator of connectivity between the Baltic and the Black Sea regions, driving the development of strategic economic activities alongside the growth of seaside tourism. Despite the region experiencing partial militarisation during this period, Lithuania's independence in the 1990s led to the enhancement of these activities and an opening to the market economy. A consequence of this transformation has been the rapid suburbanisation of the metropolitan and coastal areas that began in the 2000s (Vaitkus and Vaikuvienė, 2005; Veteikis et al., 2011; Cirtautas, 2015). Furthermore, the region is historically divided between two ethnographic areas: Samogitia (Žemaitija) in the north and Lithuania Minor (Mažoji Lietuva) in the south, each exhibiting distinct functional and cultural characteristics (Ragauskaitė, 2019). The former corresponds to the territory that was under Russian occupation, while the latter was incorporated into Prussia prior to the Soviet era.

2 THE 'GENERIC CITY' CONCEPTUAL APPROACH

This analysis draws upon the concept of the 'Generic City', developed within space syntax theories and methodologies to identify the spatial and functional similarities between cities despite their diverse cultural contexts (Hillier, 2007; Hillier, 2010).

This concept proposes that each city exhibit a dual network characterised by (1) "longer lines and nearly straight connections", indicating a foreground network, and (2) "shorter lines with more near right angle connections, and so more localised and with less linear continuity", referring to a background network.

The foreground network tends to be similar across various cities, while the background network is more specific and sensitive to cultural context. These networks, with their distinct physical and functional attributes, are evaluated using specific indexes (section 3.2).

For instance, Al Sayed (2009) compared the foreground and background networks of Manhattan and Barcelona to showcase the emergence of dynamic and adaptive urban networks. In the present study, however, the indexes traditionally used to characterise these networks are applied not in an urban context but in a territorial one. They prove to be insufficiently suited to the research objectives due to their low statistical reliability and limited differentiation between foreground and background networks. The diversity of urban and rural settlements (including individual and familial farms, villages, towns, and cities) in relation to road networks presents varying degrees of appeal for movements across the territory (Dringelis, 2015). Furthermore, the region has been shaped by multiple cultural influences — Prussian, Russian, Soviet, and post-Soviet — which have successively affected territorial organisation, complicating the modelling of these networks. Consequently, it has become essential to employ syntactic indexes that more accurately reflect the conceptual approach of the Generic City in a territorial context (Gloaguen et al., 2023).

3 SYNTACTIC TERRITORIAL INDEXES FOR SPATIOTEMPORAL MODELLING OF NETWORK STRUCTURES

3.1 Data Acquisition

The present analysis adopts a historical retrospective approach, necessitating the identification of representative analytical periods that reflect differing political, economic, social, and cultural contexts. According to the scientific literature and the conceptualisations proposed by some Lithuanian researchers regarding the urban structures of Baltic cities (Cirtautas, 2013) and rural settlements and landscapes (Bučas, 2001), three primary recurring periods are typically used for analysing the 20th and 21st centuries: the pre-Soviet (before 1945), the Soviet (1945-1990), and the post-Soviet (after 1990).

The selection of these periods is also influenced by the availability of cartographic data. Historical cartographic resources are utilised for both pre-Soviet and Soviet periods. Piškinaitė and Veteikis (2023) note that cartographic materials are still underutilised by researchers in Lithuania. For the initial period, the series 'Karte des Deutschen Reiches' (Map of the German Reich, 1870-1944) and 'Karte des Westlichen Russlands' (Map of Western Russia, 1892-1921) are employed, both at a resolution of 1:100,000. For the subsequent period, Soviet military topographic maps from 1985 at a resolution of 1:50,000 are used. The choice of these series is predicated on several criteria, including their free availability, the quality of their scanning, and the inclusion of a legend for analysis and digitisation purposes.

For the latest recent period (2023), free geographic data from OpenStreetMap (https://www.openstreetmap.org/) was extracted using the 'Over Pass Turbo' tool (https://overpass-turbo.eu/). Barrington-Leigh and Millard-Ball (2017) estimate the completeness fraction of the OpenStreetMap road network in Lithuania is approximately 97% reflecting the accuracy of the information compared to actual conditions.

The interactive, manually digitised data was then processed to exclude unwanted networks, such as footpaths, cycle paths, and occasionally utilised roads like forest tracks. This process also involved the removal of duplicate and isolated lines, as well as a check for their connectivity.

3.2 'Generic City' Indexes Adapted to Territorial Analysis

The indexes are derived from the theoretical framework that treats the network as a mathematical graph, where nodes represent network segments and links signify the connections between them. Quantitative methodologies that prioritise the topology of these segments are employed to assess various spatial configurations, including centrality, connectivity, accessibility, and movement.

Four indexes from the Spatial Network Analysis Software (sDNA) library (https://sdna.cardiff.ac.uk/sdna/) are utilised to characterise the foreground and background networks (Cooper and Chiaradia, 2020; Cooper, 2024). These indexes were initially chosen based on experiments conducted in the same study area, where their correlation with human activity data — such as population density, amenities, and light pollution — was assessed. The observed correlation coefficients, which range from 0.61 to 0.74 on average, reflect strong to extraordinarily strong relationships, making them relevant for the analysis (Gloaguen et al., 2022).

For the background network indexes, a radius of 1000 metres is applied to simulate local network behaviour.

The Network Quantity Penalized by Distance (NQPD) index is computed for both foreground and background networks. This index quantifies the number of accessible segments (network quantity) within a specified radius of a given segment (equation 1). Each segment is regarded as equally attractive, thereby allowing the focus to be solely on distance.

$$NQPD(x) = \sum_{y \in R_x} \frac{(W(y)P(y))^{nqpdn}}{d_M(x,y)^{nqpdd}} \quad (1)$$

Where,

R_x is the set of polylines in the network radius from the link x.

$W(y)$ is the weight of a polyline y.

$P(y)$ is the proportion of any polyline y within the radius.

$d_M(x,y)$ is the distance according to a metric M along a geodesic defined by M, between an origin polyline x and a destination polyline y.

$nqpdn$ and $nqpdd$ are the numerator and denominator of NQPD, usually defined as 1.

The NQPD index emphasises the most accessible areas of the network, which often align with the urban central zone, characterised by high multifunctionality.

Three indexes are exclusively used to describe the background network. First, the 'Length' index (LEN) quantifies the cumulative length of segments within a specified radius (equation 2).

$$LEN = \sum_{y \in R_x} L(y)P(y) \quad (2)$$

Where,
R_x is the set of polylines in the network radius from the link x.
$L(y)$ is the Euclidean length of polyline y.
$P(y)$ is the proportion of any polyline y within the radius.

This index can be likened to Peponis's (2008) 'Metric Reach' index, as it underscores the physical extent of connections and assesses the utilisation of network areas.

Second, the 'Angular Distance' index (ANG) captures the total angular curvature of segments within the radius (equation 3).

$$ANG = \sum_{y \in R_x} d_\theta(y_R) \quad (3)$$

Where,
R_x is the set of polylines in the network radius from the link x.
d_θ is the cumulative angular curvature along the full length of the line in degrees.
y_R is the proportion of y that falls within the radius only.

Unlike the Length index, this index focuses solely on closeness (geometrical proximity) and does not account density.

Finally, the 'Betweenness' index (BT) (equation 4) assesses the frequency with which a segment appears in the shortest paths connecting other segments within a designated radius.

$$BT(x) = \sum_{y \in N} \sum_{z \in R_y} W(y)W(z)P(z)OD(y,z,x) \quad (4)$$

Where,
N is the set of polylines in the global spatial system.
R_y is the set of polylines in the network radius from the link y.
$W(y)$ and $W(z)$ are the weight of the geodesic endpoints y and z.
$P(z)$ is the proportion of any polyline z within the radius.
$OD(y,z,x)$ are the geodesic paths between y and z that pass through a vertex x.

The Betweenness index reflects transit movements, highlighting the key segments of the network.

All indexes are standardised by dividing their value by the standard deviation, which enables comparisons across networks of varying sizes. Standardisation also accommodates the spatial resolutions of the geographic data utilised over different periods.

3.3 Machine Learning Modelling of the Spatial Structures of the Network

To identify the principal spatial structures associated with the networks and their evolution over time, the foreground and background indexes are integrated for multivariate analysis.

The networks are overlaid on a 1km-by-1km grid, and the average values of each index are calculated. The grid size corresponds to the radius value used for the background network indexes. However, it is crucial to note that the selected grid size influences the interpretation of results, as does the number of clusters.

A multivariate analysis was conducted using a K-means algorithm to minimise the variance of values grouped into clusters. Effectively generalise and visualise the results of the indexes, the number of clusters was established at four. Each cluster represents a spatial structure of the road network that corresponds to the territorial organisation, comparable both in time and space.

4 EVOLUTIONS OF FOREGROUND AND BACKGROUND NETWORKS

The foreground network has experienced considerable evolution over time. As illustrated in Figure 1, the centre of gravity of the network is gradually shifting from the south during the pre-Soviet period to the centre of the coastal region in the post-Soviet period. The NQPD index indicates a decline in regional accessibility of the network over time, with average standardised values of 6.19 for the pre-Soviet network, 5.24 for the Soviet network, and 4.22 for the post-Soviet network.

At the local level, two trends emerge: a decrease in the NQPD index from the pre-Soviet (1.06) to Soviet (0.94) periods, followed by an increase between the Soviet and post-Soviet periods (1.20) (Figure 2). These findings suggest a densification and

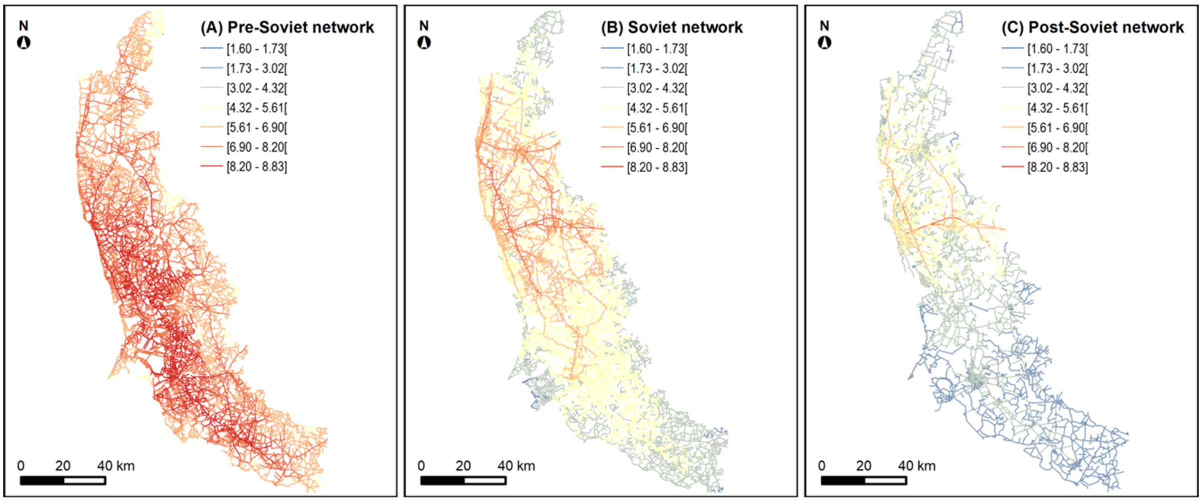

Figure 1: Spatial evolution of the foreground network between the (a) pre-Soviet, (b) Soviet, and (c) post-Soviet periods.

local expansion of the network, a trend also noted by Strano et al. (2012) in their analysis of network evolution in the suburbs of Milan. Notably, the suburbs of Klaipėda witnessed significant densification between the Soviet and post-Soviet periods.

The Length and Angular Distance indexes, which measure the potential for social interactions and the organicity of the local networks, respectively, have shown a decrease in their standardised values over time. The average value for Length in the post-Soviet period is 1.64, compared to 1.80 for the Soviet period and 1.93 for the pre-Soviet period (Figure 2). Regarding Angular Distance, the average value for the post-Soviet period stands at 1.08, in contrast to 1.17 for the Soviet period and 1.21 for the pre-Soviet period (Figure 2).

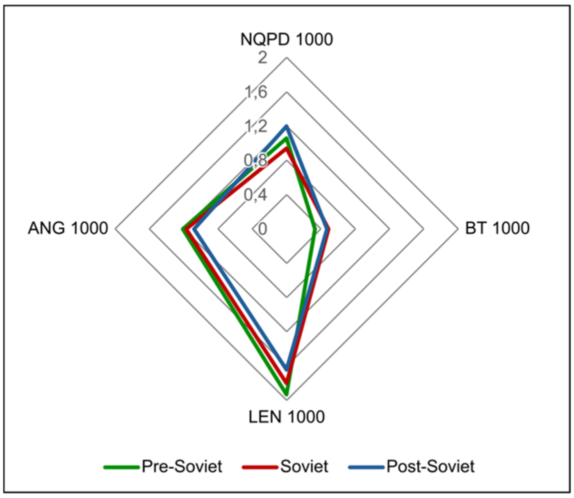

Figure 2: Quantitative evolution of background network indexes.

The betweenness index, which highlights the significance of a segment within the local network, shows an increase in the average standardised values from the pre-Soviet (0.33) to the Soviet period (0.49), followed by a stabilisation between the Soviet and post-Soviet periods (0.47) (Figure 2). This increase in betweenness values suggests that the hierarchy among routes is becoming more clearly defined over time at the local level.

5 HIERARCHY AND DYNAMICS OF NETWORK STRUCTURES

By integrating the foreground network and background network indexes into a multivariate analysis, the primary spatial structures of the Klaipėda region's spatial system are identified. These structures are characterised by (1) the key local centralities, (2) the territorial centre of gravity, (3) secondary centralities in transition and (4) peripheral areas. Their respective evolution is interpreted in relation to existing scientific literature.

5.1 Main Local Centres

The first spatial structure is linked to grid tiles that possess the highest average indexes, irrespective of the type of network (Figure 3).

These grid tiles represent the main local centralities within the network. Between the pre-Soviet and post-Soviet periods, the networks associated with the region's primary centres underwent a complete reconfiguration. In the pre-Soviet era, the main local centres were situated in the

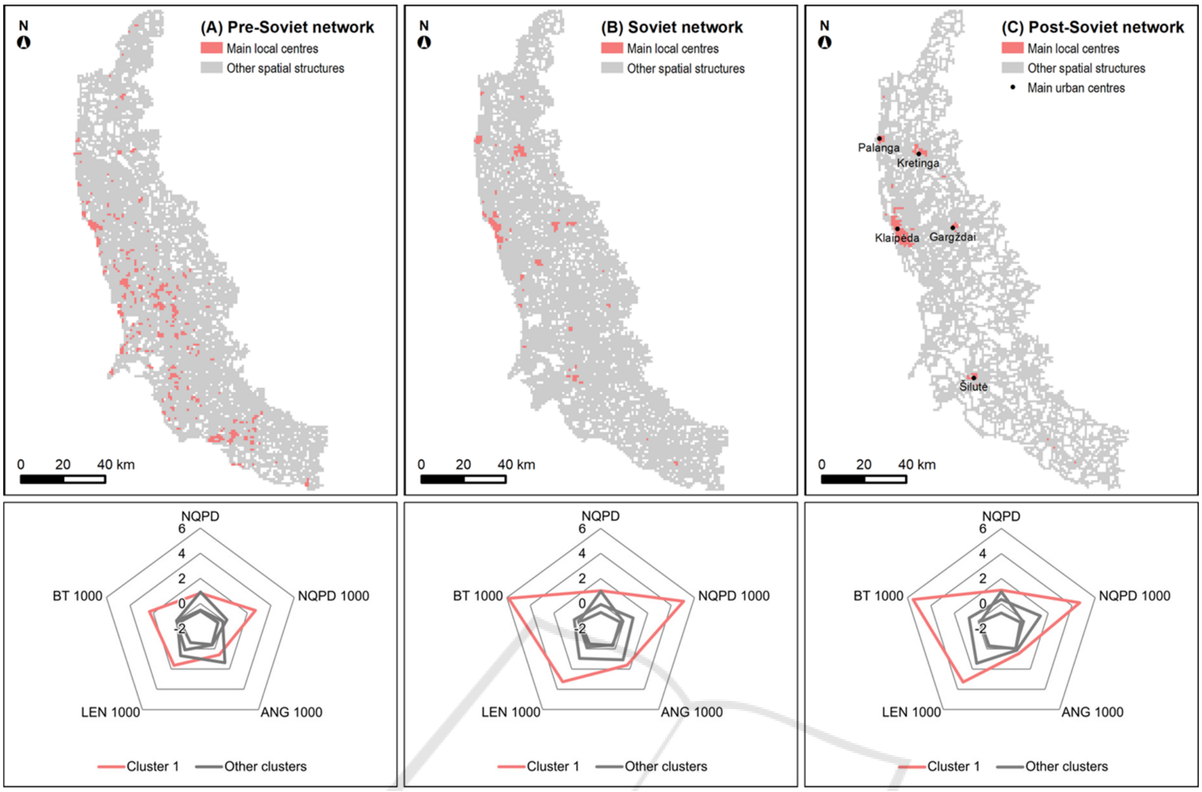

Figure 3: Spatial evolution of networks relating to local centres between the (a) pre-Soviet, (b) Soviet, and (c) post-Soviet periods.

south, with noteworthy development of individual and family farms (Figure 3a and Figure 4).

In the post-Soviet era, the primary local centres correspond to the main urban hubs of the coastal region, specifically Klaipėda, Palanga, Kretinga, Gargždai, and Šilutė (Figure 3c).

This transformation can be attributed to the agricultural and land planning policies implemented by the Soviet Union, which resulted in the dissolution of individual and family farms and their replacement with collective farms, such as 'sovkhoz' and 'kolkhozes' in the early 1950s (Gadal, 2011; Köll, 2024). The structure of the pre-Soviet individual and family farms is comparable to these main urban centres in terms of accessibility, underscoring their historical significance in the economic and territorial development of the Klaipėda region. Accessibility analysis supports this conclusion: the top 25% of values for the pre-Soviet network exceed 1.30, while the post-Soviet network shows values of 1.70, indicating a more organic and interconnected network prior to Soviet policies of land collectivisation.

The reconfiguration of the network illustrates the process of metropolisation taking place in the Baltic countries (Ubarevičienė, 2018). This process commenced during the Soviet period when territorial planning adhered to a 'hierarchical centre-periphery' model (Vanagas et al., 2002). Klaipėda was designated as a regional centre, intended to be linked

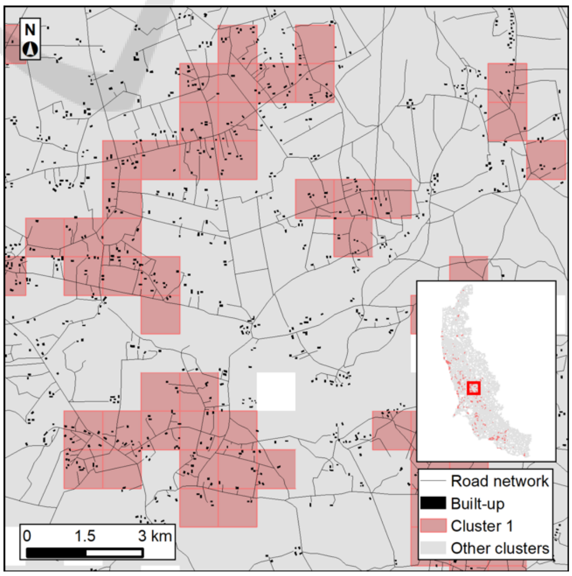

Figure 4: Network associated with local centres: the case of individual/family farms during the pre-Soviet period.

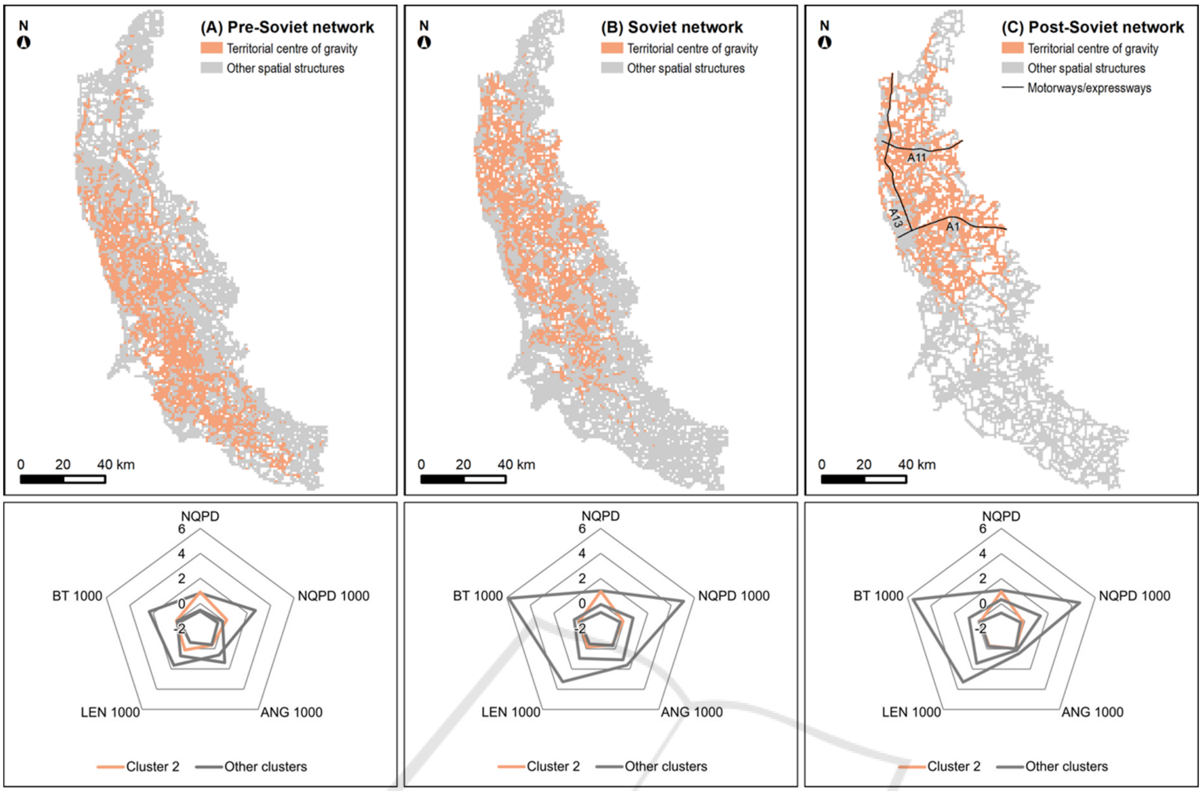

Figure 5: Spatial evolution of networks relating to territorial centre of gravity between the (a) pre-Soviet, (b) Soviet, and (c) post-Soviet periods.

to secondary regional centres through a network of smaller cities like Palanga or Kretinga. In the post-Soviet period, this process accelerated as the Soviet territorial framework persisted, leading to heightened urbanisation of the main urban centres. The findings from the Betweenness index at the local level (section 4) are particularly illuminating, revealing a more pronounced hierarchy of networks emerging from the Soviet era onwards.

5.2 Territorial Centre of Gravity

The second spatial structure is associated with grid tiles that exhibit high averages for the foreground network index (Figure 5).

These identified grid tiles correspond to the territorial centre of gravity, highlighting the most efficient networks at the regional level in terms of accessibility — networks that bolster regional economic development. The shift of the territorial centre of gravity from the south to the centre of the region is the main change observed between the pre-Soviet and post-Soviet periods (Figure 5).

Two complementary interpretations can be made regarding this spatial evolution. The first pertains to geopolitical changes within the region: during the pre-Soviet period, the southern part of the coastal region was under Prussian control and was an integral part of East Prussia, with Königsberg (now Kaliningrad) as its capital (Figure 9a). The establishment of the Lithuanian state after World War I led to a severance of the historical connections with present-day Kaliningrad oblast. The designation of Klaipėda as the administrative centre of the coastal region (currently known as 'Klaipėda apskritis') marks a significant shift in the network's centre of gravity toward the heart of this coastal region.

A second interpretation pertains to the economic transformations that have occurred since the 20th century. During the pre-Soviet period, the region's economy relied on agriculture, with the most developed networks corresponding to areas of intense agricultural activity. The presence of individual and family farms as local centres (section 5.1) supports this notion. However, in the post-Soviet era, the economy underwent a substantial transformation, realigning itself around industrial and service sectors. Consequently, the network's centre of gravity is now found in the primary industrial and tourist hotspots,

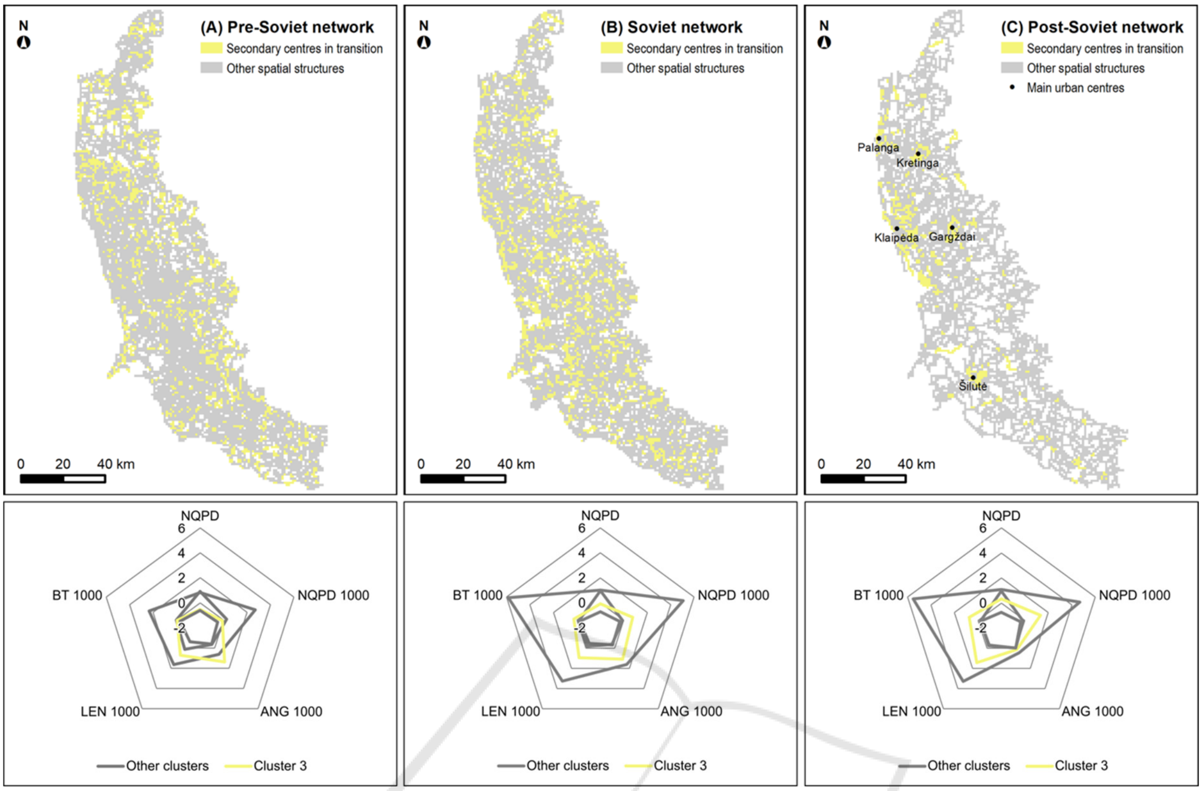

Figure 6: Spatial evolution of networks relating to secondary centres in transition between the (a) pre-Soviet, (b) Soviet, and (c) post-Soviet periods.

specifically the port of Klaipėda and the seaside resorts of Palanga and Šventoji.

It is also noteworthy that these economic shifts are intricately linked to the development of specific transport infrastructures. In this respect, motorways have played a crucial role in defining the network's centre of gravity in the coastal region (Figure 5c). The first key route (east-west) is the 'A1' motorway, which connects Klaipėda (on the Baltic Sea) with Odesa (on the Black Sea) and Moscow. According to the Soviet military maps from 1985, the motorway's construction was incomplete, aside from the sections near Klaipėda. The second major route (south-north) is the 'A13' motorway, which links Klaipėda and the northern part of the coastal region with Latvia. The third route (east-west) establishes a connection between Palanga and the regional centre of Šiauliai (outside the study area) via the 'A11' motorway, passing through Kretinga. The development of these routes has further influenced the local hierarchy of the network, as evidenced by the Betweenness index during both the Soviet and post-Soviet periods (section 4).

The trends for these first two spatial structures mirror those identified by Strano et al. (2012) in the suburbs of Milan, showcasing a transformation of the territory from rural areas to urban-industrial zones, and eventually to metropolitan regions.

5.3 Secondary Centres in Transition

The third spatial structure is associated with grid tiles that exhibit, on average, low to medium background network indexes when compared to other spatial structures (Figure 6). Across all periods analysed, the average standardised indexes for the spatial structure of the main local centres consistently exceed those of this structure: 4.15 compared to 0.66 for NQPD, 2.72 compared to 1.02 for the Length, and 4.57 compared to 0.32 for Betweenness.

This spatial structure denotes networks that are in a 'transition phase' towards main local centres (section 5.1) or peripheral areas (section 5.4). For instance, during the post-Soviet period, this cluster was situated in peri-urban zones surrounding key urban centres like Klaipėda or Kretinga (Figure 6c), which can be classified as secondary centres.

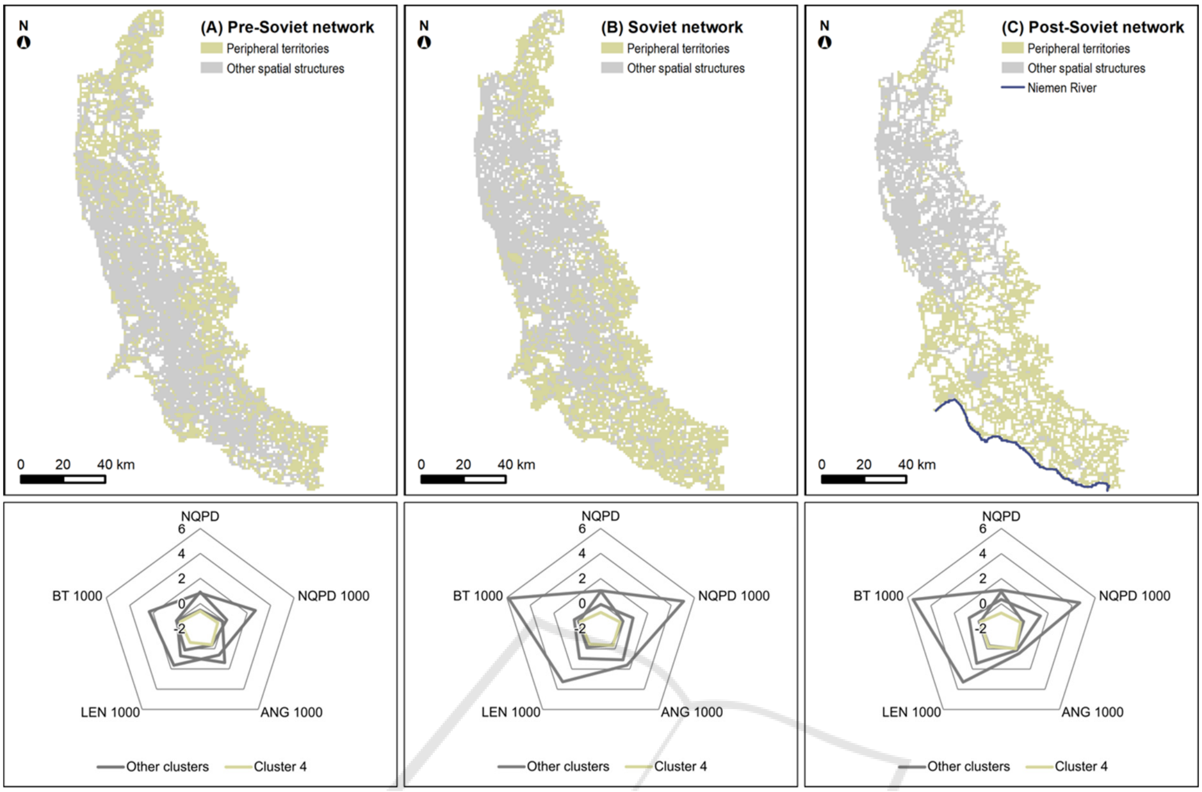

Figure 7: Spatial evolution of networks related to peripheral territories between the (a) pre-Soviet, (b) Soviet, and (c) post-Soviet periods.

5.4 Peripheral Territories

The fourth spatial structure is characterised by grid tiles exhibiting low average indexes, irrespective of the type of network (Figure 7).

The grid tiles identified within this spatial structure are linked to the peripheral networks at the regional scale. For instance, during the post-Soviet period (Figure 7c), these peripheral networks were found in the agricultural and semi-natural areas of the Niemen delta, as well as the riparian zones along the Niemen River, delineating the southern border with Russia. In comparison to the pre-Soviet era, contemporary agricultural practices are more modern but less intensive, reflecting a trend of agricultural decline (Lekavičiūtė and Gadal, 2009; Spiriajevas, 2014).

Moreover, the motorway infrastructure, which facilitates more efficient access to the network, is confined to the northern part of the coastal region. This overall marginalisation of the southern region may partially account for the observed decline in the foreground network index.

During the pre-Soviet period (Figures 7a and 9a), it is noteworthy that the peripheral networks corresponded to territories under Russian control.

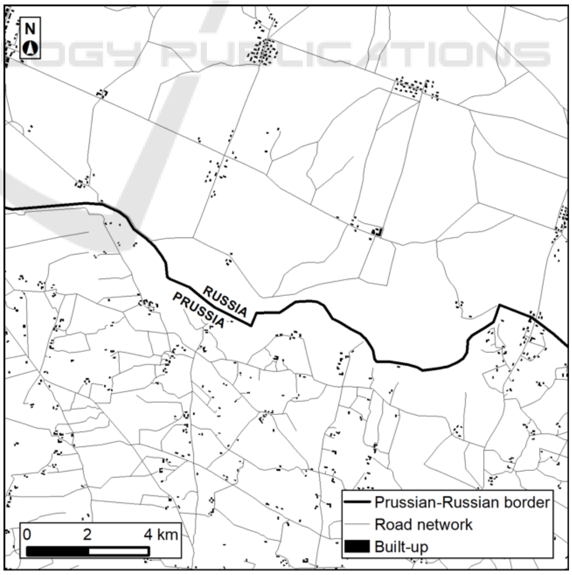

Figure 8: Patterns of spatial organisation between Prussia and Russia in pre-Soviet Lithuania.

Two distinct patterns of spatial organisation appear to emerge between the two countries (Figure 8): one explanation for this could relate to the

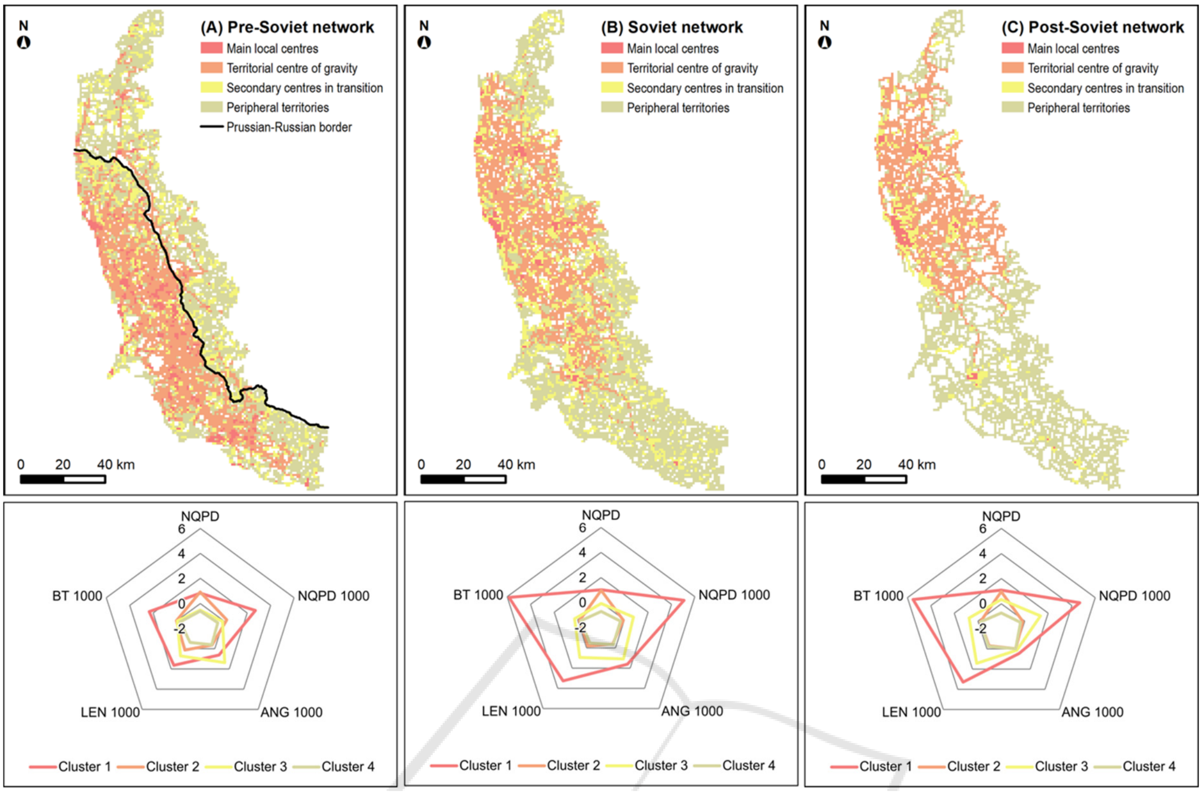

Figure 9: Spatiotemporal modelling of spatial structures relating to road network in the Klaipeda region between (a) the pre-Soviet period, (b) the Soviet period, and (c) the post-Soviet period.

differing timelines of agrarian reform. In Prussia, the reform aimed at developing the familial farming model was implemented earlier (in the early 19th century) compared to Russia, where the reform was introduced later (in the late 19th century), and the traditional street village model was retained (Jespen et al., 2015).

6 CONCLUSIONS AND PERSPECTIVES

This research analyses the evolution of spatial structures and territorial organisation in the Klaipėda region since the 20th century, utilising the Generic City concept to model road networks.

By distinguishing between foreground and background networks with indexes tailored for regional analysis, this study measures the relationship between the spatial configuration of space and its associated functions, thereby illustrating various processes at play within the Klaipėda territory.

The significant territorial restructuring observed during the pre-Soviet and post-Soviet periods is particularly evident in the integration of local urban centres along the coastal region, driven by the dynamics of metropolisation. This metropolisation was accompanied by a shift in the region's economic function from agriculture to industry and services. The development of motorway infrastructure further bolstered this territorial growth, enhancing regional accessibility while marginalising agricultural areas that once formed the core of the territory. Additionally, the collectivisation reforms and geopolitical shifts following the disintegration of the former province of East Prussia contributed to this marginalisation.

In this study, the Generic City indexes — modified and adapted for territorial analysis — proved effective in highlighting the interconnected political, economic, social, and cultural factors that influence the spatial and territorial organisation of the Klaipėda region.

The reliability of the modelling was partly validated by the alignment of results with existing scientific literature on this region. Incorporating supplementary data, such as built-up areas, land use, and land cover, could further strengthen the model if similar trends are identified. However, the indexes associated with the Generic City concept, modified for regional analysis, can only be generalised through examination in other territorial contexts exhibiting comparable dynamics. In this respect, the Baltic Sea region presents intriguing opportunities, particularly considering the rapid, intense and complex impacts of political, economic, social, and cultural changes on spatial and territorial organisation.

In this regard, the historical application of generative models remains constrained when they are trained on overly general databases. The approach developed in this research, which utilises mathematical graph models, has been tailored from generic indexes to conduct a thorough analysis of existing structures at a territorial scale. This method considers the complexities of the Baltic region, characterised by the interplay of various cultural influences, including Prussian, Russian, Soviet, and post-Soviet elements.

From a methodological standpoint, this research enables a connection between historical spatial structures and specific territorial functions, such as agricultural activities. Furthermore, spatiotemporal modelling of road network structures could serve to enhance missing or incomplete historical data in retrospective modelling studies.

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