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Spatial Analysis in GIS for Sustainable Urban Form and Transport Development

DOCTORAL THESIS

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Declaration

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Title of the doctoral thesis: Spatial Analysis in GIS for Sustainable Urban Form and Transport Development

I hereby declare that this doctoral thesis is my own work and effort written under the guidance of the tutor Lena Halounová.
All sources and other materials used have been quoted in the list of references.

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Abstract

In the modern world, due to rapid urbanization and population growth, the concept of sustainable territorial development is becoming increasingly important. It is based on the principle of effective and harmonious operation of the various components of the urban realm. In the planning process, considerable attention is paid to the functional and aesthetic features of the built environment, while geometric composition and corresponding spatial relationships are sometimes overlooked. This thesis focuses on the configuration of the road network, as an essential element of urban layout that ensures the mobility within the system and, therefore, its viability. It is intended not only to support more complex investigation of urban patterns, but also to give another perspective on the spatial interactions taking place in the urban realm. Taking advantage of modern GIS technologies, the author performs the modeling, analysis and comparison of the spatial properties of urban forms through a wide range of quantitative indicators. In order to make the study comprehensive, both the static and dynamic model of the road network in the Czech Republic are considered and discussed. The static model is aimed at a detailed examination of the geometric and topological parameters of road infrastructure, while the dynamic model investigates the interplay of accessibility, population and land use as well as changes in these indicators in the Czech Republic between 2006 and 2018. It is assumed that all three variables are interrelated and should be considered within a single model. In general, applying spatial analysis to detailed data, this work explores the topological and geometric characteristics of Czech road networks, reveals similarities and differences in their spatial organization, describes the form of relationship between their elements and tracks some historical imprints imposed on urban forms through their evolution.

Abstrakt

V současné době, vzhledem k rozsahu urbanizačních procesů a rostoucí městské populaci, se koncepce udržitelného rozvoje území stává aktuálnější. Její hlavní princip spočívá v efektivním a harmonickém fungování jednotlivých komponent městského prostředí. Je však nutno poznamenat, že ve fázi plánování se pozornost často zaměřuje na funkční a estetické vlastnosti prostředí, zatímco geometrická kompozice a prostorové interakce jsou někdy přehlíženy. Tato práce se soustředí na konfiguraci silniční sítě jako základního prvku urbánního prostoru, který zajišťuje mobilitu v rámci celého systému. Záměrem je nejen nabídnout komplexnější popis městských forem, ale také poskytnout jiný úhel pohledu na prostorové interakce probíhající v urbánním prostředí. S použitím moderních GIS autor provádí modelování, analýzu a porovnávání prostorových vlastností urbánních forem prostřednictvím široké škály kvantitativních ukazatelů. V rámci komplexní analýzy bude prostudován jak statický, tak dynamický model silniční sítě České republiky. Statický model je zaměřen především na detailní zkoumání geometrických a topologických vlastností silniční infrastruktury, zatímco dynamický model zohledňuje součinnost ukazatelů jako dopravní dostupnost, obyvatelstvo, využití území a zároveň jejich změny v letech 2006 až 2018. Předpokládá se, že všechny tři ukazatele jsou vzájemně propojeny, a proto by měly být zkoumány v rámci jednoho modelu. Celkově tato práce zkoumá prostřednictvím prostorových analýz topologické a geometrické charakteristiky silniční sítě České republiky, identifikuje podobnosti a rozdíly jejího prostorového uspořádání, popisuje vztahy mezi prvky systému a odhaluje některé rysy historického vývoje urbánních forem.

"The most incomprehensible thing about the world is that it is at all comprehensible."

Albert Einstein

Contents

Acronyms

GIS – Geographic Information System

CAD – Computer-aided design

CBD – Central business district

OLS – Ordinary least squares

MCA – Multiple centrality assessment

FCA – Floating catchment area

2SFCA – Two-step floating catchment area

OSM – OpenStreetMap

SALSC – State Administration of Land Surveying and Cadastre

CSO – Czech Statistical Office

CLC – Corine Land Cover

1. Introduction

The spatial structure of cities and its impact on the socio-economic processes taking place in them have always been of particular interest for urban planners. Even in the medieval world, before the Industrial Revolution, architects and planners of those times realized the importance of a settlement's shape. Cities were in need of a water supply and delivery of various materials such as wood, stone, etc. The development of trade routes was of vital importance for the economy. These factors forced planners to follow certain rules, mostly established through experience.

In the modern world, it is apparent that cities, which gradually transformed into agglomerations, compose the core of our civilization. In the twentieth century, the vast movement of people from rural to urban areas were observed in all parts of the world and almost all countries, which led to significant changes in the process of urbanization—the growth of urban population and transformation of urban areas. High concentration of industry, amenities, and a large number of people across relatively small territories was the result of worsening environmental and social problems. Infrastructure congestion and rapid spatial development complicated the process of urban management, especially in large cities. Thus, by the beginning of the twentieth century, a need for comprehensive urban development became apparent in the whole world. The city turned into a system that requires a coherent development of all its elements.

But what components does this system contain? The urban environment is a complex spatial system of inextricably linked parts. In this system, elements such as buildings and structures, as well as street spaces, intersections and squares, interacted equally. Additionally, the system includes many other 'local' components from unique monuments and different attractions to the ordinary elements of urban equipment or public amenities.

One of the features of this system is its dynamism with a large number of both internal and external interactions. As Jacobs (1961: 372) wrote: *"When we deal with cities we are dealing with life at its most complex and intense"*. Indeed, the complexity of the system and its different variables that need to be taken into account have always been a great challenge for researchers. Cities are stochastic systems, and the influence of some factors is not always obvious in decision-making, so one cannot solely rely on experience and political pragmatism. A good example is the United States in the 50s, when, due to some political reasons, the idea of segregating urban space on commercial, industrial and residential areas was supported. The main principle was the concentration of cottage housing in quiet, green suburban areas, which later had disastrous consequences. Due to low housing density development, cities began to grow horizontally, making private cars the main mode of transportation for citizens which exacerbated problems like pollution, noise and traffic congestion.

Today, under New Urbanism concepts, there is no doubt about the importance of controlled development of such a complex system as the city and its form in the first place. Another question arises though, presenting new challenges for researchers: *How real urban environment and interactions within it can be simulated and explained.* This dilemma is directly connected with the attempts to make the results of the planning process more predictable. In general, this doctoral dissertation was inspired by the idea of human-scale urban design so strongly supported by New Urbanists as well as the vast opportunities that modern technologies and open data offer to analysts today. The analytical capabilities possessed by computers a few decades ago were rather limited in terms of graphical tools, leaving out the potential of modeling and analysis. Today, however, mathematical, geographical and graphical tools are integrated into powerful complexes such as the geographic information system (GIS) and computer-aided design (CAD), opening new horizons for the analysis of urban form.

The concept of space[1] for urbanists and geographers has a similar definition. In both fields, it can generally be described as a form of existence of objects and relationships between them in a certain territory. On the other hand, if one looks in more detail at the aspects which describe space, it can be seen that urbanists tend to focus on the functions of space while geographers pay more attention to the geometric configuration and quantitative description. If these two views of the city will be coupled within a single framework, it creates very useful cooperation where GIS can play an important role. Within a complex definition of space, the potential of GIS can be fully applied. As Goodchild et al. emphasized: "*More methods of spatial analysis are implemented in today's GIS than ever before, and GIS has made methods of analysis that were previously locked in obscure journals easy and straightforward to use*" (Goodchild et al. in Longley 2005: 578). It is difficult to find a more suitable tool for the analysis of spatial systems. The ability to combine and integrate data from different sources and use them in a single analysis makes GIS very effective for decision-making in urban planning. Furthermore, the implementation of GIS in planning processes allows planners to look at the city space from a different angle. Instead of the traditional concerns of architects about aesthetics and functionality of a building or space, GIS reveals the importance of the whole urban system configuration, assess its integrity and identify conflicts in spatial organization. Describing the importance of an integrated planning process and its problems, this study does not imply the creation of a universal-design urban model or a single standard of urban form; this remains fully under the purview of urbanists and architects. Rather, it intends to support more complex investigation of urban patterns using GIS and to give another perspective on the spatial interactions

[1] Since space has a large number of definitions in various fields, it should be noted that in the context of this work the author refers to urban space.

taking place in the urban realm. This work is aimed at a comprehensive modelling, analysis and comparison of the spatial properties of urban areas in the Czech Republic. Particular attention is paid to the road network as the element that directly affects the shape and quality of urban realm. The empirical analysis is carried out for two models of the road system, namely static and dynamic. The static model examines the topological and geometric characteristics of urban networks in the Czech Republic. In the dynamic model, the patterns and temporal changes of spatial interactions between municipalities of the country are investigated. The dynamic model provides for the use of two sets of the Czech road network for 2006 and 2018.

1.1 Objectives

The main objectives of this work are:

- To provide an extensive summary of the composition and significance of elements of urban form as well as methods for their analysis and modeling in various disciplines (geography, urban studies, sociology, transportation planning).
- To introduce a set of indicators and calculation model that will be used for the quantitative analysis and comparison of selected urban areas.
- To examine the topological and geometric characteristics of Czech road network on detailed spatial data within the static model.
- To analyze the pattern and dynamics of spatial interactions between municipalities in the Czech Republic using gravity-based accessibility measure.
- To investigate and discuss the interplay of transport accessibility, population dynamics and land use.

1.2 Thesis Structure

The work is organized into several related chapters. Chapter 1 presents an introduction to the research field and main objectives. Chapter 2 is aimed to explain the background of the problem, describe the concept of urban space in general terms and some particularities of its elements. Chapter 3 reviews the current methods of urban form analysis. Specifically, referring to the topic of the dissertation, the possibility of using GIS for modeling the urban environment is first considered, and then various approaches to spatial analysis are studied. Chapter 4, presents the scope of the study as well as the study area and data. The methodological approach and the calculation model are also introduced in this chapter. Chapter 5 contains an empirical analysis of the static model of the Czech road network, while Chapter 6 is aimed at studying the dynamic model and spatial interactions. Finally, Chapter 7 presents the conclusion of the work.

2. Background

2.1 The Concept of Urban Form

Space of the city encompasses many different elements, which can be interpreted by a city inhabitant as a strict line of avenues and quiet alleys, giant enterprises and green parks, manifold houses and granite embankments. All of this is the modern image of the city, which has been formed over thousands of years. Today, however, the oldest settlements can hardly be called cities in the modern sense of the word. They are instead a huddle of buildings located close to each other with no delineated roads and public spaces. The pattern of such settlements was mainly determined by the location of natural resources and the character of terrain. Over the course of time, the cultural development of society had brought the need for communication and trade, so gradually expanding, such clusters began to unite and form the image of the city as we know it today. The spatial pattern of cities had been formed by the collocation and interconnection of streets and spaces—in other words, the system called *urban form*.

The Oxford English Dictionary[2] defines *form* as 'visible shape, configuration, arrangement or the way in which things/objects exist'. In the context of urban design, this interpretation will also be relevant, with only one addition—'… the way in which things/objects exist *in space*'. It should be noted that this is not just about some attractive design of urban spaces, but the form in the deeper sense of this word. Urban form embodied the physical complexity of layout of buildings, parcels, spaces and the configuration of routes that connect them (Figure 1). Similar definition gives Moudon (1997: 3)—promoting urban morphology as a significant interdisciplinary field, she describes the elements of urban form as *organisms*, which exist in a state of *dynamic interrelationship*. Circulation routes like highways, roads, sidewalks and paths allow people to be mobile and provide a movement between the other elements of urban form. Buildings and public spaces[3], on the other side, accommodate different human activities evoking the need for movement. Urban form in such a dynamic concept, as Loukaitou-Sideris explains, represents the *container of social activity* (Loukaitou-Sideris in Ceccato 2012: 6). While a certain consensus has been traced among urbanists and architects about the physical aspects of urban form, the same cannot be said about its social component.

An active debate about the interaction between society and space, as well as the role of urbanists and society in shaping urban form, has been underway since the last century. This topic

[2] https://www.oxforddictionaries.com/ (Accessed February 15, 2016)

[3] Public spaces in urban environment primarily accommodate outdoor activities, for example, recreation in parks and sport grounds.

became very popular in the heyday of modernist planning in the mid-20th century. The initial ideas set forth by modernists were (in some manner) very positive and suggested a more integrated approach to urban planning. They promoted versatile approaches in the planning process, in other words applying the method of assessing various options in relation to desired goals and then selecting the optimal option. This technique should have increased control over the urban development process and made it expert-led (Rydin 2011). However, such ambitious plans completely backfired, creating negative consequences for urban planning, for which several reasons were attributable.

(a) Urban layouts of Grammichele, Italy (b) Urban layouts of Avola, Italy

Figure 1. Hexagonal plans of two different cities
(Source: Google Earth ©, accessed April 14, 2015).

Revitalization of the economy and industry were topical issues during the postwar period, so planning trends were focused on large-scale development of urban areas with superblocks and great zones. In Europe, such rapid, global expansion often led to a situation where changes took place without an actual planning process, resulting in the plan itself being adjusted in accordance with these changes (Rydin 2011). In the United States, this problem was exacerbated by a misconception about the comprehensiveness of planning required. American planners had tried to achieve balanced urban development by designing more isolated and high-speed motorways to accommodate the expected increase in traffic (Siegel 2010). It was a quite simple recipe, which should have promoted comprehensive development, but instead turned out to be disastrous in the long-term. A more detailed discussion of the problem regarding transportation planning will be introduced in the next section.

The failure of the modernist planning model was caused by a number of reasons, however the two main ones can be singled out: political pressure, and isolation of the decision-making process from public opinion (Yiftachel 1998; Taylor 1998; Scott 1998; Siegel 2010; Rydin 2011). In the postwar period, although officially urban planning was under the cognizance of local authorities, which could on the basis of expert assessments determine goals and directions of development, in reality, were under full control of the state. In different countries, this political intervention had its peculiarities. In the United States, it began during the Roosevelt Administration, which supported two government programs that significantly influenced urban planning and development. The first one was subsidizing the construction of low-density housing in suburban areas provided by The Federal Housing Administration. This organization also implemented a set of standards for local planning authorities to separate residential areas from other functional zones (Siegel 2010). The second one was financing of interstate highways and local roads construction since the first Federal-Aid Highway Act of 1944 (1944) aimed to create new jobs as well as enhance the capacity of roads connecting suburbia (Weiner 1983). In Australia and Canada, political patronage of planning processes had a similar character. Commonwealth Housing Commission (1944) in Australia on the one hand facilitated a housing program through the socially accessible funding, but on the other, set specific development parameters: type of zoning, size of dwelling units and the desired density, which eventually caused large-scale suburban expansion (Berry 1984; Dodson et al. 2007). Almost at the same time in Canada, a government project through the Central Mortgage and Housing Corporation (1945) aimed to support the movement of middle-class Canadians in the suburbs and renew idle dwellings for low-income groups (Carroll 1989).

At first glance, one can see the positive side of these programs, which were socially oriented and contributed to both economic and industrial recovery of these countries as a whole. Concerns, however, were about the changes that greatly influenced planning practice and the approach to decision-making. Firstly, the scale of urban planning and development was so gigantic that it had lost human focus. Under such conditions development and growth became the main goals of planning, thereby replacing renovation. Secondly, the approach of mass production and standardization to the process of urban planning caused the spread of spatial monofunctionality in cities, especially in suburbia. Urban planners in such circumstances were assigned the role of executors of template planning scheme, while attempts to apply an alternative approach to the planning were reverted to the initial strategy due to high politicization of the entire process. During the entire 20th century this political pressure was the highest in Eastern Europe and other countries which were under the control of the Soviet Union. It was believed that an effective development could be achieved by using standardized production and an 'as easy as possible' template in the combined economic and urban planning. The centralized communist system in Eastern Europe concentrated power and decision-making in a single unit, which directly affected urban planning as a field and made it more, as Siegel (2010: 45) has called it, *command-and-control planning*. Considering all the above, it can be concluded that the modernist model of planning was based more on faith and interests of the establishment rather than on knowledge and expertise.

To clarify this assertion, one should ponder the following: should the space be completely controlled by the urban designer or the political establishment and, as a result, society will have to adapt to the proposed concept of the urban form? Or should we perceive the space as something abstract in which logic cannot be found and time alone will tell whether we were lucky in the planning of our cities. These issues have gained relevance among architects, urbanists and sociologists since the prevalence of modernist planning.

2.1.1 The Concept of Space in Urban Research (Space & Society)

One of the most significant pieces of work that has been devoted to the issues described above was Lefebvre's "La production de l'espace" (Lefebvre 1974). Lefebvre proposed the concept of dynamic, complex space in which the physical (natural), mental (ideas/theories) and social components are interconnected. Therefore, by studying space, it is important to see its three derivatives. The first one is the *conceived*—it reflects the way in which space is interpreted by experts (urbanists, architects, the establishment, sociologists, etc.). In this case, space is an expression of ideology, experience, or even power. The second one is *lived* space—a set of real and imaginary with a predominance of feelings. Here the place is probably more important. For example, a long distance is not an obstacle to get to a favorite park. Such a social attachment to certain places creates sustainable spatial relationships and appears to be the core in the planning process, but the conceived space still has greater influence. Finally, the third one is *spatial practices*—the process of creating social space. Again, social activities, like housing, jobs, leisure, shopping, are more important here. These activities create a tangible form of space and provide social connectedness. Spatial practices have the properties of both conceived and lived space. For instance, social activities depend on the practices of conceived (location of jobs) and lived (recreation or shopping) (Lefebvre 1974). The undoubted merit of Lefebvre's work is that he was one of the first who described the space as a complex system of dynamic relationships. He peered into the depths of the problem and created the concept of social space, moving away from the old-fashioned and primitive notion that hills, rivers or buildings represent a space. Nevertheless, his theory was based on the strong assertion that space has always been political and is composed of different ideologies. Lefebvre focuses on the development of capital as a source of power and space that subsequently formed. The political power of the center becomes stronger due to concentration here the decision-making process, but society suffers since a single center cannot effectively manage a large territory.

Because of strict control, the center almost always remains developed, but the peripheral areas are far behind.

Another noticeable concept of social space was created by Castells (2004) who also emphasized the importance of its social character, but unlike Lefebvre's politico-economic point of view, the main role in Castells' theory assigned to social relations that shape urban form. According to Castells, the urban space represents a container in which social relations are formed. In the modern city, there are two opposing movements: *space of flows* when part of a city or region belongs to a dynamic network, and *space of places* when some parts are excluded or devoid of mobility (Castells 2004). A city or its part that has become a nodal point of the network is of particular importance and has special features. The space of flows is flexible, has a high degree of freedom and can, therefore, be successfully transformed, whereas the space of places is closed and fixed. Although both of these movements are parts of a single system, their interaction quite difficult. Castells notes that for the effective existence in the global community, cities need a sustainable system of communication that includes information technology, telecommunications and transportation (Castells 1999). This view of space is more consistent with the structure of the contemporary, dynamic city. Besides information flow, Castells also accentuates physical movement of people and goods in an urban network that takes place along the network routes and these flows shape the space.

The concepts of space described above were a great contribution to the foundation of spatial planning. The pioneer work of Lefebvre changed the perception of space as a homogeneous system to space as a social product. Later, however, Castells (1977) criticized Lefebvre for the idea of radical urbanism, in which everything depends on the political establishment, and proposed his own theory of the space of flows, which is the main creative force in our society and at the same time is the key to sustainable development. Embracing a wide range of issues regarding the relationship between space and society, these theories were of great importance for the theoretical basis of socio-spatial analysis, but were too vague to be implemented in the planning practice. More precisely, they lacked a particular mechanism that would allow a quantitative description of spatial relationships in an urban environment.

One of the most successful early pieces of research that were directly applied in the decision-making process was the methodology proposed by Hillier et al. (1984) called Space Syntax. Hillier also belongs to the group of experts (Lynch 1960; Jacobs 1961; Alexander 1964), who emphasized the importance of multifunctionality of urban space; however, he tackled this problem mostly from a practical perspective. According to Hillier (1983), the failure of modernist planning was caused by a lack of knowledge on the one hand, and an incomplete understanding of the social interactions within space on the other. In practice, a very limited analysis is applied in decision-making. Priority is given to a part of the territory under development, so planners tend to perceive only this local space. A misconception that urban planning and architecture can be standardized also originated from here. In response to this issue, Hillier et al. (1984) suggested considering space as a complex system of interrelated elements that have some spatial logic. This logic will also have an impact on social life because a city is the environment of co-existence of its residents in physical surroundings: "*The ordering of space ... is really about the ordering of relations between people*" (Hillier et al. 1984: 2). Therefore, the social aspect of space is just as important as its physical configuration. Such a duality of the problem forced researchers to reconsider the approach of urban space studying. They noted:

"In the understanding of space the advance of knowledge — science — and the analysis of knowledge — philosophy — became inextricably intertwined. Speculation about the nature of space inevitably becomes speculation about how the mind constructs its knowledge of space and, by implication, how the mind acquires any knowledge of the spatio-temporal world." (Hillier et al. 1984: 30)

A purely sociological viewpoint makes the problem impossible to solve. Despite the fact that society is an integral part of the space, it is not *a spatially continuous system* (Hillier et al. 1984: 30). First of all, society is a dynamic system, i.e., it is in constant movement, development, and has changes in its characteristics and condition. Secondly, society is a non-linear system, which means that processes taking place in it at varying times under different reasons cannot be described by a universal law. If one imagines a group of people or an individual in an empty space without borders and obstacles, then the analysis becomes entirely philosophical. In this case, the relationships and movements in such space cannot be clearly described, because of the philosophical dilemma that the movement is only possible in an empty space; however, emptiness is a fiction that is non-existent in reality.

Hillier et al. (1984), therefore, proposed to move away from a purely philosophical perception of society in urban areas and look at it from a scientific point of view. Our society exists in a physical environment, represented by buildings, roads, borders and fences, which largely affect our behavior and image of the city (Figure 2, left). Hillier et al. (1984) coined a method of spatial analysis, where the objective environment is described in the form of a mathematical graph (Figure 2, right). In this graph open spaces are replaced by so-called axial lines and then the morphological structure of the whole system is analyzed (a more detailed review of this technique is presented in Chapter 3). This proposed innovative model had a very important feature—it allowed the researcher to conduct a human-centric analysis of urban system from both a global viewpoint and local, individual observation.

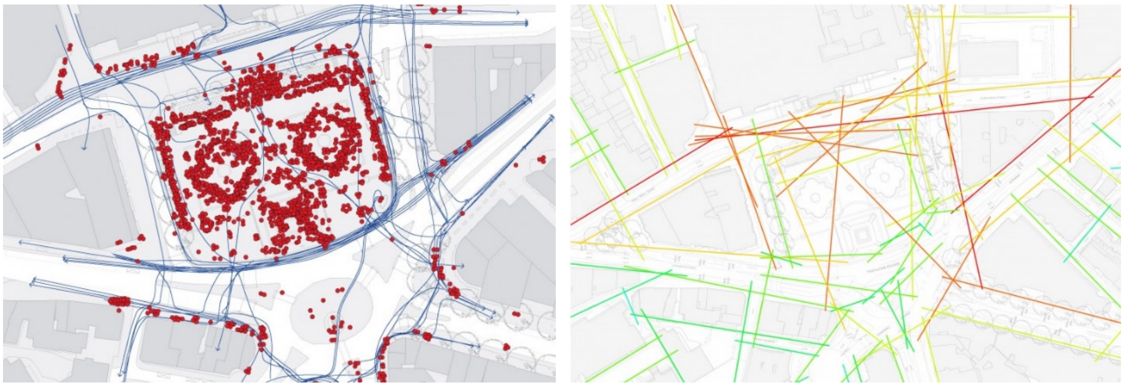


Figure 2. Pedestrian movement in and around Trafalgar Square, London (left).
Space Syntax representation of the same area. Colored lines refer to axial lines (right).
(Source: http://www.spacesyntax.com/project/trafalgar-square/, accessed March 11, 2016).

The contribution of the Space Syntax technique to the planning practice cannot be overstated, since it changed the way that space was considered in decision-making. Instead of the customary abstract model, Hillier et al. (1984) proposed a mathematical description of space, with a focus on the configuration of an urban system also called spatial grammar. The creative potential of urban designers oriented to the aesthetic appeal of place or building can be supplemented by a general picture of how the designed elements will fit into an existing environment. Although the urban planning is a sufficiently multilateral process which depends on many factors—such as the variety of projects and goals on which planners work, various traditions and approaches to urban design in different cities and countries—a set of tools for spatial analysis and data availability certainly remains a critical part of the whole process.

2.2 Transportation in Urban Environment

Cities are unique spatial and socio-economic systems that facilitate the functioning of various aspects of society. Historically, cities serve a function of spatial centers for economic growth and social transformation encouraging more and more people to move into urban areas. This success of urban life lies in the ability of cities to provide rapid movement and communication by bringing a large number of people into close proximity (Vuchic 1999). The concentration of population can increase the effectiveness of economic and social functions (Vuchic 1999); close spatial proximity or high density promotes the development of production and services through the reciprocation between producers (Henderson 2000); finally it provides savings in the infrastructure and transport costs (Rode et al. 2017). However, such advantages for the economy (social interactions as well as the effective functioning of the whole urban system) would not be possible without the circulation routes ensuring the vitality of urban space—a road network. Many studies have shown that urban roads and streets not only define the spatial arrangement of territories (Cervero in Freire et al. 2001; Rodrigue et al. 2013), but at the same time have a great influence on the processes occurring on them (Jacobs 1993; Porta et al. 2011; Barthélemy 2011; Sevtsuk 2014) and determine the degree of urban expansion (Taaffe et al. 1963; Newman et al. 1999; Bertaud 2004; Strano et al. 2012).

Streets have always been of major interest in the study of urban form as the embodiment of spatial relationship between locations. The image of the city, or in other words, our mental perception and interpretation of information embedded in urban realm is determined by a combination of movable and stable environment. Streets are dynamic—they facilitate the movement of people and goods and hence are an important part of the socio-economic system (Jacobs 1993). Jacobs, in his work *Great Streets*, which has become a classic, focuses on the street network as a key element of urban form. In the remarkably wide analysis of different street designs around the world, he demonstrates the importance of streets for sustainable urban development. *"Streets shape the form and comfort of urban communities. Their sizes and arrangements give or deny light and shade. They may focus attention and activities on one or many centers, at the edges, along a line, or they may simply direct one's attention to nothing in particular"* (Jacobs 1993: 2).

The road network is the foundation of the urbanization process. Initially, it represented an indispensable part not only for the very existence of cities, but also for their further territorial growth, when a city boundaries were drawn by the limits of the transport system and technologies. A quantitative analysis of urbanization from a morphological point of view is best exemplified by the research of Strano et al. (2012). The research team provided a study of the evolution over two centuries of the road network in the Groane metropolitan area located north of Milan, Italy (Figure 3).

Tracing the development of urban roads in different periods of time, they vividly presented a form of how a polycentric region with small villages has grown into a large metropolitan area. Furthermore, the spatial structure of road evolution is another important feature revealed in this research.

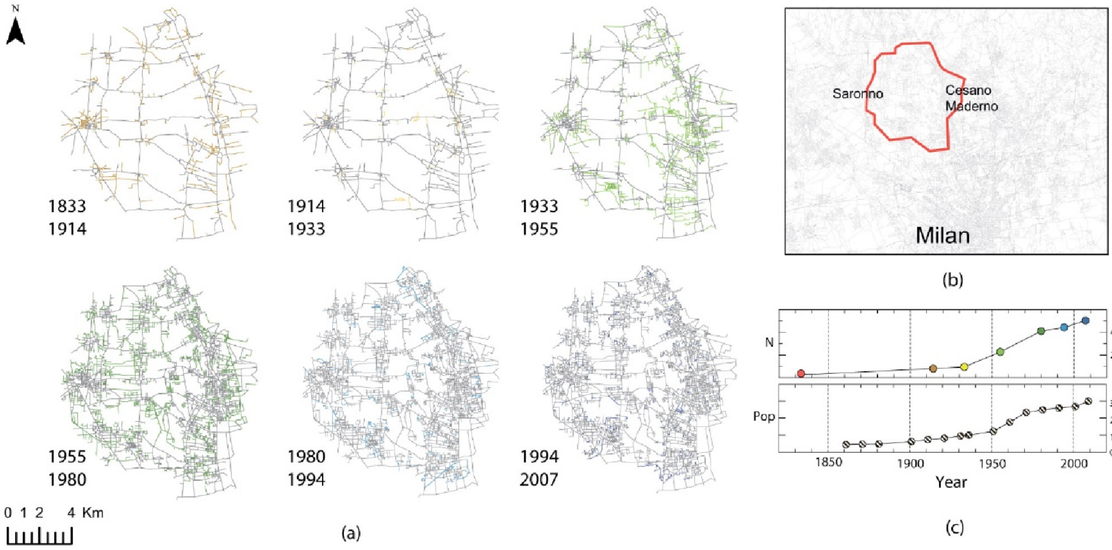


Figure 3. (a) Evolution of the road network from 1833 to 2007. (b) The location of the Groane area in the metropolitan region of Milan. (c) Time evolution of the total number of nodes N in the network and of the total population in the area. (Source: Strano et al. 2012).

It can be seen in Figure 3(a) that the network was not so much growing outside as it was inside by adding new nodes and links, which then merged together in a homogeneous system (Strano et al. 2012). To quantify changes in the urban network and show the value of each route in it, the analysis of betweenness centrality measure was applied (Figure 4).

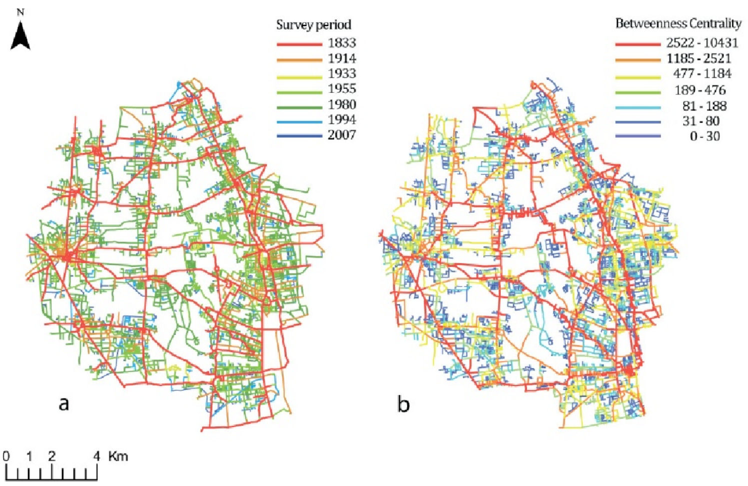


Figure 4. Colored lines indicate the time of construction of each road (a) and values of betweenness centrality for 2007 (b). (Source: Strano et al. 2012).

It is noticeable that over almost two centuries of urban development from a spread rural economy, through industrialization, and up to the modern technological world, the greatest value for the entire network and its main frame make up the roads built back in 1833. Thus, the research of Strano et al. (2012) supports the hypothesis[4] that urban streets and roads may represent a long-

[4] A large body of literature on urban history and morphology devoted to this topic. See for instance Appleyard, D. (1981). Livable streets. Berkeley u.a.: Univ. of California Pr.; Southworth, M., and Ben-Joseph, E. (1997). Streets and the shaping of towns and cities. New York: McGraw-Hill. Strano et al. (2012), however, showed a possibility of quantitative analysis of mentioned issue.

lasting component of urban form, which has an influence on spatial structure and extent of urbanization. In this context, some might argue that urban form and urban spatial structure are two identical terms referring to the configuration of a city. However, the role of transport infrastructure in the static urban environment and its significance for dynamic processes should be recognized.

2.2.1 Urban Spatial Structure

Urban transport infrastructure and its performance features create the prerequisites for the shaping of a large number of urban forms and spatial structures (Rodrigue et al. 2013).

- *Urban form* refers to the geometric configuration of static elements in urban environments such as buildings, transportation systems and the adjacent physical infrastructures.
- *Urban spatial structure* refers to the arrangement of relationships between places in urban form. It affects many aspects of people's daily lives and relates mainly to the dynamic functioning of urban form.

Sýkora (2001) notes that the spatial structure can be analyzed by tracking changes in the physical, functional and social component of a city. For example, the physical part includes the morphology of urban space—the shape of blocks, parcels and buildings. The functional part describes the purpose of different elements in the urban environment, their division and significance. The social part is represented by information on the population of the city, its density, age division, socio-economic indicators, etc.

Spatial structure is of great importance for environmental sustainability, public safety, accessibility, economy and social equity. The transport infrastructure here fulfils its fundamental purpose, which is to facilitate movement between different locations. According to the level of transport development, the urban spatial structure can be categorized by the level of centralization or dispersion (Rodrigue et al. 2013).

Until the mid-19th century, the structure of all cities was based on a high-density core with diverse activities and non-motorized transport. Walkable cities (Figure 5) were often characterized by high population density (about 100-200 inh/ha) and narrow streets (Newman et al. 1999). The advantages given by a high level of accessibility in pre-industrial cities, however, were recouped by stagnation in economic development and lack of space.

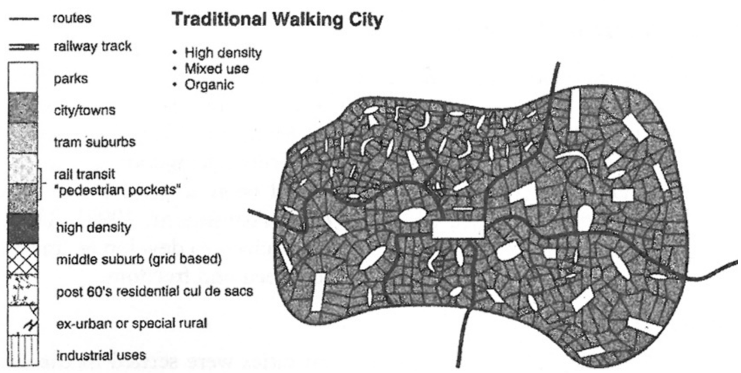


Figure 5. Model of a walkable city. (Source: Newman et al. 1999).

During the industrial revolution—which significantly affected the development of transportation—cities began to expand to accommodate more people and industry. Trains and trams significantly increased the accessibility of urban periphery and created so-called transit cities (Figure 6). Innovations in the transport system allowed fast travel and covered longer distances between subcenters that represented areas of almost the same high density as in walkable cities, but offered more space for different activities (Newman et al. 1999; Smith 2011).

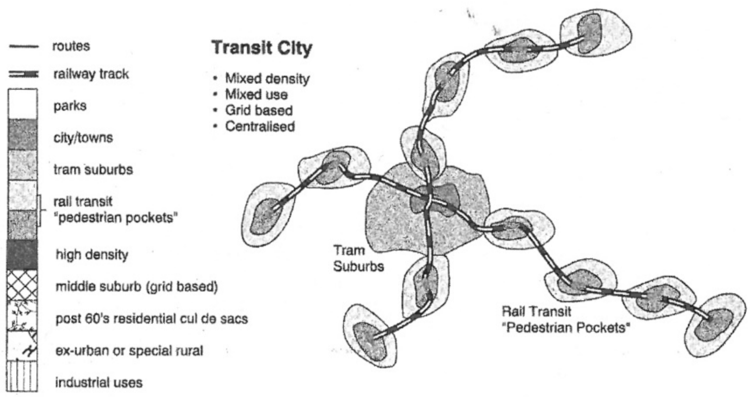


Figure 6. Model of a transit city. (Source: Newman et al. 1999).

After World War II, cars and buses became a major transportation technology that shaped our cities. Urbanization accelerated further since automobiles almost eliminated limits of spatial development and offered the opportunity for urban residents to escape from the overcrowded and noisy city core. The widespread use of automobiles also caused a significant decrease in residential density and lied in the basis of the idea of separation and isolation of functional areas (Figure 7).

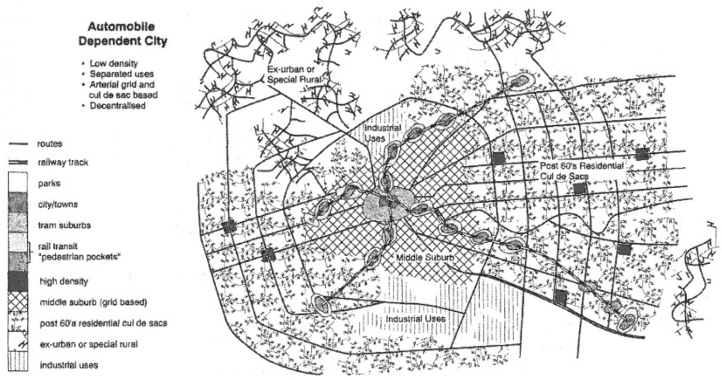


Figure 7. Model of automobile city. (Source: Newman et al. 1999).

It can be seen from these models that the transportation network is the main factor influencing the evolution of urbanized areas.

2.3 Summary

The evolution of urban forms and spatial structures, on the one hand, is the process of development, which is necessary for the harmonious functioning of society, but at the same time is a complicated process with many aspects to consider. A large amount of scientific literature dedicated to cities show that urban design is a very broad and certainly interdisciplinary field of study. The range of issues embraced by urban planning includes a variety of disciplines: architects interested in the aesthetic appeal of spaces and the preservation of the historic core; ecologists concerned about the amount of emissions and the effects of urban sprawl on natural areas; economists considering the city as a means of economic investment and business development; sociologists studying the behavior of the population and social interactions in the city; geographers investigating the patterns of development, movement and relationship in urban environment. It seems like this is an immense circle of issues, since all these topics are almost equally relevant for the existence of cities. However, they refer to, and originate from, static elements of urban form such as buildings and roads. Those urbanized areas that can be seen today are the result of long-term development and aggregation. Knowing the features and state of the current system, practitioners can successfully plan its further growth and, if necessary, set its desired shape. At the same time, if the control over the integrity of the system and its functioning is lost than city turns into a huge, clumsy organism, which grows disproportionately with chaotically located buildings, land use and complex transport infrastructure that cannot cope with the flow of traffic. Due to the irrational location of objects in the urban environment, a large number of different routes repeatedly cross each other, creating difficulties in terms of access and movement through the 'body' of the city (traffic jams). This adversely affects the internal organization and perception of the city, and has a negative impact on the environment and social interactions. Within this context, one of the main questions considered in the dissertation is: *How can properties of such a large system be presented and read?* To answer it, the presented research takes a closer look at the capabilities of GIS and analytical approaches used in spatial planning.

3. Spatial Analysis of Urban Form

3.1 GIS and Urban Planning

An inherent quality of spatial planning is its direct connection with the territory, as well as its natural and anthropogenic characteristics. As discussed earlier in the text, the process of spatial planning and management is extremely complex and ambiguous. For the purposes of spatial planning, it is important to have a mechanism with modern and comprehensive tools to collect information on territory and analyze it. Such a mechanism at a modern scientific and technical level, which is perfectly suitable to deal with mentioned issues, are geographical information systems. The paper-based documentation on spatial planning had a number of significant drawbacks: insufficient information provision of projects, the complexity of paper plans perception, impossibility of operative readjustment of project proposals, etc. The development of GIS, however, considerably affected the situation in spatial planning and fundamentally changed the approach to the study of territory and its planning. Perhaps one of the main advantages that GIS has brought in the planning process was the ability to transform descriptive and parametric information about the territory into knowledge. This process can be divided into several steps, which can be performed in GIS and will help make an effective decision (Figure 8).

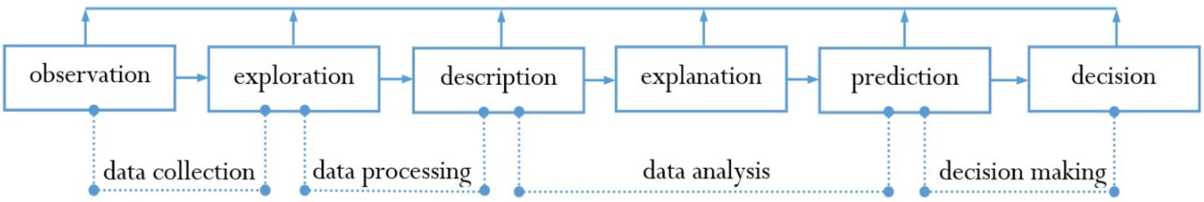


Figure 8. Implementation of GIS in planning processes.

Another great quality of GIS is the ease of storing and managing large amounts of spatial information. However, for practical use, it is much more important for this messy assembly of numbers and shapes to become understandable and usable for various purposes. The geometric component of the mapping and the possibility of using attributive information directly indicate the ability of quantitative analysis in GIS. Modern GIS is based on various mathematical models using map algebra, various statistical methods and, of course, programming languages. It should be noted that mathematical modeling in GIS depends primarily on the geographical coordinates. A pair of numbers [x; y] and in more advanced models [x; y; z], allows analysts to determine the geographic location of the object or the phenomenon being investigated and then apply the corresponding methods of mathematical analysis to it.

Today, GIS has many advantages that allow to solve multilateral problems:

- the database is not static, which allows analysts not only to update the cartographic layers, but also to introduce new features
- the possibility of combining the digital map layers in any form and composition
- the possibility to improve standard analysis tools or create a set of tools
- automation of processes when working with the database and multifunctional analysis for decision-making. For example, the choice of areas that meet specific parameters

The latter is of great importance for the study of urban form and spatial structure. For the sake of clarity, we once again raise the assertion that the city is a system—a complex of elements that are in interaction and unity (Gardner 2016). Such a definition allows us to claim that the failure of one element or its part could be the beginning of a slow dissonance of the whole mechanism and in the long run may lead to negative implications. Regardless of whether engineers want to build a new house, bridge, road or change the function of a territory, they must evaluate the decisions, taking into account their impact on the functioning of the system. A large number of concepts, suggestions and methods have been made to tackle this issue, and yet the field still remains the frontmost in the relevant literature. As a negative side, it should be mentioned that many works, despite positing seemingly strong and useful ideas, have been forgotten in electronic archives.

"…too much discussion about cities is devoid of measurement that is capable of communicating the normative language of smart growth. Much of the vocabulary of smart growth, and particularly new urbanism, is based on concepts that require new measurement methods. Examples are words such as suburb, public realm, mixed use, diversity and access. These concepts are vital to the discussion, but have been difficult to 'pin down'. In effect, the measurement, evaluation and representation of the urban realm have not kept pace with the sophistication of new ideas about how to change it." (Talen 2003: 203)

This research is largely motivated by the necessity to improve the practical perception of urban environment in a purely technical context and as a result to support the trend of smart urban and transportation development. Before proceeding to discuss methods of spatial analysis, the ways of representation of the urban realm in GIS should be reviewed and discussed.

3.2 Built Environment in GIS

The elements of the built environment, such as streets, buildings, plots and parcels represent a tangible part of space. It is these components, better jointly or divided into groups, that should be of main interest of any urban form analysis, since they constitute the very mechanism of city functioning. Roads initially gave birth to cities and then turned into incentives for their development: they provide the exchange of material, cultural and intellectual values both between people and cities. The immediate place of production of these material and intellectual values can be a settlement, district, street or even neighboring houses. It follows then that roads are the leading structure-forming part of the built environment, and buildings or places are its subordinate part where different activities are located (Figure 9). This definition of urban form implies the complexity of the system described earlier in the text and identifies two main objects for the analysis—roads and locations. If the goal is to analyze large systems (a big city or region), then only the road network can be chosen as the object of study, since buildings or other places are always located along the roads and the efficiency of road network also determines the value of locations.

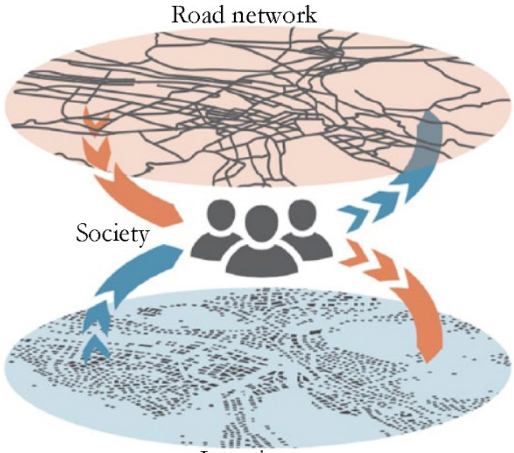


Figure 9. Illustration of layers defining urban structure and public space.
(Source: Schweitzer et al. 2016).

To clarify the above, further attention is paid to the basic concepts and parameters of the system. A system, in a general sense, implies a set of items that are in communication with each other and with the environment, forming a certain integrity or unity. Unity means completed, consisting of effectively interconnected parts (Von Bertalanffy 1972). Then the composition of a system is determined by a few categories like element, communication, relation, and structure. An element is the simplest part of the system, reflecting the composition and size of the system. A system can be divided into elements in various ways, depending on the task and goal of the study. Communication is an integral property of any system that provides both its functioning and development. In the urban realm, spatial communication ensures the functioning of static elements through the movement (dynamics). Communication creates a hierarchical order in the system, depending on the location of elements in it. Relation is the difference or identity of things in one set with another. Structure is the orderliness of the relations between a system's elements. It describes the way the system is organized and the quality of communication in the system. All these general concepts can be applied to the analysis of urban form.

The very nature of existence of transportation and travel is to satisfy the need for movement (people, goods, information). Moreover, transport infrastructure helps people overcome space that may present certain obstacles or constraints, whether human (time, speed) or physical (boundaries, topographic limitations) (Rodrigue et al. 2013). However, what makes people move around the city and why is mobility so important to us? The answer to this question is quite simple—our activities. In our daily life we constantly use geography and very often we do it unconsciously. For example, people very carefully choose a place to live, try to select the shortest and fastest route to work and when returning home, try to find the nearest supermarket on their way (Golledge 2002). The urban society deals with similar tasks every day and this generates a demand for mobility and puts into operation the mechanism called the city. The definition of urban form then becomes more specific, clearer, and able to be analyzed in GIS. Valente-Pereira (2014) gives the following definition of urban form:

"The form of the town is established in the relation between the outdoors space and buildings, which exist in a given landscape/soil. These are then the elements to be analysed by themselves, between themselves, and their relation with other urban elements." (Valente-Pereira 2014, Urban Form Elements section, para. 1).

Meadows also gives broader concept, emphasizing the significance of the spatial arrangement of elements in the form:

"... urban form is not simply a matter of descriptive geometry. A similar though sometimes less immediate imagery emerges when one turns from total to component urban form and examines the arrangements of parts within the whole. Urban form is thus presented as a vast theater in which a polyglot variety of human encounters, paths, and locations occurs: as a mosaic of "adapted spaces"; as a system for access and transaction; as a time-building system of arrangements of parts in which the manifold structures serve as points of intersection between past, present, and future ..." (Meadows in Blau et al. 1983: 16).

It should be added that the elements of urban form, as well as the relations between them, are distributed unevenly over the city territory (non-homogenous system) and it is very important in the analysis of such a system to ensure its spatial unity. This stipulates the accentuation of an urban street network as a main frame in the planning structure of the city that connects the scattered centers of socio-economic activities. The main elements in the analysis can then be presented in the form (Rodrigue et al. 2013):

- **nodes**—discrete elements with a clear-cut core, in which there is a concentration of traffic flow. Depending on the geographical scale (from local to global), elements like junctions, cul-de-sacs or in some cases even entire cities can be represented as nodes. In spatial analysis, nodes can be the start point of movement (origin) or the endpoint (destination). A node system has a specific hierarchy, where each node has a specific value that can change when adding new nodes or changing the position of existing ones (Figure 10).

- **links**—linear elements connecting nodes and directing traffic flows (urban street network). Linkages at the finest scale can embrace all city communications including footpaths. At the more generalized level these may include railroads, ferry lines and interstate routes (Figure 10).

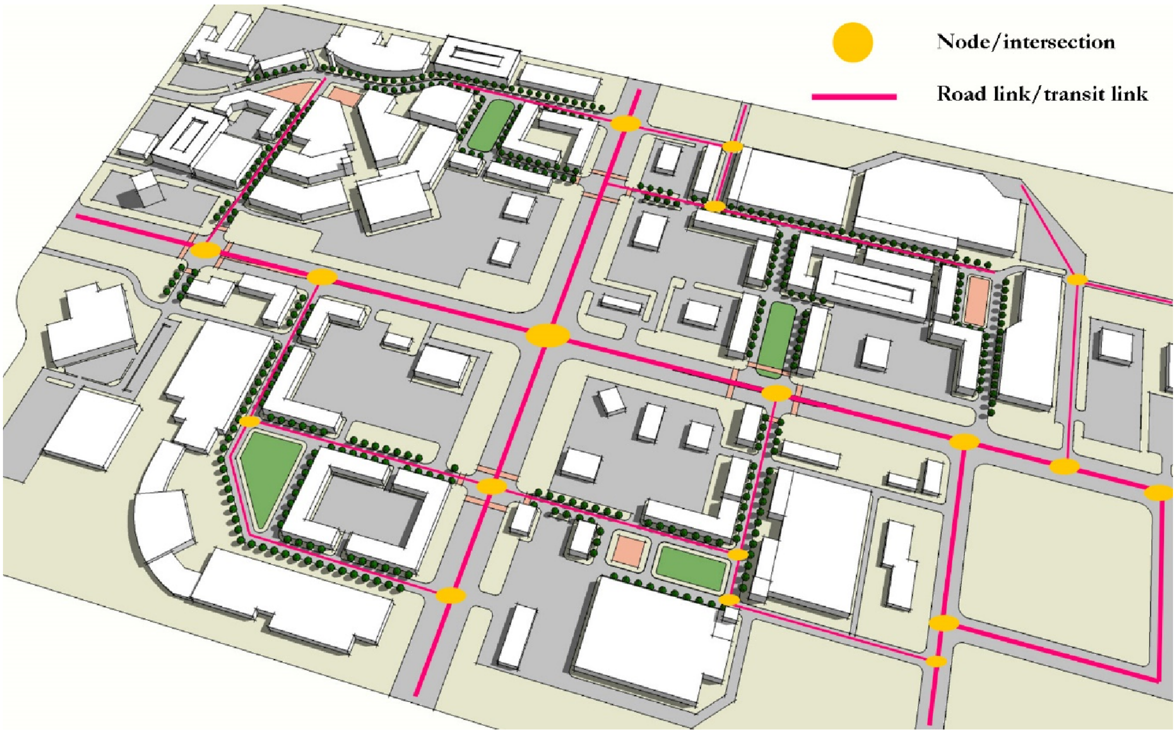


Figure 10. Representation of urban form in the form of nodes and links.
(Source: adapted from https://livingurbanism.wordpress.com/, accessed May 11, 2016).

Spatial arrangement of nodes and links provides functional coherence of an urban environment, thereby allowing us to analyze it for the purpose of connectivity, efficiency, and evaluate the results of planned changes. This finally leads to the very essence of spatial analysis in GIS environment, where *location* is the central concept. Longley (2011: 352) writes:

"Spatial analysis is a set of methods whose results are not invariant under changes in the locations of the objects being analyzed".

Location represents the foundation of all GIS. Otherwise, it would be just a mathematical data processing with inherent spatial homogeneity. Spatial analysis in this definition allows one to evaluate urban layouts from different angles and explain many phenomena taking place in it.

In general, there are three basic approaches to spatial analysis. The first is very popular in cartography and called *generalization*. It is common practice in geography to use the aggregation and simplification of map elements (objects, parcels, lines) at different scales (Davis et al. 1999; Barkowsky et al. 2000; Shea et al. 1989). This method of representation is also very convenient in analyzing data and found wide application in numerous studies as so-called aggregate methods of spatial analysis, which will be discussed in the next section. Indeed, the excessively detailed data describing urban layouts causes difficulties in presenting the results. Therefore, the information is often combined into clusters to get more vivid outlines of the observed phenomena in the overall plan. This technique is very useful in presenting information about the population (distribution, density, incomes, etc.) or analyzing traffic congestion, noise propagation, service areas, and many others when the local representation is unclear (Bertaud et al. 2003; Owens et al. 2010; Wang 2010; Farcaş et al. 2010).

The second approach examines the presence of *randomness* in the appearance of phenomena on the map. Since most of the data used in GIS is derived from local measurements and observations, especially those for aggregate analysis, the probability model can be investigated. The availability of strong statistical tools makes it possible to identify the patterns of occurrence of studied factors in the territory. This approach is used in the analysis of urbanization, urban expansion, and increase in fuel consumption (Feng et al. 2015; Triantakonstantis et al. 2012).

The third approach is *causative*. It includes the search and analysis of relationships between objects in space and mainly focuses on the study of a static environment with topology and metrics. Objects in a geographical space are always somehow connected with each other and certainly with the space itself. This can be used, for example, in the search for a suitable location on the map or for the measuring urban infrastructure (Rikalovic et al. 2014; Ford et al. 2015; Gudmundsson et al. 2013).

In the context of this work, spatial analysis is a set of tools and techniques to analyze data about objects localized in space. In a broader sense, spatial analysis can be explained as a way of investigation and description of complex systems.

3.3 Methods of Spatial Analysis

The city as a complex system is under continuous development. This is manifested in the changes of population structure, form, size and intensity of use of the developed territories, in increasing technical capacity and infrastructure thickening. These factors of development, mobile and rapidly changing, come into collision with a more stable, artificially created tangible environment. Structural analysis of the built environment interacts with the town-planning science, architecture theory and design, geography, ecology, sociology of the city and other disciplines. This makes an overview of spatial analysis techniques quite a challenge. Given the high popularity of this topic, a large number of scientific schools were formed with widely varying motivation, goals and objectives of research as well as the applicability of the results. Each research team has developed its own individual approach. In the presence of particular goals, each school studied individual properties, qualities and parameters of built environment using theoretical knowledge of certain scientific disciplines. In most cases, unidirectional and narrowly focused analysis techniques were developed. At the same time, some approaches have great potential and adaptability. The following text provides a coherent framework of quantitative metrics and approaches of the analysis, including both traditional methods popular among planners and interdisciplinary approaches. For a greater orderliness and clarity, the presented work divides the methodologies into four groups: spatially cumulative, fractals, dimensioning and graph theory. In this case, the main goal of the study is to review the methods that can be used to study urban form and most importantly implemented in GIS.

3.3.1 Spatially Cumulative Metrics

The first group of techniques, which is referred to as *spatially cumulative*, to the fullest extent reflects the multidimensionality of urban analysis. It deals primarily with the dynamic aspects of urban society. Different authors, depending on their professional interests, focus on the distribution of the population across the territory, its density, migration, aggregate economic indicators (income), travel behavior and work commute. In some cases, a static environment is also involved, such as land use mix, intensity of land use and urban expansion. Spatially cumulative measures analyze the dynamics of clusters (summarized information) of urban realm—its shape, changes, and intensity. They focus not on a separate object on the map, but rather on the area and its attributes, which are combined into a single unit to represent the overall picture. These measures are widely used by municipal administrations, since they can provide useful statistics (e.g., demographic data) and are able to be vividly visualized in GIS. On the other hand, a more comprehensive application is also possible, like finding the relationship between different phenomena.

One of the most common ways to apply the cumulative measures is to analyze the city development pattern. Dynamic processes and the self-organization of cities lead to an uneven development of the territory, which is accompanied by an increase in the concentration of population, resources and information on relatively small centers and zones. If a city has one pole, where most of the activities are concentrated, then this is a monocentric model. Most historical cities have a monocentric form. The opposite are polycentric cities, in which centers of activities are dispersed throughout the territory. However, in what manner the city model can be quantitatively described? The solution to this issue was first undertaken by economic urbanists who suggested that the study of the spatial distribution of population from the central business district

(CBD) would reveal the general trends of city development. Clark (1951) in his classic work studied the shapes of population density curves for the European and American cities during different periods of time. He found that the population density decreases as exponentially as distance from the CBD increases:

$$D(x) = D_0 e^{-bx} \tag{1}$$

where D is residential density at distance x from CBD, D_0 is the central density or the value of $D(x)$ when $x=0$, e is the base of natural logarithms, while b is the density gradient. From the equation 1, it follows that the density depends on parameter b and x, so to estimate the function ordinary least squares (OLS) regression can be used:

$$log_e D(x) = log_e D_0 - bx \tag{2}$$

The CBD is a zone of concentration of various types of amenities such as shopping, recreational, cultural. People tend to choose a place of residence close to the clusters of these services, which in turn is reflected in the uneven distribution of population across the territory. In the simplest case, if the city is monocentric, then the population density will decrease exponentially from the city center (Figure 11). If the function has a wavy structure, then the city may have signs of polycentricity.

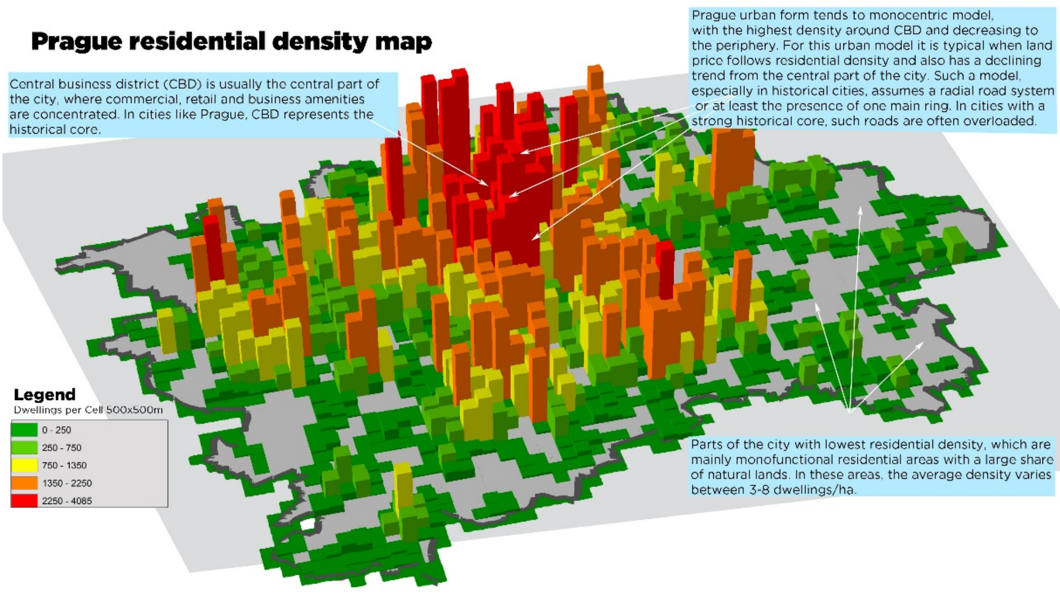


Figure 11. Prague residential dwellings density layer in 2015.

After Clark's research, a large number of studies of urban patterns were carried out using his model. The most notable works include (Muth 1969; Bussière et al. 1970; Richardson et al. 1973; Edmonston et al. 1978). Bertaud (2004) by analyzing the advantages and disadvantages of monocentric cities shows that Clark's model is also effective when comparing the spatial forms of modern cities. The most recent research, however, significantly expanded this topic to the study of decentralization of cities with respect to employment density (White 1999; McMillen 2001; Smith 2011; Craig et al. 2015) and travel behavior (Bento et al. 2005; Cooke et al. 2017).

Spatially cumulative analysis is highly effective in the simultaneous study of several phenomena (Figure 12). For example, cumulative measures allowed researchers to reveal the relationship between residential density and transport-related energy consumption (Newman et al. 1999; Ewing et al. 2010; Kenworthy 2003) and gave new momentum to the research of *automobile dependence*.

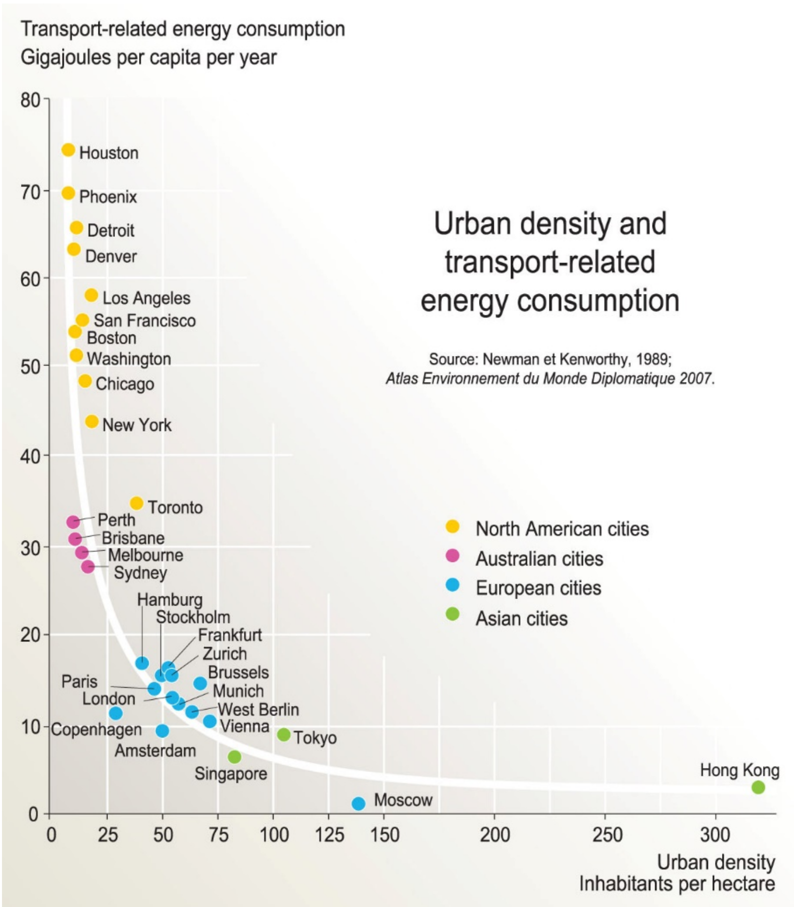


Figure 12. Urban density and transport-related energy consumption.
(Source: https://www.grida.no/resources/5414).

The development of New Urbanism concepts caused the popularization of yet another way in measuring urban phenomena with cumulative analysis. In the early 60s, the idea of a multifunctional city was not accepted by practicing urbanists and seemed rather strange. The lone voices of Jacobs (1961) and Alexander (1964) had not been heard, so the accepted principles of urban design were the comfort of residence and massive industrialization—in other words, segregation. Today, however, the situation is different and multifunctionality is a solid foundation of urbanism. There are two parameters of cumulative measures for describing multifunctionality—

density, and land use diversity. The latter can be characterized as the concentration of various activities per unit area. In urban studies, land use mix is usually seen as one of the factors of sustainable development with a few main advantages. Firstly, it increases the efficiency of public transportation since more activities are located close to each other. The proximity leads to a reduction in transport costs, emission and energy consumption (Donovan et al. 2013). Secondly, the economic productivity improves due to a high concentration of business activities, prompting profitable cooperation or competition as an incentive for development (Evans et al. 2007). Thirdly, such urban areas are more resistant to growth and more easily adapt to changes.

The quantitative analysis of land use and diversity involves a large number of different techniques, but it should be noted that the choice of a particular method is highly dependent on the available data. Some examples are presented below, starting with the simplest tracking of land use changes over time. This method is valid in urban expansion analysis and can be performed in GIS using well-known *overlay* operations. In general, an overlay tool allows to combine two or more layers to obtain an overlay map, which contains a set of spatial features of the original layers, the topology of this set, and attributes that are derived from the values of the initial objects. Patterns of land use may change over time, so the core of the analysis is to track these changes by comparing land use maps for different time periods and estimate the scale of changes. This can be easily done in most modern GIS, but difficulties can arise when collecting historical vector layers of land use. In their absence, a manual vectorization of scanned originals is usually performed, which is a rather time-consuming process (Figure 13). As an alternative, satellite imagery or aerial photos can be analyzed using remote sensing techniques for the same purposes (El Garouani et al. 2017).

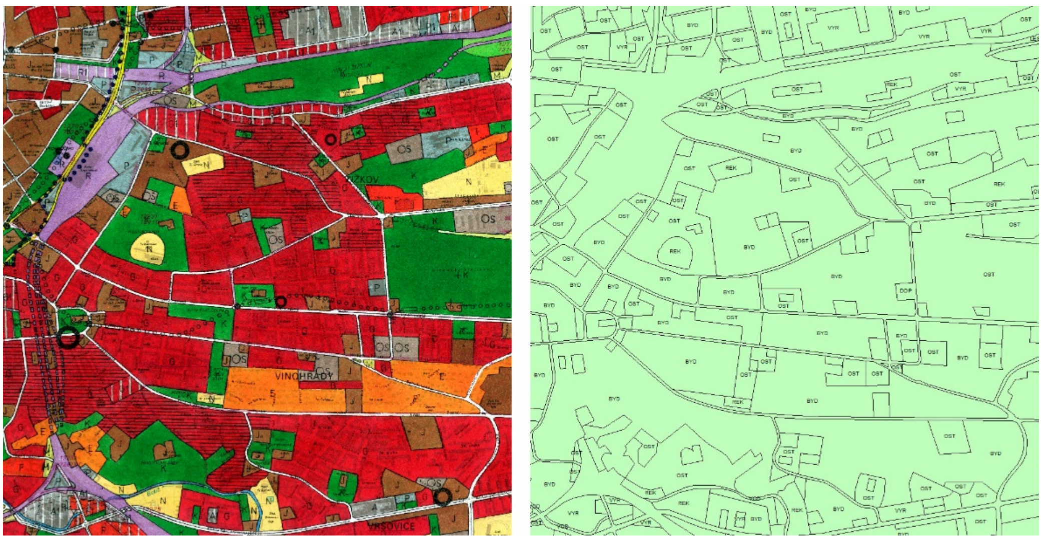


Figure 13. Scanned land use plan of Prague 1986 (left). Vectorized land use plan of Prague 1986 (right).

More advanced methods require not only cartographic analysis but also statistical interpretation, as well as more detailed attribute information. Since the main interest of this work is the analysis of big systems, the attention is also drawn to the parameters of these systems. From this perspective, the concept of entropy or the measure of order/disorder of a system should be mentioned. In urban studies, entropy is commonly used to estimate the diversity of functional categories of land at different scales. Shannon's entropy, for instance, is often used to measure both urban sprawl and land use mix using (Pradhan 2017):

$$E_{abs} = \sum_i^n P_i \log_e(\frac{1}{P_i}) \Rightarrow E_{rel} = \sum_i^n P_i \log_e\left(\frac{1}{P_i}\right)/\log_e(n) \quad (3)$$

where P_i is the percentage of land use (i.e. built-up area) in the zone i, and n is the total number of zones. The value of P_i is calculated as a percentage of the total area that the specific function occupies. The result of relative entropy analysis ranges from zero to one, where one represents dispersed land development and zero refers to a compact one (Pradhan 2017).

Simpson's diversity index is another way of land use mix analysis. The index measures the probability that two random locations in the area belong to a different category of land use (Pradhan 2017):

$$D = 1 - \sum P_i^2 \quad (4)$$

where P_i is the percentage of each land use category in the studied area.

The mentioned methods are a general case of land use mix analysis. However, individual measures are also applied to particular cases to achieve certain goals. For instance, Batty (2004) proposed a fairly elegant way of describing urban diversity by using spatial indicators. They proceed from the assumption that the high concentration of activities in the territory is also associated with high density since these activities are the center of attraction. Urban diversity in this manner can be calculated for different scales of the environment, ranging from a land parcel to a census tract. The scale in such studies, however, is a critical factor, since the very notion of diversity implies a comparison. If only a few lots is compared in terms of diversity, then one can hardly expect heterogeneity at this level. The study also discusses ways of results visualization in GIS at different scales using smoothing.

Another approach takes advantage of the large geographic databases that have emerged from the rapid development of information technology in recent decades. A multi-criteria analysis is applied to analyze the impact of land use changes on the landscape composition, mix of activities, biodiversity, or to find a suitable location for planning changes. This group of methods is mainly used to find middle ground between the economic potential of a territory and its environmental preservation (see for example Yang et al. 2008). In urban design, such analysis allows planners to find suitable areas for housing taking into account urban noise (Joerin, et al. 2001) or allocate territories for commercial use based on population density and employment maps (Chen 2014).

3.3.2 Fractal Analysis

Fractal analysis allows one to estimate the geometric properties of the urban realm. There are several basic models of urban form organization used in urban planning. The most famous of them are the Burgess concentric zone model (Burgess 2008), Hoyt sector model (Hoyt 1939) and the multiple nuclei model (Harris et al. 1945) (Figure 14).

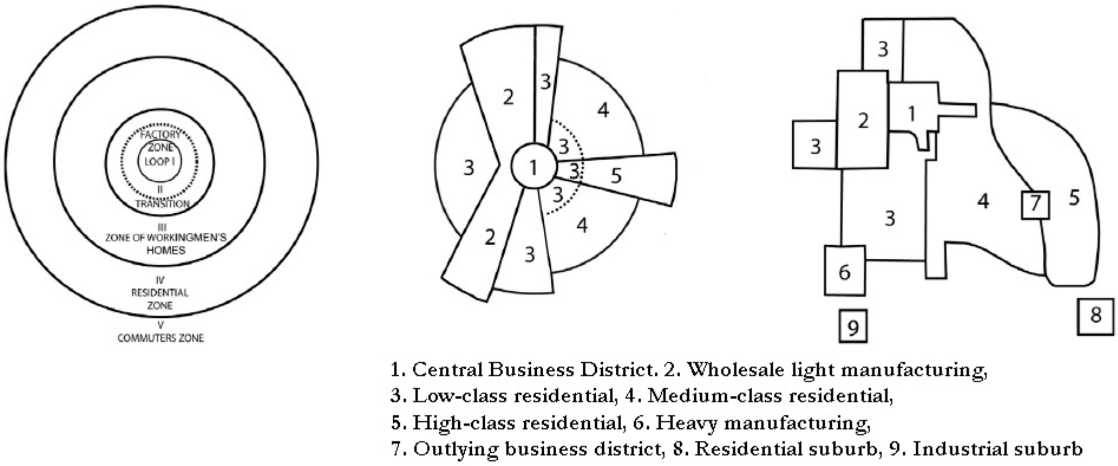


Figure 14. Classical models of urban structure: (a) Concentric zone model. (b) Sector model. (c) The multiple nuclei model. (Source: Calıskan 2009).

These models represent the spatial arrangement of an urban environment by means of ideal shapes, like a circle or a square, i.e. from the point of view of Euclidean geometry. If we look at the natural space surrounding us, then we will hardly find objects with a perfect surface or borders with smooth curves peculiar to geometric figures. Urbanists face the same reality in their attempts to analyze the pattern of cities growth or suburbanization. It seems that such large systems like cities grow in a rather incoherent way, and it is very difficult to find logic in this chaos. Regular Euclidean objects is just a mathematical abstraction, while cities— especially if the theory of self-organization is taken into account—have a more rough and meandering shape. There is, however, an exception related to the scale under which objects are examined. At a certain scale, one may note that some natural and man-made structures have a self-similarity property and they are called fractals.

Fractal theory as a method of analysis of spatial structures and patterns of relations became popular in the 80s. Batty et al. (1986) were among the first to demonstrate the potential of fractal geometry in urban studies. The self-similarity in urban patterns implicates the existence of an invariant and certain symmetry of objects at a certain scale. In the urban environment, this similarity can be observed, for example, in architectural elements (Figure 15, left), in buildings structure (Figure 15, right), and most importantly in the spatial arrangement of urban fabric.

Figure 15. Fractal structures in architectural ornaments of The BAPS Shri Swaminarayan Mandir in Toronto, Ontario, Canada (left). (Photo: Vitalii Kostin, September 2016).
Fractal geometry in The Heinz Galinski School plan in Berlin, Germany (right).
(Source: Bing Maps ©, accessed February 19, 2018).

Fractal logic can be seen in some modern urban designs. In Barcelona, for instance, the city council adopted a new plan of extensive changes in urban space in an effort to reduce air pollution and noise from motor vehicles (Bcnecologia.net 2018). The idea itself is based on the creation of so-called superblocks (Figure 16). In the coming years, the city plans to close roads for traffic in selected areas and turn them into open spaces for pedestrians. In this case, a set of superblocks consists of smaller similar building blocks. This similarity may reflect a certain degree of fractality.

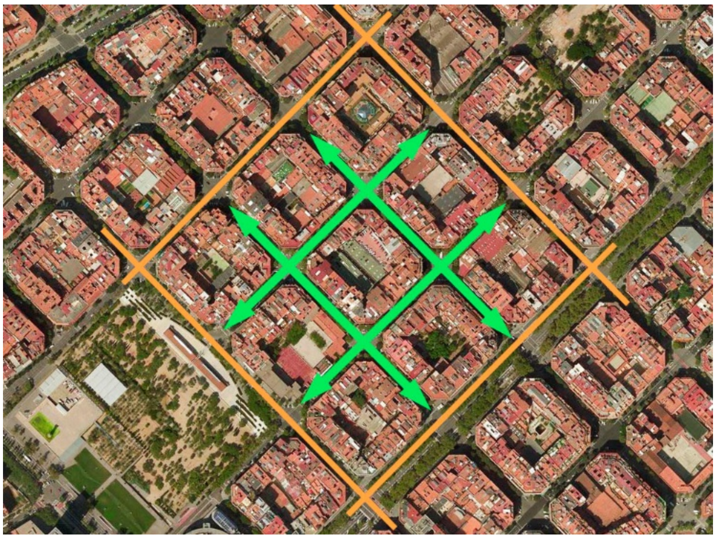


Figure 16. Superblock model in Barcelona, Spain. Orange lines represent roads for traffic, while green arrows show pedestrian paths. (Source of orthophoto: Bing Maps ©, accessed February 19, 2018).

Mathematically, fractality is measured using parameter D, which demonstrates the degree of complexity of the space or its elements at different scales (Frankhauser 2015):

$$D = \frac{\log N}{\log(1/r)} \tag{5}$$

where D is the fractal dimension index, r is a scaling factor, N is the number of similar elements in a figure. For instance, in the simplest square grid of 3x3, the number of similar elements is nine and the scale factor is three.

Index D is defined for different scales, so a map of a studied area is usually divided into cells starting with the largest size. The size of cells is gradually reduced and the parameter D is determined for each iteration. Index D usually varies between one and two. If the distribution of elements is symmetrical, then $D=2$, like in case of 3x3 square grid.

Fractal approach can be applied to various aspects of urban fabric from a general study of a settlement's shape and its irregularity to a more detailed investigation of individual urban structures. The urbanization process and its dimensions can be investigated using different shape indexes, such as compactness and form ratio, ellipticity index, elongation ratio, etc. (Chen 2016). At the same time, Shen (2002), while investigating the fractal dimension of different US cities, determined that fractals are a useful measure for urbanized areas, however they are not sufficient for the analysis of population density. The fractal dimension of a city also affects its transport infrastructure. Lu et al. (2004) demonstrated that the complexity of urban networks follow the growth of a settlement, thus large cities have a denser transportation network and provide greater access to urban space.

3.3.3 Methods Related to Dimension of Urban Form Elements

This group includes methods that assess the urban form in terms of the size of the built-up environment—primarily the dimension of city blocks, lots, buildings and the width of streets. Jacobs (1961) was one of the first to pay attention to the importance of the size of urban environments for vitality and sustainability. She agitated for small blocks in urban design, which are separated by a dense network of pedestrian streets. She saw great potential in this concept, which brings people together, and promotes the development of commercial activities, walkability and diversity. Streets are filled with life when people are given a wide variety of short routes, in contrast to large blocks with long buildings, which by their continuity interrupt social interaction and lead to the isolation of some zones.

As an example of the validity of Jacob's ideas, a reference can be made to the empirical study of Southworth et al. (1993). The authors analyze the evolution of built geometry and typology of streets as well as the pattern of lots and buildings of selected areas. By comparing several forms of urban design including grids, interrupted parallels, clustered loops and cul-de-sacs, they came to the conclusion that rapidly increasing the size of urban forms discourages walkability, makes the public space invisible and leads to isolation.

"Street systems that serve many functions can have a positive impact on a community. Designers and planners must understand that streets are more than utility corridors for motor vehicles, but rather are critical urban design elements that help shape the quality of a community's environment." (Southworth et al. 1993: 276).

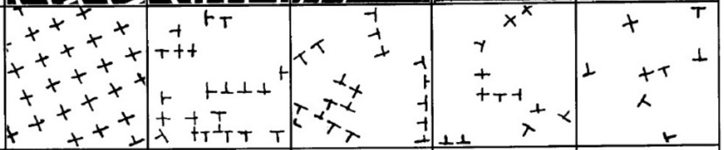
	Gridiron (c. 1900)	Fragmented Parallel (c. 1950)	Warped Parallel (c. 1960)	Loops and Lollipops (c. 1970)	Lollipops on a Stick (c. 1980)
Street Patterns					
Intersections					
Lineal Feet of Streets	20,800	19,000	16,500	15,300	15,600
# of Blocks	28	19	14	12	8
# of Intersections	26	22	14	12	8
# of Access Points	19	10	7	6	4
# of Loops & Cul-de- Sacs	0	1	2	8	24

Figure 17. Comparative analysis of street patterns. (Source: Southworth et al. 1993).

Figure 17 illustrates the results of a comparative analysis where different street patterns are characterized by the number of intersections as a feature of connectedness, street length and the number of access points as a feature of pedestrian accessibility. The figure clearly shows a gradual transformation of the regular *gridiron* pattern into modern, oddly shaped *lollipops on a stick* form with cul-de-sacs.

New Urbanists pay particular attention to the block dimensioning and street patterns. Urban sprawl, which remains the main challenge for New Urbanists, entails many other phenomena like segregation (separation of residential areas from other types of land use), isolation and automobile dependence (holes in the urban network as loops and cul-de-sacs) (Duany et al. 2010). The core of these problems lies in the loss of scale, when the individuality and creativity turns into routine standardization. New Urbanists offer to shift the attention to a more tangible level of space, namely the block and its elements (plots, buildings and streets) as a solution to the current problem.

To describe urban sprawl quantitatively, Song et al. (2004) offer several measures of urban form: connectivity, density, land use mix, accessibility and pedestrian access. The authors found that the connectivity of a neighborhood, which is given by the ratio [intersections/(intersections + cul-de-sacs)], varies depending on the age of the neighborhood. A similar trend is observed in the number of blocks as well as the length of block perimeters (Song et al. 2004). The results also support the validity of block scale design promoted by New Urbanists, since relatively new neighborhoods show a high level of connectivity, pedestrian accessibility and density.

A deeper understanding of dimensionality in city form is provided by the study of Sheer et al. (1998). The work examines the transformation in urban form that occurred over the past seventy years and how these changes have affected the interaction between urban network, lots and buildings. Through the comparative analysis of selected cities, the authors revealed a few interesting features. The spread of studied areas was reflected in all elements of urban form—especially in the size of city blocks, lots, building footprints and length of paths. The relationship between the road network and buildings was lost due to the large variety of lot sizes. Growing parcels, as well as blocks, lead to disconnection of buildings (especially for commercial use) from the roads. While large shopping centers remain connected with arterial highways, they become less accessible for pedestrians.

3.3.4 Graph Theory and Networks

The foundations of graph theory as a mathematical branch were laid out in 1736 by the mathematician Leonard Euler when considering the Königsberg bridge problem. The city of Königsberg (today's Kaliningrad) is located on the Pregel River, which divided the city into four areas with two isolated islands inside. In order to reduce trade routes and improve the access of citizens to various amenities, seven bridges were built across the river (Figure 18). At that time, the citizens began to wonder whether it was possible to find a route that would allow them to pass all seven bridges without stepping on either of them twice. The question was framed quite simply, but the solution to this problem seemed impossible. It could not be described geometrically in the absence of geometric shapes and figures in it, so it was necessary to work out a new approach that would not be related to the size of the objects but to their mutual arrangement. Euler addressed this problem by depicting it on a simplified scheme of the city area. It should be noted that initially Euler's solution was purely analytical. Representation of space in the form of graph, as we know it today, with links (paths) and vertices (locations) appeared in the XIX century and the term *graph* itself was introduced only in 1936 by König (1936). In his solution (adapted to modern terminology), Euler showed that if one wants to go through each bridge only once, then all the vertices of the graph should be even (have an even number of lines emanating from them), an exception is allowed only for two nodes. The journey can be started from an odd node and finished in another odd node. On the Königsberg plan all nodes were odd, so he concluded that in this case, it is impossible to cross all bridges along the same path. In modern graph theory, the path passing only once through each link is called the Eulerian path.

Figure 18. Illustration of the Königsberg Bridge Problem. (Source: adapted from https://www.amusingplanet.com, accessed May 25, 2017).

By solving a trivial puzzle, which served as amusement for the locals, Euler laid the groundwork for a new direction in mathematics that remains an important tool in describing space in various fields of science. Since then, a large number of methods and metrics have been developed in graph theory, some of which will be discussed below.

3.3.4.1 Interdisciplinary Graph Application

The idea of investigating spatial relations in self-organized systems through the use of network and graph theory has remained very popular since the last century. Representation of the system in the form of nodes (objects of research) connected by edges (interactions, connections) seems logical and easy to understand. This technique has been successfully used in different areas such as social networks, biology, information science, economics, geography, etc. In the last two decades, it has become widely used for urban studies as well. Using the principles of graph theory and its main measures, the spatial patterns of city environment can be analyzed to help designers and planners to better understand the mechanism of urban system for the efficient design of new spaces (Kostin et al. 2015). These measures can be useful in urban traffic flow estimation (Ogunsanya et al. 1986; Hillier et al. 1987), to evaluate the integration or connectivity of particular street in a transport network (Jiang et al. 2002; Crucitti et al. 2006; Hillier et al. 1984; Porta et al. 2008) and accessibility of road junctions or urban spaces (Hansen 1959; Sevtsuk et al. 2012; Zhang et al. 2011).

Graph theory is an area of discrete mathematics that deals with the investigation and solution of various tasks connected with graphs. A graph is a graphic model of a system that consists of a set of vertices and links representing the elements and their connections. It is peculiar for the graph that the number of paths allowing movement from one vertex to another is very diverse as well as the length of these paths. The optimization of systems is based on the idea of reducing the path between the extreme vertices of the graph. The graph has two forms of representation: graphical and matrix (Figure 19). In the connectivity matrix, the presence of a relation is fixed by one, and its absence by zero.

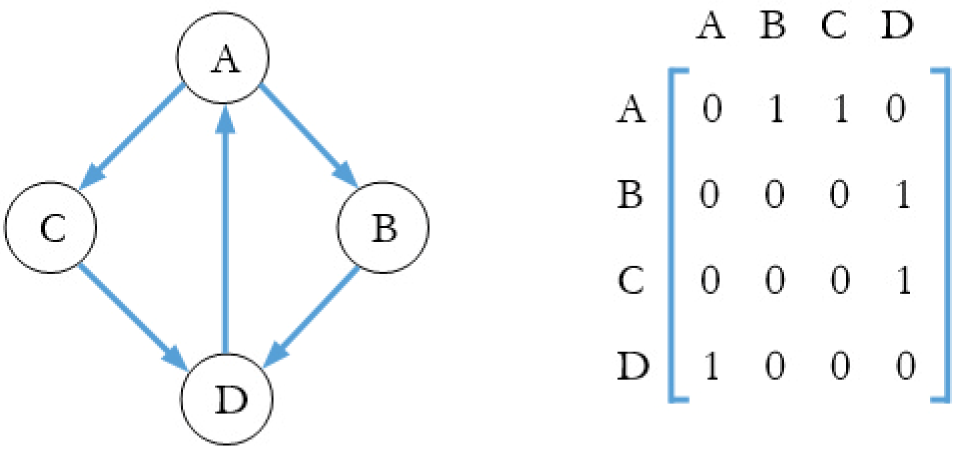


Figure 19. Graphical (left) and matrix (right) representation of a graph.

3.3.4.2 Space Syntax Approach

Probably one of the best known topological approaches for the network analysis applied to urban studies is Space Syntax, which was proposed by Hillier et al. (1984). The main idea is that space can be divided into simplified elements, which as a whole make up a network or graph where each space links to all other spaces in the system. The theory is based on three main concepts of space.

Isovist—the way of space perception promoted by Benedikt (1979), where space was represented as a set of visible areas. The very concept of isovist was defined as a set of points that are visible from a particular array station in space where the observer is located (Figure 20). The isovist theory defined the way for modeling of the urban environment in Space Syntax approach, when only public spaces (open spaces) are used in the analysis.

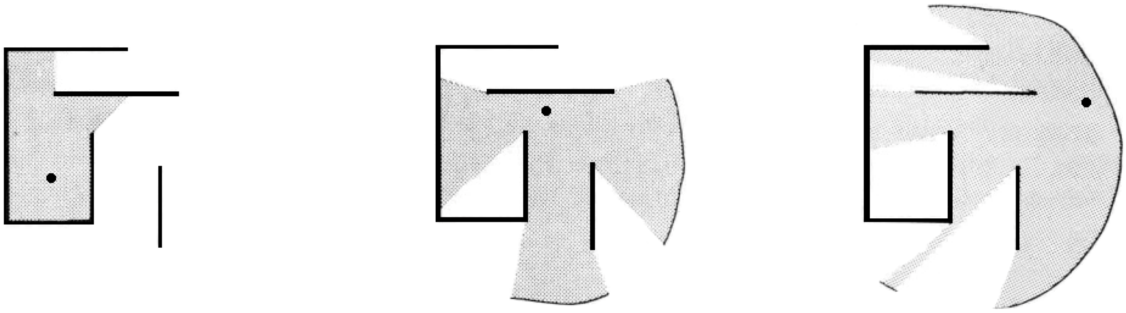


Figure 20. Isovists in a simply connected region. (Source: Benedikt 1979).

Convex space—a two-dimensional void representing the portion of space in which all its points are directly visible to all other points in the same space (Figure 21).

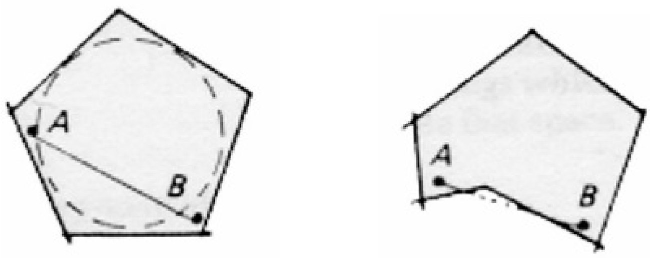


Figure 21. Convex Space (left) — all points are visible to all other points in a straight line.
Concave Space (right) — some parts of space might be hidden; there is no way to draw a line between points without going beyond the space. (Source: Haq 2001).

Axial space—these are straight lines that span the convex space in terms of visibility. Linear units cover all the available paths and connections from one convex space to another. An axial map is a global representation of an architectural space in which the individual open spaces (**convex space**) are chained by axial lines if they are visible to each other.

Figure 22 shows the interpretation of space in the Space Syntax model. Yellow polygons in Figure 22 represent **convex space**. Blue lines are **axial lines** and the main units in the analysis of space. Space Syntax method does not take into account the length of the lines or their shape, but instead the number of steps to reach a particular line (space) or the number of immediate neighbors. Such a representation of space allows urbanists to analyze some morphological properties of the system: local and global integration, connectivity and control value.

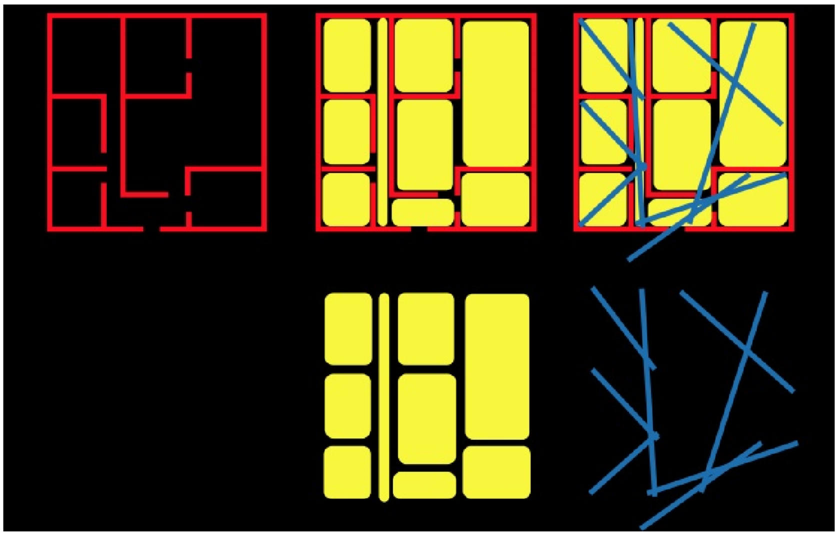


Figure 22. Different components of the Space Syntax model. (Source: Haq 2001).

The main principles of Space Syntax approach can be illustrated on the simple model of an urban environment (Figure 23). This representation is based on the hypothesis that in urban environment there are no disjoint lines, i.e., every space in the city is accessible from any other space. *Connectivity*, in this case, shows the number of lines that directly intersect any given axial line. The *control value* (cv_i) determines the degree to which each line controls its direct neighbors. This parameter is defined as a sum of the inverse connectivity values of the immediate neighborhoods of a given axial line (Equation 6). *Integration* of an axial line shows the depth of its position in the whole system. This measure is an interpretation of the topological distance well-known in graph theory (Jiang 1998; Jiang et al. 2002).

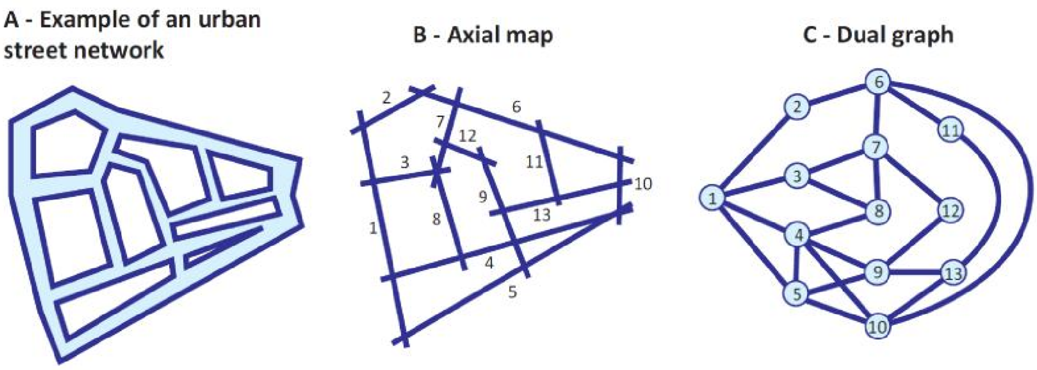


Figure 23. Dual graph representation of urban space. (Source: Jiang et al. 2002).

$$cv_i = \sum_{j=1}^{n} \frac{1}{C_j} \tag{6}$$

where n is the number of all direct neighbors of given axial line (open space), C_j is the connectivity of j-th direct neighbor of an axial line.

The concept of depth can be mathematically represented in the form:

$$De_i = \frac{\sum_{j=1}^{n} d_{ij}}{n-1} \quad (7)$$

where n is the number of axial lines (open spaces) and $\sum_{j=1}^{n} d_{ij}$ is the total depth of the ith axial line.

To evaluate the integration or segregation of axial line, Relative Asymmetry (RA) is applied to normalize the total depth between zero and one (Jiang 1998):

$$RA_i = \frac{2(De_i - 1)}{n-2} \quad (8)$$

Depth calculation is a simplified analysis of accessibility of some element in space (e.g., street). Depth is analogous to the metric distance, which represents the minimum number of steps that must be made from origin to destination. Integration, on the other hand, shows the depth of each axial line in the system with respect to all other axial lines.

3.3.4.3 Multiple Centrality Assessment Approach

Another very popular approach of urban system analysis also deals with urban streets and is called the *multiple centrality assessment* (MCA) (Porta et al. 2006). The MCA methodology to some extent resembles Space Syntax: *"… the MCA model shares with space syntax the fundamental values that refer to the structural interpretation of urban spaces for urban planning and design…"* (Porta et al. 2009: 451). However, from the point of view of calculations, MCA offers a deeper analysis of the system. In the original Space Syntax model, different elements (streets, squares, rooms in a building etc.,) are introduced in the analysis as nodes and then measured by using topological distances (Figure 23). In contrast, MCA uses a more realistic model of the physical environment in which a real street network is used as well as metric distances (Figure 24). Three main measures of street centrality are used in MCA: closeness, betweenness, and straightness (Porta et al. 2009).

Closeness centrality CC indicates the degree to which node i is close to all other nodes in the same network along the shortest paths. Mathematically, it can be described as follows (Porta et al. 2009):

$$CC_i = \frac{n-1}{\sum_{j \neq i}^{n} d_{ij}} \quad (9)$$

where n is the total number of nodes in the network, and d_{ij} is the shortest distance between nodes i and j. In such a manner, the closeness centrality measure shows the proximity of a street in respect to all other streets.

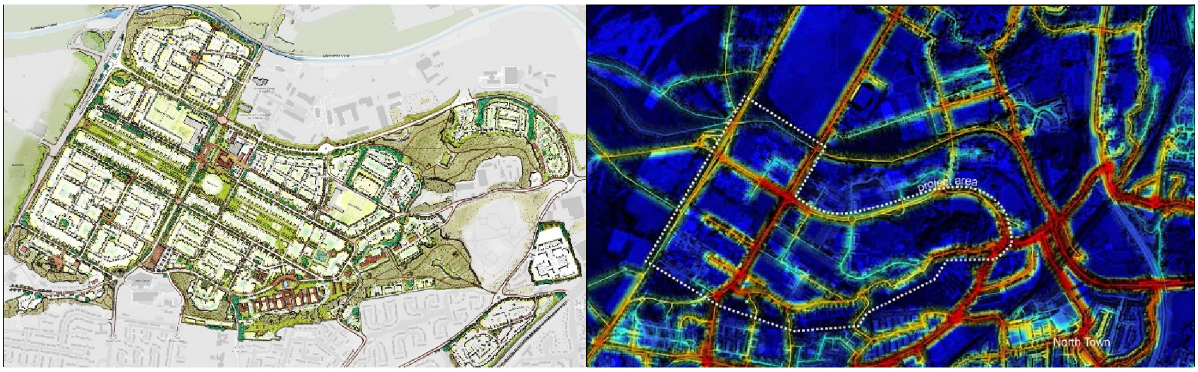


Figure 24. Illustrative masterplan for Wellesley, Aldershot (left).
MCA representation of street activity (right).
(Source: http://www.urbandesigndirectory.com/practices/place-logic, accessed February 27, 2017).

Betweenness centrality *BC* measures the extent to which node *i* lies on the shortest paths between other nodes in the network. The first formal and commonly-used definition was proposed by Freeman (1977). This measure is also referred to as the importance of a vertex since nodes with a higher value of betweenness have greater control over movements between others and their removal from the system will considerably affect communications between other nodes. Betweenness centrality is defined as follows (Porta et al. 2009):

$$BC_i = \frac{1}{(n-1)(n-2)} \sum_{i \neq k, j \neq k}^{n} \frac{n_{jk}(i)}{n_{jk}} \tag{10}$$

where n_{jk} is the number of shortest paths between nodes *j* and *k*, and $n_{jk}(i)$ is the number of these shortest paths that contain vertex *i*.

Straightness centrality *SC* measure is based on the idea that the communication between two vertices is better if they lie on a straight path. It compares the actual distance between vertices, taking into account path irregularity with the straight line distance (Euclidean distance) (Porta et al. 2009):

$$SC_i = \frac{1}{n-1} \sum_{j=1, j \neq i}^{n} \frac{d_{ij}^{Eucl}}{d_{ij}} \tag{11}$$

where d_{ij}^{Eucl} is the Euclidean distance between nodes *i* and *j*, d_{ij} is the shortest distance between nodes *i* and *j*.

MCA methodology allows researchers to describe a place with using centrality measures. The theory is reliant on the assumption that places which have a central position in the network are likely to become popular. Such places in an urban system are subsequently characterized by high permeability—hence the variety of services and higher land value.

3.3.4.4 Accessibility in Transportation Networks

From the large body of literature on the subject of smart city growth, there are several basic concepts that are the foundation on which the ideas of New Urbanism are built. These concepts are compactness, diversity, walkability or, in other words, human-scaled urban design. In order to understand and apply these planning principles in practice, appropriate quantitative research and meaningful outcomes are required. The highest priority in modern urban design, according to New Urbanists, is placemaking and proximity. Different measurement approaches of urban form, whether they use principles of graph theory (Space Syntax, MCA) or represent cumulative measures, inherently refer to the accessibility of urban location. This is not surprising since accessible neighborhoods and public spaces are directly associated with the notion of sustainable urban form and transport development. Accessibility has an impact on the social and economic performance of the territory. Change of transport accessibility leads to changes in the existing system of population displacement. If it increases, so does the attractiveness of the territory, causing an influx of population and trade development.

In recent years, the capabilities of spatial analysis in GIS, on the one hand, and availability of detailed spatial data on the other, open new directions for empirical studies of interactions in terms of accessibility. Over the past seventy years, more than one hundred techniques have been proposed for transport accessibility evaluation on different scales, from the neighborhood scale to the country level. Thus, depending on the goals set for the researcher, various characteristics and parameters are included in the modelling process. Some techniques take into account only a simplified model of space (eg. Euclidean distance instead of metric) without spatial resistance factor, while in others, various dependence functions are used in order to describe the influence of distance on location attractiveness. Depending on the algorithm, these methods are divided into the following main groups:

- Topological
- Spatial Separation
- Cumulative Opportunities
- Spatial Interaction
- Gravity-Based Accessibility

The following text summarizes the description of the main accessibility calculation methods, their advantages and limitations.

Topological Accessibility

Topological accessibility is a generalized method which is suitable for the analysis of all types of networks and widely used for transport systems (Jiang et al. 2004; Ducruet et al. 2011). The graph elements are presented by any street segments connected with a transport network as well as by end-start points of each segment and road intersections. The node accessibility is determined as the sum of the shortest paths (number of steps) between the analyzed location point and all the other locations in the system. It is defined as follows:

$$TA_i = \sum_{j=1;\, j \neq i}^{n} d_{ij} \tag{12}$$

where TA_i is topological accessibility of node i, d_{ij} is the topological distance (number of links) between nodes i and j, n is the number of vertices in the graph.

The topological method analyzes the existence or lack of links between the vertices, while the quantitative characteristics of the system are not involved in the analysis. This limitation makes the method only useful for simple comparison of urban networks but not for a complex urban analysis.

Spatial Separation

This type of measure computes the node accessibility as a weighted average of the travel times or distances to all other destinations (Bhat et al. 2000). The Euclidian, or network distance, are used in the analysis, however without a space impedance parameter. To make the model more accurate the travel time should be used instead of metric distance. In this case, the effort of space overcoming will also, in part, be included in the model. The methodology to estimate accessibility with a travel time as the effort required to reach a location was proposed by Allen et al. (1993) and was expressed in the following form:

$$SSA_i = \frac{1}{n-1} \sum_{j=1}^{n} t_{ij} \tag{13}$$

where SSA_i is the spatial separation accessibility of node i, t_{ij} is the travel time from point i to j, n is the number of points under consideration.

On a larger scale of territory, the methodology also enables analysts to compare the accessibility of different cities or metropolitan areas. General accessibility of the metropolitan area, according to Allen et al. (1993), can be calculated as the average value of accessibility of all points in it.

$$SSA_G = \frac{1}{n}\sum_{i=1}^{n} SSA_i = \frac{1}{n(n-1)}\sum_{i=1}^{n}\sum_{j=1;j\neq i}^{n} t_{ij} \tag{14}$$

where SSA_G is the spatial separation accessibility of a territory, SSA_i is the spatial separation accessibility of node i, t_{ij} is the travel time from point i to j, n is the number of points under consideration.

This measurement is easy to calculate and does not require a large amount of information. The technique can also be effectively implemented in GIS and, depending on the availability of data, some spatial parameters can be included in the model: metric distance, travel time or transportation costs. However, the origins and destinations are treated equally during the calculation, which can hide some important dependencies from the researcher.

Cumulative Opportunities

The next accessibility measure is cumulative opportunities, which take into account distances as well as the objective of a trip. Point accessibility, in this case, is calculated as the sum of potential activities that can be reached within a specified distance or travel time threshold (Bhat et al. 2000):

$$COA_i = \sum_t O_t \tag{15}$$

where COA_i is the cumulative opportunities accessibility of node i, and O_t represent the opportunities that can be reached within a threshold.

There are many improvements and additions to this measure for the specific purposes of the analysis; however, destinations remain the major object of the study. This measure is often used for evaluation of accessibility to employment. The only data required for the analysis is the location of jobs within a search radius. The main disadvantage of this method is that with the increase in the threshold, close and far opportunities are treated equally; it does not consider the resistance factor.

Spatial Interaction

The method was proposed by Wilson (1971). In his study, Wilson described four cases of spatial interaction: the unconstrained case, the production constrained case, the attraction constrained case, the production-attraction constrained. The latter case is the most universal and assumes a combination of all the previous one. The main advantage of this method is the ability to take into account the parameters of both origins and destinations. The calculation of accessibility implies the product of the quantitative characteristics of origins and destinations, the exponential distance decay function and the balancing factors.

$$SIA_{ij} = A_i B_j O_i D_j f(c_{ij}) \tag{16}$$

where SIA_{ij} is the measure of interaction between points i and j, A_i and B_j are the balancing factors, which are calculated to ensure that the constraint equations are satisfied, O_i is a some quantitative parameter in point i, D_j is a some quantitative parameter in point j, $f(c_{ij})$ is the distance decay function.

Balancing factor A_i ensures that the outgoing flow from origin i (e.g., the number of trips) corresponds to its quantitative parameter (e.g., the population size). B_j equalizes the incoming flow to destination point j with its quantitative parameter (e.g., the number of jobs).

$$A_i = \frac{1}{\sum_j B_j D_j f(c_{ij})} \tag{17}$$

$$B_j = \frac{1}{\sum_i A_i O_i f(c_{ij})} \tag{18}$$

The main disadvantage of this group of methods is a relatively complicated calculation procedure. The analysis requires a large amount of data and information, which subsequently determines its quality. In this regard, the spatial interaction method has received limited application in practice.

Gravity-Based Accessibility

The most widely used measure for urban accessibility is the gravity-based accessibility, also called potential accessibility. The gravity-based accessibility evaluates point reachability to any other points in an urban system, where more distant or less weighted points will have a lesser impact on the final result. This is achieved by introducing a distance decay parameter and weight of destinations (Bhat et al. 2000; Geurs et al. 2004):

$$GA_i = \sum_{j=1}^{n} W_j f(c_{ij}) \tag{19}$$

where GA_i is the gravity-based accessibility of node i, W_j is a weight of node j, $f(c_{ij})$ is the distance decay function.

Gravity-based accessibility measure is useful in describing a number of interesting urban phenomena but requires more data for the analysis. Using a distance decay function with impedance parameter allows the researcher to perform more realistic modeling of spatial interactions. On the other hand, the choice of a function and its parameters require additional analysis of statistical data on trips.

Supply to Demand Accessibility

A group of methods called supply-to-demand accessibility used primarily in the field of health care can also provide new opportunities for urban studies. The approach is based on the so-called *floating catchment area* (FCA) model, initially developed from potential accessibility methods. In the earliest studies (Peng 1997; Wang 2000) a catchment area was defined as a buffer zone (with the selected threshold) around each housing location, and the jobs-housing ratio defines the job accessibility for that area. The catchment area moves from one location to another and gradually defines the accessibility for locations. Figure 25 illustrates a graphical example of FCA (Wang 2015).

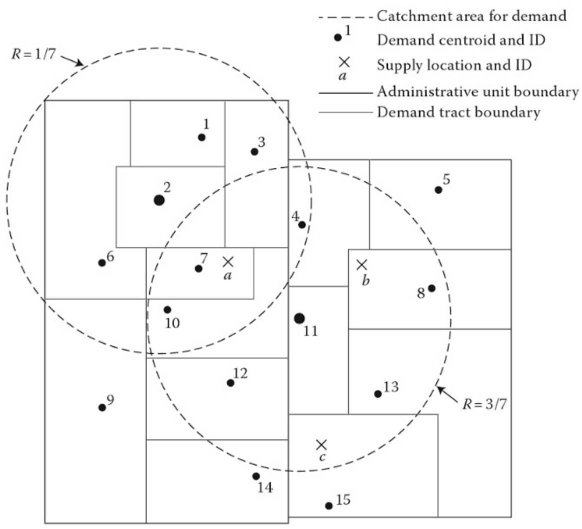


Figure 25. Example of floating catchment area model with a circle catchment. (Source: Wang 2015).

A catchment area represents a buffer with a radius equal to the threshold distance value. For walking, this value usually varies between 600 and 800 meters, though an exact threshold can only be determined on the basis of statistical data and surveys. The buffer is built from the centroid of the area (block, neighborhood) under investigation and the accessibility within the area is defined as the ratio of the supply points to the demand points (it can also be weighted by population). For instance, a buffer with a centroid at point 2 covers seven black dots (seven consumers) and one cross 'a' (one supplier). Then the accessibility of this area will have the ratio 1/7 (Wang 2015).

The main problem in a basic FCA model is the assumption that supply points within a buffer zone are all equally available to residents inside the buffer. But the distance between residents and supply points may be larger than a given threshold distance, like the distance between point 13 and supply 'a' in Figure 25. This problem can be avoided by using the two-step floating catchment area (2SFCA) method (Luo et al. 2003). As the name indicates, the model uses two steps for accessibility calculation:

Step 1 (availability of supply). To determine the strength of supply *j*, it is necessary to find how many housing locations *k* are within a threshold (distance or time) d_0 from location *j* and then compute the supply-to-demand ratio D_j.

$$D_j = \frac{S_j}{\sum_{k \in \{d_{kj} \le d_0\}} W_k} \tag{20}$$

where W_k is a weight coefficient (density, number of population, etc.) for location *k*, S_j is the number of services (number of shops, jobs, physicians) at location *j*, d_{kj} is the distance or travel time between locations *k* and *j* (Luo et al. 2003).

Step 2 (accessibility for demand). To determine the strength of demand *i*, it is necessary to find how many supply locations *j* are within a threshold (distance or time) d_0 from the area centroid and summarize the ratios in overlapping service areas.

$$A_j = \sum_{j \in \{d_{ij} \le d_0\}} D_j = \sum_{j \in \{d_{ij} \le d_0\}} \frac{S_j}{\sum_{k \in \{d_{kj} \le d_0\}} W_k} \tag{21}$$

where d_{ij} is the distance or travel time between locations *i* and *j* (Luo et al. 2003).

In Figure 26, gray areas represent catchment areas (travel time). The supply location 'a' has eight black dots (residents), so the ratio will be 1/8. For point 7 in the same catchment area, the accessibility will be 1/8=0.125. However, point 4 falls under two catchment areas and access to 'a' and 'b' suppliers. The accessibility for residents at 4 will then be the sum of ratios 1/8+1/4=0.375.

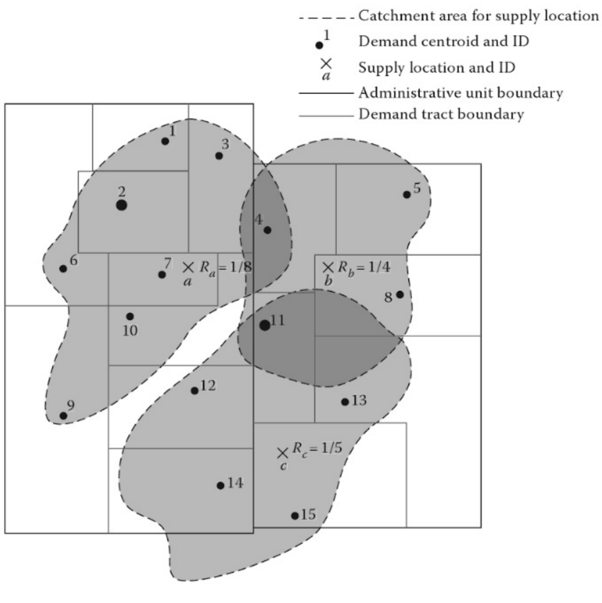


Figure 26. Two-step floating catchment area with travel time. (Source: Wang 2015).

An incomparable advantage of FCA methods lies in their ability to consider both the weight of origins as well as destinations. For example, a scholar can allocate large suppliers (hospitals with a larger capacity) by a simple weight coefficient and make them more attractive for consumers. The same can be applied for consumers, which can be weighted by dwelling density or population.

Extension and improvement in this methodology are also possible, as there is a room for its adaptation to various purposes of the planning process. One of the possibilities is to change the way that distance/travel time is entered in the calculation. In most cases, the simple Euclidean distance is used and if a distance threshold says of 1 kilometer (0.62 mi) is set, then all destination points within the given value will be considered equally accessible, and points outside the threshold will not be counted in the calculation. The methodology can be improved by introducing a transportation network and distance decay in the model. In this case, the distance is an indicator that shows the strength of the relationship between parts of urban space (Smith et al. 2015).

A decay function controls the effect of distance in the network, so more distant points will have less influence on the result. This reflects a social component, when people tend to travel longer distances for a job and shorter for shopping. The physical component, in turn, is reflected in the patterns of road network, which should also be included in the model. Then equations 20 and 21 can be rewritten as:

$$D_j = \frac{S_j}{\sum\limits_{k \in \{d_{kj} \le d_0\}} W_k \cdot f(c_{kj})} \tag{22}$$

where $f(c_{kj})$ is the distance decay function, which is taken depending on the study objectives and data availability.

$$A_j = \sum_{j \in \{d_{ij} \le d_0\}} D_j \cdot f(c_{ij}) = \sum_{j \in \{d_{ij} \le d_0\}} \frac{S_j}{\sum\limits_{k \in \{d_{kj} \le d_0\}} W_k \cdot f(c_{ij})} \tag{23}$$

Analysis using the 2SFCA method requires a large amount of input data since both origin and destination should have a quantitative attribute. Besides, the multistage calculation algorithm on a vast scale may be too demanding to hardware.

The distance decay function is an important parameter, which is introduced in models of many modern studies dedicated to accessibility estimation. To date, there are a large number of variations in the distance decay function, however, they can be classified into five basic groups, well-known in mathematics.

A *threshold* function involves setting threshold values where abrupt function change occurs (Figure 27). The values remain unchanged at a preliminarily selected distance from the start point.

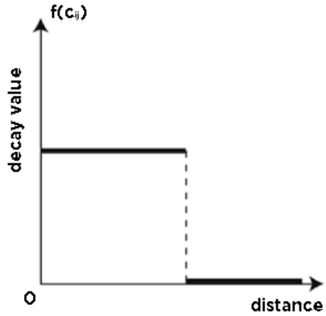


Figure 27. A threshold distance decay function (Wang 2012).

A *linear threshold* function also implies setting a threshold distance from the origin point, where its values do not change (Figure 28). A linear decrease occurs, however, when the function exceeds the threshold value.

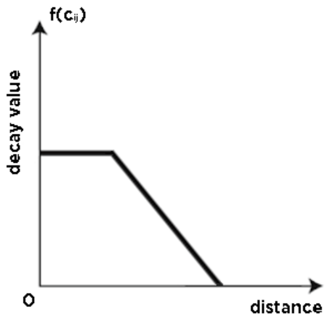


Figure 28. A linear threshold distance decay function.

Gravity-type functions imply the inverse relationship between distance and function value (Figure 29). A distance decay parameter will proportionally decrease with larger distances.

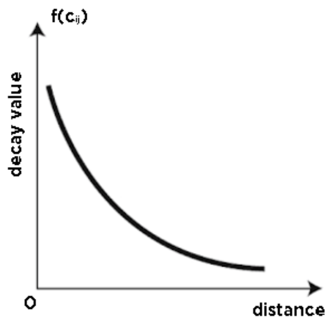


Figure 29. Gravity-type distance decay function (Wang 2012).

The value of a *Gaussian* function changes slightly for points located close to each other (Figure 30). However, with a growing distance the function slope increases and at some point approaches infinity while the value becomes essentially equal.

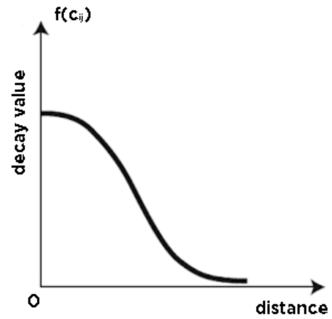


Figure 30. A Gaussian distance decay function (Wang 2012).

A *kernel* function is a certain combination of gravity-type and threshold functions (Figure 31). Function values change smoothly with increasing distance, but at some point (threshold) the curve breaks, so the points located beyond the threshold will be ignored.

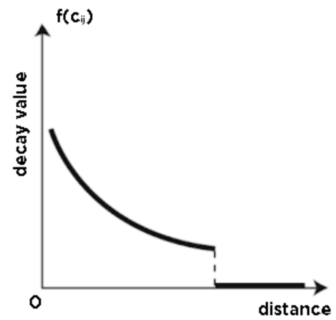


Figure 31. A kernel distance decay function (Wang 2012).

An *exponential* function with a threshold is a flexible version of the classical threshold function (Figure 32). When exceeding the threshold value, the function does not break, but changes over to exponential with a smooth decrease.

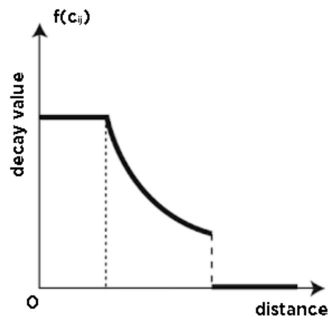


Figure 32. An exponential distance decay function (Wang 2012).

In general, using the distance decay function in accessibility assessment can also complicate the modeling process. The type of function and the value of its parameters depend on the trip purpose and it is not always possible to obtain comprehensive statistics on travel behavior for each case study. In addition, values of the function determined for a specific territory cannot be applied to another one (i.e. large scale). In this work, as a compromise between the available data and the scale of the study area, the gravity-based model will be used to analyze the spatial interaction between municipalities in the Czech Republic. In order to conduct a large-scale analysis, a multivariate approach to setting the parameters of distance decay function is used. A more detailed description will be presented in Chapter 4.

3.4 Summary

There are many empirical measures and methods of spatial analysis of urban forms. The presented review mentions the most significant and popular techniques among geographers, architects, and urbanists. Each of them has their own uniqueness and allows one to consider the complex structure of urban realm from different angles.

Cumulative measures allow researchers to map statistical information on the territory, population, environment and economy. The results of such studies are well interpreted due to the simplicity of the investigated quantities (persons per hectare, household income, etc.). Most of the initial data for research can be downloaded from the web of different authorities like statistical offices or departments of planning and development. On the other hand, taking into account the complexity of space, this group of methods does not fully explain the patterns of relations in the built environment, especially when it comes to rather fuzzy concepts such as 'land use mix'. While segregation is a fairly simple notion that can be observed by the example of many cities in North America and Australia, the same cannot be said about diversity. Moreover, while being the core idea of modern urban movements, to this day there is no clear quantitative description of land use mix. The following example will help to illustrate some of the ambiguities.

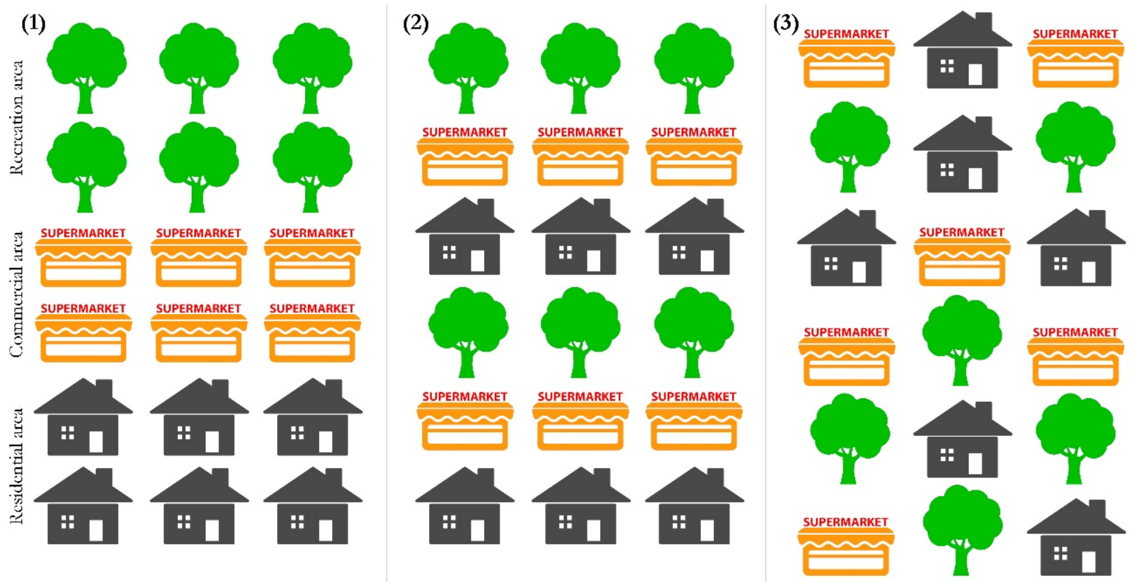


Figure 33. Different types of diversity in an urban area with the same proportion of activities. (Source: adapted from Manaugh et al. 2013).

Figure 33 shows the scheme of three fictitious urban areas with different land use patterns. The first plan is a typical segregated area where the land use is strictly divided into three neighboring blocks (residential, commercial and recreation). On the second plan, the same types of land use are distributed more evenly over two blocks, where all three types of activities are presented. Finally, the third plan shows a more diverse form of organization, where each parcel has access to all types of activities (Manaugh et al. 2013). An interesting fact is that the proportion of land use mix for all three plans will be the same, since the activities on parcels are not changing. What does change is the spatial arrangement of land use, and thus the ease of access. In this example, spatial organization, as well as the road network, will be crucial for urban realm.

Fractal methods investigate primarily the geometric features of the built environment. Through the fractal analysis one can estimate the degree of order in a seemingly chaotic composition of buildings, roads and parks. Urbanists of the old school saw orderliness in the form of perfect rectangular figures and strict lines, while modern urban movements don't hesitate to use fractal geometry to create more ingenious design. Besides the architectural application and pattern analysis, fractals can also be found in transportation studies, especially in matters of spatial coverage. The service area polygon represents the easiest way of coverage description. However, for road networks this polygon is not continuous and has a lot of gaps in its structure. Fractal analysis allows researchers to determine the spread of these gaps in the service area and estimate the degree of its coverage (Banos et al. 2011). At the same time, it should be noted that the main drawback of fractal methods is the overly strict definition of form dependencies. Fractal dimension implies that changes in observed pattern and changes in scale must follow a power law distribution (Jiang et al. 2013). This often causes problems, for example, when using simplified urban models after generalization or smoothing.

Whereas fractal geometry examines the patterns of urban organization, dimension methods describe the influence of individual local elements and their size on spatial relationships. Dimensioning is usually applied to a local scale, due to a large number of objects under study (parcels, buildings). The main approach of this group is the comparison of local forms and their size, which creates a certain subjectivity of the results. A disadvantage that should be mentioned is that most of the studies employing the dimension approach are devoted to the historical evolution of the urban environment, which in turn requires detailed historical data and their digitalization.

Finally, the last and fairly extensive group of methods considered in literature review is the graph theory. To this day, graph theory remains the most applicable technique for the analysis of urban systems. Perhaps the main reason for such popularity of graph theory is the ability to provide a relatively simple and logical description of urban layout and analyze hierarchical relations, structural patterns and other morphological features of a city. Many classical measures for graph analysis that are widely used to this day were proposed by Kansky (1963). Over time, urbanists and architects also drew their attention to the theory very popular among sociologists—centrality. Today in the field of urbanism, two very popular approaches can be distinguished—Space Syntax and MCA. Although both methods deal with the same phenomena, there are two main differences between them. The first one lies in the representation of urban system. In its original form, Space Syntax ignores some physical characteristics of the built environment, such as the shape of routes and their length, while the MCA approach introduces road network with metric distances in the analysis. The second difference lies in the very measures used to analyze urban system. Space Syntax refers to topological graph measures, where the number of steps or connections are used as a unit of distance. In contrast, MCA applied a set of centrality measures to urban graph.

In terms of practical calculations, there are several platforms (tools and toolboxes) for analyzing various characteristics of transportation networks. They use different methodologies and algorithms, but some quantitative measures remain similar for all. For example, GIS extensions like Axwoman (Jiang 2015) and Space Syntax Toolkit (Gil et al. 2015) are based on Space Syntax approach. Both tools allow one to create axial maps and calculate basic Space Syntax indices, such as connectivity, control value, depth and integration of axial lines. Others like NetworkX (Hagberg et al. 2008) and OSMnx (Boeing 2017) Python packages use the principles of classical graph theory to analyze networks in a spatial domain. Their apparent advantage is a wide range of topological and geometric measures that allow one to investigate spatial networks, including OpenStreetMap (OSM) data processing and analysis on directed graph. However, they do not offer the opportunity to explore more sophisticated (dynamic) characteristics like spatial interaction between locations (including resistance factor, travel time or weight). Standalone Python packages not as intuitive as modern GIS software platforms. In this sense, GIS software provides more freedom when manipulating geographic data, which is especially important in evolution analysis and simulation of transport system dynamics. Among the available tools for network analysis implemented in GIS software, several should be mentioned like UNA Toolbox (Sevtsuk et al. 2012), sDNA (Cooper et al. 2018) and ComplexNetGIS (Caschili 2010). The techniques are presented as toolboxes for ArcGIS software and sDNA also compatible with QGIS. The set of metrics in the mentioned toolkits is different, however, a common feature is the presence of classical centrality measures. The considered tools, however, do not offer simultaneous analysis of road networks within both static and dynamic model, so it would be appropriate for the purposes of this study to prepare more suitable algorithm.

The next part of this work will be focused on an empirical analysis of urban systems in the Czech Republic. Special attention is given to the detailed modeling and analysis of road networks in a spatial domain. The methodology that will be used is aimed at studying networks from two perspectives, namely, static and dynamic. In order to explore the complex interactions in built environment, accessibility is also considered together with population dynamics and land use.

4. Data and Methods

In this chapter, the object of the study, as well as the models and used measures of analysis, will be presented in greater detail. The methodological basis of the work consists of two models. The static model is aimed at studying the topological and geometric characteristics of the system, which describe its basic structure. The dynamic model explores changes in spatial interactions in the system over time. In particular, the evolution of accessibility patterns, as well as changes in population and land use between 2006 and 2018, are considered.

4.1 Scope of the Study

Of the great variety of elements that fill the urban environment, buildings and roads represent its main constituent parts. These elements are vital since they simultaneously breed and construct spatial relationships. Buildings represent the component of urban form where almost all of our daily journeys begin and end. In addition, they contain most of our main activities. The roads, on the other hand, give us the opportunity to get to different locations. If someone tries to choose which element is more important for the city, this would be tantamount to the question, "which came first: the chicken or the egg?". When choosing for the analysis such a complex structure as the urban form, the researcher unveils a huge field with a large number of directions and a different exploration degree. In such conditions, it is only a matter of compromise which direction to choose.

This work focuses on a study of the road network and there are several reasons for this. In order to provide a comprehensive spatial analysis, it is necessary to consider the system as a single interconnected organism. Connectedness of space in the built environment is primarily provided by roads. Whatever construction engineers would like to build they firstly make a path to the construction site for transportation of materials (Figure 34). Later this temporary path turns into paved road providing access for the citizens. Roads connect urban space and fill it with life, while buildings represent a container where this energy is stored. Besides that, places containing our daily activities mainly located along the roads. The efficiency of the road network determines the value of locations.

Figure 34. Illustration of a temporary road on a construction site.

In the long-term, roads also represent the most sustainable element of the system. The urban network is constantly evolving, but new routes almost always come from the main arteries laid several decades or even centuries ago.

If one asks a layperson what he or she thinks about urban form, a very interesting answer can be obtained, freed from confusing logic and excessive terminology used in the academic community. When people hear the collocation *urban form*, their imagination begins to create a picture of diverse streets of Paris which radiate from the Arc de Triomphe; winding paths of Venice and its narrow squares; the strict lines of Manhattan with a proud Statue of Liberty looking from afar. The bedrock of this beautiful abstract model on a subconscious level is created by streets. They can literally shape the parcels and cut the edges of buildings, such as the Flatiron Building in New York, which was erected on a triangular lot, formed when laying Fifth Avenue between 23rd Street and Broadway (Figure 35a). Or similarly, the Gooderham Building, lodged between Wellington Street and Front Street in Toronto, Canada (Figure 35b).

Figure 35. (A) The Flatiron Building in New York, USA. (B) The Gooderham Building in Toronto, Canada. (Photos: https://www.thousandwonders.net/, accessed November 15, 2017).

Topographic features and natural obstacles also influence the spatial development of our cities, which is subsequently reflected in the beautiful patterns of the network. These interesting combinations of form can be observed on the plan of London, where the graceful bends of the Thames are imprinted in the road network of the old city (Figure 36a). In the typical planned city of Perth in the west of Australia, the Swan River breaks the familiar gridiron and loop patterns (Figure 36b). However, in Bordeaux, the urban geometry, on the contrary, follows the curve of the river and forms a crescent-like structure (Figure 36c). In the self-organized city of Istanbul, the Bosphorus divides the city into two almost equal parts with their own geometries and singularities (Figure 36d).

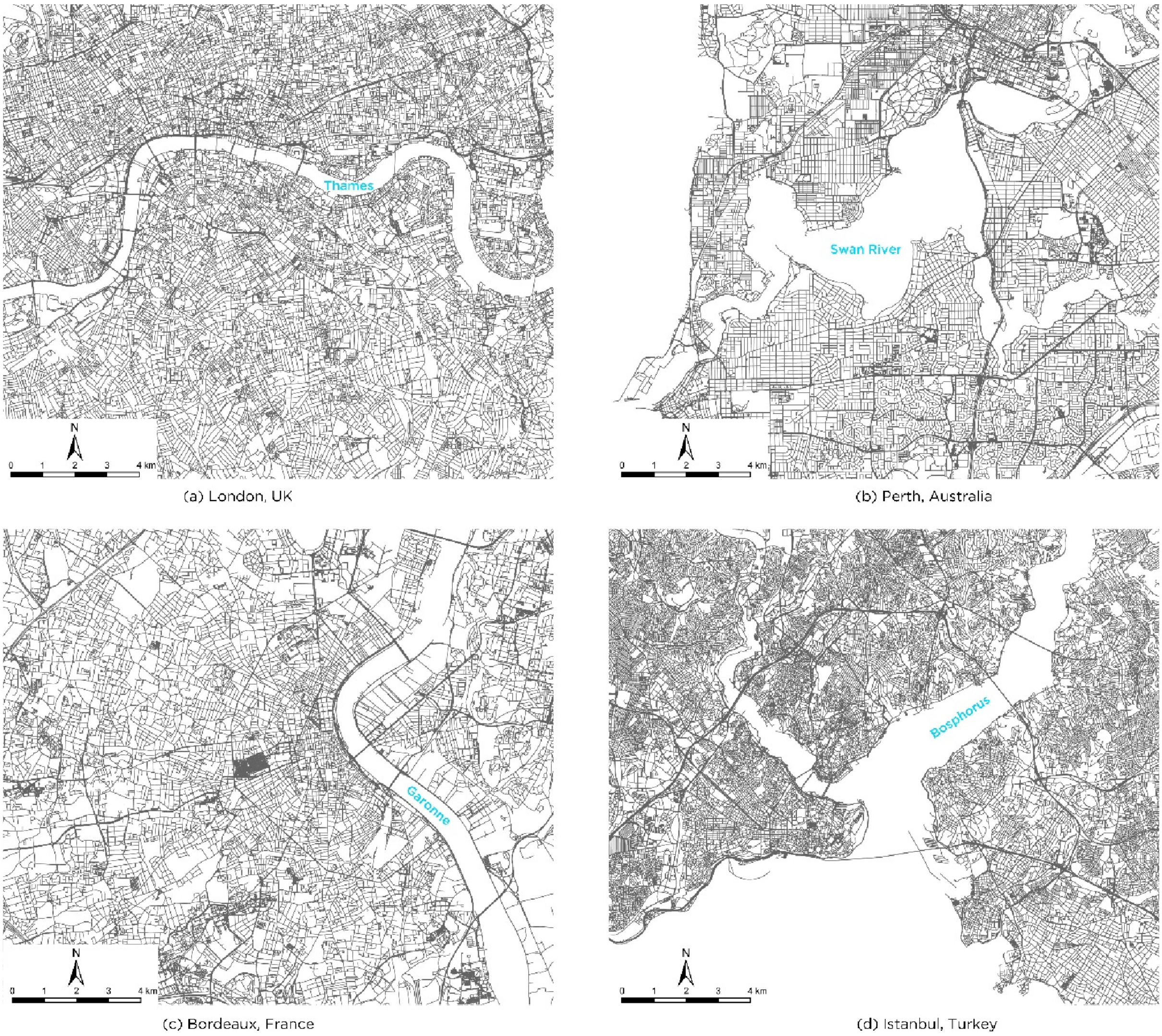


Figure 36. Hydrographic imprint in the plans of city networks.

The streets of our cities in general also follow the features of the terrain. In Trento (Italy), for example, growth occurred in the vertical axis, since horizontal development from the east and west is limited by mountainous terrain (Figure 37a). A similar pattern can be seen on the plan of the French city of Cauterets, located in the valley of the Gave de Cauterets (Figure 37b). The high mountains of the Pyrenees squeeze the city from the east and west, giving it a characteristic oblongish form. Queenstown (New Zealand), on the contrary, developed along the horizontal axis along Lake Wakatipu on the south and high mountains on the north (Figure 37c). Natural obstacles can strongly bend urban roads, such as in Chur (Switzerland) (Figure 37d). The central part of the city has a familiar radial road system, however, on the south-east the network is narrowed by mountains, where the arcs are replaced by zigzags.

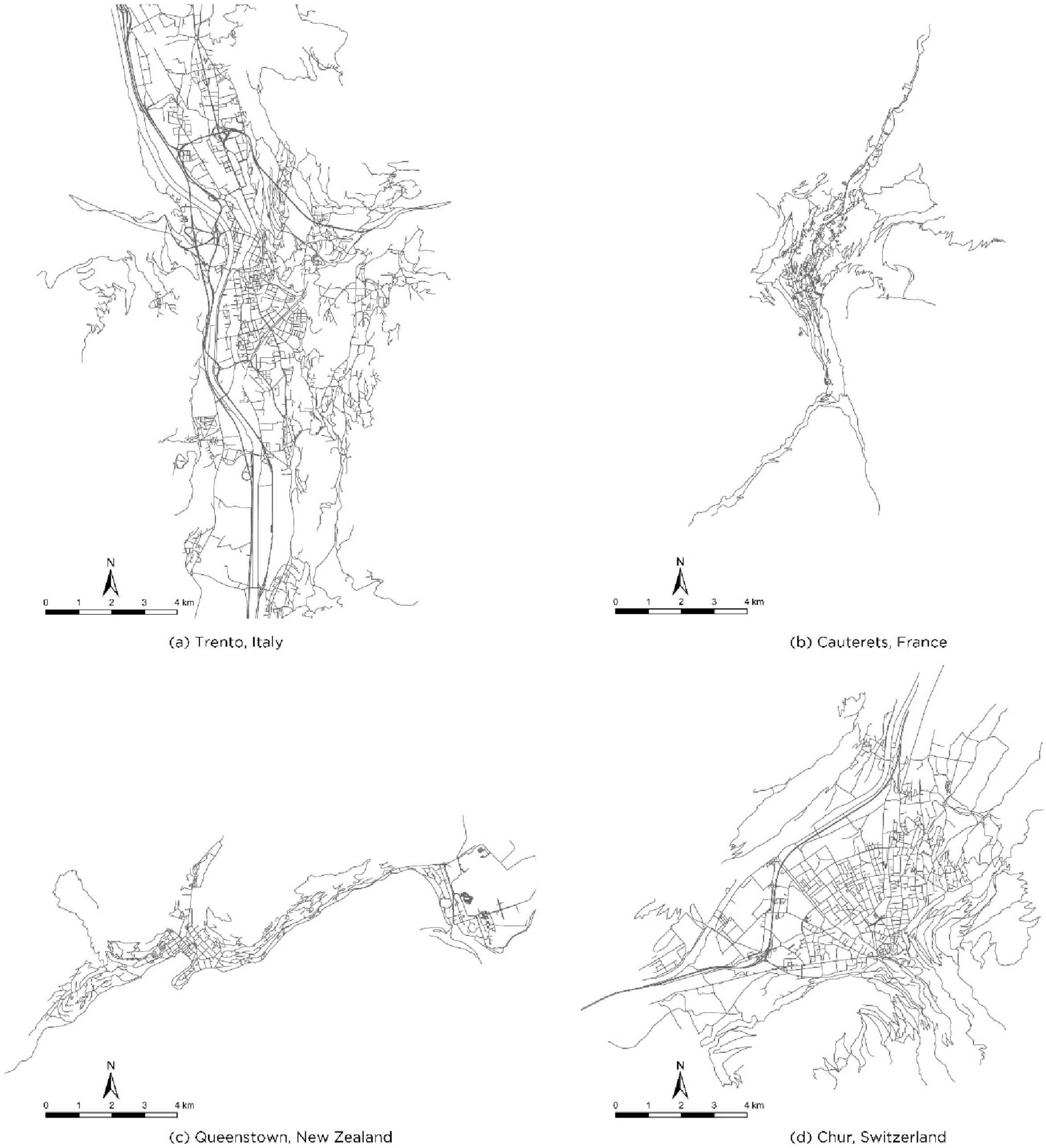


Figure 37. Topographical imprint in the plans of urban networks.

Such a visual perception of city networks is the simplest way to analyze urban form. One can see in them order or some kind of randomness, unique natural patterns, signs of regularity, intentional planning, as well as free self-organization. If we look at a building in a similar way, we will also notice the height of a skyscraper, the strict shape of a panel building or the unique architecture of a Gothic cathedral. However, this view will always be local and isolated from the rest of the system. At the same time while looking at the street plan, one will see a graceful form that can only be perceived in an aggregate manner. This form is very diverse, but in any case, it is beautiful, as it reflects a multi-year development and sometimes centuries-long history.

4.2 Context of the Practical Framework

This study considers two concepts of urban form—sustainability and continuity.

Sustainability is an important parameter of large flexible systems that shows their ability to develop while at the same time preserve the uniqueness, despite the negative factors of the external environment and possible internal conflicts. Urbanization is an example of such conflicts, which creates additional risks for cities and makes them clumsy. Sustainability, as well as the vulnerability of an urban area, can be understood through the simulation and analysis of various components of the system, such as the road network, spatial interaction, population, and land use. Flexible systems are ready to respond to and absorb possible conflicts, and adapt more quickly to new conditions and policies.

Continuity is a concept that represents the system as an integral whole in modelling, analysis and planning. It is worth noting that a consistent system does not necessarily mean a structure with only one centroid. A system of any size can be formed from many subsystems, which are, however, interconnected and create a single contour. Continuity can be seen in the example of a road network where various administrative units or locations are interconnected by links of different class and quality.

The road networks that will be presented further in the text have their unique spatial structure and form, which generally affect the functioning of the entire system. The interaction between places occurs through the road network, so its analysis is essential for planning.

4.3 Representation of Urban Realm and Data

The city, as an object of modeling, can be represented in several ways, including master plans, satellite images, historical maps, mathematical graphs or 3D models, depending on the goals set for the researcher. The development of the complex network theory in the last few decades and the rapid increase in the analytical capabilities of GIS make it possible to sufficiently simulate and analyze road networks in a link-node format. This is a very versatile technique of quantitative description of a built-up environment, which, moreover, can be simultaneously used in both static and dynamic models.

The link-node format is a well-known type of system modeling from graph theory. However, in modern conditions, when the availability of detailed data has ceased to be a problem, classical graph theory takes on a slightly different look. For instance, a link is no longer just a straight line connecting two abstract points, but a polyline which usually follows the shape of a real road segment and additionally carries important information in the form of attributes (coordinates, length, direction, etc.). Nodes, in turn, represent connecting points or end points of polylines. In addition to the typical sequence number, they may also contain a descriptive attribute such as weight parameter reflecting their importance in the system. It should be noted that the use of attribute information of system elements depends on the calculation model. For a static model, the number of elements and the length of polylines are important attributes. However, in a dynamic model, for a comprehensive analysis of spatial interactions between locations, the set of important attributes expands and includes the length, the road category, the average speed of traffic, the direction of movement and the weight of nodes. This study uses this modern representation of networks with real geometry of elements in an empirical analysis.

Data for the study were taken from multiple sources. Since the main GIS platform for empirical analysis was ArcGIS software (v. 10.4), all preliminary data were stored in a file geodatabase (.gdb). The first set of data necessary for the study consists of polygon layers. These represent different levels of territorial division of the Czech Republic such as municipalities and administrative regions (NUTS 3). The data set was obtained from the State Administration of Land Surveying and Cadastre (SALSC). To perform an empirical analysis, a detailed road network was used covering the entire territory of the Czech Republic. In addition, the country's 2006 road network was reconstructed in order to explore the dynamic model. The main sources for network data were the geographic base data of the Czech Republic (ZABAGED®) and OSM. The Trimble[5] service, which allows one to access relatively large areas, were used to extract data from OSM. In order to conduct a comprehensive network simulation, it was necessary to combine the qualities of these two data sets. This is primarily due to the use of a dynamic model where inter-urban accessibility and its evolution in the period between 2006 and 2018 are investigated. The ZABAGED® data set contains an attribute of the road category, required to determine the traffic speed in the calculation of accessibility. At the same time, OSM data contains information about unidirectional traffic roads providing more realistic modeling. Certain types of roads were selected from the detailed preliminary data, depending on the model being analyzed, but in general, the basis of the study are automobile roads. For the static model aimed at the topological and geometric properties of the network, a more detailed data were used including primary and secondary roads except for private or closed ones. In the case of a dynamic model, the focus shifts to spatial interactions and intercity accessibility estimation on a nationwide scale. Thus residential streets were excluded from the road network. After reducing the number of roads the obtained network contains motorways, 1st class roads, 2nd class roads and 3rd class roads. For the accessibility

[5] https://www.trimble.com (Accessed May 21, 2018)

evolution analysis, it was necessary to reconstruct 2006 road network. Data were compared between multiple sources, such as the ZABAGED® 2006 network, OSM 2006 historical files from planet repository, Google Earth and historical orthophoto from SALSC. The OSM 2018 network was used as the canvas for reconstruction. The final 2006 road network consists of motorways, expressways (R), 1st class roads, 2nd class roads and 3rd class roads. All data were projected to S-JTSK Krovak East North coordinate system (EPSG: 5514). Besides, networks for static and dynamic models have been carefully adjusted to avoid typical errors like overlapping lines, dangles and disconnected lines. As a result of data processing, detailed layers of the road network were prepared for an empirical analysis. When calculating accessibility between municipalities, the fastest route between points is chosen based on the time needed to overcome road segments. The time parameter is set depending on the category of road. A more detailed description is presented in subchapter 4.5.2. Additionally, the dynamic model used data on population from the Czech Statistical Office (CSO) and land use data taken from Corine Land Cover (CLC).

4.4 Study Area

Over the past few decades, the study of urban form has taken one of the leading places among the various areas of research. Currently, there are three main disciplines involved in the study of cities and their constituents—urban design, geography and transportation research. The boundary separating these three fields of study gradually dissolves. In the Czech Republic, urban research is primarily aimed at studying the composition and structure of urban space. Studies in urbanism and geography are intertwined most closely. Among them several can be mention like the work of Sýkora et al. (2011), Burian (2011), Ouředníček (2003), Špačková et al. (2016) and others. Researchers are examining transformations in the boundaries of areas (parcels), changes in their functional use (land use), analyzing the characteristics of built environment (height, density) and the organization of individual parts of the city. Studies on transportation are mainly aimed at investigating the accessibility of the territory and commuting patterns. Several works to be mentioned are Halás et al. (2014), Horak et al. (2014), Hudeček (2010). The main motivation of this thesis is to conduct a comprehensive analysis of the structure and dynamics of the road network in the Czech Republic. In order to do so, static and dynamic network models are considered. In the first case, the study of topological and geometric characteristics is carried out in a comparative manner. The road network of the Czech Republic is divided into separate regions or higher-level territorial self-governing units, according to the current administrative division of the Czech Republic. Discussion and comparison of quantitative indicators are made between these regions. Although Prague, as the capital, belongs to the highest territorial unit (NUTS 3), to preserve the size similarity in the sample it is considered as a part of the Central Bohemian Region.

In addition, a structural comparison of selected large cities as the main centroids in the country's transport system is also provided. In each region, five cities were selected. The first fourteen cities represent the administrative centers of each region, including Prague. The rest of the cities were chosen according to population starting from the highest value (Figure 38). In a dynamic model, the road network is considered as a cohesive whole without separation. Accessibility will be investigated between all municipalities of the country.

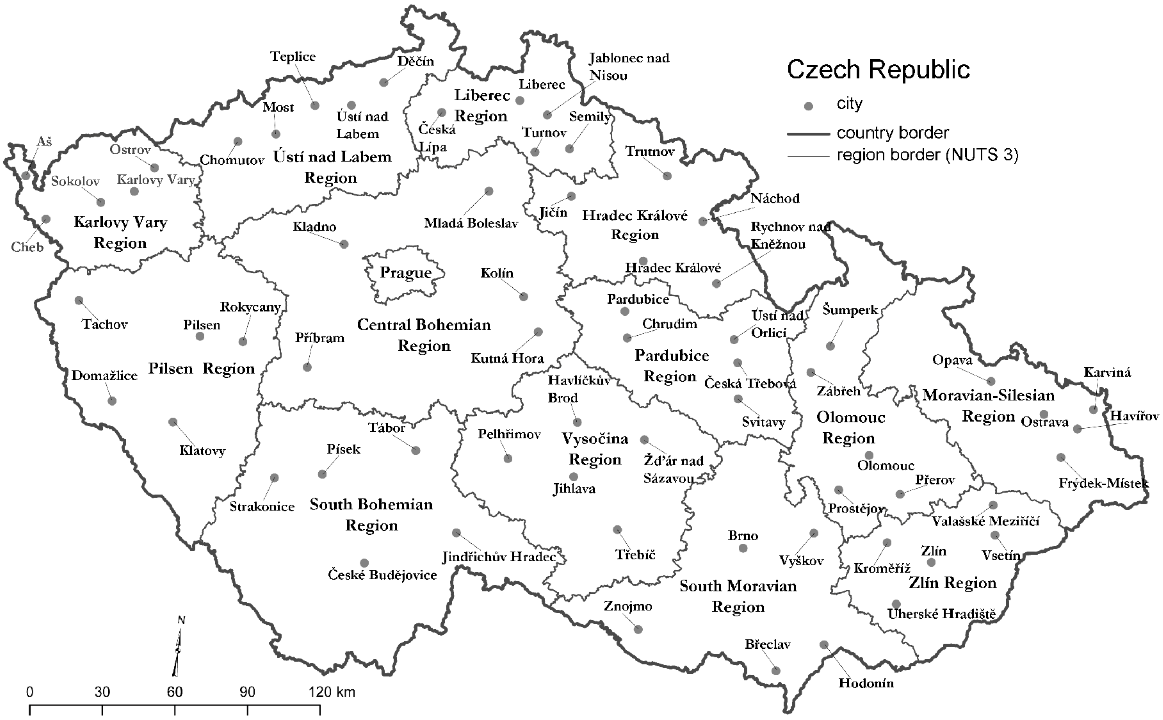


Figure 38. Representation of the study area.

In general, the study area covers a territory of 78371 km^2 for thirteen regions of the country and the capital Prague with a total network length of 107616 km. The selected cities in a static model spread across 4481 km^2 and the length of their network is 16732 km.

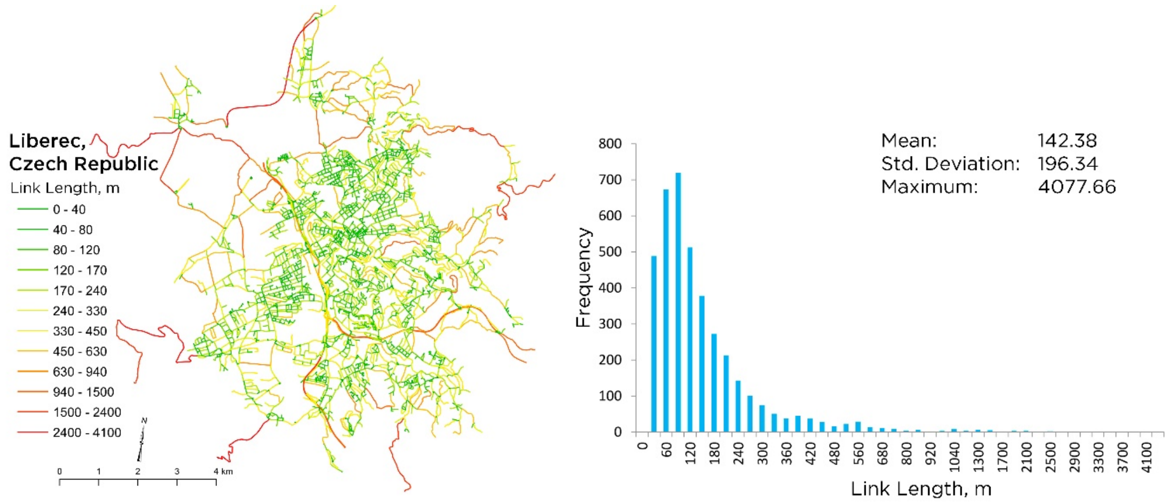
4.5 Methodological Approach

From the spatial graph used in the analysis of transportation network, it is possible to extract a large amount of different information about its properties. Having a plan of roads, one can simply apply the visual perception and determine which of the networks is more dense, more rectilinear or tortuous. On the other hand, some parameters cannot be estimated by the eye, such as the size of the network, its efficiency, compactness or location accessibility. In order to provide a quantitative analysis of the study area, a set of different measures is applied to spatial networks. Some of them were developed decades ago, while others are relatively new. Below is an overview of the measures used in the static and dynamic models.

4.5.1 Topological and geometric measures in the static model

The first group of parameters is usually used for the basic description of road networks. It includes the length and counting the number of network's integral elements, such as number of nodes (N_{nodes}), number of links (N_{links}), number of junctions ($N_{junctions}$) and total length of links (L_{links}). These parameters do not require complex calculations. A link is a polyline that represents a road segment. One link corresponds to one polyline enclosed between two nodes. A node or vertex is usually a point feature where several polylines are connected or a single polyline ends. The junction, on the other hand, represents the point where at least three polylines converge. The length of the links is taken from node-to-node, and the sum of the lengths gives the total value (L_{links}).

Figure 39 illustrates the example of length distribution on the plan of Liberec. The shortest links are concentrated in the central part of the city, with a relatively dense network. Closer to the periphery of the city, the length of segments increase, mainly because of roads connecting neighboring towns, as well as sections of highways passing through the city. The length of links can also be a simple characteristic of spatial interaction between locations as the impedance parameter.



(a) Representation of different length classes (b) Frequency distribution of links length

Figure 39. Measure of length illustrated on the plan of Liberec.

A simple count of elements can carry more information about real-world networks when studying more closely. For example, nodes are usually characterized depending on the order or degree, which is determined by the number of connected links. The most common junctions in real networks connect three (N_{deg3}) or four (N_{deg4}) road segments. In addition, roads often end in dead-ends or cul-de-sacs (N_{deg1}). To present the overall picture and take into account more complex junctions connecting five or more roads, an average value of node degree (Deg_{avr}) is taken. The degree indicates the importance of a node for a network. Usually, removing a node with a high degree can disrupt system connectivity. At the same time, road networks with high Deg_{avr} are more cohesive.

Another straightforward measure that can be applied in a static model is density. This study uses the classical density concept, which measures the concentration of events or elements per unit area. In the case of nodes, their number per square kilometer of a region or a city is calculated:

$$\rho_{nodes} = \frac{N_{nodes}}{Area} \tag{24}$$

The density of junctions ($\rho_{junctions}$) and links (ρ_{links}) is calculated in a similar way.

The next group of measures of the static model reflects the interplay of topological and geometric features of road networks.

The level of connectivity in a network can be measured by the beta index (β_{inx}). This measure defines the density of connections in the network as the ratio (Rodrigue et al. 2013):

$$\beta_{inx} = \frac{N_{links}}{N_{nodes}} \tag{25}$$

where N_{links} is the number of links in the network and N_{nodes} is the number of nodes in the network. The values of the index can vary considerably starting from zero to infinity. Usually, disconnected and tree-like networks have a value of index less than one. Networks with one cycle, in which nodes and links create a closed loop have β_{inx} equal to one. If an internal link is added to this closed loop, then the index value will be greater than one (Rodrigue et al. 2013). Thus, networks with a large index value are denser (have more links) and offer a greater variety of routes. It should be noted, however, that this index does not take into account the length of the segments in any way.

The diameter is the next index regarding network structure. It allows one to estimate the extent of a graph by determining the length of the shortest path (L_{max}) between the most remote nodes (Rodrigue et al. 2013). This parameter can also be weighted by the travel time or fuel consumption index.

$$d = L_{max}\{i, j\} \tag{26}$$

Pi index is defined as the ratio of the total length of the network (L_{links}) to the value of its diameter (d):

$$Pi = \frac{L_{links}}{d} \tag{27}$$

This measure also define the extent of a graph, however with respect to its diameter. A high value of *Pi* index indicates a more developed networks, while lower value reflects simple networks.

Pi index also displays the shape of networks as a measure of length per diameter (Rodrigue et al. 2013).

Closeness and straightness refer to a group of measures known as centrality measures. Initially, measures of centrality were introduced in sociological research, but later they gained popularity in other disciplines involved in the analysis of complex networks. The closeness centrality allows to estimate how close a node or link is to all the other elements in the graph. The closeness of location *i* in a graph *G* can be defined as the inverse of the sum of all shortest paths from *i* to all other locations in *G*. It is defined as follows (Porta et al. 2009):

$$CC_i = \frac{N_{nodes}-1}{\sum_{j\neq i} d_{ij}} \tag{28}$$

Straightness centrality shows to which extend the shortest paths from location *i* to all other locations in graph *G* match a straight line. This measure assumes that the communication between locations is effective if the route connecting them resembles a straight line. Straightness is similar to the detour index, with the difference being that it takes into account the cumulative effect of all routes from the location. It is defined as follows (Porta et al. 2009):

$$SC_i = \frac{1}{N_{nodes}-1} \sum_{j\neq i} \frac{d_{ij}^{Eucl}}{d_{ij}} \tag{29}$$

where N_{nodes} is the number of nodes, d_{ij} is the shortest path length between nodes *i* and *j*, d_{ij}^{Eucl} is the Euclidean distance between the same nodes.

Organic ratio is a measure that allows one to determine whether a city or an area was either planned, or developed as self-organized. In most urban areas, the distribution of node degree has a maximum value of three or four. The organic ratio then can be described as (Courtat et al. 2011):

$$OR = \frac{N_{deg1}+N_{deg3}}{N_{nodes}} \tag{30}$$

where N_{deg1} is the number of nodes with a degree of 1, N_{deg3} is the number of nodes with a degree of 3 and N_{nodes} is the number of nodes in the network.

Planned cities have a fairly homogeneous network with a gridiron structure. Cells can be in the form of a square or a rectangle, which is a very effective and simple standard. Most nodes in such networks have a degree of 4 (e.g. Manhattan island), thus $OR \simeq 0$. In self-organized cities, on the other hand, the networks developed without imposing the standardized patterns, so their structures are characterized by the predominance of nodes with a degree of 3 and 1 ($OR \simeq 1$) (Courtat et al. 2011).

4.5.2 Measures of spatial interaction in the dynamic model

The model implies two properties that provide its dynamic basis. The first is the purpose of the road network itself, which serves to ensure the mobility and viability of the urban environment. Here, spatial accessibility emerges as one of the main indicators of the efficiency of the transportation system. The second is the change of the network associated with its evolution. These dynamics can be examined jointly with changes in population and land use for a more complete picture.

There are many approaches to assess transport accessibility in the literature (see subchapter 3.3.4). The simplest method involves measuring the distance from the origin to the destination, and the shorter the distance, the better the accessibility. However, this approach does not take into account the potential offered by both the road network (e.g. connectivity, speed) and the territory (attractiveness). It is assumed that the higher the attractiveness of the territory, the better will be its accessibility. At the same time, if the attractiveness of two destinations is the same, then greater accessibility will demonstrate by the one that is easier to reach. To take into account these features, the study utilizes the gravity-based accessibility method in the analysis. Accessibility is usually proportional to the size of the opportunity and inversely proportional to the transportation cost (gravity model). It should be noted that accessibility in this thesis is investigated only for private transport. It is assumed that travel conditions (season, weather, day/night) are the same for all points of interest.

The general description of the gravity-based accessibility is the following (Bhat et al. 2000; Geurs et al. 2004):

$$GA_i = \sum_{j=1}^{n} W_j f(c_{ij}) \tag{31}$$

where GA_i is the gravity-based accessibility of the area i, W_j is the weight (mass) of the area j, c_{ij} is the general transportation cost separating i and j, while $f(c_{ij})$ is a distance decay function.

In order to perform an empirical analysis, three parameters should be set for the equation 31, namely the mass of the destination, the transportation cost, and type of distance decay function. First, it is worth mentioning that the dynamic model is designed to investigate inter-municipal accessibility and track its changes on a nationwide scale between 2006 and 2018. The centroids of municipalities' road network serve as origin/destination points with the population being a weight parameter. At this stage, however, several problems arose. Firstly, it would not be correct to represent large cities, such as Prague, Brno, Ostrava or Pilsen by only one point. The most suitable solution for these cities is to use the centroids of the city districts, which would act as separate municipalities in the calculations. In this scenario, it becomes necessary to check the availability of population data for 2006 and 2018 at the district level. Detailed data for Prague were taken from the CSO. In case of Brno, Ostrava and Pilsen districts, however, only the 2011 census was available as a data source. To extract the population data for each district separately, a large number of available demographic and economic reports as well as articles on the development of mentioned cities were examined. As a result, the four largest cities will be introduced in the model by 119 points, of which Prague is represented by fifty-seven points, Brno by twenty-nine points, Ostrava by twenty-three points, and Pilsen by ten points. All other municipalities will be represented by one centroid.

In general, this study implies that accessibility of cities is becoming an important factor in their growth, as the intensity of interactions between them increase. In this case, the population may be an indicator of attractiveness for the labor market or commercial development (Biosca et al. 2013). At the same time, population is the force that molds the space, therefore it can be assumed that improvement in accessibility of the territory increases its vulnerability to urban expansion. Suburbanization is an example of such expansion. The high accessibility of suburban areas makes them more attractive for housing and commercial activities, but at the same time, these territories become vulnerable, especially their natural resources (agricultural land and forests) where development usually takes place. Thus, in order to keep the urban development process under control, it is important to assess the dynamics of changes in accessibility, the spatial distribution of population and changes in land use, including urbanized and natural areas. Special attention is given to these issues in the dynamic model.

4.5.2.1 Transportation cost

Transportation cost is a critical parameter in estimating spatial accessibility. The most commonly used cost parameters are Euclidean distance, network distance, Manhattan distance, travel time or economic costs (e.g. monetary or fuel). Not all of them, however, fully describe the complexity of spatial interactions. The Euclidean distance does not take into account the features of the road network, therefore the spatial component is excluded from calculations. Model with network distances implies the use of the urban network, however, only one of its components is taken into account—the length of roads. The problem that arises here is that the distance along two separate routes may be the same, but if roads fall into different categories the speed of overcoming them will be different. The use of economic costs in the calculations may require a large amount of data that is not always possible to obtain. Considering the above, the travel time is used as a cost parameter in calculations. In this case, the speed of overcoming each section of roads plays a key role.

There are many factors that affect the speed of traffic, but among the most significant ones, several can be distinguished like the road category, road width, curvature, slope, road surface, speed limits, land use type in the area where the road passes, season, traffic load and vehicle's characteristics (Hudeček 2008). In practical calculations, however, many of these factors are very difficult to consider due to lack of data. Another problem is that considering the size of the study area it would be troublesome for all the mentioned factors to be taken into account simultaneously. In this regard, given the available data and their quality, the category of roads and land use will serve as the main factors affecting average traffic speed. The categories of roads for 2018 OSM dataset have been adjusted to align with data from ZABAGED® 2018. The adjustment of road categories for 2006 was carried out in accordance with the 2006 version of ZABAGED® data. Land use data for the relevant period were taken from CLC. Specifically, the attention was given to urbanized areas (continuous and discontinuous urban fabric) where average traffic speed is lower than outside the city. The average speed values were taken from (Hudeček 2008) and with some adjustments were assigned to each section of roads (Table 1).

Table 1. The average speed values used in road network

Road type	*Average speed (km/h)*	
	Within urbanized area	*Outside urbanized area*
Motorway	-	115
Expressway (for 2006)	-	110
1st class roads	40	80
2nd class roads	30	70
3rd class roads	20	40

To obtain the time impedance value that can be used in accessibility analysis, the following equation was used (Hudeček 2008):

$$t = \frac{L_l \cdot 60}{v} \tag{32}$$

where t is the time impedance in minutes, L_l is the road segment length in kilometers, v is the average speed in km/h. As a result, the attribute *travel_time* was added to both datasets for 2006 and 2018.

4.5.2.2 Distance decay function

The distance decay function is an important parameter when using gravity-based accessibility method. There is a wide variety of decay functions however the most commonly used are (Östh et al. 2016; Ma et al. 2018):

the power-decay function $f(t_{ij}) = t_{ij}^{-\beta}$ (33)

the exponential-decay function $f(t_{ij}) = e^{-\beta t_{ij}}$ (34)

the Gaussian-decay function $f(t_{ij}) = e^{-t_{ij}^2/\beta}$ (35)

Compared to real observations, the power and exponential functions tend to decline too fast from the origin (Ingram 1971). This is not entirely correct when studying automobile accessibility. Using the Gaussian (convexo-concave) function is more appropriate in this case since it has a smoother decline of values near the origin and best reflects the migration of the population (Grasland et al. 2000).

In equation 35, the unknown quantity is the impedance coefficient β, whose value affects the decline rate of the function. Ideally, β should be set according to travel behavior data in order to ensure the best fit of decay function. The calibration process should be based on reliable and detailed data, which is usually taken from censuses (Halás et al. 2014; Tesla et al. 2015). The problem, however, arises from the fact that values calibrated for a specific study area cannot be transferred to another territory. In addition, the purpose of trips for which function parameters are determined is of great importance. With the absence of all necessary information for setting function parameters, an alternative multi-scenario approach can be employed when β values will depend on the predetermined fraction P of the population that will be taken into account in the accessibility score at the time t_{ij} (O'Kelly et al. 2003):

$$e^{-t^2/\beta} = P \tag{36}$$

The most commonly used value of weight fraction P in literature is 0.5 (O'Kelly et al. 2003; Östh et al. 2016). Thus, from equation 35 the β can be expressed as:

$$\beta = -\frac{t^2}{\ln(0.5)} \tag{37}$$

Table 2 presents six β values that will be utilized in accessibility analysis.

Table 2. Impedance coefficient values used for the Gaussian decay function

Travel time (min)	*β value*
10	*144.269*
20	*577.078*
30	*1298.426*
40	*2308.312*
50	*3606.738*
60	*5193.702*

Algorithms for accessibility estimation on detailed data can be very time-consuming and demanding to hardware. In order to optimize the calculation process, the threshold parameter is used, namely the maximum travel time. This forced step is caused by the large scale of input data for the dynamic model covering the entire country. In general, the study area contains more than 6000 points representing municipalities. The analysis of mutual accessibility of such a large number of points would make the calculation too long, if at all possible. Given this fact, the threshold is set to 120 minutes.

4.5.3 Calculation Model

The analytical part of the work, including calculations and network modeling, is performed using ArcGIS 10.4. In addition, the ArcGIS Network Analyst extension is used to solve routing tasks. In order to automate calculations, a set of tools was developed in ModelBuilder environment (Figure 40). Each tool contains several steps representing both standard functions available in ArcGIS as well as additional processes programmed in Python.

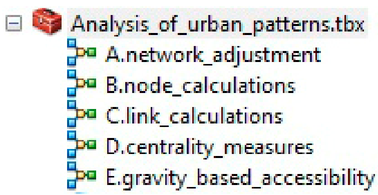


Figure 40. A set of tools used for calculations (can be found on the attached CD).

The first tool A.network_adjustment was used to prepare the preliminary network data for further analysis within the static and dynamic models. For example, in real-world networks, roads that intersect in one plane form a junction. The same connectivity rule is applied to modeled networks. In addition, for roads carrying unidirectional traffic, two types of standard Network Analyst weights are assigned, such as 'FT' allowing the traversal of a link along the digitized direction, and 'TF' allowing the traversal against the digitized direction. These features are used in routing tasks.

The next tool B.node_calculations forms the nodes of the network for a static model and calculates several indicators, including number of nodes, number of junctions, node degree, separately calculates the density of elements (nodes, junctions and links), total link length, beta index, counts the number of dead-ends, the number of junctions with the degree 3 and 4, calculates the organic ratio. It should also be noted that at the end of roads that are cut off by administrative borders, the nodes are not created. This is due to the fact that, in reality, these roads continue beyond the borders of a city (region) and it would be incorrect to add a node there, which topologically will represent a dead-end.

The C.link_calculations and D.centrality_measures tools require the creation of the Network Dataset, since they use the length of the shortest path in the calculation of indices within a static model. The Network Dataset is created from the output file of A.network_adjustment tool. The C.link_calculations tool determines the diameter and pi index for the network, while D.centrality_measures calculates Euclidean distance, closeness and straightness.

The E.gravity_based_accessibility tool is designed for network analysis within a dynamic model. It calculates values of inter-municipal accessibility for six impedance coefficients. The Network Dataset is also created from the output file of A.network_adjustment tool which contains information on links with unidirectional traffic. The population of municipalities for the corresponding periods is used as a weight parameter. The tool is applied separately to the 2006 and 2018 network datasets.

5. Spatial Analysis within the Static Model

The static model is primarily aimed at studying the topological and geometric characteristics of the road network. It is noteworthy that spatial networks can exhibit different properties at different scales. Therefore, in this chapter, the quantitative analysis and comparison of the network structure are conducted for the NUTS 3 regions and selected LAU 2 cities of the Czech Republic.

5.1 Exploratory Analysis of networks at the NUTS 3 level in the Czech Republic

Table 3 contains the basic topological and geometric characteristics of networks for thirteen regions of the Czech Republic ordered by the population starting from highest to lowest. Please note that Prague is presented as a part of the Central Bohemian Region to preserve the size similarity in the sample. The analysis at this scale shows a fairly wide range of values.

Table 3. Basic characteristics of studied regions and their road networks

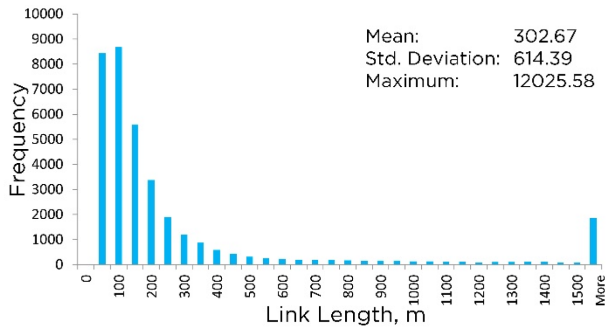
№	*Region*	*Population 1.1.2018**	*Area (km^2)*	N_{nodes}	N_{links}	$N_{junctions}$	*Total L_{links} (km)*
1	*Central Bohemian*	2647308	11424.52	84223	112341	64869	22401.29
2	*Moravian-Silesian*	1205886	5430.52	35094	44836	25628	9755.99
3	*South Moravian*	1183207	7185.87	33173	43037	24892	9380.07
4	*Ústí nad Labem*	821080	5338.64	25803	33911	19710	7884.36
5	*South Bohemian*	640196	10058.16	27579	36055	21006	10912.84
6	*Olomouc*	633178	5271.53	21908	28133	16203	6762.49
7	*Zlín*	583056	3961.50	19078	23611	13385	5049.01
8	*Pilsen*	580816	7648.59	24075	31256	17910	8928.40
9	*Hradec Králové*	551089	4759.22	20157	26220	15156	6729.06
10	*Pardubice*	518337	4519.56	19236	24942	14403	6284.84
11	*Vysočina*	508916	6795.09	21164	27640	16125	8357.77
12	*Liberec*	441300	3163.61	17165	22647	13239	5185.26
13	*Karlovy Vary*	295686	3310.12	9929	12791	7340	3588.01

* The data on population is taken from the CSO.

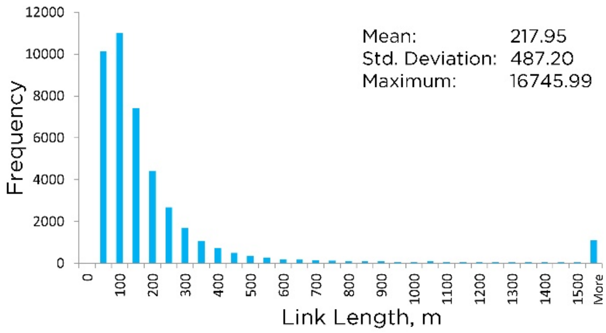
The Central Bohemian Region represents the largest urban area in terms of all indicators presented in Table 3, which is unsurprising due to its central position in the country. A significant impact on the network structure here is having Prague as a main centroid for interstate highways. In terms of size, the Liberec Region has the smallest area; however, the Karlovy Vary Region distinguished by low values of other parameters. This western region of the country has a rich environmental resources (forests, cliffs, mineral water springs), including landscape protected areas and military training area (Hradiště), which together have an impact on the features of the road network.

When comparing the two extremes from Table 3, it can be seen that the largest region has nine times as many nodes and junctions as the Karlovy Vary Region, nine times as many road links and its traffic network is six times longer. In general, the average size of urban region in the Czech Republic is 6000 km^2, its road network is 8500 km long and has 27600 nodes of which 20700 are crossroads.

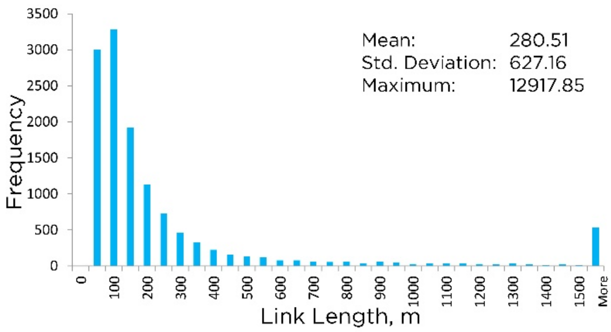
The length of roads is an important attribute that displays spatial configuration of the network. Long roads of high category usually represent the backbone of the network, while short streets allow one to trim off the distance between locations. The length may also reflect the degree of urbanization as link length typically decreases in areas with a high built-up density. Figure 41 shows the chart of link lengths distribution for four regions of the Czech Republic.



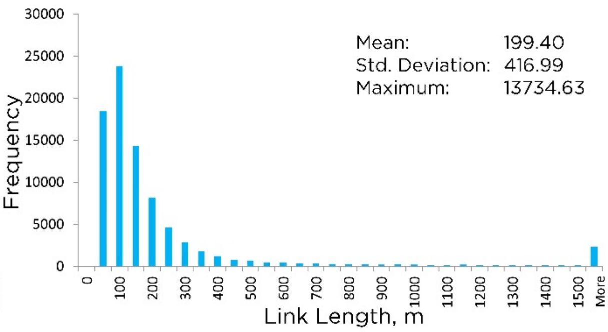
(a) Link length distribution for the South Bohemian Region



(b) Link length distribution for the South Moravian Region



(c) Link length distribution for the Karlovy Vary Region



(d) Link length distribution for the Central Bohemian Region

Figure 41. Length distribution charts for selected regions.

Common to all studied networks is the trend towards shorter links, which is considered more efficient and sustainable since networks with short segments offer a greater variety of routes. The distribution of link lengths has a similar shape for all thirteen regions with a single peak in the range of 50 to 150 m. When examining the lengths in more detail, however, greater differences between networks can be noticed. The South Moravian Region has the highest number of short segments in the network, where 93% of roads lie in the length range of 1-500 m, reflecting the typical dimensions of a dense urban environment. In the same region, 4.5% of roads have a length between 500-1500 m and 2.5% are longer than 1500 m. The South Bohemian Region, in contrast, has the longest streets, where 86% of edges are in the range of 1-500 m, 9% have a length between 500-1500 m and 5% are longer than 1500 m. The Karlovy Vary Region also belongs to those with elongated links. Its network has 88% of roads that belong in the range of 1-500 m, while 8% are in the range of 500-1500 m and 4% are longer than 1500 m. In the Central Bohemian Region, 93% of links lie in the length range of 1-500 m, 4.7% have a length between 500-1500 m and 2.2% are longer than 1500 m.

With topological quantities from Table 3 it is possible to read the basic characteristics of a network, however, they can also be used further for a deeper analysis of the system. Table 4 presents an exploratory analysis of road networks for thirteen regions. The parameters given here also reflect a wide variety of values, since the same topological characteristics from Table 3 were used for their calculation.

Table 4. Exploratory analysis of NUTS 3 road networks

№	Region	ρ_{nodes} (1/km)	$\rho_{junctions}$ (1/km)	ρ_{links} (km/km²)	Deg_{avr}	β_{inx}	N_{deg1}	N_{deg3}	N_{deg4}	Organic (OR)
1	*Central Bohemian*	7.372	5.678	1.961	2.660	1.334	19354	55062	9537	0.884
2	*Moravian-Silesian*	6.462	4.719	1.797	2.546	1.278	9466	22686	2888	0.916
3	*South Moravian*	4.616	3.464	1.305	2.587	1.297	8281	22131	2676	0.917
4	*Ústí nad Labem*	4.833	3.692	1.477	2.618	1.314	6093	17440	2217	0.912
5	*South Bohemian*	2.742	2.088	1.085	2.606	1.307	6573	18755	2214	0.918
6	*Olomouc*	4.156	3.074	1.283	2.553	1.284	5705	14615	1562	0.928
7	*Zlín*	4.816	3.379	1.275	2.467	1.238	5693	12198	1165	0.938
8	*Pilsen*	3.148	2.342	1.167	2.588	1.298	6165	15558	2295	0.902
9	*Hradec Králové*	4.235	3.185	1.414	2.592	1.301	5001	13415	1709	0.914
10	*Pardubice*	4.256	3.187	1.391	2.582	1.297	4833	12799	1582	0.917
11	*Vysočina*	3.115	2.373	1.229	2.601	1.306	5039	14530	1557	0.925
12	*Liberec*	5.426	4.185	1.639	2.628	1.319	3926	11809	1394	0.917
13	*Karlovy Vary*	2.999	2.217	1.084	2.559	1.288	2589	6568	747	0.922

The Central Bohemian Region has the most dense traffic network leading in all three density indicators (nodes, junctions and links length per sq. km of the territory). It is followed by the Moravian-Silesian Region, which also stands out for its high network density. At the other end of the range is the South Bohemian Region, which however has a specific landscape with a predominance of wooded areas (in the south-west) and agricultural land. Being the second largest region of the country, it has the lowest values for all areal density indicators. In terms of overall efficiency, this means that its network has an enlarged cell structure, which increases travel distance between locations. This is confirmed by the average link length in the network, which for the South Bohemian Region has the highest value of 303 m. The Central Bohemian Region has the opposite extremum for the average link length with a value of 199 m. Figure 42 displays the general trend for the study area when the average link length decreases with increasing density of nodes. The relationship has a logarithmic form with $R^2 = 0.864$. Such a pattern is unsurprising since when new junctions added to the network, they form finer cells in it thereby reducing the distance.

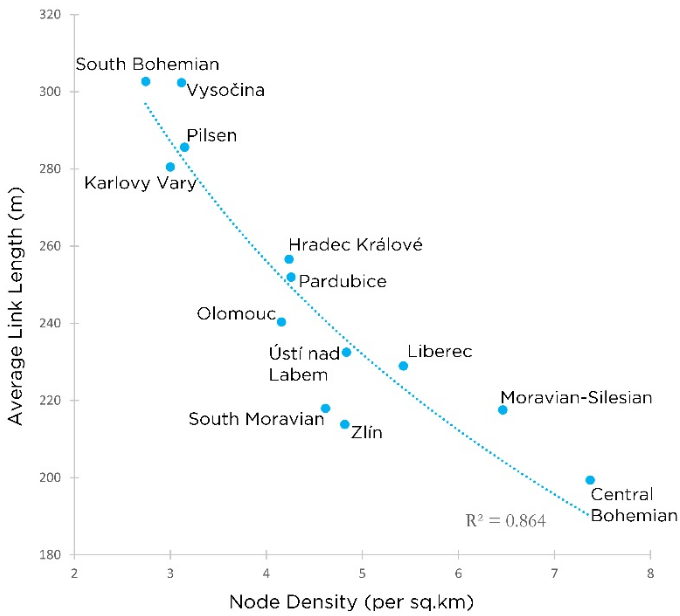


Figure 42. Average link length in studied networks versus the density of nodes.

A node degree is a straightforward parameter to characterize vertices and connectivity in the network. The values of average node degree (Deg_{avr}) for the Czech regions lie in a narrow span between 2.467 and 2.660, with the average value of 2.584 over all regions (from Table 4). It is interesting to note that the value of 2.584 for the entire country is lower than the average node degree of 2.86 for the interstate road network in the US presented in (Gastner et al. 2006). The US interstate network does not include a dense grid of local urban roads, however its value of the average order is still somehow bigger than that of the Czech network with local roads. Usually, in highly urbanized areas, the road network tends to be a parallel rectangular shape with the predominance of junctions with degree 3 and 4. This is primarily due to human understanding of the ideal shape, the economic feasibility and ease of construction. The overall value of 2.584 indicates an irregular web-like structure of the network with a large number of three-arm junctions, some cul-de-sacs and a low count of rectangular grids. To confirm that last assumption, the pattern of network evolution can be investigated using the organic ratio (*OR*) and node degree values. Urban networks with the predominance of degree 3 and 1 can be considered as organic, i.e., they grew gradually following the natural evolution of urban areas without strict typology (Courtat et al. 2011). On the other hand, structures with a typical degree 4 or higher are coherent and consist of planned shapes (grid-like). With the exception of the Central Bohemian Region, the rest of considered networks have the organic ratio value greater than 0.9 with an average of 0.92 for the entire country (see Table4). This value shows that 92% of the territory of the Czech Republic is self-organized. Most of the Czech cities have a strong historical core, so the road network evolved independently from settlement-to-settlement without imposing a single global pattern. For the sake of contrast, in the well-known planned cities such as Indianapolis or New York (especially Manhattan Island), the value of organic ratio will be less than 0.5 showing a significant predominance of typical four-arm junctions from the total number of nodes.

The distribution of node degree for all studied regions has a typical single peak at the value of 3, then decreases exponentially and usually ends at the rarest value of 6. Figure 43 shows the distribution of node degree for the Central Bohemian and Zlín Regions as well as the mean value describing a typical urbanized region in the Czech Republic in a semi-log scale.

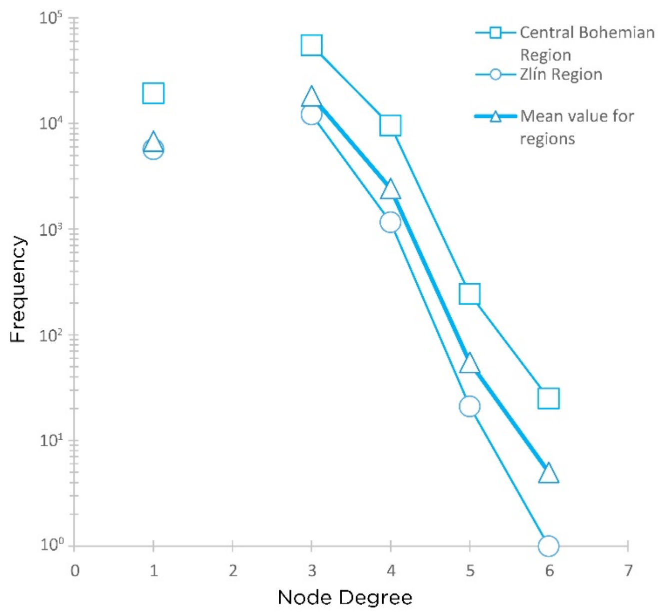


Figure 43. Histogram of node degree distribution for selected regions.

The range of node degree values (N_{deg1}, N_{deg3}, N_{deg4}) represent a very homogeneous structure (see Table 4). The relative difference between the maximum and minimum value is about 6% on average. For example, in the Liberec Region, 23% of nodes have a degree of 1, while in the Zlín Region this value is 30%. The number of nodes with a degree of 4 is very low for all regions. These vertices represent junctions with four arms and their high percentage in the network indicates its gridiron pattern. In the Central Bohemian Region network, 11% of nodes have a degree of 4, however, this value is still very low for the network to be considered as a regular grid. In the Zlín Region, only 6% of junctions have four arms, which is the smallest value among the study regions. The average region of the Czech Republic has 25% of dead-ends, 66% of nodes with a degree of 3 and only 8% of nodes with a degree of 4. The average value of beta is 1.3, which is relatively low and corresponds with a high number of three-way junctions.

In the context of sustainability and safety rate, the four-arm junctions are more dangerous. T- and Y-junctions usually have fewer accidents and injuries than four-arm junctions. The main reason for that is having far less points of possible collision when compared to four-arm junctions (Wolhuter 2017). It is also may be assumed that the priority of movement is clearer at three-arm junctions, so there is less chance of a driver making a mistake. They also accelerate traffic flow in the network due to lower waiting time.

Another important observation can be made by analyzing the relationship between the degree of nodes and the length of the attached links (Chan et al. 2011). The degree of a node in some way represents the variety of possible routes, while the link length determines the amount of space that must be overcome in order to reach the desired location. The application of the Pearson correlation coefficient to the mean values of node degree and link lengths showed a very weak relationship between the variables. To examine the presence of some trend, a more detailed analysis of the quantities was performed. In this regard, for each degree value found in studied regions, the distribution of the average length of roads that emanate from it was considered. Figure 44 represents a chart in which the horizontal axis shows the average link length for the four classes of node degree.

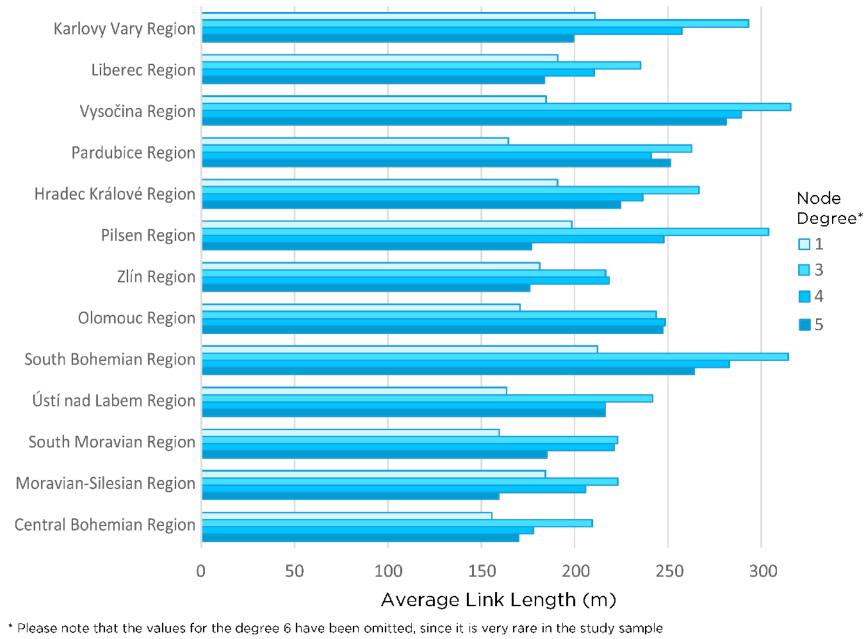


Figure 44. The distribution of the average length of roads that emanates from nodes with the corresponding degree.

The overall chart, which takes into account individual regions and the degree of nodes, depicts a clearer relationship between variables. It can be seen that shorter road segments converge at the nodes with a higher degree. The form of the relationship looks similar for the studied regions. Roads that lead to dead-ends are characterized by a short length; after that, however, the link length increases sharply for the degree of 3 and then gradually falls with growing node degree (Figure 44). This trend is well-visible on the chart of the average value of the same indicators over all regions (Figure 45).

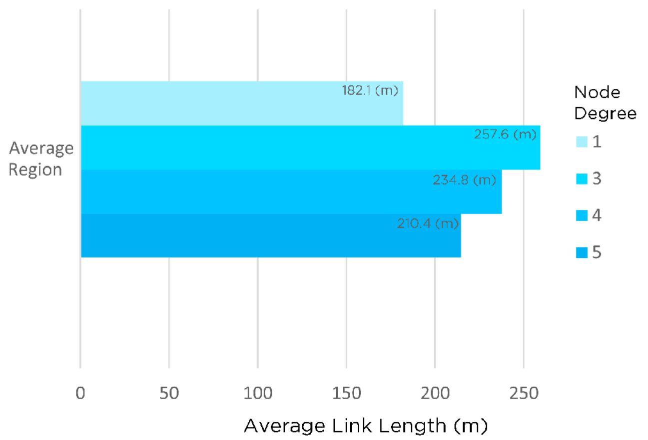


Figure 45. The distribution of the average length of roads that emanates from nodes with the corresponding degree in the average region.

Such behavior in the distribution of quantities can mainly be explained by the scale of studied networks. As it was already identified in this study, urban networks in the Czech Republic are self-organized, with a great predominance of three-arm junctions and in general have a web-like pattern with irregular cells. These characteristics are also combined with a polycentric structure, where cities and small settlements represent nodules in the web with a relatively high density of roads. Since most of the networks have an irregular form, the connection between these nodules is made through curved, and at the same time, long roads (Figure 46). In almost all cases, with the exception of the Zlín and Olomouc Regions, the longest roads are observed at three-arm junctions, which dominate both in the dense municipal networks and transregional highways. In this regard, the sustainability of the networks should be viewed from two perspectives. The presence of a large number of three-arm junctions in organic networks may contribute to better safety rates. At the same time, the length of roads at typical three-arm junctions is somehow longer than that at the other nodes. From this perspective, four-arm junctions connect shorter segments. Besides, gridiron structures usually offer a greater variety of routes. Due to the high connectivity of roads, there is also a better provision of short cuts between different locations in such networks. This duality should be the subject of discussion when choosing a transportation planning strategy. One can also note that in most cases, the shortest roads are connected to a dead-end (Figure 45). It can be explained by the fact that in regional networks, dead-ends do not usually appear on arterial roads. The links that lead to dead-ends are very short in length, since most of them belong to residential networks and are often truncated by private land or represent a driveway.

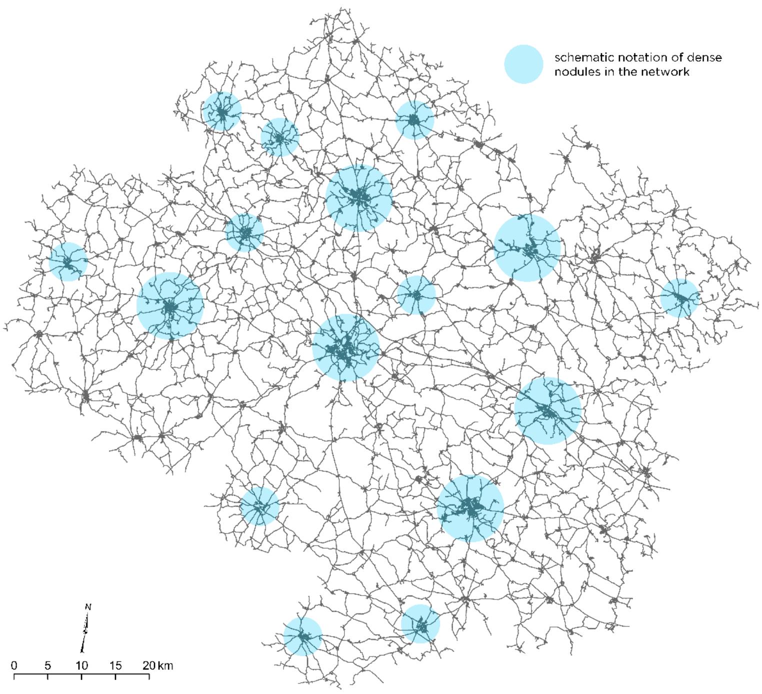


Figure 46. An example of an irregular structure of a road network in the Vysočina Region.

5.1.1 Summary

This section presents the results of an empirical analysis of road networks at NUTS 3 division level in the Czech Republic. Macro-scale analysis aimed at studying the main characteristics, helped to reveal similarities and differences of urban networks, to describe the form of relationship of their elements and to track some historical imprints imposed on urban form at a large geographical unit. The results show that the properties of studied networks vary from region to region, however, at the overall, some common patterns can be determined.

The development of urban areas in the Czech Republic occurred through self-organization. This is confirmed by the values of the organic ratio and significant predominance of nodes with a degree of 3 in all regions of the country. Such urban systems grow independently without strict planning or imposing a certain pattern. Spatial evolution and interaction gradually led to the unification of settlements, thereby giving a form to the entire urban system. On the macro-scale, self-organization leads to another common trend for studied regions, when the most numerous three-arm junctions connect on average the longest streets. In this regard, it is possible to identify some peculiarities of the typical network structures. In general, three-arm junctions demonstrate better safety rates, due to fewer collision points (Wolhuter 2017). On the other hand, nodes with higher degree provide better communication between places and offer more route options. These factors should be considered when planning transportation networks.

Among the characteristics of individual regions, several qualities can be identified. The Central Bohemian and Moravian-Silesian Regions can be referred to as the most urbanized. It is worth mentioning that the dense network of Prague has a significant impact on indicators of the Central Bohemian Region. The Moravian-Silesian Region ranked as the second most populous and its network has one of the densest structures. Urban form here is primarily determined by the industrial capacity, which was the main driving force behind the formation of a dense road network, especially in the southeast. The region also belongs to those with the shortest streets having the average length of 218 m. In terms of network density, the least urbanized areas are the South Bohemian Region and the Karlovy Vary Region, which have a stretched road networks with the longest average segment length of 303 m and 281 m respectively. The presence of vast natural landscape as well as large military areas have a strong influence on the network of these regions.

5.2 Exploratory Analysis of networks at the LAU 2 level in the Czech Republic

This section continues the analysis of networks within the static model, however, the attention is shifted to the LAU 2 level. Despite the fact that cities in the sample belong to the same country and the same urban traditions, not all of them were developed by a one standard scenario. For example, their administrative significance as well as natural obstacles have a strong influence on the overall network structure. The complete analysis outcomes for the entire sample can be found in Appendix A. In the following text, a short version of the results is presented. Basic topological and geometric characteristics of selected networks are presented in Table 5.

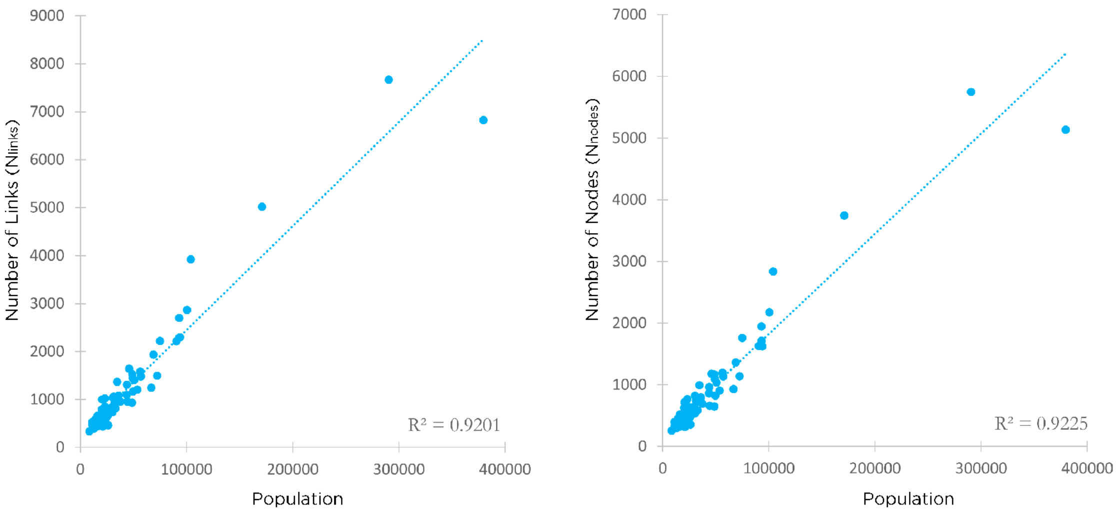
Table 5. Basic characteristics of selected cities and their road networks

№	*City*	*Population 1.1.2018**	*Area (km^2)*	N_{nodes}	N_{links}	$N_{junctions}$	*Total L_{links} (km)*	*Avr. L_{links} (km)*
1	*Prague (max.)*	1294513	496.17	20136	28664	16570	3590.901	125.276
2	*Semily (min.)*	8421	16.31	255	335	193	62.397	186.259
3	*Vsetín*	26109	57.61	355	464	262	105.253	226.839
4	*Kladno*	68804	36.97	1361	1936	1129	210.637	108.856
	County seats:							
5	*Brno*	379527	230.18	5136	6825	3866	1034.038	151.507
6	*Ostrava*	290450	214.22	5749	7669	4408	1138.442	148.447
7	*Pilsen*	170936	137.67	3745	5020	2769	654.063	130.291
8	*Liberec*	103979	106.09	2838	3923	2324	558.566	142.382
9	*Olomouc*	100494	103.33	2177	2865	1622	416.340	145.319
10	*České Budějovice*	93863	55.60	1625	2300	1313	306.453	133.24
11	*Ústí nad Labem*	93040	93.97	1712	2289	1318	364.859	159.396
12	*Hradec Králové*	92917	105.68	1946	2701	1551	397.757	147.263
13	*Pardubice*	90335	82.65	1630	2218	1258	310.177	139.845
14	*Zlín*	74947	102.83	1761	2221	1235	331.031	149.046
15	*Jihlava*	50724	87.87	1035	1408	827	251.425	178.569
16	*Karlovy Vary*	48776	59.08	1166	1528	877	229.159	149.973

* The data on population is taken from the CSO.

The considered networks show a wide variety of basic characteristics. Prague has the most complex and developed network, which leads in all topological and geometric parameters. Being the capital of the country, the city is of great importance for political, economic and social aspects. The internal structure of Prague's network is distinguished by a great variety of elements. Narrow, old streets are intertwined with modern highways forming a dense and diverse urban system. Another extreme in the sample is the city of Semily, which demonstrates the minimum values of all basic indicators.

The first observation concerns the size of selected cities and the complexity of their networks. It should be noted that the geographical size of a city is not always an effective measure, since it only represents a horizontal dimension. On the other hand, the population can grow both horizontally and vertically (e.g. housing with tower blocks). If we measure cities by population and plot them against topological characteristics, a strong linear relationship between these values can be seen, with $R^2 = 0.92$. Figure 47 shows the relationship between city population and number of nodes/links. Networks in more populous cities are more evolved.

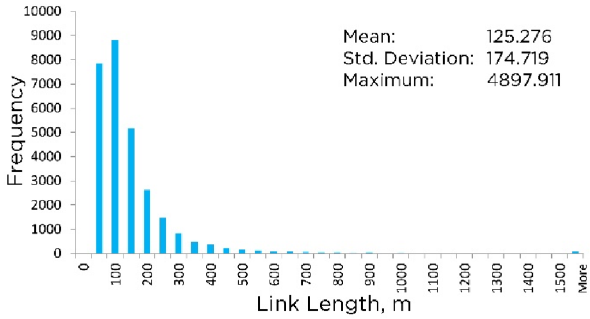


* Please note, that for the clarity of picture, Prague is not plotted on the chart

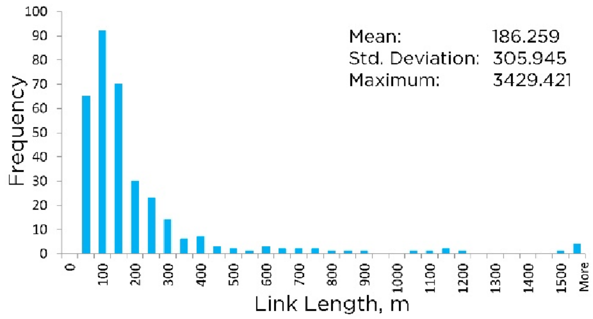
Figure 47. Population versus the complexity of studied networks.

From a purely economic point of view, it can be said that large cities offer more labor market opportunities and in general are more commercially attractive than small settlements. If one looks at the list of the most economically powerful agglomerations, one will see at the top such large metropolises like New York, London, Tokyo, Singapore, etc. (CityLab 2018). This success is largely due to the ability of big cities to maintain and expand people's interaction, which affects the overall economic indicators. In this context, the urban economy is highly dependent on the quality of the network and its size.

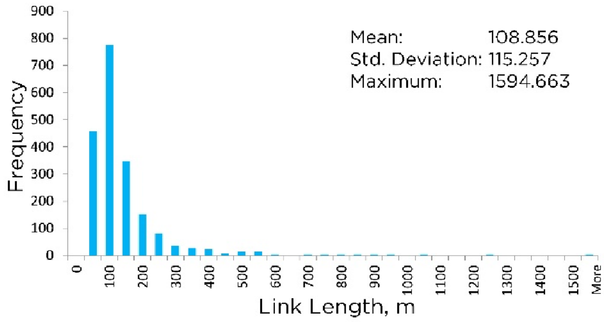
As was mentioned in the previous section, some topological attributes directly affect the efficiency of urban systems. For cities, distance or route length is not only associated with travel cost but also represents the simplest indicator of accessibility. The length of links is a typical geometric parameter of road networks. Looking at the values of the average length of roads in the studied sample, it can be seen that Kladno represents the network with the shortest length, which is 109 m (Table 5). On the other side of the range is the city of Vsetín, with the average length value of 227 m. It is interesting to note that the total length of roads in Kladno is twice that of Vsetín (210 km against 105 km), nevertheless, the typical segment length is on 118 meters greater in Vsetín. In this case, the complexity of the network, as well as the features of the territory play a key role. Vsetín arose and developed along the river bank, so the shape of its urbanized area (omitting forests) is stretched in a narrow band from west to east. Transverse growth from the river, however, was limited to cross-country terrain and the road network has spread in the line of valleys. Under such conditions, network densification is very difficult, thus long roads going along natural patterns increase the average link length.



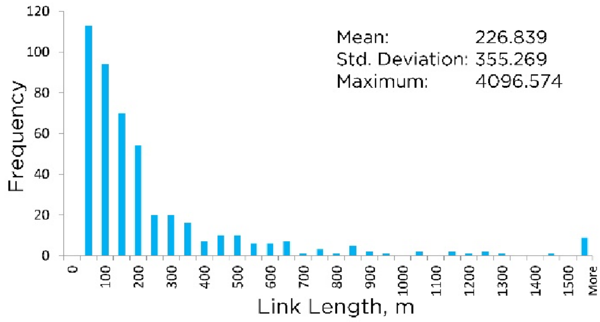
(a) Frequency distribution of links length for Prague



(b) Frequency distribution of links length for Semily



(c) Frequency distribution of links length for Kladno



(d) Frequency distribution of links length for Vsetín

Figure 48. Length distribution histograms for selected cities.

The length distribution in the sample has a typical form with a distinct peak in the range of around 100 m (Figure 48). In general, more than 90% of the roads in selected networks are shorter than 500 m. Several cities have a higher ratio of short segments than others; among them are Prague (97.6%), České Budějovice (97.9%), Prostějov (97.8%), Jablonec nad Nisou (98.1%) and Kladno (98.4%). Two extreme values can be distinguished from the sample. Kladno, as mentioned earlier, has a network with the shortest elements, so that 98.4% of its roads lie in the length range of 1-500 m, 1.6% have a length between 500-1500 m and only 0.05% of links are longer than 1500 m. Vsetín, on the other hand, has the longest links in the network, where 89.2% of roads are in the range of 1-500 m, 8.8% have a length between 500-1500 m and 2% are longer than 1500 m.

As in the case of NUTS 3 regions, the next step is an exploratory analysis of selected LAU 2 networks. Table 6 presents the values for the part of the sample, while the full results are presented in Appendix B.

Table 6. Exploratory analysis of selected LAU 2 road networks

№	City	ρ_{nodes} (1/km)	$\rho_{junctions}$ (1/km)	ρ_{links} (km/km^2)	Deg_{avr}	β_{inx}	N_{deg1}	N_{deg3}	N_{deg4}	Organic (OR)
1	*Prague (max.)*	40.583	33.396	7.237	2.836	1.424	3566	12913	3512	0.818
2	*Kladno*	36.815	30.540	5.698	2.821	1.422	232	916	207	0.843
3	*Jablonec nad Nisou*	37.569	30.113	6.386	2.754	1.393	234	773	166	0.854
4	*Mladá Boleslav*	22.831	19.199	4.923	2.858	1.449	105	444	107	0.832
	County seats:									
5	*Brno*	22.313	16.795	4.492	2.641	1.329	1270	3207	626	0.872
6	*Ostrava*	26.836	20.577	5.314	2.647	1.334	1341	3776	613	0.890
7	*Pilsen*	27.203	20.114	4.751	2.659	1.341	976	2118	629	0.826
8	*Liberec*	26.752	21.907	5.265	2.747	1.382	514	2020	297	0.893
9	*Olomouc*	21.068	15.697	4.029	2.603	1.316	555	1381	236	0.889
10	*České Budějovice*	29.224	23.613	5.511	2.805	1.415	312	1013	293	0.815
11	*Ústí nad Labem*	18.219	14.026	3.883	2.649	1.337	394	1137	174	0.894
12	*Hradec Králové*	18.413	14.676	3.764	2.752	1.388	395	1254	287	0.847
13	*Pardubice*	19.718	15.218	3.752	2.696	1.361	372	1012	244	0.849
14	*Zlín*	17.126	12.011	3.219	2.502	1.261	526	1063	169	0.902
15	*Jihlava*	11.778	9.411	2.861	2.686	1.360	208	737	89	0.913
16	*Karlovy Vary*	19.735	14.843	3.879	2.570	1.311	289	802	73	0.936

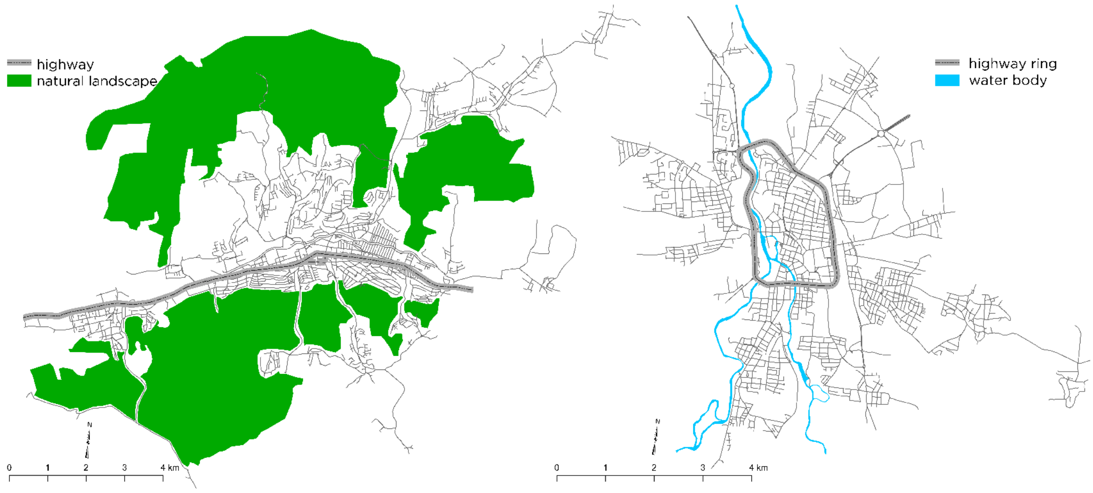
In terms of network density, Prague is the undisputed leader, whose network has the largest number of nodes, links and junctions per unit area. Kladno and Jablonec nad Nisou are also distinguished by high values of indicators. Following Prague, both cities stand out for their high density of nodes and junctions. This corresponds with the early observation that more than 98% of their roads are short.

Connectivity along with network density, represents one of the main concepts promoted by New Urbanists. Connectivity is mainly associated with a variety of paths between locations in a city. Typical measures of connectivity are node degree and beta index. The values of Deg_{avr} for selected networks vary from 2.491 for Pelhřimov and 2.858 for Mladá Boleslav. The average value of 2.665 for the entire sample is greater than that obtained for regional networks, however it still confirms the earlier finding that the development of urban areas in the Czech Republic occurred in the form of self-organization. The spatial form of most networks has not been defined by a global planning process, but evolved organically through the connections between individual centers. The patterns of studied networks are quite diverse, with a large number of three-arm junctions and sometimes with small and unevenly distributed grids. In this sense, organic networks are much more difficult to change and transform than, for example, rectangular strict grids.

The variation of β_{inx} in studied networks is insignificant and ranges from 1.261 for Zlín city to 1.449 for Mladá Boleslav, showing a similar pattern of connectivity in the entire sample. The average value of 1.353 for all cities seems to be rather small compared to the generally accepted β_{inx} of 1.4 or higher (Marshall et al. 2009). In fact, only eleven cities in the sample show β_{inx} greater than 1.4 (see Appendix B). It should be appreciated that the value of 1.4 was taken from practical experience and is highly dependent on the history and traditions of urban planning for a specific territory. When using β_{inx} in planning practice, several factors should be considered. A high index value implies the creation of additional links between junctions, which will increase total connectivity. However, there may come a situation when some motorists will drive off the highway and cut their way through local streets. Thus, some design features like narrowing residential streets or traffic restrictions for trucks should be provided. The mentioned theoretical and practical measures are successfully applied by some cities in their planning regulations. The US cities like San Antonio, TX and Cary, NC suggest β_{inx}=1.2 as sufficient for good connectivity while in Orlando, FL the desired index value is 1.4 (Marshall et al. 2009). As a part of a Smart Transportation strategy, local authorities in Pennsylvania and New Jersey are guided by a comprehensive program aimed at improving the quality of the transport system. Along with architectural and social projects, the program offers to evaluate the structure of the network using three measures: beta index with the desired minimum value of 1.4, junctions per square mile and route directness (NJDOT 2008). As can be seen, quantitative analysis is useful not only in theoretical research but also in urban network design.

It can be seen from Table 6 that the distribution of β_{inx} and Deg_{avr} values have a similar form. The highest value of Deg_{avr} in Mladá Boleslav is simultaneously reflected in the highest β_{inx}. The same applies to Zlín, which has the lowest β_{inx} and the second lowest value of Deg_{avr}. Nodes with a higher degree often contribute to improved local accessibility. Usually, such nodes transmit more traffic and passengers, since they provide several alternative routes. At the same time, the node degree can only be increased by adding a new link to the network. With a constant number of nodes and a growing number of links, values of Deg_{avr} and β_{inx} will increase.

A more detailed analysis of the characteristics associated with nodes allows one to reveal their influence on the spatial structure of urban networks. The city of Zlín contains the highest number of dead-ends (N_{deg1}), where 30% of network nodes have a degree of 1. The overall effect of this is expressed in low values of Deg_{avr} and β_{inx}. Looking at the existing pattern of the city's road network, one can see its two main constraints in the form of green areas on the north and south (Figure 49a). Natural obstacles clench the city on both sides and create disorder in its structure. Only one highway (I/49) passes through the city, so the development of all local roads begins from it. As moving away from the main artery, the local network acquires a dendritic structure with a large number of dead-ends and several cul-de-sucs. Such a structure is characteristic for a linear tree networks (Marshall et al. 2009). The main disadvantage here is the emergence of several isolated districts that are significantly distant from the main corridor. The length of the journey may also increase, as it is often necessary to go back to the main corridor. The sustainability of linear tree networks can be improved by connecting remote locations through the additional links between their centers. Another way is to create a second intraurban artery that would embrace a part of the city, so its form will be close to concentric or radial.



(a) Urban form features of Zlín (b) Urban form features of České Budějovice

Figure 49. Comparison of urban patterns of Zlín and České Budějovice.

Interesting patterns can be seen in the network of České Budějovice. Of the total number of nodes in the city, about 18% have a degree of 4. This is the highest value followed by the city of Prague (17%) and is also reflected in the lowest organic ratio (0.815). Its network can hardly be called rectangular, however, some grid structures can be easily spotted on the city plan (Figure 49b). The network rather represents a combination of small gridiron patterns embraced by a ring of main highways. In practice, this usually means that the central part of the city can be easily reached, since all radial roads are linked to the main ring. Connectivity in the network is also relatively high. For example, České Budějovice is among the cities with β_{inx} greater than 1.4. The main radials are usually highways, so the speed of traffic also increases. In general, this form of networks is very efficient, since it combines the advantages of both gridiron and radial systems. In the case of České Budějovice, however, the problem is the presence of only one ring representing a backbone of the street network. On the main ring, local traffic merges with transit, causing congestion, noise and pollution. A multiple ring system would be more efficient for even traffic flow, but only if the city limits allow it.

Another interesting interplay can be observed between node degree and the length of corresponding links. As in the case of the regional networks, the distribution of the average road length for each node degree is plotted. Due to a large amount of data, only a part of the distribution is shown, specifically for thirteen county seats (Figure 50). Unlike regional networks, there is no clear trend here that nodes with a higher degree have shorter links. In some cities, four-arm or five-arm junctions connect roads of greater length. There are several factors that cause the dispersion of length values. When studying global networks, such as regional from the previous section, one can appreciate a wide variety of nodes and road types (motorways, highways, local roads, driveways, etc.). The influence of some very long roads on the average value may be reduced due to numerous shorter ones that belong to the same degree of a node. In the case of municipal scale, however, the total number of nodes for each degree is important. When studying various complex systems, one can often observe their hierarchical structure, when only a few nodes in a graph have a high degree and a large number of nodes have a low degree (Rodrigue et al. 2013). In studied networks, the most frequent three-arm junctions mainly connect residential or secondary roads, while rare four-arm and five-arm junctions appear on the 1st and 2nd class roads connecting cities or districts. Usually, at least one elongated segment leads at such a junction, which causes an increase in the average length of links that are attached to the nodes with the highest degree.

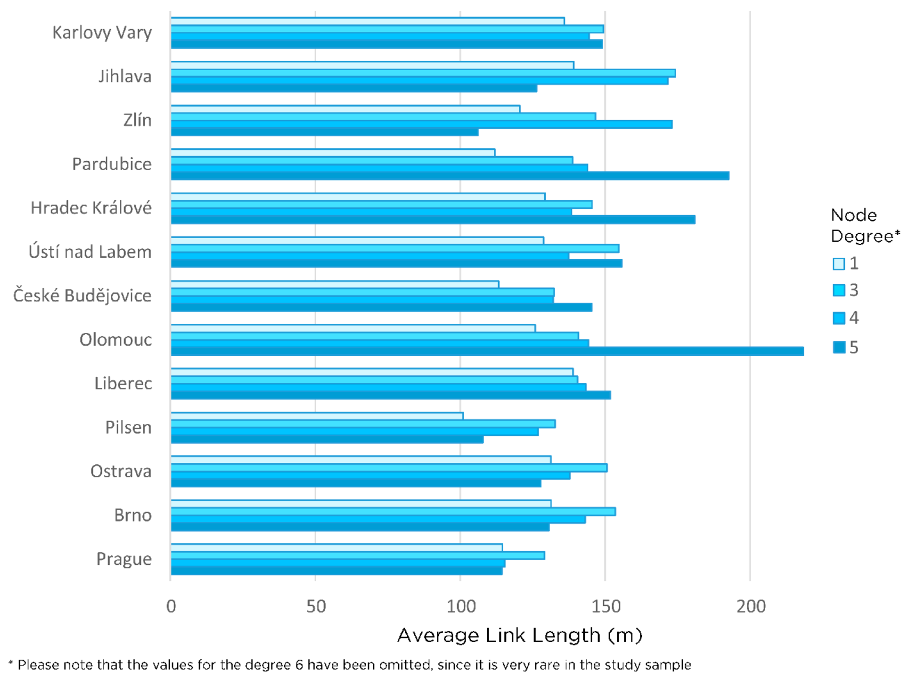


Figure 50. The distribution of the average length of roads that emanates from nodes with the corresponding degree in selected cities.

In some cities, dense clusters of nodes with a high degree contribute to reducing the average length of links. For instance, the distribution of road lengths in Pilsen corresponds to that observed in regional networks. On average, the most numerous three-arm junctions connect the longest roads, while the segments converging at four-arm and five-arm junctions are somehow shorter. There are several cluster zones in the city, like in Pilsen 2 and Pilsen 3 districts, where nodes with the degree of 4 predominate. These compact areas have a dense network and relatively short roads. In the entire network of the city, there are only a few nodes with a degree of 5 and they are located in the center of these cluster zones, so the length of the roads associated with them is even shorter. This is an example of how small subsystems can, in aggregate, affect some characteristics of a bigger system. A completely different situation is observed in Pardubice, where the urban network has only two nodes with a degree of 5. Each of them contains one long segment that leads to the main road. Due to the small number of nodes, lengthy roads have more weight in local networks than in regional ones. The same applies to nodes with a degree of 4. While in the core of the city a dense network forms relatively short paths, only a few nodes in less urbanized neighborhoods increase the average length.

If we plot the distribution of average road lengths depending on node degrees across the entire sample of sixty-six cities, we will see a familiar trend from regional networks (Figure 51). Typical for self-organized systems three-arm junction contain longer roads (155.2 m on average) than regular four-arm junctions (148.7 m on average). For nodes with a degree of 5, the link length is even shorter (137.9 m on average), apparently due to the contribution of large cities with denser networks.

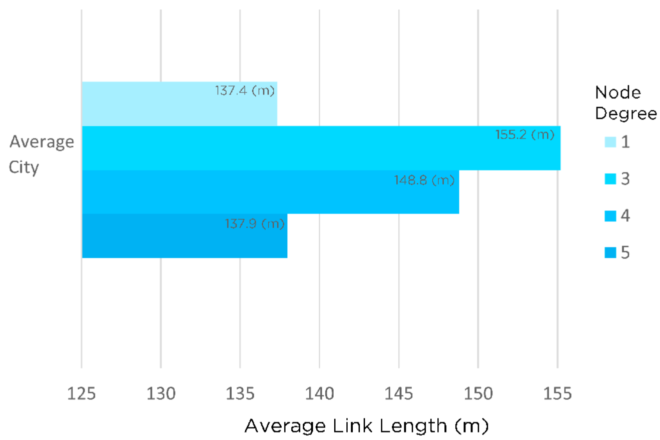


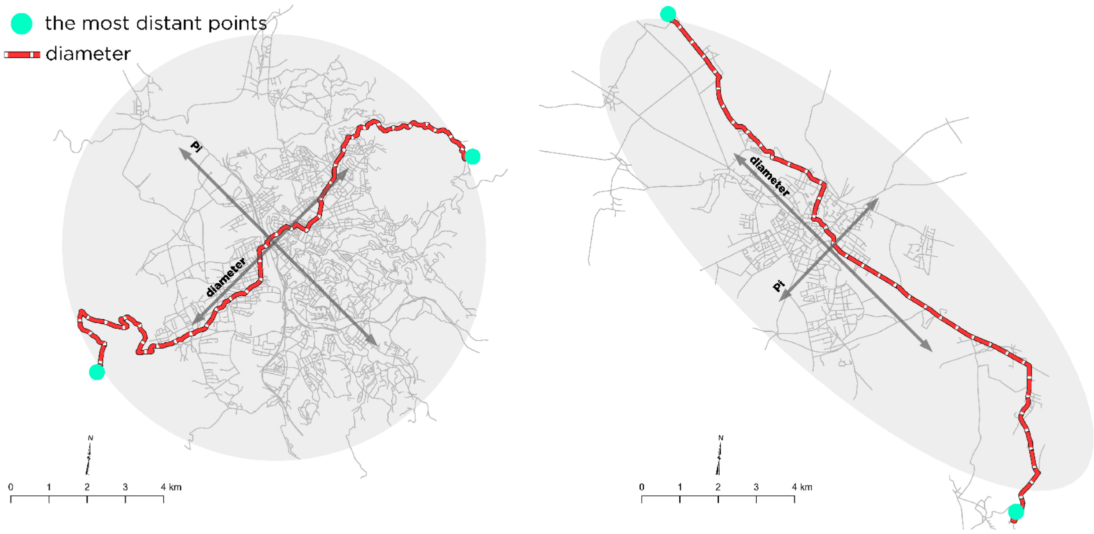
Figure 51. The distribution of the average length of roads that emanates from nodes with the corresponding degree in the average city.

The last group of metrics discussed within the static model relate directly to their spatial nature. They involve the determination of the shortest path between nodes of the road network. It should be noted that links with unidirectional traffic are taken into account in the calculation of indices. Table 7 presents the short version of results, while a full overview of values for all cities in the sample can be found in Appendix C.

Table 7. Measures related to shortest route in selected LAU 2 road networks

№	*City*	*Diameter (km)*	*Pi index*	*Avr. straightness*	*Avr. closeness*
1	*Prague (max.)*	37.921	94.697	0.721	0.000172
2	*Opava*	19.283	13.203	0.752	0.000227
3	*Znojmo*	18.396	8.755	0.715	0.000262
4	*Vyškov*	18.065	6.636	0.714	0.000327
	County seats:				
5	*Brno*	30.759	33.618	0.729	0.000134
6	*Ostrava*	24.411	46.637	0.715	0.000114
7	*Pilsen*	18.703	34.970	0.731	0.000161
8	*Liberec*	19.087	29.264	0.735	0.000226
9	*Olomouc*	22.724	18.322	0.713	0.000205
10	*České Budějovice*	15.603	19.641	0.725	0.000240
11	*Ústí nad Labem*	20.155	18.103	0.704	0.000185
12	*Hradec Králové*	14.515	27.403	0.725	0.000225
13	*Pardubice*	24.613	12.602	0.706	0.000217
14	*Zlín*	22.491	14.718	0.710	0.000184
15	*Jihlava*	17.114	14.691	0.692	0.000259
16	*Karlovy Vary*	14.808	15.475	0.659	0.000241

The first two measures to pay attention to are the diameter and the pi index. They can be used to describe the efficiency of the overall form of networks and the degree of their development. In terms of size, road networks can be measured in several ways. For example, in this study, the size of networks has already been estimated using topological characteristics such as the number of nodes and links. Another method involves measuring networks using the total length of all road segments in them. The diameter allows one to show the extent of the network along the major axis, which is the distance between the two furthest points in the system. Pi index, in turn, takes into account the degree of network development along the axis perpendicular to the diameter and allows one to estimate the spatial shape of the network. The main idea of these measures can be illustrated by the following example. Two networks may have the same diameter, such as Liberec and Opava (about 19 km), but in terms of overall spatial form, these networks are very different (Figure 52). In Liberec, the longitudinal (along the diameter) and transverse (perpendicular to the diameter) development of the city's network is proportional, while in Opava, the longitudinal development prevails over the transverse. As a result, with the same diameter, the value of the pi index for Liberec is several times larger than for Opava.



(a) Network shape of Liberec (b) Network shape of Opava

Figure 52. The diameter and pi index in measuring overall network shape.

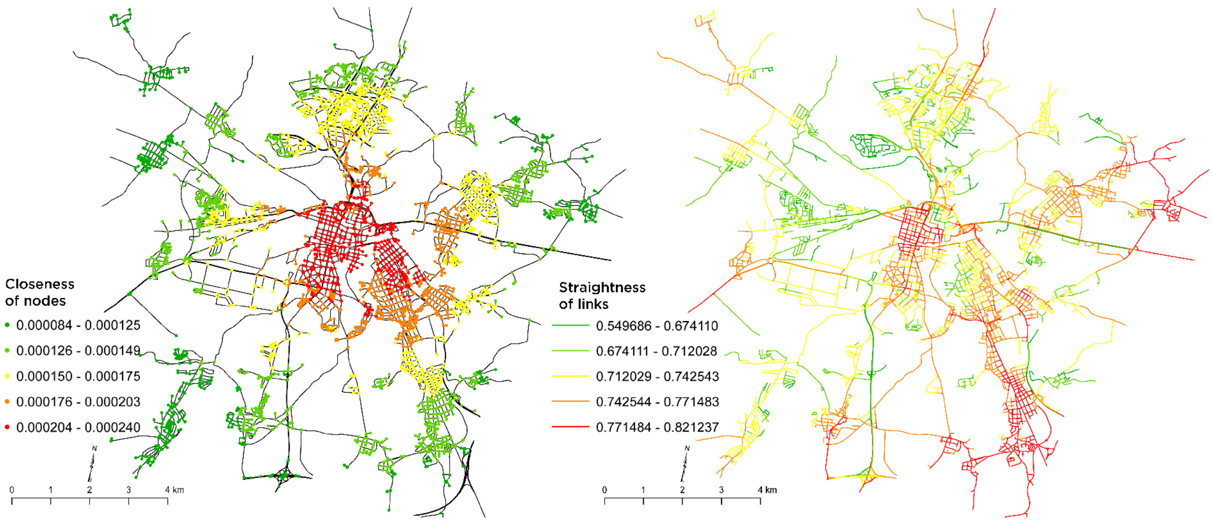
A similar situation may arise, when the two road systems are identical in terms of total network length, but the distribution of this length in space may be different. In this case, a small diameter indicates that the segments of the urban network are distributed more evenly throughout the territory, while a large diameter shows a single dominant direction of network development. For instance, in the studied sample the elongated cities like Pardubice, Zlín, Opava, Znojmo and Vyškov have a significant diameter and a small pi value. The networks of these cities have a single distinct axis of development, which is not always beneficial in terms of traffic distribution. In Klatovy and Děčín, the long diameter connects the low-urbanized areas at the opposite parts of cities. The largest diameter is observed in Prague, however, the transverse development of the network from the longest axis here is very intensive, so the pi index also represents the maximum value for the sample. The city of Vsetín is distinguished by the lowest value of the pi index. Due to the natural features mentioned earlier, the network of this small town shows a diameter almost similar to large regional centers. If the road network is developing in a single direction, there may come a situation when its elongated structure will be inefficient for use. In this scenario, some urban areas may be isolated, while others will be congested. The main characteristic here is the configuration of routes that result from the current network geometry.

To analyze the joint effect of the system configuration and the roads shape on intraurban communication, measures of straightness and closeness can be used. Closeness can be considered as the simplest indicator of accessibility, while straightness allows one to describe the shape of the shortest paths between locations in the urban realm. It can be assumed that a node is more accessible if the routes leading to it from all other nodes resemble a straight line (Porta et al. 2009).

In this case, the efficiency of the system will be determined by how easily the traffic flows through the network.

It should be noted that when solving routing tasks, links with unidirectional traffic have an impact on the values of indicators. For example, Karlovy Vary and Jihlava have the most curved paths among the county seats. The average straightness values of their networks are 0.659 and 0.692 respectively. However, if straightness is calculated on undirected links, the obtained values will be 0.708 for Karlovy Vary and 0.757 for Jihlava, which is an increase of 7% and 9%, respectively. In fact, for an undirected network, the straightness value for Jihlava will no longer be the lowest among the county seats. Therefore, these features of real-world networks should be considered in their modelling.

The results of straightness and closeness analysis can also be presented in the form of color patterns. Figure 53 presents the distribution of the two quantities on the plan of Pilsen city.



(a) Closeness of nodes (b) Straightness of links

Figure 53. The resulting layers of centrality indices for Pilsen city.

One of the disadvantages of closeness index is that it often depicts a monocentric pattern when high index values are concentrated in the central part of the city. The distribution of straightness on the other hand emphasizes somewhat different areas. Higher scores for straightness get the places located along the elongated but straight roads, especially those without unidirectional traffic. Such roads usually provide a direct and easier connection between different parts of the city.

It is interesting to note that in Figure 53 the highest values of closeness and straightness are concentrated in those parts of the network where four-arm junctions prevail. The trend can be verified by the analysis of frequencies of node degrees and the corresponding values of closeness and straightness for thirteen county seats. In Table 8, the four-arm junctions as well as more complex five-arm junctions demonstrate the highest closeness and straightness on average. One of the main reasons is that highly ranked nodes often represent the main hubs in the system and they also offer a greater variety of travel directions so most of the shortest paths lead through them. In the planning practice, regular four-arm junctions can contribute to improving traffic flow and the accessibility of locations.

Table 8. Frequency of node degrees and the corresponding values of closeness and straightness for thirteen county seats

Node degree	*Absolute frequency*	*Relative frequency*	*Avr. Closeness*	*Std. Deviation*	*Avr. Straightness*	*Std. Deviation*
1	10717	0.212	0.000184	0.0000404	0.693	0.051
3	32401	0.640	0.000198	0.0000433	0.718	0.048
4	7244	0.143	0.000212	0.0000405	0.726	0.044
5	240	0.0047	0.000216	0.0000323	0.723	0.042

5.2.1 Summary

In this section, a fairly wide range of road networks of various sizes and with different geometric properties was analyzed and discussed. Very often, topographic or natural features strongly influence the configuration of networks and their quantitative characteristics. This can be seen in both, county seats (e.g. Zlín, Karlovy Vary) and small towns like Vsetín. Nevertheless, even in the absence of large natural barriers, the quantitative characteristics of self-organized systems may differ significantly. This can be observed in the distribution of link lengths in dependence to the degree of the node from which they originate. The size of the studied systems is also very diverse. Besides the usual total length measure, the diameter and pi index may bring valuable information that allows one to track the extent of a city in the longitudinal and transverse directions. The configuration of routes in the network is another important indicator discussed in this section. The general trend observed in county seats shows that highly ranked nodes have better closeness and straightness rates. In this connection, regular networks with a predominance of four-arm junctions are more robust against potential network breaks. This is due to the fact that, when one of links is excluded, regular structures offer several symmetrical detour paths. While in self-organized systems, the sudden elimination of link may significantly disrupt the flow of traffic.

It should be pointed out that the static model carries only a certain piece of information necessary for a comprehensive understanding of road networks. Accessibility and adjacent dynamic processes in the territory represents another integral part of urban realm. The next chapter expands the analytical context of the work to the study of Czech road system within the dynamic model. It includes an empirical investigation of the network in a spatial and temporal context.

6. Spatial Analysis within the Dynamic Model

In modern city, the transportation infrastructure is one of the most loaded objects, which, however, must meet numerous requirements, including quality service of urban areas. Accessibility is a concept that allows one to evaluate the efficiency of the network in terms of spatial interactions. In a broader sense, accessibility reflects the effort that must be made to reach a certain place.

This chapter presents an analysis of intercity accessibility in the Czech Republic from a spatial and temporal perspective. Accessibility will be considered as a dynamic property of the road network and its changes between 2006 and 2018 will be examined here. These periods were chosen based on the completeness and quality of the available data. The accession of the Czech Republic to the European Union was also not so long ago (specifically in May 2004) from the starting date. The methodological approach is presented in section 4.5.2. The analytical part of this chapter, along with accessibility, also considers changes in population and land use in the period under review. The author concludes this chapter with an analysis in which all three components of the urban realm (population, accessibility and land use) are combined to get a single output as the potential vulnerability of land to urbanization.

6.1 Population and Land Use Dynamics

The settlement structure of the Czech Republic is very peculiar and is primarily characterized by a very large number of low-populated towns against which large regional centers are strongly distinguished (Svobodová et al. 2013). In 2018, the population of all thirteen county seats was slightly over 27% of the population of the Czech Republic.

Figure 54 presents a resulting layer reflecting the population dynamics between 2006 and 2018. The warm colors on the surface show the areas where an increase in population has occurred. The thick black line depicts the boundary of thirteen regional centers (county seats). The clear trend that can be seen on the resulting layer is the hot areas near main urban cores, especially around Prague, Brno, Pilsen, and České Budějovice. This is an abundant sign of ongoing suburbanization processes around urban centers. In essence, by merging hot areas around all regional centers, one can get an idea of the size of agglomerations and their extension. The largest positive population growth (an increase of more than 2000 inhabitants in absolute terms) occurred on the outskirt of Prague as well as in cities of Liberec, Pardubice and in few urban districts of Brno. On the other hand, some cities have experienced a significant population decrease. Many of them located in the Moravian-Silesian Region. For example, Havířov absolute difference in population between 2006 and 2018 was 12 045, for Karviná it is 9 863.

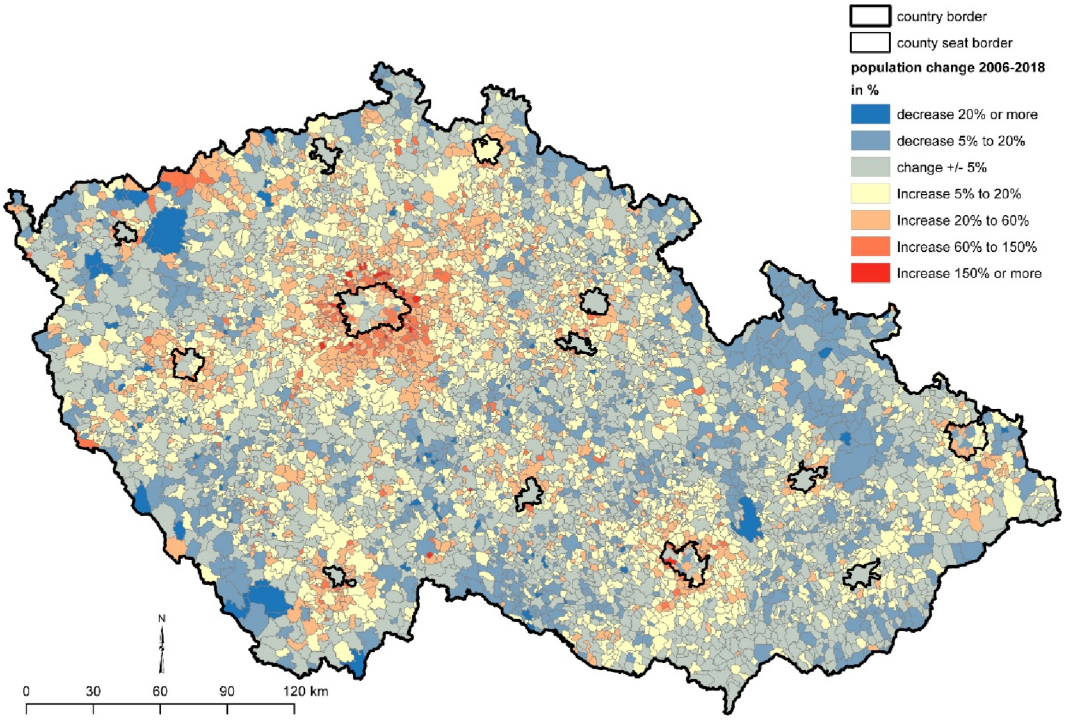
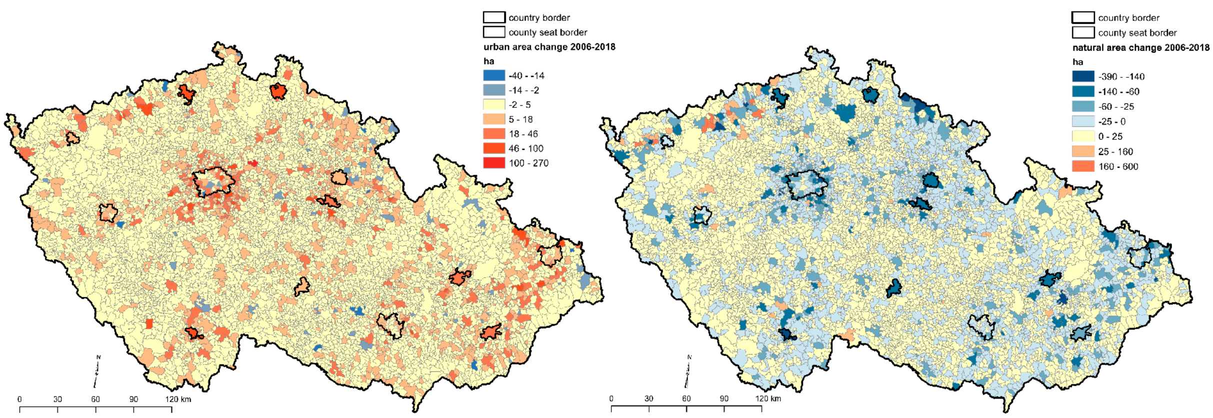


Figure 54. Population change between 2006-2018 (%).

Urbanization is a direct product of population movement. Such a movement usually has two directions. The movement to the inside is caused by the socio-economic benefits that contribute to the resettlement of people to large cities. The movement to the outside, on the other hand, corresponds to resettlement of people to the edge of cities or close to their borders. It is caused by the desire for a quiet/comfortable life that is offered by rural areas but with preservation of the socio-economic benefits of large cities. In both cases, population movement is often reflected in land use, specifically in its change. To meet the needs of the population, urban expansion extends primarily to natural land (agricultural and forests). Thus, the dynamic model further focuses on the analysis of land use changes for the studied time period.



(a) Changes in Urban Area (b) Changes in Natural Area

Figure 55. Absolute changes in land use between 2006 and 2018 (ha).

Figure 55a depicts absolute changes in urban land, while Figure 55b shows changes in natural land that occurred between 2006 and 2018. The growth of urban area, as well as a decrease in natural, can be easily spotted in county seats and their immediate vicinity. In both cases, the general trend of changes is similar to the one observed in population displacement. In fact, the population change for studied period is positively correlated with the growth of urbanized land, with r=0.904. The resulting layers obtained from the dynamic model of population and land use change carry important information. In essence, they represent a common pattern of urbanization/suburbanization in the Czech Republic. The presented observations on population displacement are consistent with the early findings of Sýkora et al. (2012) and are supplemented by an overall picture of land use dynamics. These results, however, need to be expanded on yet another important attribute of urban development—spatial accessibility.

6.2 Accessibility Estimation

The results of accessibility analysis using six different impedance coefficients are presented in Figures 56 and 57. Application of several β values allows us to reflect the impact of county seats on the pattern of spatial interaction. With low impedance values, in particular 144.269 (layer *a* in Figures 56 and 57) and 577.078 (layer *b* in Figures 56 and 57), one can readily identify the main regional centers and their significance on the local scale. Starting from the layer *c*, the influence of Prague becomes more noticeable and individual hot spots begin to merge into one area. On the layers *d*, *e*, *f*, the local influence of individual counties is practically absent. With high β values, the significance of the main traffic arteries on a national scale begins to manifest itself, however, not as strong as the weight of the population and the exceptional position of Prague. The oldest and at the same time the longest motorway D1 connecting the three main metropolitan areas of Prague-Brno-Ostrava stands out the most. The accessibility pattern with the highest β exactly replicates the course of D1 motorway.

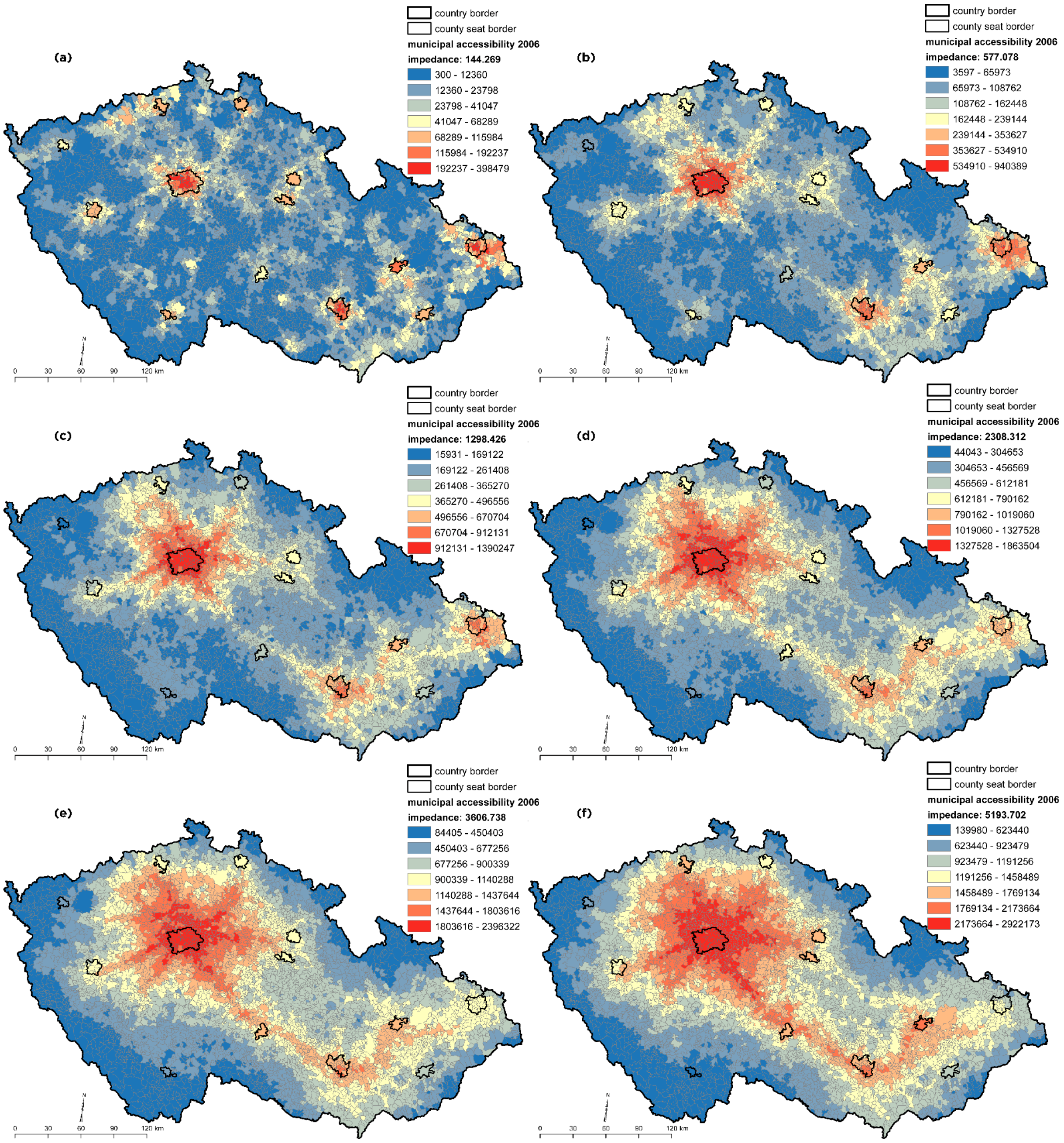


Figure 56. Municipal accessibility patterns for 2006.

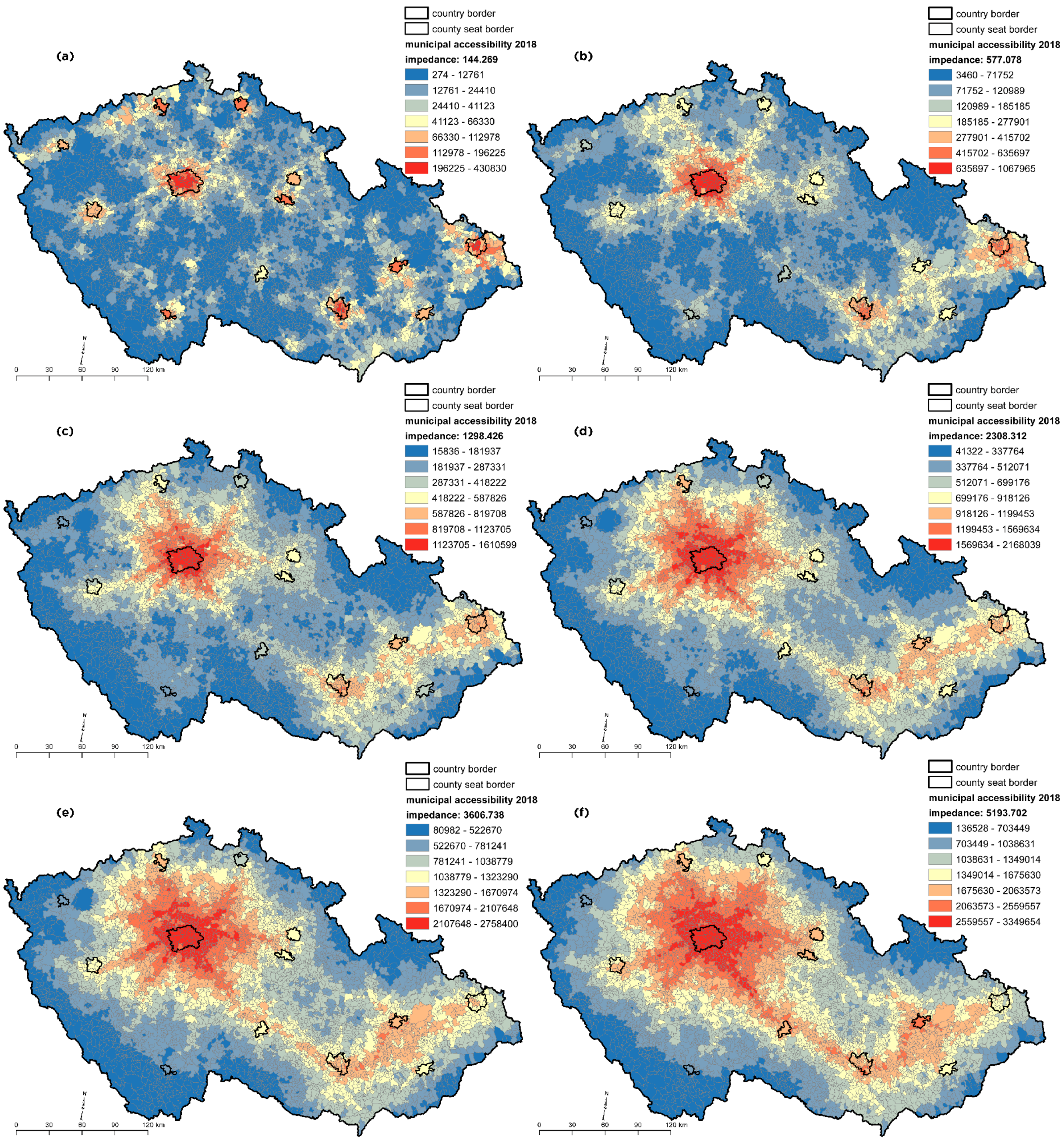


Figure 57. Municipal accessibility patterns for 2018.

Continuing the discussion on accessibility pattern, the author further analyzes its relative change between 2006 and 2018. In such a manner, it is possible to trace how the evolution of the network affects the dynamics of the spatial interaction between municipalities. In the presented model, these dynamics are influenced by new road construction and population displacement. Figure 58 shows the surfaces of the relative change of accessibility for six impedance values. The hottest spots on the surfaces mainly correspond to the areas where a new transportation infrastructure was built. For example, a noticeable hot spot appears in the south-east of the country between the metropolitan areas of Brno, Olomouc, Ostrava and Zlín. The gains in accessibility here are associated with the completion of several sections of the D1 motorway, like the one leading from Brno to Zlín and part of the section that connected Ostrava with the Czech motorway network (Figure 59).

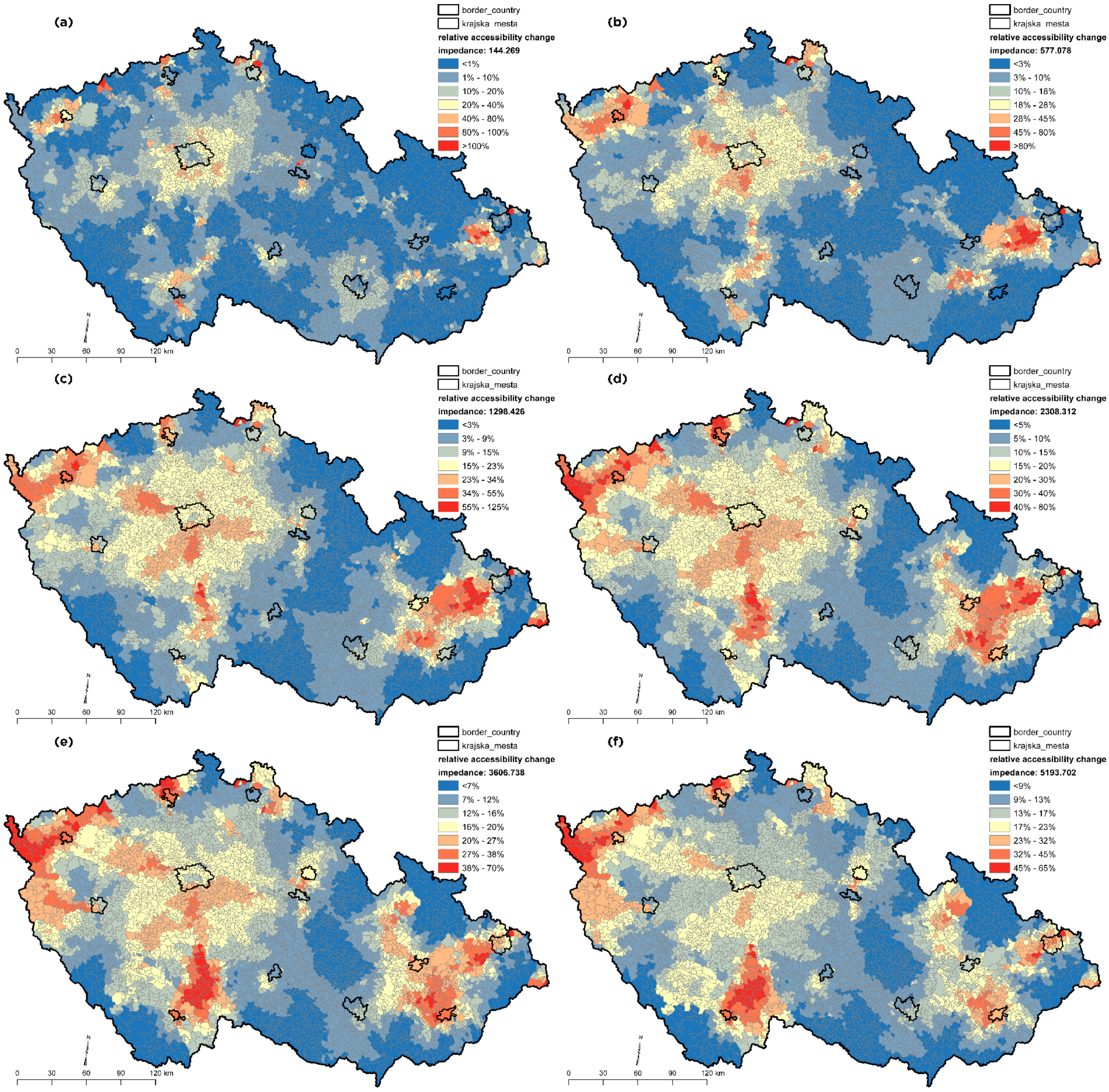


Figure 58. Relative change in accessibility between 2006 and 2018.

Several major infrastructure projects that appeared by 2018 can also be mentioned, such as the construction of the D3 sections, located between Prague and České Budějovice; laying the western part of the D6 between Karlovy Vary and Cheb city; the completion of the D8 in the north of the country near Ústí nad Labem; D11 section near Hradec Králové and the southern part of the D0 near Prague. The impact of new transportation links on changes in the spatial interaction between municipalities is clearly visible in Figure 58 for all β values.

Figure 59. Construction of the D1 near Ostrava in 2006 (left). The same section in operation in 2018 (right). (Source: Google Earth ©, accessed December 10, 2018).

Summary of national average accessibility values and their relative change are presented in Table 9. Improvement of spatial communication between cities occurs smoothly with an increase in the impedance coefficient. It can be concluded that the evolution of the road network in the studied period had the greatest positive effect on long journeys.

Table 9. Mean accessibility scores and their relative change

Year	*Impedance (β)*					
	144.269	*577.078*	*1298.426*	*2308.312*	*3606.738*	*5193.702*
Mean accessibility 2006	21600	118526	309545	585862	922762	1279122
Mean accessibility 2018	23598	133383	353117	673193	1063957	1476727
Relative change	+9.3%	+12.5%	+14.1%	+14.9%	+15.3%	+15.5%

6.3 Urban Expansion

It is interesting to note that in the case of the lowest β, the improvement in accessibility gains the suburbs of large cities (see Figure 58). This is explained by the fact that the construction of new sections of roads opened up more rapid access of the suburbia to regional centers. With high β values, increased accessibility mainly spreads along corridors with high-quality infrastructure. The picture becomes more complete if we return to the earlier observations about population displacement and land use change. In fact, all three components are interconnected.

Accessibility and transport infrastructure development are considered to be the main forces engendering the process of urbanization. Accessibility motivates people to move and at the same time provides the prerequisites for land use change (Verburg et al. 2004; Kasraian et al. 2017).

Usually, improving the accessibility of territory means its better communication with a developed urban center. This is just what can be seen in the presented case study. Under such conditions, urbanization often occurs around large cities and turns into suburbanization. The larger the city, the greater will be the areal extent of suburbanization (Kasraian et al. 2017).

The direction of potential urban expansion is a problematic aspect of city growth. Conversion of land from natural to urbanized occurs rapidly and often without adequate planning (Kim et al. 2003). Information on the possible spread of urbanization would make the planning process more efficient. Thus, the task is to determine the extent of the spatial influence of large cities on their surroundings. Since urbanization is directly related to accessibility, it can be assumed that if the territory has good accessibility and is located near a big urban area, then it will probably be exposed to urban expansion (Kasraian et al. 2017). On the other hand, for development to occur, it is necessary to fulfill an important condition—the availability of vacant land. The most "suitable" for urban growth are usually natural/undeveloped lands.

In order to combine all three variables into one thematic layer, which will allow one to determine the spread of potential urban growth, the classical density measure can be adapted (people per km^2) and extended to the network component. This can be done using the ratio of spatial accessibility to the area of undeveloped land. The same logic as the density gradient and the urban-rural gradient is followed here (Clark 1951; Uchida et al. 2010). The difference in the spatial distribution of the population depends on the quality of communication between cities. People usually tend to live in areas that provide good accessibility with the urban core (Uchida et al. 2010). Using the accessibility instead of the net population, the impact of potential newcomers depending on their remoteness from a specific territory is also taken into account. At the same time, using the area of undeveloped land in the denominator, we thereby emphasize its vulnerability. The smaller the area of undeveloped land in a settlement, the more stress it will experience from urbanization.

Figure 60 presents a resulting layer of the land's vulnerability to urban expansion. Since the main interest is to explore the potential impact of individual urban centers, the accessibility values at the minimum impedance coefficient are used.

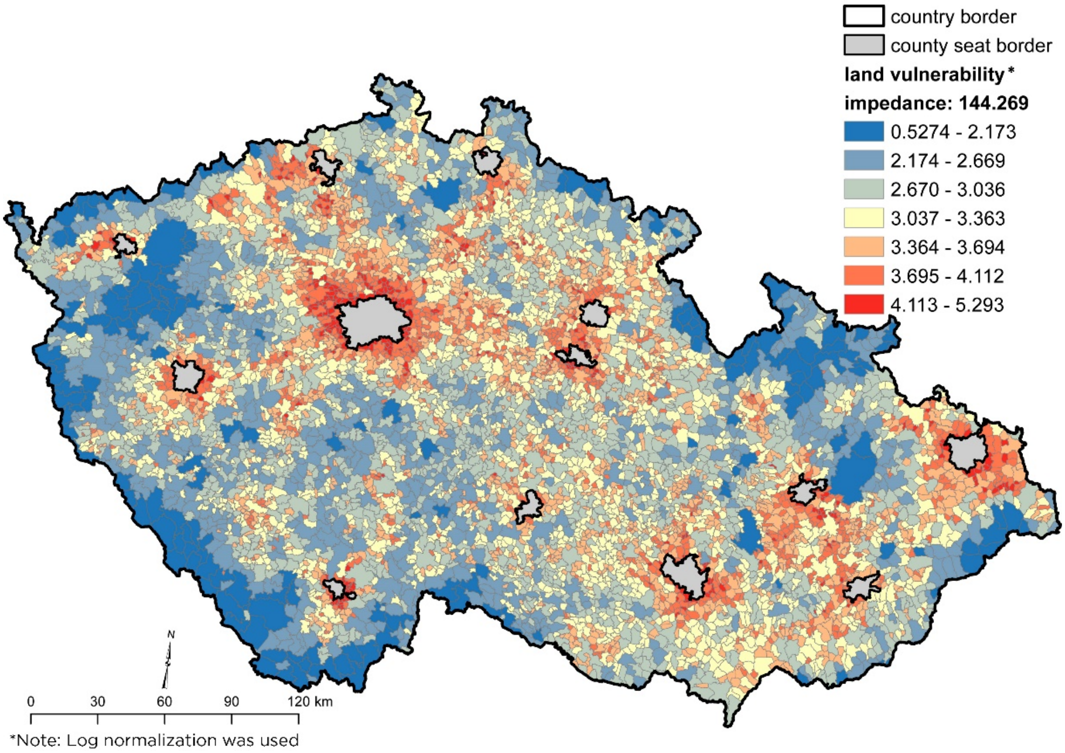


Figure 60. The resulting layer of the potential vulnerability of land to urbanization.

Potential urban expansion primarily spreads over the surrounding landscape of large cities. Settlements in the metropolitan area of Prague and territories located along important transportation hubs are most vulnerable. The proximity to core and size of the settlement play an intrinsic role here. Less stress on natural land is experienced by big municipalities in the periphery of the studied area, which do not have fast connection with urbanized core.

It should be noted that vulnerability is represented only as a possible trend of urban sprawl emanating from the interaction of population, accessibility and land use. The scale of urban sprawl in the Czech Republic is not as large as, say, in the USA, however, in recent years, rapid changes in land use and population dynamics have been observed (Ouředníček et al. 2008). These changes are alarming, as they often spread to natural areas in an unmanaged way. In this regard, the land vulnerability model allows one to outline the overall trend of possible urban growth and get more information about complex spatial interactions.

7. Conclusion and Future Work

The road infrastructure is one of the most significant and at the same time the most loaded element of urban systems. It is of key importance for economic development as well as social interactions. This study presents the analysis, modeling and comparison of the road networks of the Czech Republic across the different territorial units. The main motivation for the research was the aspiration to contribute to the studying and understanding of the spatial structure of the Czech urbanized areas, through a comprehensive investigation of spatial data. In essence, this study is based on the premise that the synergy of typological and geometric parameters of the road infrastructure as well as patterns of spatial interactions form a united set of determinants of urban system quality.

The contribution of this work can be found in both theoretical and empirical terms. From a theoretical perspective, a rigorous and interdisciplinary overview of research devoted to urban space, its perception, description and modeling in various fields were introduced. This topic is very popular and covers a wide range of different disciplines, such as sociology, urban science, architecture theory and design, geography, ecology etc. Special attention to space and its dynamic component was initially paid by urban sociologists. The field has made a particular contribution to understanding how a static environment affects spatial relationships and vice versa. However, as noted in this thesis, a sociological view on the problems of urban planning should be supplemented by a solid empirical grounding. Therefore, a wide variety of quantitative approaches and measures for analyzing and describing urban systems has been considered. Particular attention was paid to their applicability in practice, advantages and disadvantages.

From an empirical perspective, this study carries valuable information that reflects both the historical imprints imposed on the urban networks in the Czech Republic and their present structure resulting from a long development. The analysis within the static model revealed that the development of urban areas in the Czech Republic occurred through self-organization with the predominance of a large number of three-arm junctions in the networks. Such urban systems usually grow independently without strict planning or imposing a certain pattern. Spatial evolution and interaction gradually led to the unification of settlements, thereby giving a form to the entire urban system. In the transportation planning practice, this property should be considered from two perspectives. In general, the presence of a large number of three-arm junctions in self-organized structures may contribute to better safety rates. The main reason for that is the presence of a smaller number of possible collision points when compared to four-arm junctions. Besides, it is assumed that the priority of movement is clearer at three-arm junctions, so there is less chance of a driver making a mistake. On the other hand, regular networks with the predominance of four-arm junctions provide better communication between places and offer more route options. This is especially important when local breaks appear in the network. When one of the links is excluded, regular structures offer several symmetrical detour paths. While in self-organized systems, the sudden elimination of link may significantly disrupt the flow of traffic. In addition, it was found that the average length of links that are connected at four-arm junctions is shorter than those at three-arm junctions.

The dynamic model, which was also considered in this thesis, was primarily aimed at the empirical investigation of the Czech road network in a spatial and temporal context. Accessibility here serves as the prime indicator of the spatial interactions between the set of centers and sub-centers constituting a united system. The model utilized a flexible approach to accessibility estimation with multiple impedance values in order to reflect the varying degree of influence of urban centers on the resulting scores. Despite the fact that modeling of road networks on a nationwide scale, including temporal component, can be both time-consuming and hardware demanding, it is, however, very important. Firstly, it allows one to assess the effect of implemented infrastructure projects on the quality of intercity communications. Secondly, it makes allowance for the population potential, which stakeholders use as a factor facilitating business activities, commercial prosperity or depicting possible labor force supply. Finally, the study indicates that the interplay of accessibility, population potential and land use can provide valuable information about possible urban expansion. In general, the development of transport infrastructure and improved accessibility promote the growth of urbanized areas. This, in turn, makes undeveloped lands in well accessible locations more vulnerable to urban expansion. Considering transport accessibility, population potential and land use within a single model, a resulting layer reflecting the interplay of these characteristics is created. The obtained information can be used to raise the awareness of planning authorities about the potential spread of urbanization.

To summarize, the results gained from the calculation model offer not only a description of the familiar topographic and geometric characteristics of road networks but also a more comprehensive exploration of the spatial interactions through gravity-based accessibility. It should be noted that the conducted study still leaves room for further improvements. In particular, the dynamic properties of transportation networks can be considered not only in conjunction with the population factor but also with the socio-economic indicators of the territories. Moreover, the vulnerability measure requires a more detailed study on a fine scale, taking into account a wider range of data on land use, population income, as well as additional indicators of the territory attractiveness (e.g. land prices, the presence of protected areas, etc.). It is assumed that given current trends in the development of suburbia, this topic will also be relevant in future studies.

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Appendix A

Table 10. Basic characteristics of selected cities and their road networks (complete results)

№	*City*	*Population 1.1.2018**	*Area (km^2)*	N_{nodes}	N_{links}	$N_{junctions}$	*Total L_{links} (km)*
1	*Prague*	1294513	496.17	20136	28669	16570	3591.018
2	*Brno*	379527	230.18	5136	6825	3866	1034.038
3	*Ostrava*	290450	214.22	5749	7669	4408	1138.442
4	*Pilsen*	170936	137.67	3745	5020	2769	654.063
5	*Liberec*	103979	106.09	2838	3923	2324	558.566
6	*Olomouc*	100494	103.33	2177	2865	1622	416.340
7	*České Budějovice*	93863	55.60	1625	2300	1313	306.453
8	*Ústí nad Labem*	93040	93.97	1712	2289	1318	364.859
9	*Hradec Králové*	92917	105.68	1946	2701	1551	397.757
10	*Pardubice*	90335	82.65	1630	2218	1258	310.177
11	*Zlín*	74947	102.83	1761	2221	1235	331.031
12	*Havířov*	72382	32.08	1140	1498	835	201.606
13	*Kladno*	68804	36.97	1361	1936	1129	210.637
14	*Most*	66644	86.94	931	1247	728	207.605
15	*Opava*	57019	90.56	1135	1481	832	254.592
16	*Frýdek-Místek*	56334	51.56	1195	1583	882	259.869
17	*Karviná*	53522	57.52	906	1205	681	198.456
18	*Jihlava*	50724	87.87	1035	1408	827	251.425
19	*Teplice*	49563	23.78	824	1166	691	154.799
20	*Děčín*	49226	117.70	1092	1446	832	245.876
21	*Karlovy Vary*	48776	59.08	1166	1528	877	229.159
22	*Chomutov*	48666	29.26	649	934	537	136.822
23	*Jablonec nad Nisou*	45771	31.38	1179	1642	945	200.390
24	*Mladá Boleslav*	44167	28.91	660	956	555	142.30
25	*Prostějov*	43798	39.04	963	1309	754	155.23
26	*Přerov*	43565	58.45	863	1100	615	154.80
27	*Česká Lípa*	37405	66.10	692	954	557	148.149
28	*Třebíč*	36050	57.58	795	1082	618	159.753
29	*Tabor*	34467	62.22	994	1367	807	196.539
30	*Znojmo*	33719	65.89	784	1035	592	161.062
31	*Příbram*	32867	33.45	586	817	477	115.076
32	*Cheb*	32171	96.36	718	953	538	203.451
33	*Kolín*	31355	34.99	742	1059	608	141.383
34	*Trutnov*	30577	103.32	821	1041	584	185.687
35	*Písek*	30119	63.23	533	738	424	134.415
36	*Kroměříž*	28897	50.98	637	827	463	128.376

37	*Šumperk*	26151	27.88	489	677	380	88.468
38	*Vsetín*	26109	57.61	355	464	262	105.253
39	*Uherské Hradiště*	25215	21.26	502	659	378	82.006
40	*Břeclav*	24797	77.30	591	801	465	121.688
41	*Hodonín*	24683	63.30	448	631	343	98.087
42	*Sokolov*	23438	22.92	375	519	297	81.552
43	*Chrudim*	23133	33.21	650	852	482	121.533
44	*Havlíčkův Brod*	23101	64.93	768	1022	580	158.349
45	*Strakonice*	22888	34.68	457	619	351	104.738
46	*Klatovy*	22288	80.83	597	826	464	169.566
47	*Valašské Meziříčí*	22200	35.43	636	815	463	124.577
48	*Jindřichův Hradec*	21460	74.28	547	760	442	136.743
49	*Vyškov*	20999	50.42	444	592	343	119.879
50	*Žďár nad Sázavou*	20994	37.06	317	440	250	78.916
51	*Kutná Hora*	20536	33.07	714	1003	593	122.035
52	*Náchod*	20132	33.35	625	794	447	118.155
53	*Svitavy*	16937	31.33	438	606	349	75.618
54	*Ostrov*	16865	50.40	325	450	258	82.968
55	*Jičín*	16480	24.96	380	541	312	80.324
56	*Pelhřimov*	16105	95.24	521	661	370	135.463
57	*Česká Třebová*	15512	41.00	366	511	299	82.308
58	*Turnov*	14312	22.71	431	575	329	93.727
59	*Ústí nad Orlicí*	14163	36.37	450	590	333	99.465
60	*Rokycany*	14074	30.67	392	541	310	92.165
61	*Zábřeh*	13666	34.60	333	438	250	81.344
62	*Aš*	13245	55.84	307	442	259	83.572
63	*Tachov*	12706	40.85	296	393	223	77.933
64	*Domažlice*	11233	24.62	361	476	272	73.964
65	*Rychnov nad Kněžnou*	11088	34.99	397	530	295	94.089
66	*Semily*	8421	16.31	255	335	193	62.397

* The data on population is taken from the CSO, available online at: https://www.czso.cz/csu/czso/

Appendix B

Table 11. Exploratory analysis of selected LAU 2 road networks (complete results)

№	City	ρ_{nodes} (1/km)	$\rho_{intersections}$ (1/km)	$\rho_{junctions}$ (km/km^2)	Deg_{avr}	β_{inx}	N_{deg1}	N_{deg3}	N_{deg4}	Organic (OR)
1	*Prague*	40.583	33.396	7.237	2.836	1.424	3566	12913	3512	0.818
2	*Brno*	22.313	16.795	4.492	2.641	1.329	1270	3207	626	0.872
3	*Ostrava*	26.836	20.577	5.314	2.647	1.334	1341	3776	613	0.890
4	*Pilsen*	27.203	20.114	4.751	2.659	1.341	976	2118	629	0.826
5	*Liberec*	26.752	21.907	5.265	2.747	1.382	514	2020	297	0.893
6	*Olomouc*	21.068	15.697	4.029	2.603	1.316	555	1381	236	0.889
7	*České Budějovice*	29.224	23.613	5.511	2.805	1.415	312	1013	293	0.815
8	*Ústí nad Labem*	18.219	14.026	3.883	2.649	1.337	394	1137	174	0.894
9	*Hradec Králové*	18.413	14.676	3.764	2.752	1.388	395	1254	287	0.847
10	*Pardubice*	19.718	15.218	3.752	2.696	1.361	372	1012	244	0.849
11	*Zlín*	17.126	12.011	3.219	2.502	1.261	526	1063	169	0.902
12	*Havířov*	35.533	26.026	6.284	2.592	1.314	305	692	141	0.875
13	*Kladno*	36.815	30.540	5.698	2.821	1.422	232	916	207	0.843
14	*Most*	10.708	8.373	2.399	2.660	1.343	203	640	87	0.905
15	*Opava*	12.533	9.187	2.811	2.582	1.305	303	703	127	0.886
16	*Frýdek-Místek*	21.247	15.682	4.620	2.607	1.325	313	732	146	0.874
17	*Karviná*	15.751	11.839	3.450	2.614	1.330	225	582	98	0.891
18	*Jihlava*	11.778	9.411	2.861	2.686	1.360	208	737	89	0.913
19	*Teplice*	34.648	29.055	6.509	2.791	1.415	133	598	92	0.887
20	*Děčín*	9.278	7.069	2.089	2.630	1.324	260	717	114	0.895
21	*Karlovy Vary*	19.735	14.843	3.879	2.570	1.311	289	802	73	0.936
22	*Chomutov*	22.184	18.356	4.677	2.809	1.439	112	438	98	0.847
23	*Jablonec nad Nisou*	37.569	30.113	6.386	2.754	1.393	234	773	166	0.854
24	*Mladá Boleslav*	22.831	19.199	4.923	2.858	1.449	105	444	107	0.832
25	*Prostějov*	24.667	19.314	3.976	2.658	1.359	209	667	85	0.909
26	*Přerov*	14.765	10.522	2.649	2.506	1.275	248	545	70	0.919
27	*Česká Lípa*	10.469	8.427	2.241	2.723	1.379	135	480	76	0.889
28	*Třebíč*	13.807	10.733	2.774	2.674	1.361	177	525	91	0.883
29	*Tabor*	15.977	12.971	3.159	2.719	1.375	187	713	93	0.905
30	*Znojmo*	11.898	8.984	2.444	2.601	1.320	192	521	71	0.909
31	*Příbram*	17.517	14.259	3.440	2.734	1.394	109	415	62	0.894
32	*Cheb*	7.452	5.583	2.111	2.614	1.327	180	459	75	0.889
33	*Kolín*	21.204	17.375	4.036	2.810	1.427	134	485	119	0.834
34	*Trutnov*	7.946	5.652	1.797	2.508	1.268	237	515	68	0.916
35	*Písek*	8.429	6.706	2.126	2.724	1.385	109	353	71	0.867

36	*Kroměříž*	12.496	9.083	2.518	2.560	1.298	174	396	66	0.895
37	*Šumperk*	17.538	13.629	3.173	2.724	1.385	109	300	77	0.836
38	*Vsetín*	6.162	4.548	1.827	2.575	1.307	93	228	33	0.904
39	*Uherské Hradiště*	23.616	17.782	3.858	2.588	1.313	124	337	41	0.918
40	*Břeclav*	7.645	6.015	1.574	2.689	1.355	126	398	66	0.887
41	*Hodonín*	7.077	5.418	1.549	2.670	1.409	105	281	62	0.862
42	*Sokolov*	16.365	12.961	3.559	2.696	1.384	78	256	40	0.891
43	*Chrudim*	19.573	14.514	3.659	2.557	1.311	168	434	48	0.926
44	*Havlíčkův Brod*	11.829	8.934	2.439	2.628	1.331	188	491	88	0.884
45	*Strakonice*	13.178	10.121	3.020	2.665	1.355	106	292	59	0.871
46	*Klatovy*	7.386	5.740	2.098	2.705	1.384	133	377	84	0.854
47	*Valašské Meziříčí*	17.951	13.068	3.516	2.527	1.281	173	418	45	0.929
48	*Jindřichův Hradec*	7.364	5.950	1.841	2.726	1.389	105	383	58	0.892
49	*Vyškov*	8.807	6.804	2.378	2.608	1.333	101	316	26	0.939
50	*Žďár nad Sázavou*	8.553	6.746	2.129	2.710	1.388	67	208	42	0.868
51	*Kutná Hora*	21.590	17.932	3.690	2.777	1.405	121	513	77	0.888
52	*Náchod*	18.742	13.404	3.543	2.514	1.270	178	395	52	0.917
53	*Svitavy*	13.979	11.138	2.413	2.728	1.384	89	291	57	0.868
54	*Ostrov*	6.448	5.119	1.646	2.705	1.385	67	220	38	0.883
55	*Jičín*	15.224	12.499	3.218	2.771	1.424	68	263	49	0.871
56	*Pelhřimov*	5.470	3.885	1.423	2.491	1.269	151	334	35	0.931
57	*Česká Třebová*	8.927	7.293	2.008	2.765	1.396	67	251	48	0.869
58	*Turnov*	18.977	14.486	4.127	2.622	1.334	102	290	37	0.909
59	*Ústí nad Orlicí*	12.374	9.157	2.735	2.578	1.311	117	289	44	0.902
60	*Rokycany*	12.779	10.107	3.005	2.717	1.380	82	257	53	0.865
61	*Zábřeh*	9.624	7.225	2.351	2.580	1.315	83	224	26	0.922
62	*Aš*	5.498	4.638	1.497	2.850	1.440	48	213	42	0.850
63	*Tachov*	7.246	5.459	1.908	2.578	1.328	73	202	21	0.929
64	*Domažlice*	14.664	11.049	3.005	2.598	1.319	89	239	33	0.909
65	*Rychnov nad Kněžnou*	11.347	8.432	2.689	2.607	1.335	102	249	44	0.884
66	*Semily*	15.632	11.831	3.825	2.584	1.314	62	175	18	0.929

Appendix C

Table 12. Measures related to shortest route in LAU 2 road networks (complete results)

№	*City*	*Diameter (km)*	*Pi index*	*Avr. closeness*	*Avr. straightness*
1	*Prague*	37.921	94.697	0.000172	0.721
2	*Brno*	30.759	33.618	0.000134	0.729
3	*Ostrava*	24.411	46.637	0.000114	0.715
4	*Pilsen*	18.703	34.970	0.000161	0.731
5	*Liberec*	19.087	29.264	0.000226	0.735
6	*Olomouc*	22.724	18.322	0.000205	0.713
7	*České Budějovice*	15.603	19.641	0.000240	0.725
8	*Ústí nad Labem*	20.155	18.103	0.000185	0.704
9	*Hradec Králové*	14.515	27.403	0.000225	0.725
10	*Pardubice*	24.613	12.602	0.000217	0.706
11	*Zlín*	22.491	14.718	0.000184	0.710
12	*Havířov*	10.341	19.497	0.000285	0.714
13	*Kladno*	9.872	21.336	0.000289	0.724
14	*Most*	16.590	12.576	0.000293	0.693
15	*Opava*	19.283	13.203	0.000227	0.752
16	*Frýdek-Místek*	15.894	16.350	0.000263	0.678
17	*Karviná*	17.479	11.354	0.000305	0.729
18	*Jihlava*	17.114	14.691	0.000259	0.692
19	*Teplice*	9.983	15.506	0.000377	0.680
20	*Děčín*	21.154	11.623	0.000221	0.663
21	*Karlovy Vary*	14.808	15.475	0.000241	0.659
22	*Chomutov*	8.791	15.563	0.000384	0.681
23	*Jablonec nad Nisou*	11.083	18.081	0.000348	0.723
24	*Mladá Boleslav*	11.944	11.914	0.000331	0.658
25	*Prostějov*	12.509	12.408	0.000372	0.746
26	*Přerov*	14.555	10.635	0.000281	0.709
27	*Česká Lípa*	15.048	9.845	0.000332	0.690
28	*Třebíč*	12.149	13.149	0.000364	0.696
29	*Tabor*	13.280	14.799	0.000280	0.672
30	*Znojmo*	18.396	8.755	0.000262	0.715
31	*Příbram*	9.324	12.342	0.000370	0.724
32	*Cheb*	18.724	10.866	0.000282	0.665
33	*Kolín*	10.733	13.159	0.000372	0.706
34	*Trutnov*	17.639	10.527	0.000258	0.718
35	*Písek*	10.792	12.455	0.000365	0.659
36	*Kroměříž*	13.281	9.665	0.000349	0.688
37	*Šumperk*	7.807	11.332	0.000529	0.728
38	*Vsetín*	17.659	5.960	0.000356	0.683

39	*Uherské Hradiště*	10.761	7.621	0.000381	0.704
40	*Břeclav*	14.052	8.659	0.000382	0.717
41	*Hodonín*	12.530	7.828	0.000566	0.711
42	*Sokolov*	9.747	8.367	0.000527	0.689
43	*Chrudim*	11.810	10.290	0.000355	0.652
44	*Havlíčkův Brod*	14.291	11.080	0.000331	0.691
45	*Strakonice*	9.634	10.871	0.000398	0.742
46	*Klatovy*	21.286	7.966	0.000292	0.748
47	*Valašské Meziříčí*	13.133	9.486	0.000362	0.708
48	*Jindřichův Hradec*	12.252	11.161	0.000343	0.728
49	*Vyškov*	18.065	6.636	0.000327	0.714
50	*Žďár nad Sázavou*	10.185	7.749	0.000447	0.724
51	*Kutná Hora*	8.207	14.870	0.000426	0.742
52	*Náchod*	13.024	9.072	0.000355	0.673
53	*Svitavy*	6.934	10.905	0.000581	0.774
54	*Ostrov*	12.119	6.846	0.000490	0.663
55	*Jičín*	8.101	9.916	0.000472	0.696
56	*Pelhřimov*	16.554	8.183	0.000350	0.692
57	*Česká Třebová*	12.331	6.675	0.000534	0.715
58	*Turnov*	8.276	11.325	0.000407	0.652
59	*Ústí nad Orlicí*	11.507	8.644	0.000427	0.699
60	*Rokycany*	8.969	10.276	0.000550	0.684
61	*Zábřeh*	12.685	6.413	0.000432	0.684
62	*Aš*	8.371	9.983	0.000548	0.738
63	*Tachov*	9.242	8.433	0.000564	0.709
64	*Domažlice*	9.328	7.930	0.000555	0.717
65	*Rychnov nad Kněžnou*	9.069	10.374	0.000443	0.691
66	*Semily*	9.659	6.459	0.000570	0.641