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The Analysis of Networks Space Structures as Important Elements of Sustainable Space Development

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Abstract. Space as the entirety of elements occurring within it and their configuration, is subject to analysis for purposes of optimizing activities connected with it, or generally speaking, optimal spatial management including predicting its future states and preventing spatial conflicts. Geospatial analysis is a complex process, the essential components of which are the collection, modelling and analysis of spatial data. Drawing proper conclusions is largely dependent on the type of spatial model developed. The author carries out the characterization of selected types of network models for purposes of spatial analysis in the sustainable development of space, providing examples of modelling various elements of space on the form of a network. She also touches on the aspect of hierarchy and scale-freeness in these models, as well as the possibility of predicting future states of space, and also using the properties of network models in decision processes to achieve sustainable development.

Keywords: model, network, scale-free, safety space development.

Conference topic: Sustainable urban development.

Introduction

According to the idea of sustainable development, aspiring to fulfil the needs of man as well as improving the living conditions of the population cannot lead to the degradation and disturbance of the state of equilibrium in nature (SDKP 2017). The degradation of the natural environment had never before been as extensive as in current times. Such a situation poses a serious problem and encourages the search for solutions in many fields of knowledge. This also pertains to fields connected with architectural activities, e.g. the development of urban areas, including transportation systems and public spaces. One of the basic needs of humans is the sense of security. People cannot live and function properly in areas where they feel threatened. Therefore, when planning spatial development investments, they should be planned in such a manner that allows these areas to be as safe as possible. Such an approach will make it possible to avoid activities connected with future redesigning of space and making changes which are costly and have a negative influence on the environment. Activities connected with the rehabilitation of areas which had been previously incorrectly developed will also be avoided. Thus, new methods of modelling space (including network methods) and spatial analysis are sought in order to improve efforts aimed at achieving sustainable development.

Spatial management should make it possible to meet the current as well future needs of man. In order to ensure optimal spatial management, in accordance with the principles of sustainable development, this space should be analyzed adeptly. Spatial analysis, also referred to as geoinformation analysis, is a process aimed at obtaining reliable spatial information regarding the problematic situation that is of interest to us, and answers to the posed questions regarding the object, phenomenon or process, by way of analyzing spatial data. In order for the data to be analyzed, it must first be obtained and presented in a proper form - thus a model must be developed.

The ability to model space and phenomena taking place within it as a network makes it possible to analyze their structure, determine their nature, and make use of the properties characterizing it.

Network models describing space

A model is the depiction of a structure, object or subject in a simplified manner. The relationships occurring between these structures, objects or subjects can also be presented using models. This is the schematic representation of a certain individual, unitary subject, or an entire class of subjects. Representation covers certain properties of the original, especially those which will make it possible to adequately imagine the original as a whole. The essence of a model in science is the concept of structural similarity, or the isomorphism between the subject – model, and its representation, which comes down to the unambiguous, mutual adequacy of relationships determining these structures (Chojnicki 1966). They represent only those characteristics of reality which are important from the perspective of the carried out analysis, leaving out characteristics which, in the given case, are less important or not as significant. Models may take the following forms: iconical, analogue, word or symbolic (Domański 2011). Special characteristics of model structures are: selectivity, structuring, suggestiveness and approximation. The last of these results from the first characteristic – selectivity; a model is not a complete, precise and final reflection (representation) of reality, but merely – or as much as – its estimate – approximation (Domański 2011).

A specific type of models are network models. Albert-László Barabási, in his book titled "Linked – How everything is connected to everything else and what it means for business, science and everyday life" (Barabási 2003b), does a very good job of characterizing these structures. These models describe space as a system comprising nodes and links. The general definition of a network describes these structures as a collection of interconnected points, with the possibility of these points being connected physically, e.g. as in the case of cities being connected by roads, or by certain relationships, e.g. the increase or decrease in value. These models are widely applied in analyses, including geoinformation analyses (Bajerowski *et al.* 2003; Bajerowski, Kowalczyk 2013; Amaral *et al.* 2004; Biłozor, Szuniewicz 2008).

There are many network structures which can be classified in many ways. Basic types of networks include random networks (Fig. 1a, Fig. 2a) as well as scale-free networks (Fig. 1b, Fig. 2b) (Barabási *et al.* 1999; Barabási *et al.* 2000; Cohen 2002; Barabási 2003a; Barabási, Oltvai 2004; Barabási 2005).

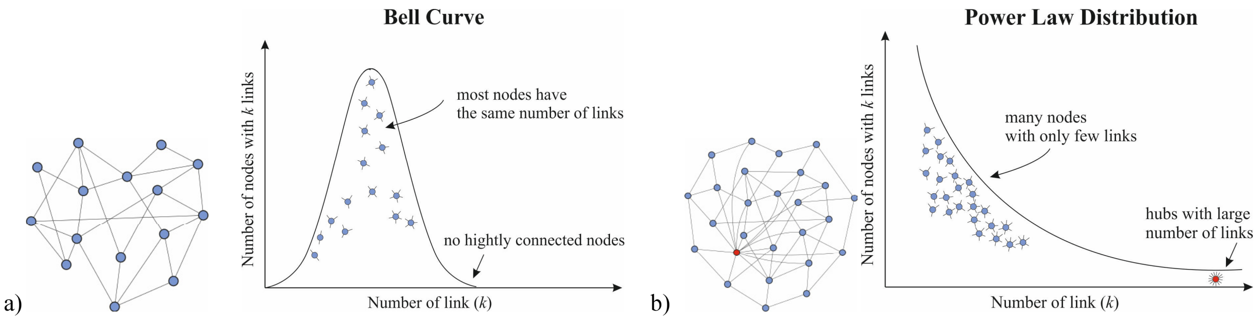

Fig. 1. Network structures. a) random network, b) scale-free network (Source: own analysis)

A very illustrative example of these two kinds of networks is given by Barabási (Barabási 2003b). Normal distribution, characteristic of random networks, describes a national highway network. In this network, the nodes are the cities in the USA, and the links are the major highways connecting them (Fig. 2a). As for a scale free network, it can be identified with an air traffic system, also in the USA (Fig. 2b).

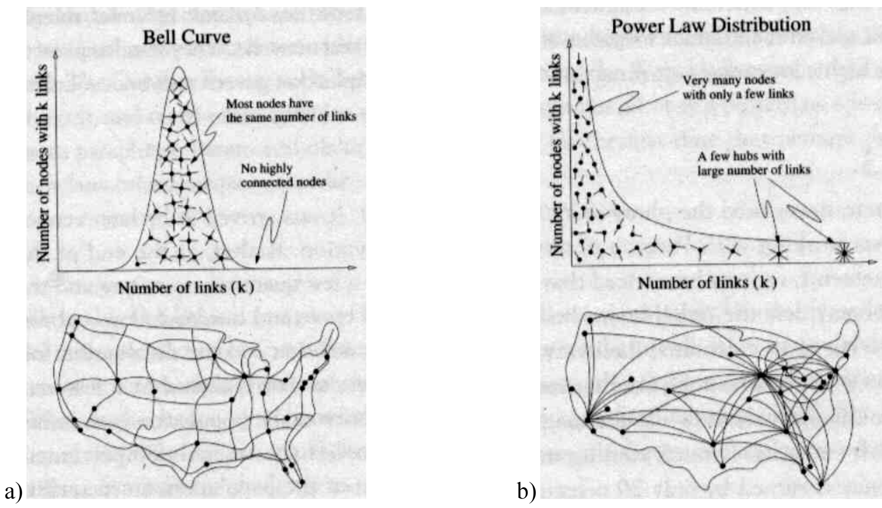

Fig. 2. Network structures. An example of interpretation of degree distribution for realistic structures,
a) a national highway network in USA b) air traffic system in USA (Source: Barabási 2003b)

These networks, possessing their specific random or scale-free character, contain nodes and links, differing in terms of their distributions and special characteristics. Random networks and free-scale networks may have certain similar features due to their structure – modularity (Fig. 3a) and hierarchy (Fig. 3b), and can also possess both of these features simultaneously (Fig. 3c).

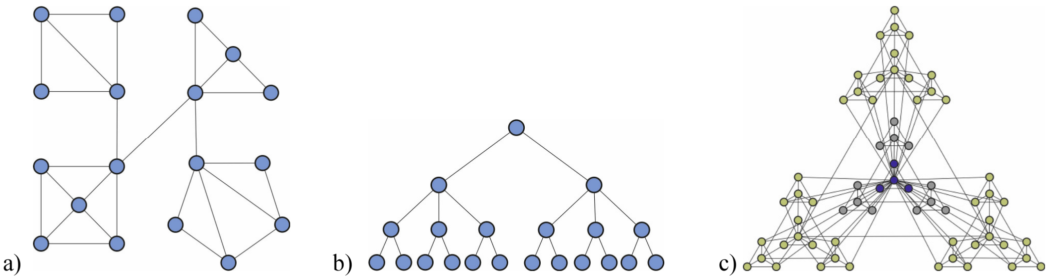

Fig. 3. An example of network's construction. a) modular network, b) hierarchical network, c) modular and hierarchical network (Source: own analysis; Barabasi, Bonabeu 2003)

Random networks can be compared to a volleyball or fishing net, in which each knot (node) has approximately the same amount of links. Free-scale networks, on the other hand, are characterized by the presence of nodes with significantly higher than average numbers of links. These nodes are referred to as centres or hubs. Free scale networks differ significantly from random networks. As presented in Figs. 1 and 2, the bell curve distribution of node linkages is characteristic of a random network, whereas power law distribution describes scale-free structures. Extremely important in the structure of a free-scale network is the occurrence of above-mentioned hubs. These hubs, having an incomparably higher amount of links than other nodes, are the critical points of the entire structure. It is estimated that destroying anywhere from 5% to 15% of network hubs can lead to the complete deterioration of the network and dysfunctionality of the system. Therefore, if the structure of a network is found to be that of a free-scale network and hubs are identified within it, concrete actions aimed at improving the structure and strengthening its resistance may be taken. More on free-scale networks and their characteristics is written by Bajerowski and Biłozor (2005); Albert and Barabási (2002); Barabási and Bonabeau (2003).

Another means for the structural analysis of a network is graph theory. The general definition of a graph states that it is a mathematical structure with the use of which the relationships occurring between objects may be presented and studied. The structure of a graph comprises a set of vertices between which edge connections may exist. It is assumed that each edge finishes and starts at one of the vertices (Wilson 2008).

Similarly as in graph theory, network vertices can be represented as objects or values characterizing these objects, while links as the relationships between them. The present study, however, uses the term network as opposed to graph.

The links between nodes in a network can be considered assuming that a connection exists between two nodes – bilaterally. In graph theory, such a structure can be compared to a graph. But what if the link between nodes has a direction? What if such a link "works"/"is" in only one direction? In graph theory, such a structure can be compared to a directed graph. There exist networks whose structures are composed of nodes interconnected by a certain relationship, e.g. minimal increase in value. Developing such a model is based on linking nodes, which have their own values, in such a way that the value from one node to the next minimally increases. Such a connection is characterized by a direction and "works" in only one way. Such a model has been developed and used for managing landscape potential in urban areas as an important element of sustainable development (Kowalczyk 2014, 2015). Similar modelling has been used in the process of creating and analyzing from vertical crustal movements, as well as creating a model of a Triangulated Irregular Network on the basis of geospatial data (Kowalczyk, A., Kowalczyk, K., 2014a, 2014b; Kowalczyk *et al.* 2011). This type of modelling is also applied in activities connected with planning transportation systems in the most rational manner, e.g. due to public transport. A specific case is modelling the transportation system for purposes of safety, e.g. capacity and continuity of flows of roads accessible to pedestrians and motor vehicles (A – bridges) or a transportation system accounting for the need for evacuation and access by emergency vehicles. The present study looks at two cases of modelling the same spatial data. The first example assumed that the nodes in the analyzed network are the intersections of roads, while links are the physical connections by a road (Fig. 4).

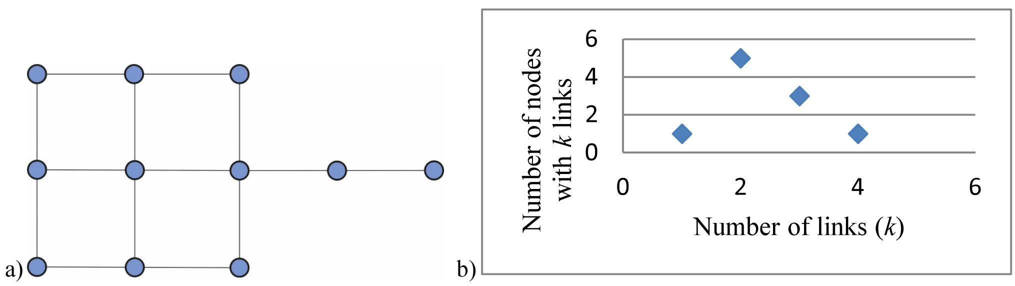

Fig. 4. a) The network with the nodes which are the intersections of roads. Links are the physical connections by a road, b) distribution of node linkages (Source: own analysis)

The second case pertained to a situation in which nodes comprise, similarly to above, the intersections of roads, whereas the connections are a relationship – the minimal distance to the node (Fig. 5). In this case, the node generated only one link to another node, which is the nearest. Let us assume that these distances were determined on a physical road. The links can be generated using, e.g. Dijkstra's algorithm or A* algorithm (Sedgewick, Wayne 2011; Ruohonen 2013).

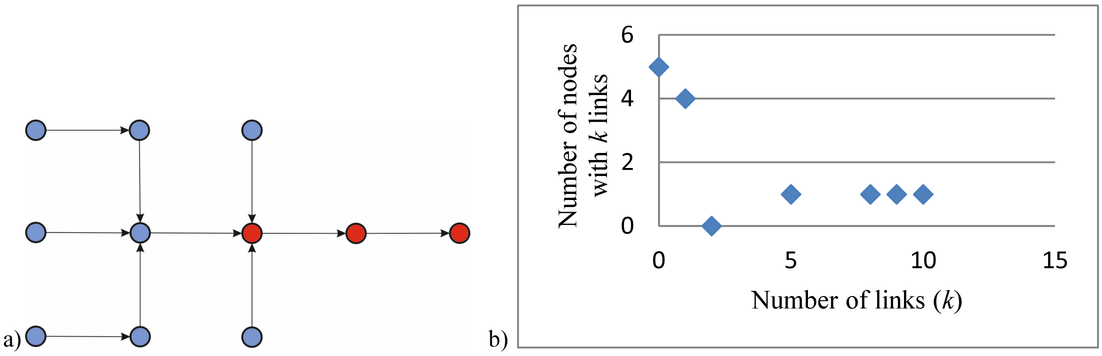

Fig. 5. a) The network in which nodes comprise, similarly to above, the intersections of roads, whereas the connections are a relationship – the minimal distance to the node, b) distribution of node linkages (Source: own analysis)

In the above-given examples, we can see two networks (Fig. 4 and Fig. 5) with the same number of nodes – N. What differentiates the two networks is the nature of the links. In the first network, links exist between nodes without a directional dependency. Modelling with such assumptions were conducted by Kowalczyk (2010, 2013). An examples of similar modelling are presented below (Fig. 6).

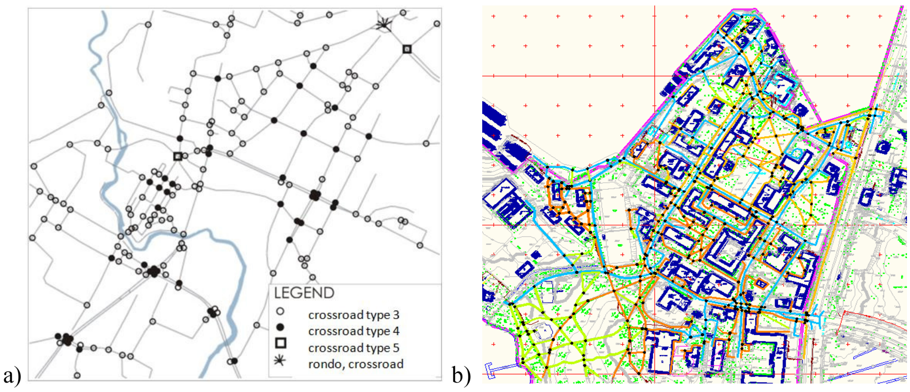

Fig. 6. An examples of network models of communication system (roads) in which links exist between nodes without a directional dependency a) model of the communication system network in the Olsztyn city (Poland) with links and nodes (Source: Kowalczyk 2010); b) networks of communication systems: color light blue – a network of vehicular traffic, orange and bright green – a network of pedestrians traffic, black points – nodes of the web (Source: Kowalczyk 2013)

In the second model (Fig. 5), new approach, which is the main object of this research, links exist with the assumption that the link is only in a single direction (directed graph). Thus, the number of links (E edges) differ from one another. The distribution of the degrees of vertices P(k) is different in each case. This distribution informs us about the number of nodes with a given number of links in the analyzed network. Such information is key to further planning and design works connected with designing transportation systems, both on a micro as well as macro scale. The above demonstrates that, in the first case, where links were treated as bilaterally important, the character of the network was determined as random. It follows that the majority of vertices of this network have more or less the same number of links, and there is a lack of characteristic elements, such as network hubs (Fig. 4b).

In the second case, for which it was assumed that the link between nodes constitutes a dependency, the character of the network was described as scale-free. This is demonstrated by the distribution of the degrees of vertices. It was, therefore, possible to identify node which play the role of hub in this network (Fig. 5b). This provided information on which elements of the entire structure are the most important, and the destruction of which (lack of serving their function) will lead to the complete collapse of the entire structure, in this case the functioning of the transportation system.

Knowledge of the character of a network, as a scale-free structure, allows for drawing further conclusions. If only two hubs are identified in an analyzed network, it can be stated that the functioning of these two hubs determines the functioning of the entire network. Works consisting of changing the degree of "scale-freeness" of a network can therefore be carried out on the model, thus designing nodes which would become additional hubs and increase the resistance of the entire network, assuming additional functions in the case of one of the hubs being destroyed. This knowledge also shows which element ought to be protected and developed in order to prevent the dysfunctionality of the system.

Conclusions

The process of modelling data into structures and its proper interpretation are of key importance in the process of analyzing the model and further activities aimed at achieving sustainable development. The aim of the studies was to determine the possibility of network modelling, especially in the case of one-directional links. The studies indicated that transportation systems modelled into network structures may vary in terms of their character. This results mainly from the assumptions regarding the bilateral character of relationships in a system. Systems in which links were generated bilaterally – without directional dependency of the relationship, exhibited different properties despite having the same number of nodes. In the network model for which it was assumed that a link comprises a dependency, a direction of links was generated. In this case, some network nodes generated significantly greater amounts of such links than others, determining the scale-freeness of the system.

The analyzed example shows that hubs can be identified in transportation systems of a free-scale character. In this case, these were the nodes of a network which, through their links, constitute the most important elements of the network. These critical points often determine the functioning of the entire system; in the case of a transportation system, this being its capacity and flow capabilities. It is the hubs of a given network that "receive" the majority of links of the remaining system. They thus become the "Achilles' heel" of the system. In the case of a transportation system, this leads to congestion, especially if there is a need to carry out evacuations, and severe difficulties in the passage of emergency vehicles. This information is key to further planning and design works connected with designing transportation systems, and thus, the concept of sustainable development.

Spatial planning with an awareness of the existence of network structures allows for optimizing planning activities in such a way that eliminates the need for redesigning these structures in the future and, thus, incurring costs connected such a need, including the rehabilitation of deteriorated areas, as well as expenses connected with increasing security. Therefore, network modelling and analyses ought to play an important role in the evaluation and simulation of city development aimed at achieving sustainable development.

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