DEVELOPMENT AND ANALYSIS OF A COMMUNICATION NETWORK SYSTEM MODEL FOR FIRE SERVICE OPERATIONS

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Abstract

Models are built for the purpose of analysis and making optimal decisions in all aspects of life. Network models represent a very large group of systems occurring in space. Creating network models, their analysis and identification in terms of construction and character allows for optimization of activities related to the analysed system and issues. The communication system can be presented as a network model. It is part of important spatial structures and plays a very important role in the vitality of these structures, such as cities and villages, as well as in people's everyday lives and their safety. In this aspect, it is an important part of critical infrastructure. The communication system is a necessary element for ensuring proper operations of Fire Brigade groups. His analysis carried out by building a network model and defining its character, allows undertaking actions related to the improvement of the Fire Brigade's accesses to events. The research which has been done on the tested area are a proposal of a complete network analysis method of the communication system for the Fire Brigade actions.

Key words: network model, safety, GIS, spatial analysis

Introduction

Communication systems are among the most important spatial structures shaping daily human life. Enabling free and organised movement of people, they constitute an important element of the safety system as part of critical infrastructure (KOWALCZYK, 2013). One of the functions of roads, walkways, wheeled and pedestrian traffic routes of all kinds is to facilitate effective (i.e. efficient and safe) movement of persons, property and rescue units in the event of danger, in the shortest time possible. The Fire Service, being the organised formation responsible for prevention of and response to all sorts of threats (except crime), in order to protect human life and health, property, and the environment, requires effective communication structures. Their effectiveness should be the result of not only good repair, but also distribution – location and capacity ensuring accessibility. Communication structures should allow the Fire Service to reach the site of an incident not only when the entire system is functional, but also when some of its elements have been disabled. Network modelling and geospatial data analysis (BAJEROWSKI, KOWALCZYK, 2013) are necessary for understanding the relations between various elements of a communication system and safety operations in the purview of the Fire Service.

The Network Model

One could say that modelling is the essence of science (CIEŚLIŃSKI, 2002). Half the battle for one's research is choosing the right model, which will correctly describe the fragment of reality one is investigating, irrespective of whether the model is verbal, graphic or mathematical (BAJEROWSKI, KOWALCZYK, 2013; CIEŚLAK et al., 2016; RENIGIER-BIŁOZOR, BIŁOZOR, 2015; BIŁOZOR, RENIGIER-BIŁOZOR, 2016; OGRODNICZAK et al., 2017a; OGRODNICZAK et al., 2017b; OGRODNICZAK, RYBA, 2017).

The concept of a model is ubiquitous in the literature. Its two primary meanings are presented in CHOJNICKI (1966). The first meaning of the word *model* provided by Chojnicki is that of a good example, worthy of emulating. In the second meaning, the word signifies a simplified, approximate version of another thing or structure. Models can be used to schematically represent individual objects or whole classes of objects. The model does not represent the original entirely but is only capable of representing some of its properties – especially those which make imagining the entire original easier (CHOJNICKI, 1966).

The classical model theory has a slightly different view of this concept. It rests on structural similarity, or isomorphism, between the modelled thing and its representation. The relations between those structures are reduced to a one-to-one correspondence (bijection) between them. In keeping with the classical concept, BAJEROWSKI (2003), following CHOJNICKI (1966), distinguishes two fundamental models. In the stricter sense, model E and model Ē, and in the generalised sense:

- Template model E(w) and Ē(w),
- Representation model E(o) and Ē(o).

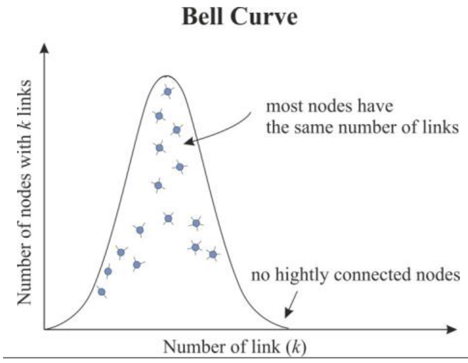
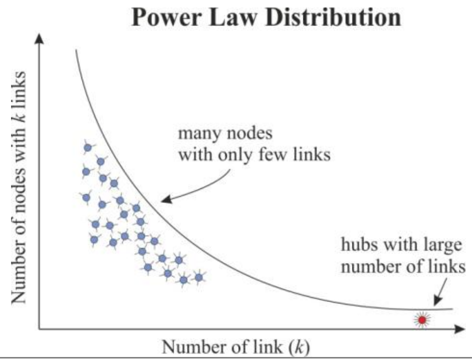
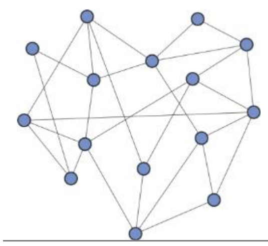
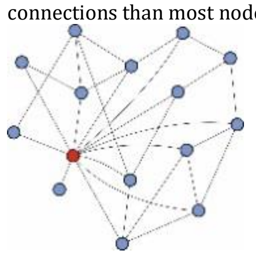
In the first case, *object P is the template model E(w) of an object or class of objects P' if and only if person O maps object P' or class of objects P' to object P in such a way that structure S' or part of structure S' of object P' is isomorphic to structure S of object P* (BAJEROWSKI, 2003).

In the second case, *object P is the representation model E(o) of an object or class of objects P' if and only if person O maps object P to object P' in such a way that structure S of object P is isomorphic to structure S' of object or class of objects P'* (BAJEROWSKI, 2003).

A network model can be defined as a structure composed of nodes and connections between those nodes. Connections may be physical (e.g. crossroads connected by roads) or they may represent relationships (e.g. people connected by literature citations).

Networks may have different structures and characters. Mapping structures existing in the real world onto network models lets one gain information and knowledge on their forms, and consequently – their properties. Geospatial data analysis makes a very important distinction between random networks and scale-free networks. Apart from common elements, i.e. nodes and connections, they are significantly different from each other, as shown in Table 1.

Table 1. General characteristics of random networks and scale-free networks.

Random networks	**Scale-free networks**
The random network structure has roughly the same number of connections to nodes, and the distribution in such a network is represented by the characteristic Poisson distribution curve.	The structure of scale-free networks is characterized by different number of connections to nodes, and the distribution of this network is represented by the power function.
	
No centers (hubs) - nodes that have more connections than the average number of connections to nodes.	Occurrence of centers (hubs - red spot) - nodes with more connections than most nodes of the entire network structure.
	
There is no preferential connection selection in a particular hierarchy.	There is a preferential selection of connections in a given hierarchy - when a new node appears, it tends to bind to nodes with a high number of bindings, and this favorable feature makes the nodes more and more interconnected in opposition to their neighboring nodes with fewer connections.
Random cutoff (sometimes referred to as an attack on a node or nodes), that is, the permanent or temporary destruction of a given number of nodes, leads to break down of the whole network structure into smaller, separately functioning networks. The structure can be severely damaged.	Resilience to random attacks - An accidental attack on a node does not have such a devastating impact on scale-free network as it has on random network Thanks to the heterogeneous structure, there are always connections that continue to hold the entire network in active state.

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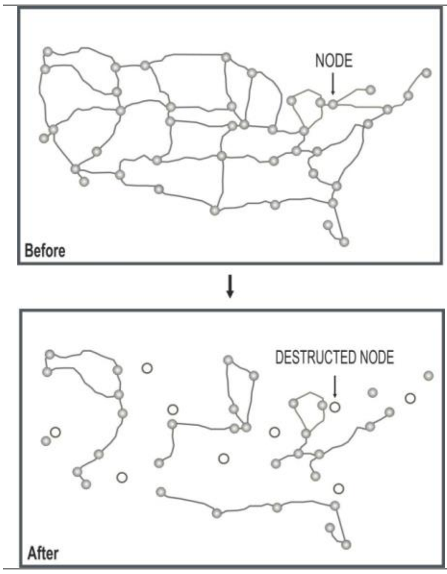
<td>
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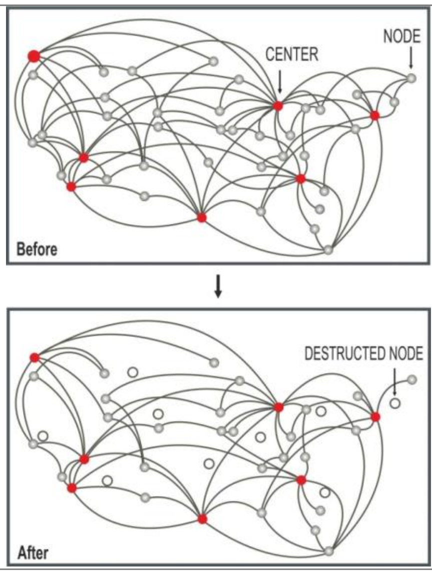
<td>
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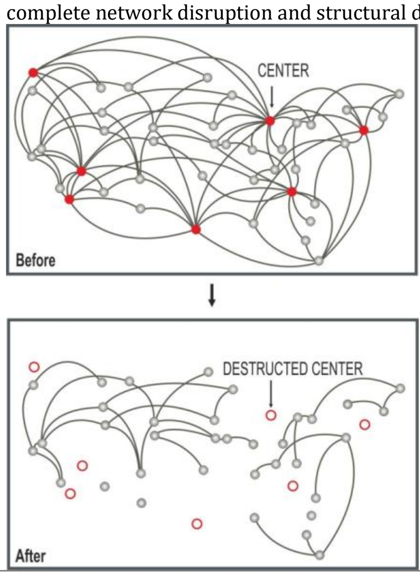
<td>No centers in the network structure.</td>
<td>Huge sensitivity to the deliberate exclusion of centers from the network structure - these networks are very sensitive to attacks organized intentionally at a given point - the network center. Intentional attack on several centers can lead to complete network disruption and structural disfunction.

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<td>Rarely appearing in real world.</td>
<td>They characterize many spatial structures and are universal in usage.</td>
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Source: (BEDNARCZYK et al., 2018; KOWALCZYK, 2015; KOWALCZYK, 2017; BARABASI et al., 2000; BARABASI, 2003; BARABASI, 2005; BARRAT et al., 2004; BIŁOZOR, SZUNIEWICZ, 2008; KOCUR-BERA, 2014).

Therefore, deciding whether the network in question is random or scale-free is crucial since it lays a scientific foundation for the optimisation of activities and decision-making. A network identified as scale-free must have hubs in its structure. This information may be vital when it comes to the structure's proper functioning or preventing its failure. For more information on random and scale-free networks, see: BEDNARCZYK et al., 2018; KOWALCZYK, 2015; KOWALCZYK, 2017; BARABASI et al., 2000; BARABASI, 2003; BARABASI, 2005; BARRAT et al., 2004; BIŁOZOR, SZUNIEWICZ, 2008; KOCUR-BERA, 2014.

For the purpose of this analysis, it should be assumed that a communication system's network model is an approximate version of its structure, exhibiting only those characteristics which are necessary for geospatial data analysis for Fire Service operations. The model schematically represents certain individual elements of the communication system: intersections as nodes and roads as connections. These generate the model's network structure and can, in such form, undergo full analysis and modifications simulating the structure's specific behaviors. The nodes and connections of the network, besides existing and representing physical connections, can endow the network structure with parameters expressing, for instance, the number of passing cars (in the case of nodes) or the flow direction (in the case of connections).

A number of useful model definitions relating directly to communication structures or systems has been presented by DOMAŃSKI (1963). The anisotropic model and models leading to its development are especially noteworthy. Among these are:

- the travelling salesman model – having the simple requirement to find the shortest route from a given residential area of type p through all n residential areas of that type in a region, this model, however, requires defining a hierarchy of routes in the network, starting with the layout of main routes, through the secondary, tertiary and miscellaneous. A shortcoming of this model is an insufficient cohesion of routes (DOMAŃSKI, 1963). One of the solutions to the travelling salesman problem is the Hamiltonian cycle (BIAŁYNICKI-BIRULA et al., 2014). It is a closed path through a graph which visits each vertex of the graph only once (except for the first vertex, being at once the beginning and the end of the cycle). Finding a Hamiltonian path remains an open question since there are methods for finding near-optimal solutions, but none that are conclusive. This method can be effectively employed mainly with a small number of vertices, since as the number of potential solutions grows, it becomes more problematic to check all the solutions and select the path which is, in fact, the shortest.
- the telephone exchange model – derived from construction of telephone networks, this model defines the location of a network's central office so that 'its connection with street cabinets, which gather lines from individual telephones, requires the least length of copper wire' (DOMAŃSKI, 1963). The central point Q of such a network is defined by:

$$\varphi(Q) = \sum_{i=1}^{n} c_i r_i = min, \tag{1}$$

where c_i is a positive number proportional to the cost of a unit length of wire connecting the exchange Q with the street cabinet P_i, and r_i is the length of wire QP_i' (DOMAŃSKI, 1963).

The advantage of this model is having variables proportional to the cost of a unit of length of the path. Its disadvantages are: the incompleteness of the layout, disregard of the regional hub already present, and disregard of factors other than the minimisation of economical distances in defining the hub location. This model is best employed analysing small local areas, especially those with new investments in which the location of the hub is discretionary (DOMAŃSKI, 1963).

- the centralised network model – stemming from a number of assumptions, this model defines the optimal shape of a road network in order to minimise the cost of communication. It begins with a given area with a defined border and a center towards which all traffic is directed. Also given is the number of roads *m*, and their endpoints – *R*, which are located at the area's border. Furthermore, access roads must be parallel to each other. The solution is arrived at with calculus of variations. For more information on the centralised network model, see: *Zespoły sieci komunikacyjnych* (DOMAŃSKI, 1963).

The analysis of these three models and their shortcomings has revealed the need for a different model describing a communication network – the anisotropic model.

According to DOMAŃSKI (1963) it is a function of the hierarchy, relative positioning, and dimensions of roads of various kinds constituting a system.

$$M_z = f(\gamma, \varphi, \beta), \tag{2}$$

where:

M_z – construction of a communication system network,
φ – relative positioning of roads,
β – dimensions of roads in the system,
γ – hierarchy of roads.

One of the assumptions of this model is that it would generate lower cost than road systems constructed based on more traditional models of communication networks. It rests on the following principles of operation:

- the flow of traffic on a main (primary) road is greater than on a side (secondary) road,
- the relative angle of roads should not exceed 180 degrees,
- the number of main roads should be less than the number of side roads, in a node the number of main roads should be less or equal to the number of side roads,

- the cost of main road construction is greater than the cost of side road construction, the cost of movement of mass on main roads is lower than on side roads, and total unit cost of main communication is lower than that of side communication,
- the ratio of total unit cost of main communication to total unit cost of side communication is constant,
- if the unit cost of intermodal transport is lower than the cost of direct transport on a side road, the side and main road are complementary, whereas if the unit cost of intermodal transport is higher than direct transport on a side road – the side road substitutes the main road,
- access traffic (short range) and direct traffic (middle and long range) on side roads are equal,
- cargo density in an intermediate area, serviced by side roads, which is located between two main roads, is less than the cargo density in the area adjacent to the main road.

DOMAŃSKI (1963) bases his model on the concept of anisotropy since he has proven that the main properties of roads are anisotropic, i.e. dependent on direction. He distinguishes between the directions of main roads and side roads serviced by different kinds of communication. Fig. 1 shows a layout of roads in an anisotropic model. In a communication system relying on main and side roads, access roads are perpendicular to the main road, whereas in direct communication, aiming for the shortest connections, the regular grid of side roads is flattened towards the main road.

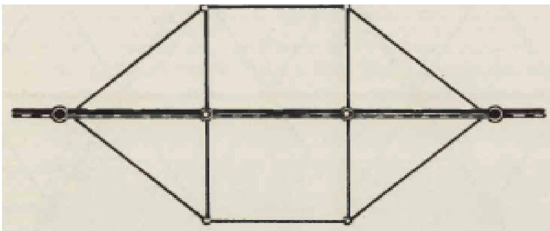

Fig. 1. A theoretical anisotropic layout.
Source: (DOMAŃSKI, 1963)

Fig. 2 shows the entire anisotropic model. The influence of deforming factors noticeably weakens with the distance from the main road, which results in a tendency for a square or equilateral triangular layout. However, some places show irregularities, resulting from the continuity of roads which must be connected to the main road (DOMAŃSKI, 1963).

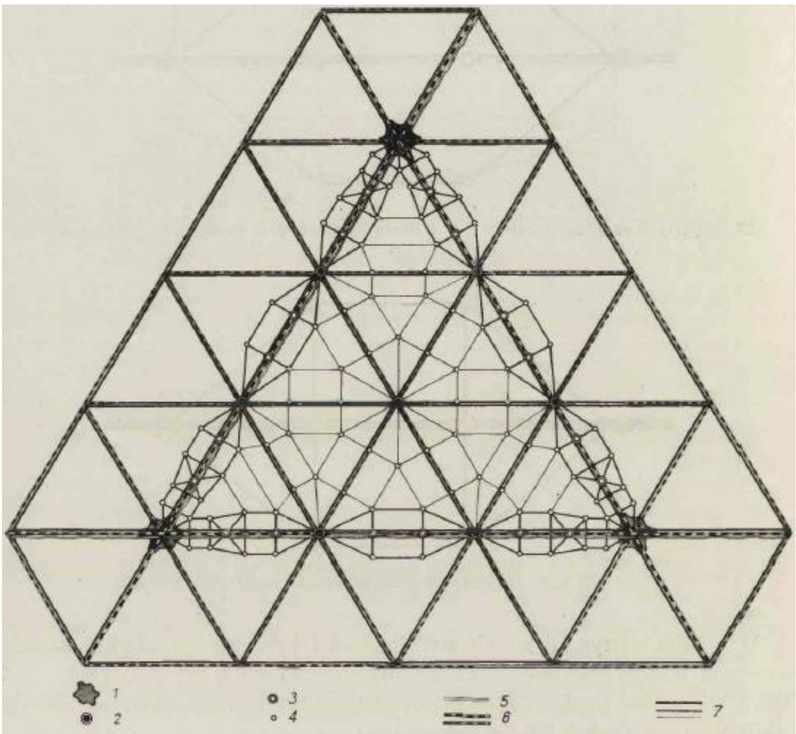

Fig. 2. Anisotropic model of a system of communication networks.
Key: 1 – 1st class nodes; 2 – 2nd class nodes; 3 – 3rd class nodes; 4 – 4th class nodes; 5- rivers; 6 – railroads; 7 – roads.
Source: (DOMAŃSKI, 1963).

Domański's analysis (1963) shows that the shape of a communication network depends on two distinct tendencies:

- The tendency of each node (residential area, intersection) to connect with other nodes. A geometric representation of this behaviour would be the set of straight lines connecting all nodes to each other
- The tendency to merge many directions into one, with the assumption that traffic can only use roads technically intended for it. "Advantageous" directions attract more traffic and thus the hierarchy of main and access roads is formed.

Building a communication network model

A network model of a communication system has been created for a typically urban test area. It has comprised a residential area with semi-detached housing of two or more residences, as well as apartment buildings of up to seven storeys. The communication system model reflects the existing road network for wheeled transport (Fig. 3).

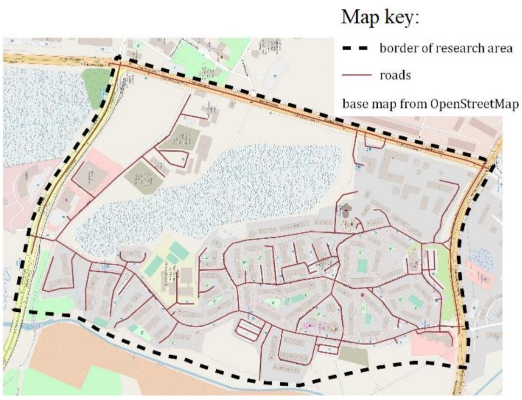

Fig. 3. Research area – part of Olsztyn, Poland. Warmińsko-Mazurskie Voivodeship.
Source: Own analysis.

Construction of the model began with data collection and standardisation for the purpose of creating a database. Inventory has been taken in the field. This form of data gathering is especially useful for information about mobile spatial elements, e.g. parked cars and other objects that can change their location.

The next step was the development of a vector network model of the communication system. An open-source software suite QGis 3.0 was used for this purpose. Two models, A and B, were developed as a result. Model A (Fig. 4) shows the communication system network with nodes representing intersections and connections representing physical connections within the space of the test area.

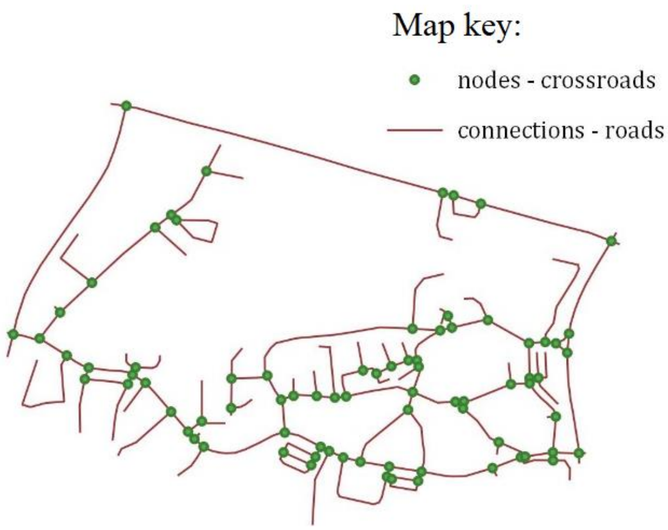

Fig. 4. Model A - the network model of the communication system. Nodes – crossroads. Connections – physical connections between nodes.
Source: Own analysis.

Model B (Fig. 5) shows the same structure but includes other features and relationships relevant for the analysis. These include: directions of traffic (one-way and two-way roads), access gates to fenced areas, speed bumps, road capacities and mobile features (parked cars preventing the passage of a fire engine). Traffic direction is generally irrelevant for rescue units, but civilian inhabitants, even under special circumstances such as evacuation, will follow normal traffic rules.

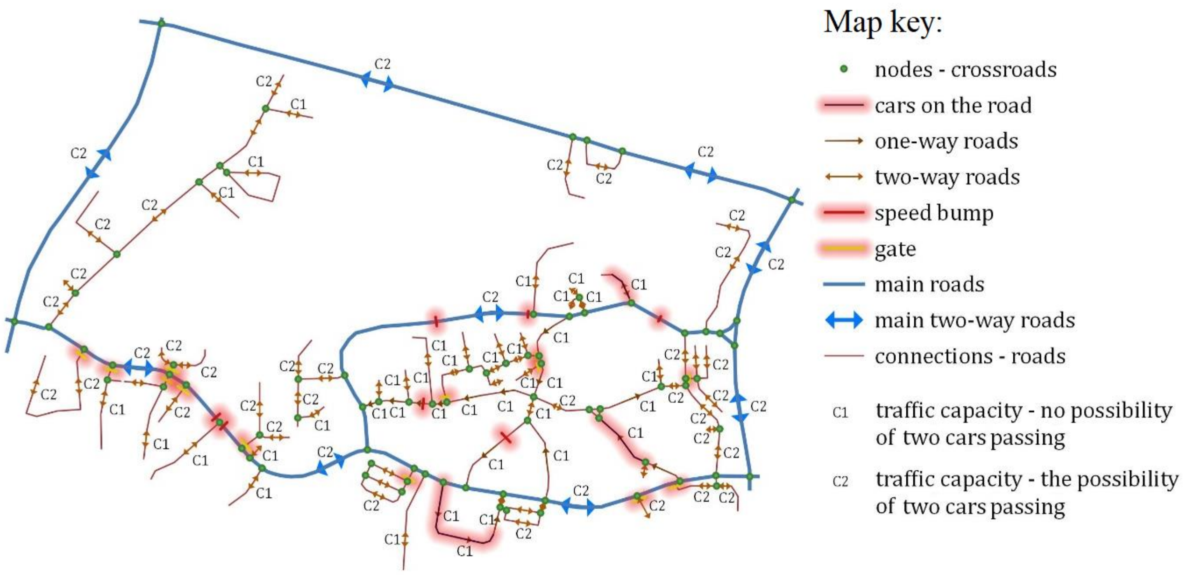

Fig. 5. Model B - the network model of the communication system with additional features.
Source: Own analysis.

Geospatial Data Analysis of the Network Model of a Communication System

Digital cartographic modelling methods allow for the inclusion of additional information in the form of thematic layers, e.g. about roads on which pavements and part of the road are filled with parked cars. This is a common impediment to reaching the site of the incident quickly.

Analysis of model A revealed 79 nodes, including: 70 3-way intersections, and 9 4-way intersections. No 5, 6, 7, or 8-way intersections have not been identified.

Tab. 1. Inventory of intersection types and their numbers.

								The total of all intersections of all types
Intersection type		3	4	5	6	7	8	
Number of intersections	0	7	9	0	0	0	0	79

Source: Own analysis.

A network of this kind (model A), where nodes represent intersections and connections are roads for vehicular traffic (with no specified direction), can be characterised as random. The distribution of nodes and connections has a single maximum. The network structure has no apparent hubs, i.e. nodes with an exceptionally high number of connections. Under the criteria of model A construction, no vital points whose disabling could seriously impair the whole system can be identified within the network. But are the nodes of the network indeed equivalent and all connections representative of the same type of road? Analysis of model B, including additional characteristics and relations such as traffic directions, speed bumps and mobile features (parked cars), reveals other attributes of the network.

Analysing model B, it is apparent that it possesses features resembling an anisotropic model. The foremost of these is the road hierarchy. Fig. 5 shows the main roads and side roads connected to them. Traffic flow on main roads is greater than on side roads. Another feature also exhibited by the discussed model is the smaller number of main roads as compared to side roads. One can observe that in the network model of the communication system, access roads are perpendicular to main roads. The anisotropic model typically exhibits two kinds of road layouts: triangular and rectangular. The developed model also exhibits these kinds of structures. In some parts of the structure one can also observe the typical flattening of the road layout. Some of the roads do not connect at right angle but converge in a single point. Layout flattening is meant to shorten the travel time between two points.

Models A and B developed for this analysis constitute two networks (Fig. 4 and 5) with the same number of nodes N. One of the differences between these networks is the character of their connections. Model A presents a network in which connections between the nodes have no defined direction. In the other model, connections are defined either for one or two directions. Thus, the number of connections (or *edges*) E is different for the two models, as is the node degree distribution P(k). Degree distribution describes the number of nodes with a given number of connections within a network (KOWALCZYK, 2017). Model B presents a network in which one can distinguish hub nodes strategic for the operations of the Fire Service. The disabling of those hubs will greatly impede the functioning of the whole network and, in consequence, delay the arrival of Fire Service to the site of the incident. The nodes in question are marked in the figure with Roman numerals I through X. Although these nodes physically have only 3 or 4 connections, in fact they can be said to have many more since they funnel traffic from other streets and thus form additional connections. Knowing this enables planning rescue operations in the event of any of these nodes being disabled. It provides the basis for constructing nodes and connections which will increase the robustness of the communication system network as a whole. An example of such an alteration to the model is shown in Fig. 6. Adding new connections and creating new main nodes increases the resilience of the communication system in the event of other nodes being damaged (in this case I, II, and V especially). New connections enable alternative routes.

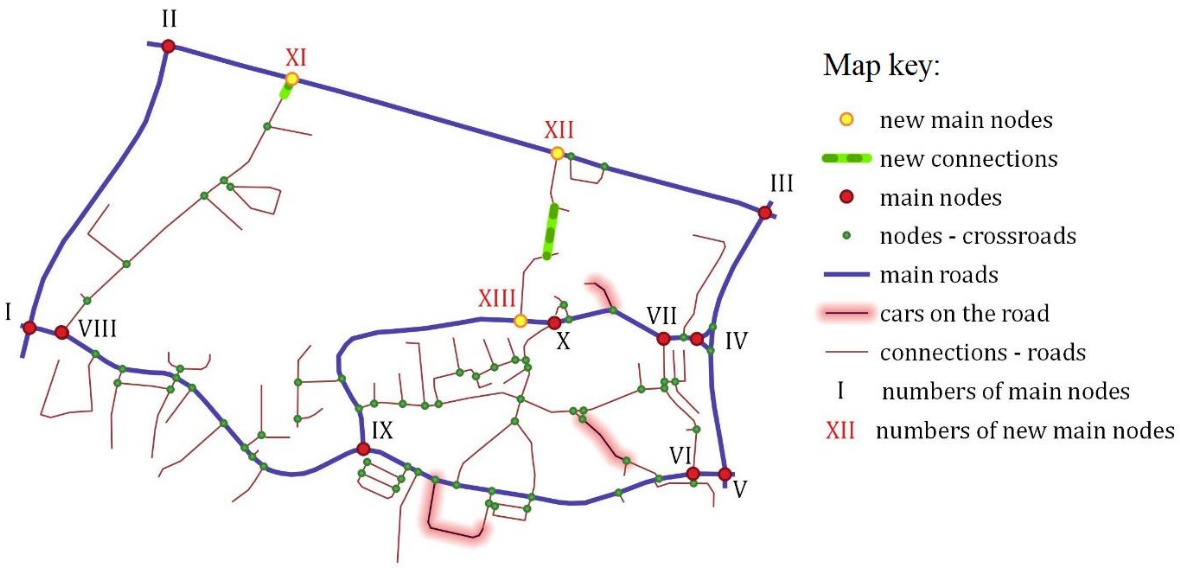

Fig. 6. Network model with new connections and main nodes.
Source: Own analysis.

Conclusions

The purpose of this study was to develop a network analysis method of a communication system for Fire Service operations. This objective has been achieved through particular goals including:

- accumulation and standardisation of data concerning the number of road connections and the number of intersection nodes in the network model, types of roads, traffic volumes,
- development of the communication system's network model, using cartographic modeling,
- model analysis, using random and scale-free model theory,
- forming conclusions.

This method of geospatial data analysis enables to optimise Fire Service operations and is a useful tool for increasing safety, e.g. in developing evacuation plans, analysing communication system resilience to node or connection failure, and designing new elements of a communication network.

Network modelling and geospatial data analysis allows for a better understanding of the relationships existing between communication systems and safety measures. It proves useful in identifying strategic network elements in a given structure. This enables the implementation of preventive measures, such as ensuring smooth traffic flow or protecting nodes from damage (e.g. by introducing traffic control signals or collision-free intersections allowing for one traffic direction at a time). This minimises the chance of vehicle collisions or accidents, which would impede traffic flow. These measures will allow prompt arrival of rescue units at the incident site.

The geospatial data analysis presented above shows the importance of properly defining the model. Relying solely on an analysis of scale-free structures based on intersection types may lead to erroneous results, showing only random structures. That is why a communication-system-type analysis was performed first, in order to determine that the network exhibits features of an anisotropic structure: that it has a characteristic road hierarchy, access roads are perpendicular to main roads in the model, and in direct communication, which optimises for shortest connection time and side roads are flattened towards the main road. The model includes directions of traffic and capacity modified by mobile spatial features – parked cars. Further analysis revealed vital points (nodes), which testifies to the presence of an underlying scale-free structure. Therefore, the developed model and its geospatial data analysis open up new possibilities for research into the dependencies in the network structures of communication systems. Beyond the present analysis treating intersections as nodes, further research should investigate traffic flow through each intersection, and again analyse the model for scale-free structures. Altering the character of a node may reveal completely different dependencies than the ones identified in random structures.

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