GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 19 • Number 3 • 2025

https://doi.org/10.7494/geom.2025.19.3.5

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Analysis of Road Network Structure Using Scale-Free Network Theory in Context of Potential Fire Department Interventions in Urbanized Area

Abstract: Roads are essential to fire departments for saving lives and protecting health. The development of urban structures and the increasing complexity of transport systems necessitate the search for novel solutions and tools for spatial analyses in safety terms. This study aims to determine whether the city's transport system network exhibits scale-free network characteristics and whether crucial center nodes can be identified for the efficient functioning of the entire system. The study developed two transport system network models: one based on the Topographic Objects Database, and the other on data from devices that record vehicle traffic at selected nodes. Both were found to follow the bell-shaped curve characteristic of random networks; however, the second network model differed significantly from the first model due to the identification of nodes that could potentially act as hubs in an emerging scale-free network. A simulation was conducted to model the impact of cutting off these crucial nodes (centers), with a visualization of the network structure's behavior. In conclusion, using scale-free network theory to optimize FD operations is reasonable and useful. In this scenario, the transport system network displays scale-free characteristics, thus allowing for the identification of the most crucial functional points of the entire structure.

Keywords: GIS, network analysis, scale-free network theory, transport system, safety

Received: November 14, 2024; accepted: April 7, 2025

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1. Introduction

Fire departments (FDs) are one of the three main emergency services that assist in Poland in the events of accidents, incidents, and emergencies; they can be considered to be one of the largest service providers in the country. These units are involved in various tasks that are aimed at protecting people and property – ranging from providing first aid to firefighting. At the same time, they are involved in operations to repair damages or defects, including those that affect critical infrastructures. In Poland, fire department units are divided into the State Fire Service (SFS, in Polish: Państwowa Straż Pożarna) and the Voluntary Fire Service (VFS, in Polish: Ochotnicza Straż Pożarna). The former is a professional formation with specialized sections, whereas the latter consists of community-based organizations that are comprised of volunteers who also receive training but operate mainly as associations.

To provide assistance, services of all types must arrive at the scene of an incident. Currently, floating and flying vessels are also available, but their use by FDs is infrequent and limited to special cases. Given the above, the primary means of transport for FDs include fire trucks and cranes [1]. These vehicles are designed to be driven on the roads that are intended for motor vehicles. The quality and number of these roads determine whether fire department units will be able to reach the scene of an incident in time. Roads are functionally linked facilities that enable supplies, transport, and rescue services and ensure the continuity of the functioning of the state as part of the critical infrastructure [2]. The term 'critical infrastructure' was introduced by the act of April 26, 2007, on crisis management [2]; according to this document, these include those facilities, systems, and services that are crucial to the security of the state and its citizens and ensure the smooth functioning of the administrations and institutions. The act identifies a total of 11 systems, including energy supply, communications, transport, and health care; the destruction of or damage to any of these systems could significantly affect the lives and properties of citizens. The tasks that are associated with this infrastructure do not boil down to solely protecting it completely from harmful incidents; possible faults should also be short-lived, easily repairable, and not cause major damage, which is linked to the design of such an infrastructure and the operators of the individual systems. It is therefore essential that, as channels for rescue units for accessing possible incidents, roads should be conduits with as low a risk of dysfunctionality as possible. This issue was the motivation behind the undertaking of this study and the search for new methods for road network modeling and analysis for safety purposes.

The use of GIS tools in transport network analysis has been reported in the road network analysis of Guwahati city using GIS [3], among others. This paper focused on demonstrating how a network analysis operated using ArcGIS software and how it could assist in solving transport problems. The conclusion of the article indicated that the tool was highly effective. Network analyses enabled determinations of the shortest and most optimal routes to destinations. There have also been studies that have described case studies; e.g., a road network analysis for timber transportation from a harvesting site to area mills [4]. Such studies have already considered specific places of departures and specific places of arrivals; these can be likened to the subject matter of this article to some extent. The aforementioned paper confirmed the effectiveness of the Network Analyst tool in ArcGIS in terms of finding the shortest routes from harvesting sites to area mills. It is worth pointing out that the examples that were given were related to very densely built-up areas. In Poland, there are far more spaces in urban areas that are not occupied by buildings.

SFS units are most commonly located within city boundaries and in the vicinities of important facilities – the protection and security of which are crucial to the functioning of the state [5]. Due to the progressive development of cities, urbanized and urban areas are occupying more and more space. Consequently, the densities of buildings, winding roads, and large numbers of people may impede rapid access to the scene of an incident. Several studies on network analyses have also been carried out to optimize the operations of these units; this was addressed by M. Borowska-Stefańska, for example, who examined the fire department's accessibility to buildings that were located in flood plains in one of the poviats (administrative units) of Łódzkie Voivodeship [6]. Using GIS software, it was demonstrated that all of the facilities that were adopted for the analysis could be reached within 15 minutes if both the local SFS and VFS units were considered. However, no work has focused on combining the scale-free network theory with the determination of the importance of nodes with an analysis of a road network, vehicle pass loads, and accessibilities to areas of potential interventions.

Referring to the theory, networks can generally be divided into random networks and scale-free networks; these have been addressed by Barabási [7], Bonabeau [8], and Broido and Clauset [9], among others. In their book *Evolution of Networks*, Dorogovtsev and Mendes [10] described in detail the research trends and directions that concerned the development of networks after 2003 (which saw a breakthrough that was precisely due to the development of the complex and scale-free network theories).

Overall, the network concept focuses on the assumption that there are points (nodes) and lines that connect them; through these, there is travel between the points. With a random network, there are a similar number of links between the nodes [11]; within the structure of such a network, therefore, most nodes have roughly the same number of links. In principle, there is no preferred choice of links in this network. A characteristic feature of a random network structure is that the exclusion of a random node (or multiple nodes) can lead to a breakdown of the network into smaller structures that operate independently. Thus, the data distribution over the diagram should show a Poisson distribution or a similar image (Fig. 1a) [7].

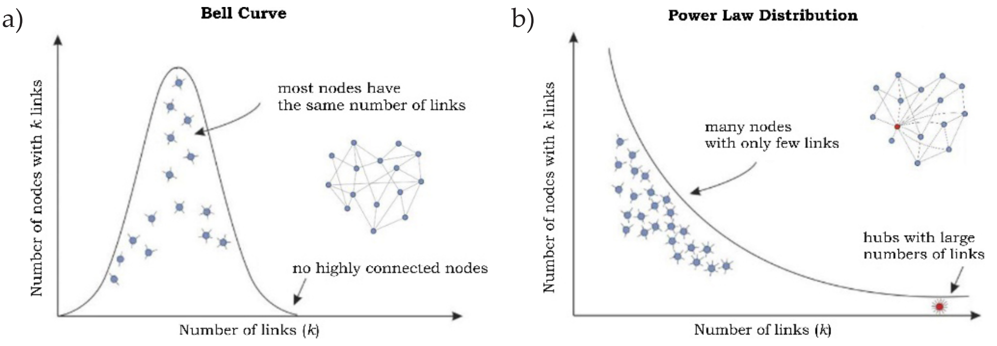

Fig. 1. Model distributions of numbers of nodes and links for two network types: a) random networks; b) scale-free networks

Source: based on [7, p. 71]

As for scale-free networks, there is a varying number of links to the nodes. This is evident in the distribution, which will be characterized by a power-law distribution in this case [11, 12] (Fig. 1b). The preferentiality of the links also occurs; this means that new nodes tend to connect to those nodes with large numbers of links. Nodes with such a large number of links (specifically characteristic of scale-free networks) have been referred to as hubs of network centers in the literature on the subject [11]. The random exclusion of a node (or multiple nodes) in a scale-free structure does not significantly affect the entire network (Fig. 2) [8].

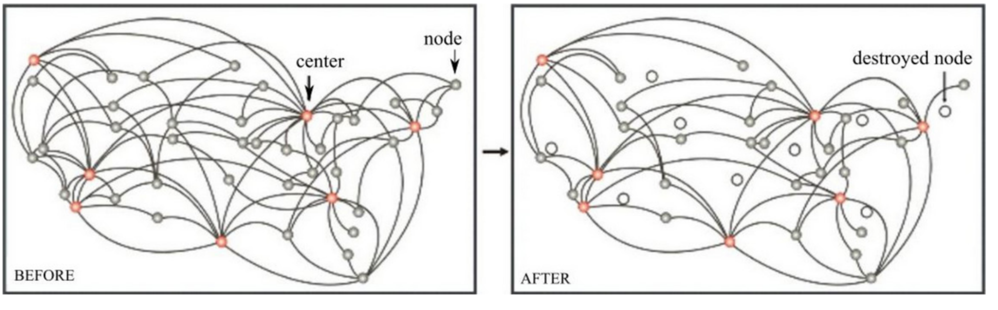

Fig. 2. Random exclusion of functionality of nodes in scale-free network

Source: [8, p. 57]

On the other hand, the elimination (or even temporary exclusion) of a center/hub's functionality from a network can dramatically affect the entire system and even destroy the network structure so that it no longer operates (Fig. 3).

In a study on the structure of scale-free networks, Kocur-Bera [13] demonstrated that the road network in Poland exhibited elements of scale-free networks. This study, however, covered a large area (the entire country), with certain data having been generalized.

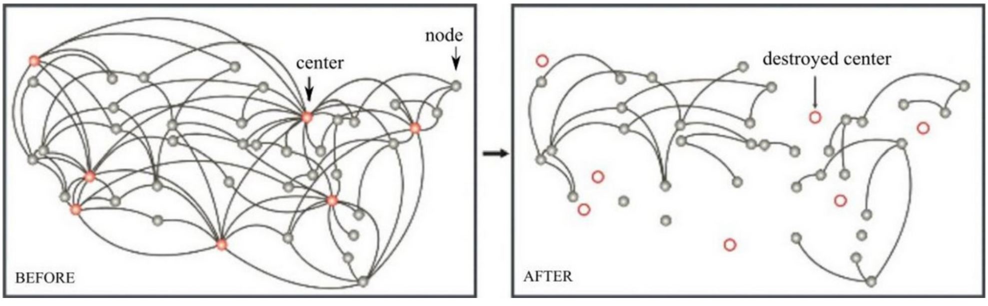

Fig. 3. Deliberate exclusion of functioning of centers in scale-free network
Source: [8, p. 57]

The present article demonstrates the need for spatial analyses when examining the resilience of a transport system in terms of assistance provision by a fire department. The analysis is aimed at determining whether a transport system network exhibits scale-free characteristics and, consequently, whether center nodes (which are crucial to the functioning of the entire system) can be identified. An attempt was also made to compare the results of this study with a statistical analysis of fire department unit departures to show the relevance of the phenomenon under study.

2. Characteristics of Study Area and Data for Analyses

The study area was the city of Olsztyn, which is located in northeastern Poland. Olsztyn has an area of 88.33 km^2 and is inhabited by approximately 173,000 people [14]; this translates into a population density of 1925 people per 1 km^2. The population structure in selected residential communities in Olsztyn is shown in Figure 4, along with the transport system network [15].

In Olsztyn, there are two fire-protection services: the State Fire Service (SFS), and the Voluntary Fire Service (VFS). Both are uniformed units that are equipped with specialized equipment and are dedicated to combating fires, natural disasters, and other local hazards. They also perform specialized rescue operations; these are understood as any actions that are taken to save life, health, property, or the environment and eliminate the causes of fires, natural disasters, or other local hazards [16–18]. After being alerted, the firefighters set off to the scene of an intervention. Alerting is the time that it takes for the rescue services to be dispatched from their stationing locations; this is determined from the moment an alert is received by the control center operator and relayed by the team leader to the moment that the alerted forces depart from their locations [19].

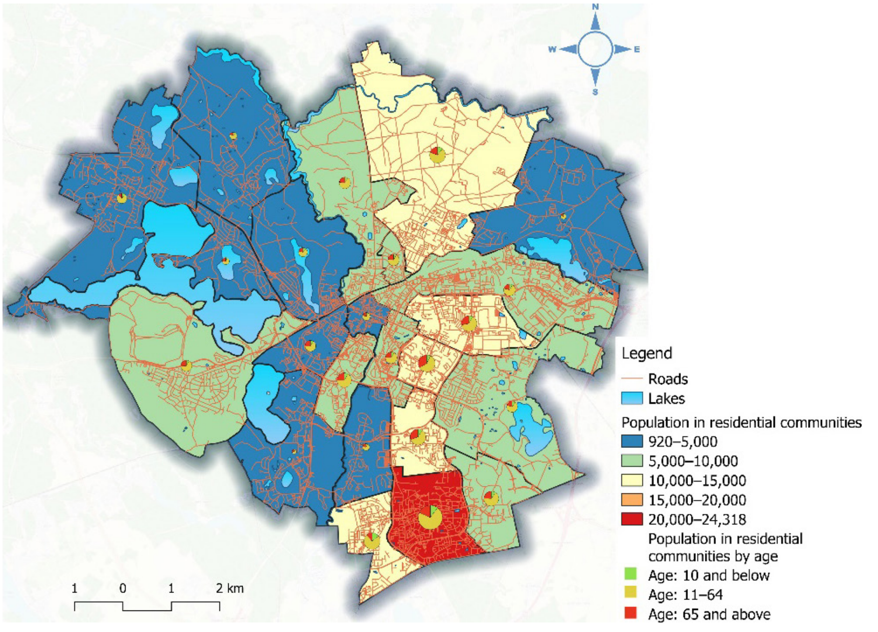

Fig. 4. City of Olsztyn, its demographics in residential communities, and its transport system network

2.1. Geodata

The analysis used data that concerned the following:

– interventions to incidents and locations of fire department units (characteristics provided in Subsection *Statistical Analysis of Data from SFS and VFS Operations in Selected Area*);
– roads and crossroads (characteristics provided in Subsection *Data for Network Model – Roads and Crossroads*);
– residential community boundaries [20] (provided at beginning of Section 2);
– number of passes through selected crossroads (characteristics provided in Subsection *Data on Traffic on Selected Nodes of Network under Analysis*).

Statistical Analysis of Data from SFS and VFS Operations in Selected Area

SFS keeps records of its interventions. An XLS-format database was received from the Olsztyn Municipal Headquarters of the State Fire Service; this detailed the dates and times of the receipts of notifications, the types of incidents, the coordinates (longitude and latitude), and the numbers of teams (i.e., firefighting subdivisions that are comprised of three to six people who are equipped with vehicles that have been adapted to perform rescue tasks). The data covered the period from November 1, 2017, through November 14, 2023, and referred to interventions in Warmińsko-Mazurskie Voivodeship. During this period, a total of 24,803 notifications were recorded. Table 1 shows an extract of this database.

Table 1. Extract of obtained database

Date and time of receiving notification (dd.mm.yyyy)	Type	Longitude	Latitude	Teams
1.11.2017 5:54	MZ/M	20° 57′ 31.65″E	53° 51′ 49.71″N	1
1.11.2017 6:02	P/M	20° 26′ 44.82″E	53° 45′ 01.26″N	1
1.11.2017 6:28	MZ/M	20° 16′ 49.02″E	53° 34′ 52.89″N	1
1.11.2017 9:12	MZ/M	20° 45′ 25.83″E	53° 58′ 39.89″N	1
1.11.2017 10:32	P/M	20° 29′ 40.57″E	53° 47′ 39.35″N	2

Source: archive data of the State Fire Service in Olsztyn (https://www.gov.pl/web/kmpsp-olsztyn)

Analysis in GIS database programs requires an appropriate adjustment of the table so that the program can read this information. Diacritical marks were removed from the column names, spaces were replaced by an underscore character, and the names were simplified to make them as short as possible. On the left side, a column with ordinal numbers was added. The moment of receiving a notification was divided into 'date' and 'time' columns. The notification types were also divided into a 'type/kind' column. The longitude and latitude coordinates were converted from degrees, minutes, and seconds to a format that included only degrees. The last column was left unchanged (except for its name). The overall effect is shown in Table 2, which is a segment of the new table.

Table 2. Extract of database adapted to GIS programs

No.	Date (dd.mm.yyyy)	Receipt of notification	Kind	Type	Longitude_E [°]	Latitude_N [°]	Teams
1	24.05.2018	2:35	P	BD	20.552972222	53.787422222	64
2	2.08.2019	7:43	MZ	M	20.463586111	53.586325000	44
3	3.09.2022	17:34	P	BD	20.716333333	53.984519444	33
4	3.05.2023	19:37	AF	Z	20.377647222	53.709800000	29
5	7.04.2022	1:09	P	S	20.512091667	53.776000000	28

Source: own elaboration based on archive data from State Fire Service in Olsztyn (https://www.gov.pl/web/kmpsp-olsztyn)

In principle, all of the incidents that were received by the fire departments were classified according to three categories: a fire, a false alarm, and a local hazard. Each of these groups was further subdivided into several types. As for a fire, distinctions were made among small, medium, large, and very large fires; these were determined by the area or volume that the fire has taken hold of. If, however, the area could not be estimated, the number of extinguishing agent streams that were used to put the fire out was determined. False alarms included malicious alarms and 'bona fide' alarms; the latter group was divided into small, local, medium, and large hazards. This group included other incidents that were not classified as a fire or a false alarm; e.g., a car accident, extreme natural phenomena, or major damage to buildings. Table 3 shows a visualization of the discussed classification to increase the clarity of the paper. Abbreviations of incidents (which represent the first letters of the names that were included in the original database) are also provided in brackets.

Table 3. Classification of incidents according to State Fire Service

	Incident		
	Fire	Local hazard	False alarm
Scale of incident or type	small	small	malicious
	medium	local	detection systems
	large	medium	bona fide
	very large	large	–

The data from the table was imported into the QGIS program, and the incidents were placed on the map as point objects by using the column that included the latitudes and longitudes. A total of 10,126 data points were analyzed on incidents within the Olsztyn boundaries. The individual incident types were then exported into separate layers. The incidents were then classified; the results are provided in Figure 5.

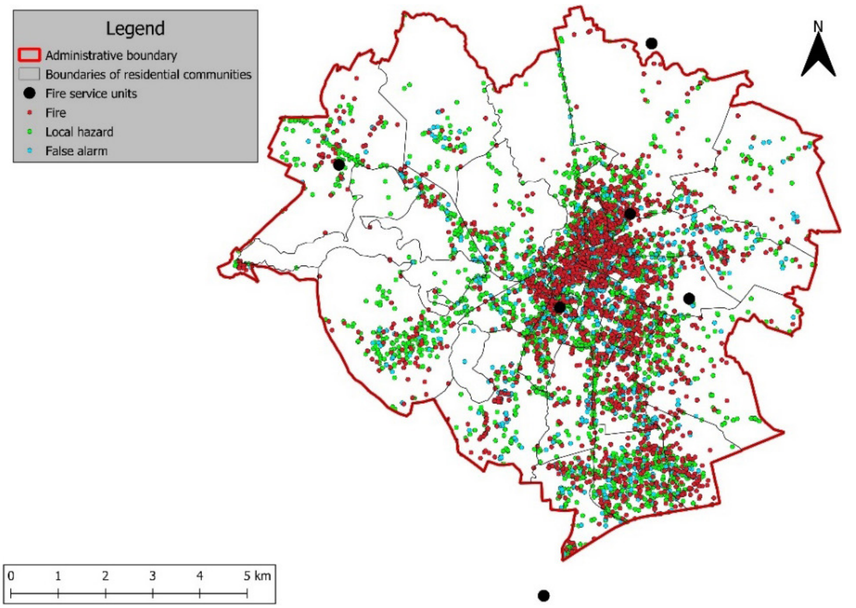

Fig. 5. Locations of SFS intervention sites in Olsztyn during period of 2017–2023
Source: own study based on [5, 20, 21, 23]

An analysis was carried out, and a quantitative model of the incidents in the individual residential communities was developed and divided into three main incident categories and subcategories. The operation yielded shapefile layers that included attribute tables with counted incidents in the individual residential communities of the city. The results are summarized in Table 4.

Table 4. Number of classified incidents in different areas of Olsztyn

Name of residential community or lake	Fires					Local hazards				False alarms			
	Small	Medium	Large	Very large	Total	Small	Local	Medium	Total	Malicious	Detection systems	Bona fide	Total
Zatorze	73	1	0	0	74	58	187	1	246	1	6	41	48
Dajtki	74	1	0	0	75	62	160	12	234	1	9	27	37
Podleśna	180	2	1	0	183	99	298	14	411	2	25	58	85
Zielona Górka	43	0	1	1	45	10	55	1	66	0	18	11	29
Kętrzyńskiego	249	3	1	0	253	199	337	14	550	7	146	81	234
Pojezierze	153	2	0	0	155	108	257	8	373	2	96	64	162
Śródmieście	131	1	0	0	132	69	166	19	254	0	101	36	137
Grunwaldzkie	119	0	0	0	119	51	174	5	230	3	59	22	84
Podgrodzie	122	0	0	0	122	85	274	19	378	0	72	35	107
Kościuszki	111	1	0	0	112	83	256	6	345	2	191	35	228
Kormoran	158	0	0	0	158	93	264	6	363	3	70	44	117
Mazurskie	88	0	0	0	88	33	117	3	153	1	4	21	26
Kortowo	66	0	0	0	66	14	104	1	119	0	145	12	157
Brzeziny	36	0	0	0	36	23	55	2	80	0	26	10	36
Nagórki	114	0	0	0	114	61	222	9	292	1	72	49	122
Jaroty	153	3	0	0	156	106	250	8	364	1	19	63	83
Pieczewo	86	0	0	0	86	34	77	3	114	1	13	21	35
Generałów	44	0	0	0	44	31	84	5	120	1	7	22	30
Gutkowo	58	2	0	0	60	19	129	19	167	0	35	13	48
Redykajny	11	0	0	0	11	9	36	1	46	0	5	10	15
Likusy	29	2	0	0	31	14	89	2	105	0	50	15	65

Table 4. cont.

Name of residential community or lake	Fires					Local hazards				False alarms			
	Small	Medium	Large	Very large	Total	Small	Local	Medium	Total	Malicious	Detection systems	Bona fide	Total
Nad Jeziorem Długim	47	0	1	0	48	33	141	9	183	0	69	20	89
Wojska Polskiego	121	1	0	0	122	87	344	16	447	6	131	44	181
Ukiel Lake	3	0	0	0	3	11	7	10	28	1	4	1	6
Kortowskie Lake	0	0	0	0	0	0	1	0	1	0	0	3	3
Total	2269	19	4	1	2293	1392	4084	193	5669	33	1373	758	2164

Source: own study based on archive data from State Fire Service in Olsztyn (https://www.gov.pl/web/kmpsp-olsztyn)

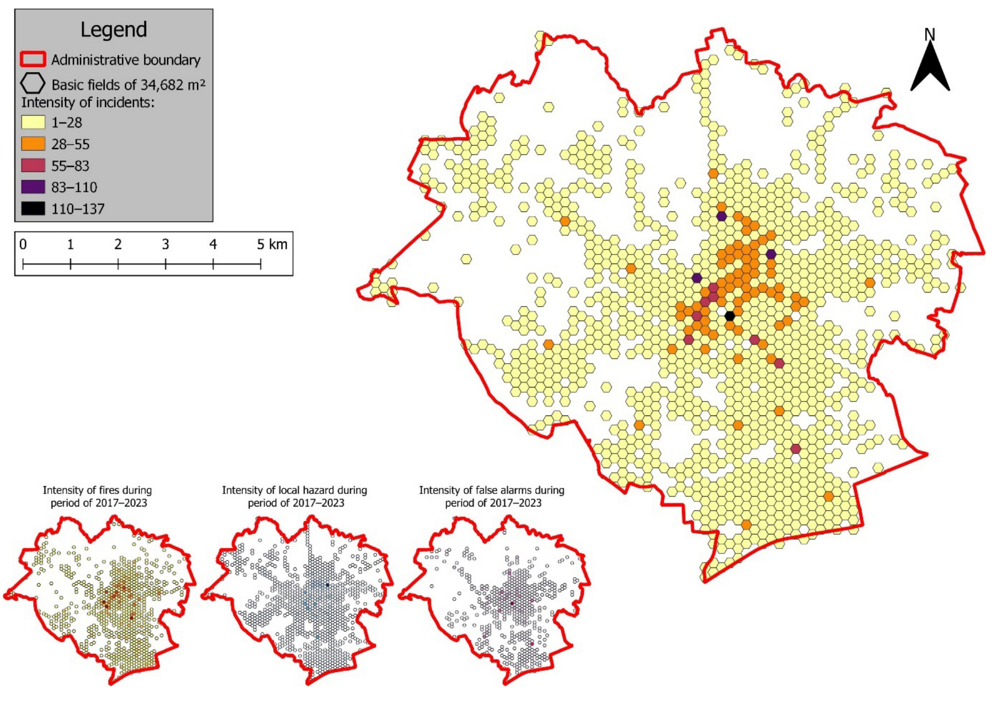

Fig. 6. Intensities of all types of incidents in Olsztyn during period of 2017–2023

Source: own elaboration based on archive data from State Fire Service in Olsztyn (https://www.gov.pl/web/kmpsp-olsztyn)

The incidents are also presented on the maps below due to the density analysis, which enabled the visualization of the intensity of the points on fragments of space by dividing them into basic assessment fields (i.e., polygons of the same size). The analysis adopted artificial hexagon-shaped fields with a height of 200 m and a length of 200 m; these corresponded to an area of 34,682 m². The data was visualized in five classes by adopting equal-interval-classification methods. The results are shown in Figure 6.

The above analysis was necessary for carrying out further research on the road network model and indicating the weights of the strategic crossroads in terms of the functionality of the network system. The final inference sought an answer to the following question: were the areas through which most of the vehicles passed those in which the most of the incidents occurred? If the answer was affirmative, this would increase the weights of these crossroads throughout the system. At the same time, this led to further conclusions (e.g., the need for a high level of protection for these constituents). These considerations are provided in Sections 3 and 4.

Data for Network Model – Roads and Crossroads

For the study, vector data was extracted from the Topographic Objects Database (BDOT10k) from the National Geoportal [21]. The data covered roads and streets (Fig. 8) that were considered to be links in the context of the analysis; in turn, the nodes were the intersections of these roads. In the GIS analysis context, a network is understood as linear geometry, whereas intersections are understood as points. An analysis of such a structure must contain both of these constituents; i.e., nodes and links to the nodes. The specific nature of the modeling of this data is provided in Subsection 3.1.

Data on Traffic on Selected Nodes of Network under Analysis

For the purposes of the study, data was acquired from the Roads, Greenery, and Transport Authority (in Polish: Zarząd Dróg, Zieleni i Transportu, ZDZiT) in Olsztyn. The data shows the loads on 91 Olsztyn crossroads between the years of 2010 and 2023 [24]. The information on the crossroads did not include their coordinates but only their street names. A separate point layer was created that marked the centers of the aforementioned 91 crossroads. In the table of attributes, a column with the vehicle loads and columns that contained the numbers of carriageways and roads that entered each node were added (as was determined using BDOT [21]). This study used data from May 2021, as the most recent data was largely incomplete or originated from a period when some crossroads were not in use. The obtained data was often marked as erroneous, crossroads under reconstruction, or damaged detectors. A period with as much reliable data as possible was chosen; this period followed the renovation of the road infrastructure and the installation of tram networks in the area under analysis. It should be noted that the construction of further tram lines in the study area is still ongoing; nevertheless, the aim of the study was to create a new methodology for analyzing transport systems; if the proposed method yields valuable results, it will be applicable to analyses at any time when data is available. Figure 7 shows the locations of the crossroads under consideration; i.e., those at which the measurements were carried out. The map was supplemented to include roads, residential community boundaries, administrative city boundaries, surface waters, and wetlands. Numerical data on the maximum load on each crossroad was used for further operations, taking complete and reliable data into account.

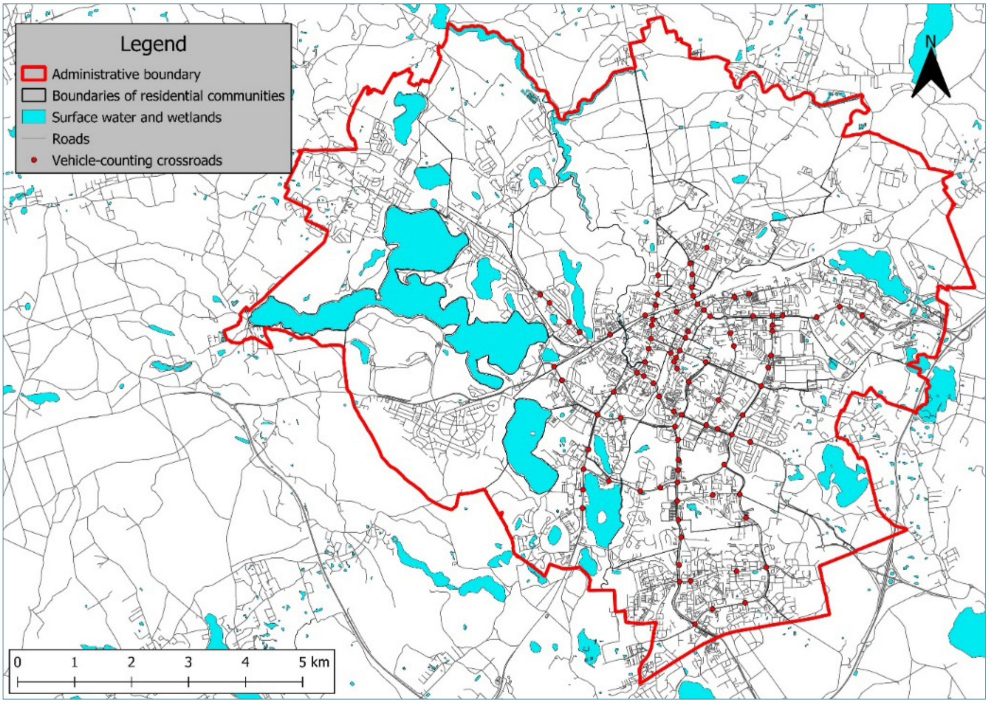

Fig. 7. Locations of vehicle-counting crossroads
Source: own elaboration based on [20–22, 24]

3. Methods

3.1. Network Model Construction and Analysis

This study developed two network models. In the first network model, the nodes are crossroads, and the links between the nodes are roads. This model is shown in Figure 8.

As the data for the construction and analysis of the second network model was only available for the 91 selected crossroads, the analysis of this first model also only took these crossroads into account. Their locations are shown in Figure 7. The distributions of the nodes and links are shown in Figure 9 and Table 5.

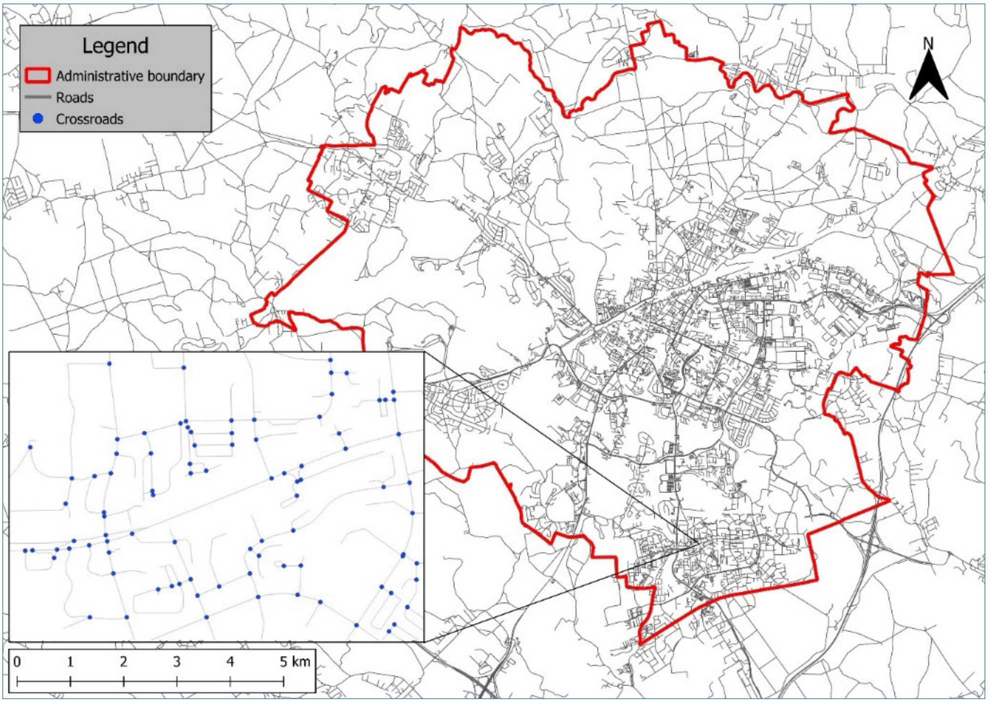

Fig. 8. Transport system network model with network nodes
Source: own elaboration based on Topographic Objects Database

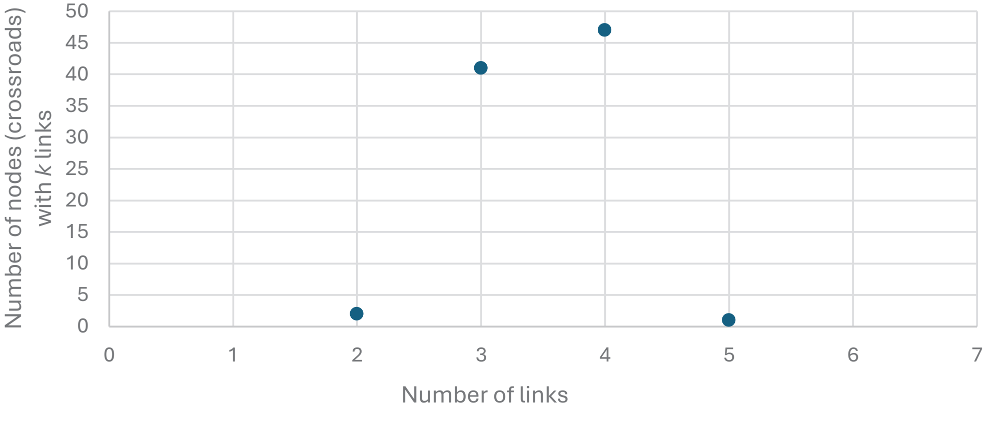

Fig. 9. Distributions of numbers of nodes and links in first network model (where nodes are crossroads, and links between nodes are roads)

Table 5. Numbers of nodes with particular numbers of links in first network model

Number of connections	Number of nodes
2	2
3	41
4	47
5	1
Total	91

As can be seen in the diagram above, this network had the nature of a random network in which most intersections had roughly the same number of links (i.e., three or four). Nodes with numbers of links that deviated significantly from the average are not found here. It can, therefore, be concluded that no network centers were found within this structure. It is also evident that this raised a topic for discussion, as it is logical that, in any traffic-system structure, there are nodes (intersections) that play more important roles than most of the other nodes of the network. For this reason, it was decided to create a second network model that was based on different data.

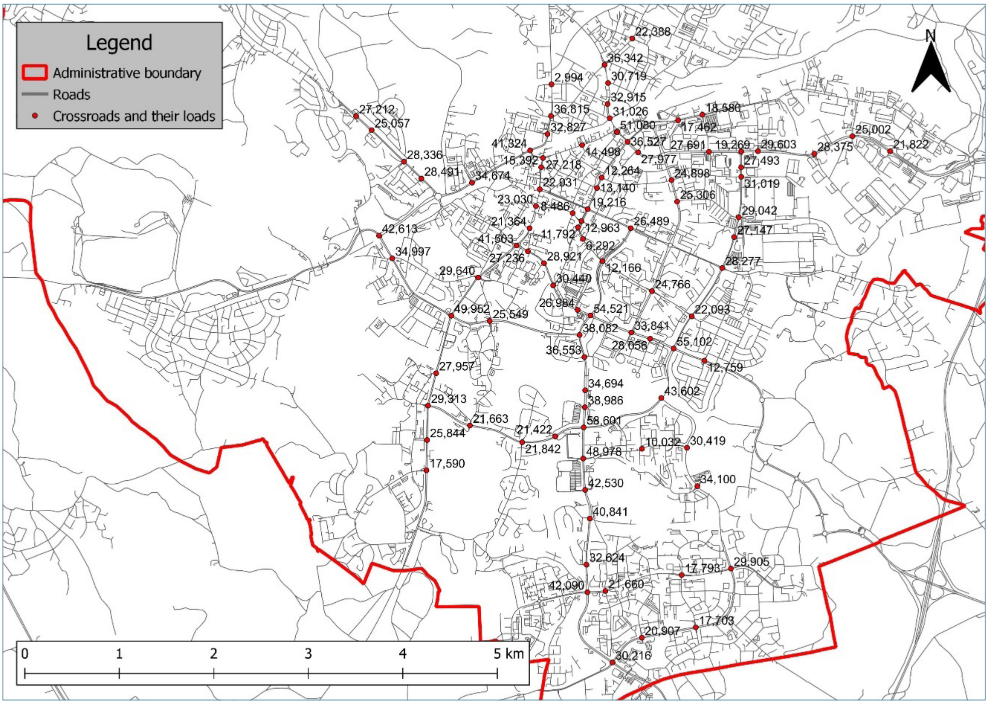

Fig. 10. Network model based on data from traffic-monitoring devices and systems

In the second network model, the nodes also represented crossroads (i.e., the physical intersections of roads), whereas the links were the physical vehicle passes from a selected day during the year 2021 at the crossroads at which the measurements were carried out. The justification for the choice of data is provided in Subsection *Data on Traffic on Selected Nodes of Network under Analysis*, whereas the model of this network is shown in Figure 10.

As already mentioned, a crossroads is considered to be a node in the second model, and the number of vehicles that crossed the node (load) is considered to be the number of links. Table 6 shows an extract of the data for analysis.

Table 6. Extract of raw data for development and analysis of second network model

No.	Name of crossroad (node)	Date (dd.mm.yyyy)	Load	Max/hour
1	Niepodległości/Śliwy/Mochnackiego/Szrajbera	1.05.2021	41,503	3384
2	Pieniężnego/Staszica	1.05.2021	21,364	1660
3	Pieniężnego/Plac Jedności Słowiańskiej/22 Stycznia	1.05.2021	23,030	1833
4	Pieniężnego/1 Maja/Piłsudskiego/11 Listopada	1.05.2021	22,931	1620
5	1 Maja (pedestrian crossing near the theater)	1.05.2021	15,392	1089
6	1 Maja/Partyzantów	1.05.2021	27,218	1996

Source: own elaboration based on ZDZiT data (https://zdzit.olsztyn.eu/)

The next step of the analysis in the data model was to develop network models and generalize the data; this was performed by classifying the data and developing a histogram of the data that showed the distributions of the nodes and links (Fig. 11).

This action was reasonable, as an overall presentation without such a division (classification) presented the data in too much detail without revealing the trends (as can clearly be seen in the diagram in Figure 12).

The histogram (Fig. 11) shows the number of intersections according to the load intervals that were determined. An equal interval of approximately 10,000 links was applied; thus, creating six intervals (classes) (Fig. 11). The result of the analysis was a distribution that was similar to a Poisson distribution, which suggested the random nature of the system. Nevertheless, it can be clearly seen that, at the end of this histogram, a group of data points that were divided using this (bisection) classification method was clearly distinguished.

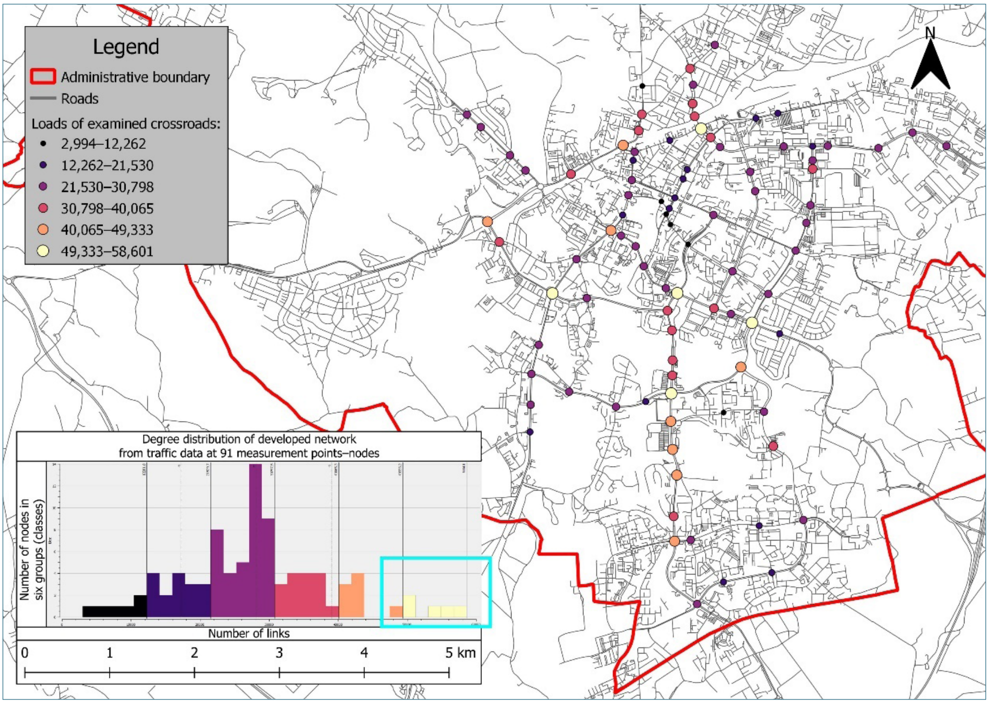

Fig. 11. Second network model: loads on crossroads (links in network) are grouped by equal-interval method

Source: own elaboration based on ZDZiT data (https://zdzit.olsztyn.eu/)

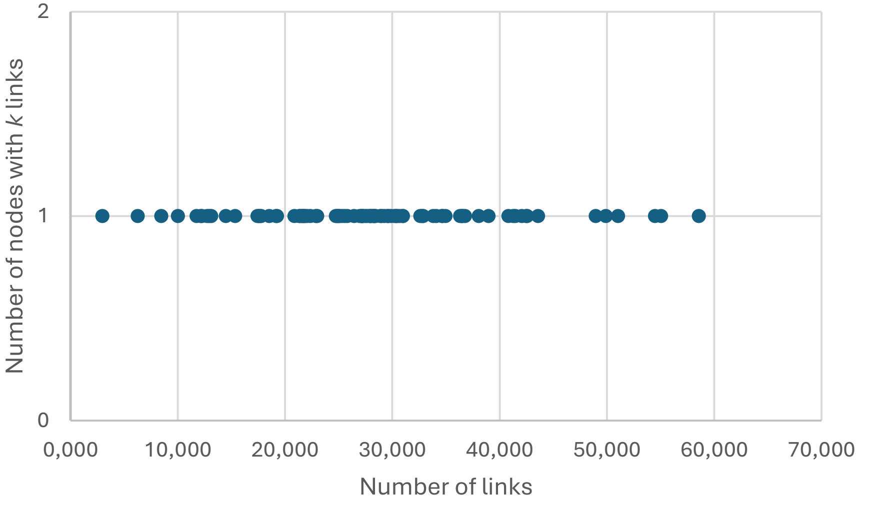

Fig. 12. Distributions of nodes and links in analyzed network from traffic data without establishing classes

Source: own elaboration based on ZDZiT data (https://zdzit.olsztyn.eu/)

4. Discussion

The analysis of the first developed model showed that it was of a random network nature (Fig. 9). In the second case of the developed network model concerning the data on vehicle passes, the result of the analysis was also a distribution that was similar to a Poisson distribution; this suggested the random nature of the system, yet this distribution already showed a different structure. As previously mentioned, it can be seen here (Fig. 11) that, at the end of this histogram, a group of data points that was divided using this (bisection) classification method was clearly distinguished. Therefore, another classification method was used; i.e., the Jenks method, which groups data while searching for natural gaps or intervals between these data points. The results are shown in Figure 13.

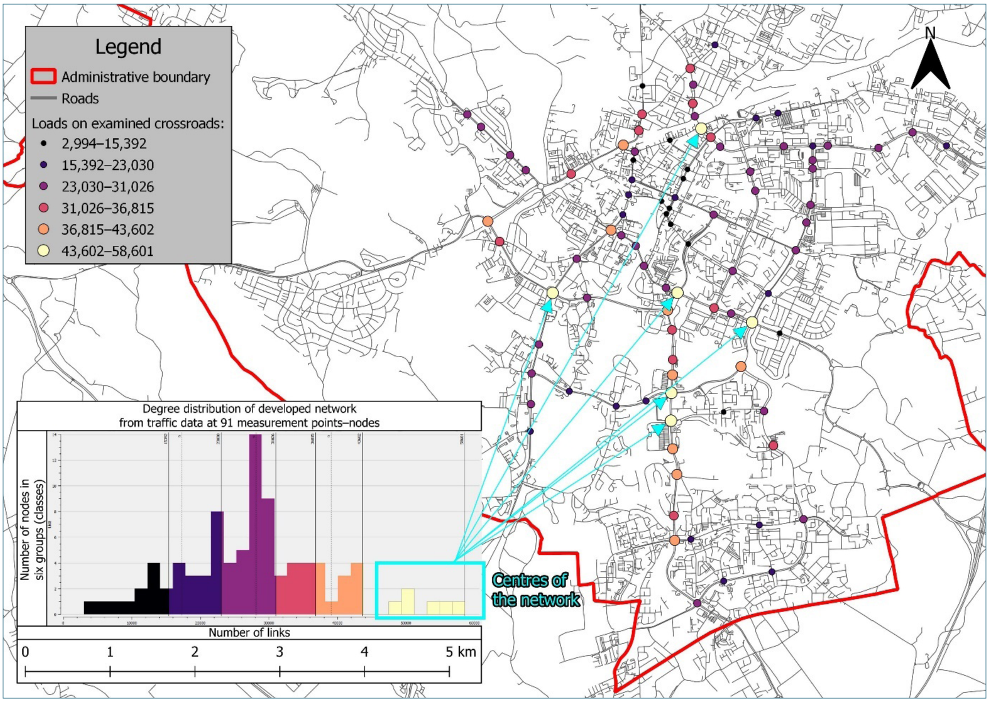

Fig. 13. Second network model: loads on crossroads (links within network) grouped by (Jenks) natural-break-classification method

Such modeling and interpretation of the data revealed a group of data points that deviated from the average in some way. It can therefore be concluded that, despite the random nature of this network, a certain type of scale-free character (or, perhaps, simply the beginning of the formation of a scale-free structure) was revealed. Consequently, the identified group of nodes in the outlier data group (as can be seen in the histogram in Figure 13) may represent the emerging (or, perhaps, already existing) centers of a scale-free network. In this group, there were six nodes (or centers) that were mainly located in the central and southern parts of the city.

In view of the above conclusions, important questions to ask are these: how does a scale-free network emerge? Is it formed from a random network, or is it scale-free from the very beginning? While analyzing this issue, Bajerowski and Biłozor [25] emphasized the need to pay attention to the fact that random and scale-free networks (which are completely different in terms of their internal structures) certainly form a master (common) network; at the same time, scale-free networks likely cannot be formed without the prior emergence of random networks; at least, this seems to be the case for networks that operate within a geographical space. Bajerowski and Biłozor [25] wrote that one could venture to conclude that scale-free networks could only emerge because random networks existed previously in a particular area where, through trial and error (i.e., stochastically), we learned about the space and about its geography; only later did it become possible to organize links while omitting irrelevant and previously randomly generated nodes. Random networks are, therefore, the prerequisite for the emergence of scale-free networks, as they are part of their history. It is therefore possible that there is an algorithm for the transition of a network from one state into another, as it appears that randomness and a scale-free character are just two states of the same network; the transformations of random networks into scale-free ones are, therefore, likely possible through qualitative changes in the communication media (the media of innovation diffusion). The model of the emergence of a random network and a scale-free network can be represented graphically (as is shown in Figure 14).

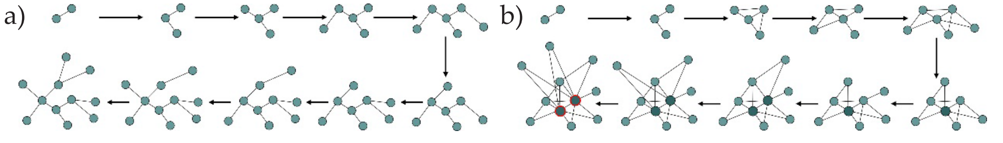

Fig. 14. Growth – emergence of networks: a) random; b) scale-free

Source: [11, p. 87]

It can therefore be assumed that the identified network nodes (Fig. 13) are emerging and, perhaps, already existing centers of a scale-free network. Thus, their weight in the entire network structure is of paramount importance. According to the theories of these types of networks, when they are destroyed or damaged (or when their functionalities are stopped), such networks disintegrate. In practical terms, this means that the traffic system becomes paralyzed; however, it also means that the fire department units cannot pass through, and access to certain areas becomes severely restricted. In order to base this discussion on specific statements and make it even more interesting, an analysis of stopping the functionalities of these nodes was additionally conducted. This stopping of the functionality for a transport system can, in practice, represent the total physical destruction of a crossroads for an extended period of time (e.g., a terrorist attack, carriageway subsidence, etc.) or stopping due to blocked passages, which may last for shorter periods but can be largely unpredictable (e.g., accidents, strikes, blockades, or cultural and sports events). To check how the network structure would behave as a result of blocking the functionality of the six nodes (network centers), the QGIS program was used for analyzing network structures, along with its accompanying tools. These are designed to determine the range of access from a specific location within a set time (or at a set distance) at a predetermined vehicle speed; this enables us to determine (with some approximation) the travel of a fire department unit within a predetermined time from the unit's headquarters. The map below (Fig. 15) shows the ranges of the travel of the fire department units that are present in Olsztyn within five minutes at a set speed of 50 km per hour (marked in green) and when we assume the same conditions but with the nodes-centers being cut-off (marked in red).

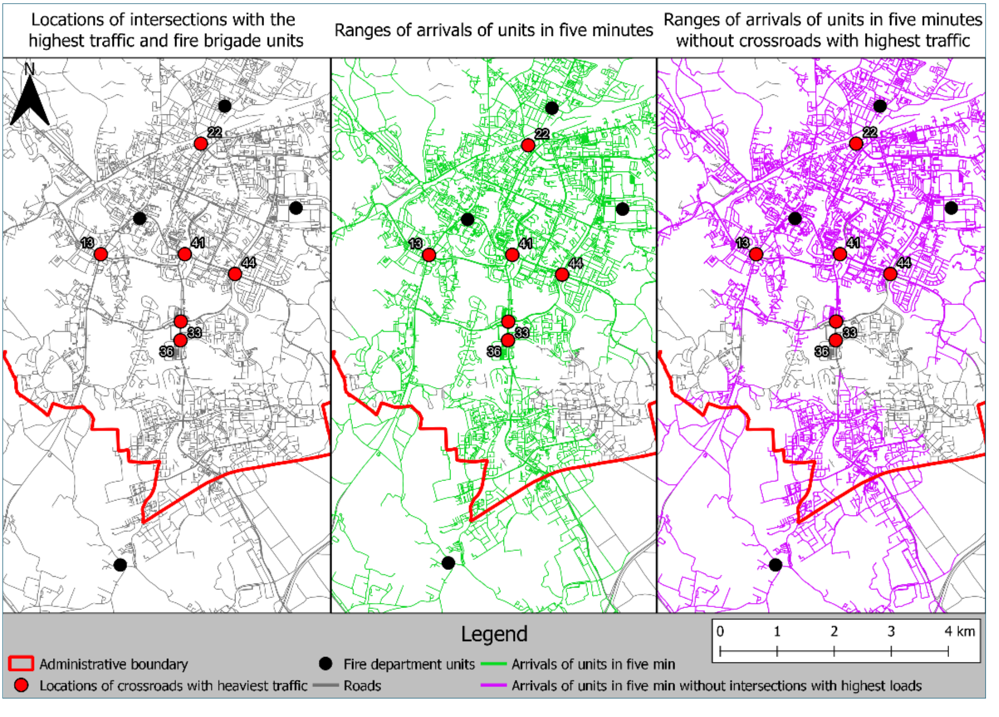

Fig. 15. Ranges of arrivals of fire department units within five minutes (with and without crossroads with heaviest traffic)

The analysis showed that, in the area under analysis, the FD was able to reach most spaces within five minutes; however, some areas (highlighted in gray) would take a little longer to reach. As can be seen in the simulations above (Fig. 15), cutting off these six nodes-centers in the emerging scale-free network (red points) could lead to the cutting off of significantly large areas from accessibility for the FD and their rapid arrival at the scene of an incident (up to five minutes). Combined with their importance as network centers through which most vehicles pass, this could lead to other conclusions: that these centers need to be protected, and that the situations of their dysfunctionality need to be considered. It is also evident how important the role that is served by the Bartąg VFS unit (located in the southern part of the analyzed area) is in this system. It is located outside the city boundaries, but it was taken into account because it was presumed that it could be strategically important for the analysis. This was indeed confirmed; without it, the area with no accessibility would be considerably greater (Fig. 16).

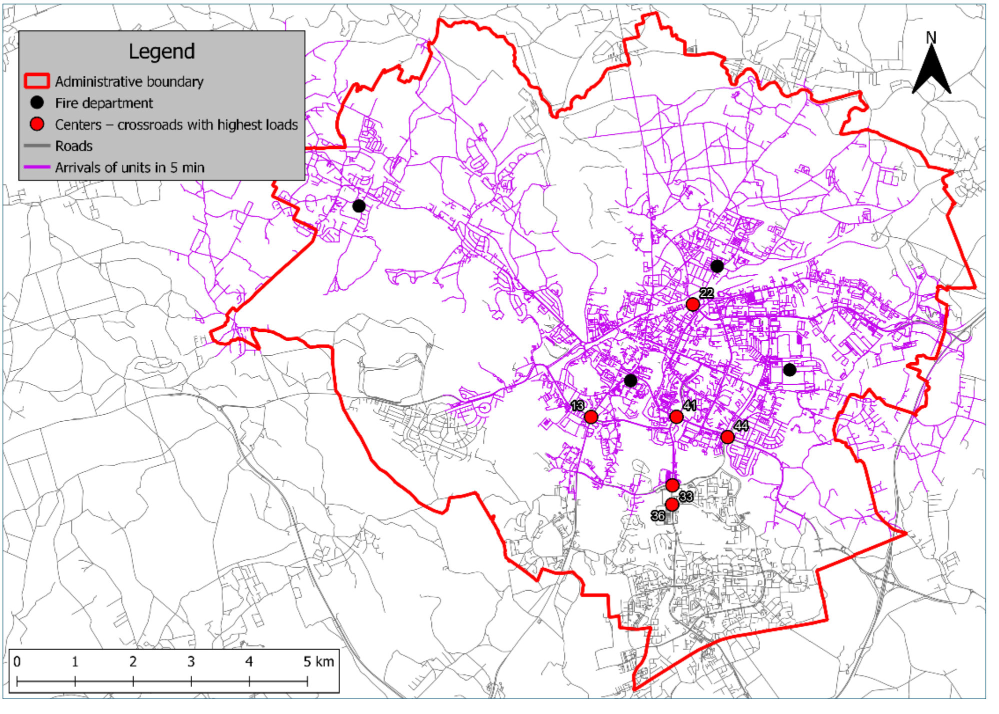

Fig. 16. Simulation of FD unit travel within five minutes with no supporting VFS units located outside boundaries of Olsztyn

When looking at the distribution of the interventions to incidents (Figs. 6 and 17) and the locations of the centers, it can be seen that these nodes are important in terms of access to the areas with incidents (statistically, the most numerous). The cutting-off of a node center will not result in the loss of accessibility to an incident, but it will definitely extend it. It should also be noted that the cutting off of such a center results in other vehicles being unable to pass through it and searching for bypasses, thus creating traffic jams that will impede FD rescue vehicles.

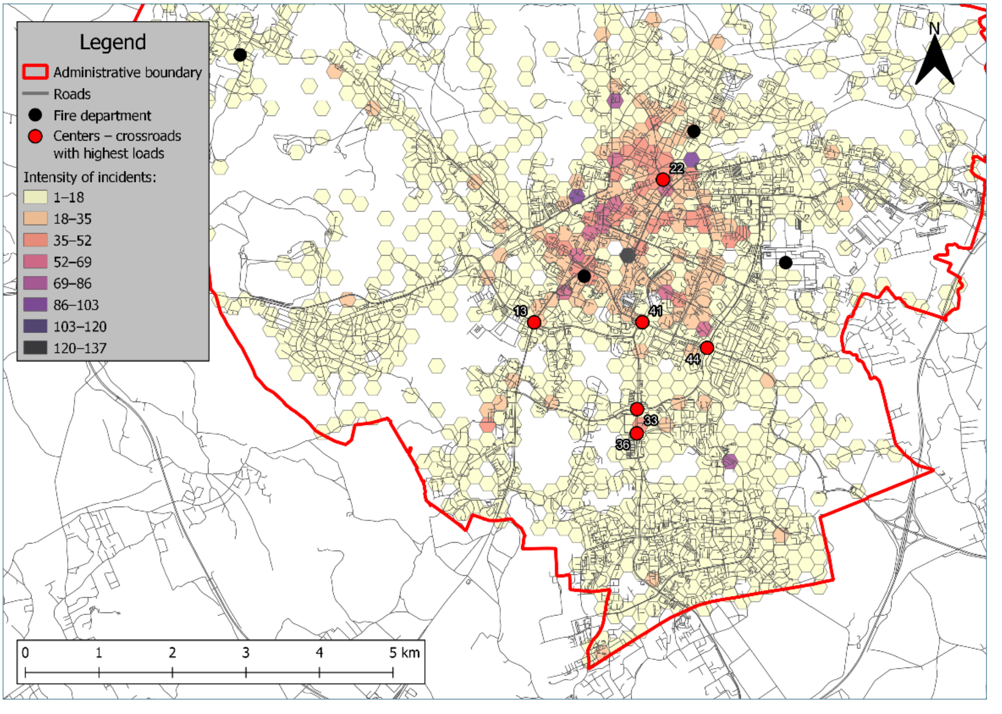

Fig. 17. Intensities of all types of incidents during period of 2017–2023 (with center locations and fire department unit locations)

This could lead to another conclusion: these centers should be protected, and the transport network structure should be expanded in such a way as to generate further selected nodes as centers. This is because, in theory, the more centers in a scale-free network, the more resilient they are to random damage; also, the dysfunctionality of a single center can lead to a situation where other network centers adopt their roles.

5. Conclusions

The analysis was aimed at determining whether a transport system network may exhibit scale-free network characteristics and, consequently, whether center nodes (which are crucial to the functioning of the entire system) could be identified.

An attempt was also made to compare the results of this study with the statistical analysis of fire department unit interventions in order to show the relevance of the phenomenon under study. The study demonstrated that, in the construction of a network model and its subsequent analysis, the data (including geodata) undoubtedly plays the most important role.

Two network models were created – both with the nodes being represented by the same elements (i.e., crossroads); however, the links were represented by different elements. In the first network model, the links were physical road links, and in the second model, the links were the numbers of vehicles that passed each crossroad per day (the maximum data from a single measurement day). The first model presented a random network structure in which most of the nodes had roughly the same numbers of links; therefore, most of the crossroads that were subjected to analysis were of the three- and four-inlet types. According to the theory, this meant that such a network contained no centers; i.e., the most important nodes in the structure of the entire network – the exclusion, destruction, or functionality cut-off of which could lead to a significant disintegration of the network or a serious disruption in its functioning. The second model also suggested a structure of a random nature. Nevertheless, it was apparent that a group of six nodes (deviating from the whole) was distinguished at the end of the model when looking at the distributions of the nodes and links in this model. Therefore, it could be concluded that the nodes that were found in this group may have been the centers of an emerging scale-free network. This conclusion followed from an analysis of the literature on the subject, where it has been described that a scale-free network could indeed emerge from a random network.

The references to the statistical analyses and simulations of the cutting off of the traffic system network structure centers confirmed the effectiveness of the application of the scale-free network theory in analyses of this type. The models showed that the locations of the selected centers (in the city center) often converged with the routes to the greatest numbers of incidents. Therefore, this was an additional argument that indicated the significance of these objects.

Consequently, one can venture to say that an analysis of a transport system as a network is a new and valuable tool for studying safety concerns in fire department operations. The analysis also showed that the data that is appropriate for this type of network modeling is the data on vehicle traffic at crossroads. The six centers that were identified were the most important nodes within the network structure; these are of strategic importance, as cutting off their functionality may cause significant disruptions in the functioning of the entire transport structure. It is therefore necessary to care for and protect them while also considering actions that are aimed at strengthening other selected nodes that could, over time, become centers of this network (thus, strengthening its structure). This is very important information that considerably supports the planning and management processes in urbanized areas.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CRediT Author Contribution

A. M. K: conceptualization, data curation, investigation, methodology, resources, writing – original draft, writing – review & editing.

A. G: data curation, formal analysis, investigation, software, validation, visualization, writing – original draft, writing – review & editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work that is reported in this paper.

Data Availability

Most of the data that was used in this study is public. Data about the loads at the intersections is restricted and was obtained from the ZDZiT that is located in Olsztyn. This data can be obtained by contacting us via email: bok@zdzit.olsztyn.eu. The data about the fire department is restricted and was obtained from the State Fire Service in Olsztyn. This data can be obtained by contacting them via email: sekretariat@straz.olsztyn.pl.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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