

THE USE OF NETWORK ANALYST TOOL AND 2SFCA METHOD TO ASSESS FIRE SERVICE EFFECTIVENESS IN A CITY, AS EXEMPLIFIED BY ŁÓDŹ

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Summary

The article presents the results of research aimed at defining the potential effectiveness of fire services in the city space. The spatial scope of the analysis comprised the city of Łódź and a 20-kilometre ring around it, which was introduced in order to avoid an artificial barrier in the form of a city boundary. The study comprised all fire departments located within this area as well as individual elements of its built environment, which may be subjected to or otherwise pertinent to interventions of fire fighters. The use of the ArcMap Network Analyst tool and the 2SFCA method allowed us to specify time accessibility of fire service operations; spatial accessibility of individual elements of the city infrastructure to fire service activities; the load of individual fire stations; and the minimum number of departments necessary to take action within the assumed, defined arrival time for intervention.

Keywords

Network Analyst • 2SFCA • spatial accessibility • fire service • Łódź

1. Introduction

The Fire Service in Poland functions as an organization based on professional fire service (the State Fire Service and the Military Fire Service) as well as community fire service (the Volunteer Fire Service). Professional fire service, as a uniformed unit with specialist equipment, came into existence with the aim of fighting fires, natural disasters and other local hazards [article 1 paragraph 1 of the Act on the State Fire Service].

The tasks of volunteer fire departments result from the Act of August 24, 1991 on fire protection. The volunteer fire departments work for the benefit of civil protection, fire protection and rescue services, but they also take preventive action aimed mainly at young people on a broad scale. The main aims and tasks of volunteer fire departments, resulting from their charters, include activities aimed at fire prevention, participation in rescue missions conducted in the event of fires, other dangerous events and natural disasters as well as notification of the population about the existing hazards [msw.gov.pl, accessed: 04.08.2015].

The State Fire Service, combined with its volunteer counterpart, constitute the core of the National Fire and Rescue System. The goal of the said system is to standardize rescue activities undertaken in situations, which pose a threat to life, health, property or the natural environment [Żuber vel Michałowski 1995].

The basis for the elaboration of this article was an attempt to specify, with the use of spatial statistical methods, how the tasks imposed on the fire service by the legislator are accomplished in a big city from the theoretical and spatial viewpoint. In this way, the formulated research assumption conditions both the methodological and the cognitive aim of the analysis. The first concerns the elaboration of research results on the basis of aggregating Network Analyst in ArcMap and the two-step floating catchment area method [Cheng et al. 2015] so as to assess how the uniformed services function. The latter, in turn, evaluates the effectiveness of fire services in Łódź, at the same time, constituting the verification of the algorithm adopted in the research results.

Each of the subsequent stages of the research entailed the use of new research tools, the aggregation of which brought synergy effects. These stages included: defining time accessibility [Gutierrez et al. 1998; Escobar-García et al. 2015] of fire departments; classifying various structures (land use elements) in Łódź according to fire fighters' arrival time; indication of spatial adjustment of the distribution and rank of fire departments to the distribution of buildings and the city's road network; specification of the minimal number of fire departments necessary to ensure potential safety of Łódź, according to individual arrival time ranges in the event of intervention.

Upon including volunteer fire departments in the National Fire and Rescue System, i.e. since 1995, the range of activities of volunteer fire fighters increased greatly. Volunteer fire departments co-operate closely with the State Fire Service and other entities and institutions in order to ensure safety of citizens on their area (towns and municipalities), as well as to support the neighbouring areas as a part of operating reserves, or in the scope of agreements on mutual help. It is also worth pointing out that, in everyday practice of a volunteer formation, we observe is a shift from the earlier dominance of the issue of fire prevention and fire extinguishing to other forms of rescue services, including, most of all, technical rescue during road events where other techniques of rescue operations are put into practice [msw.gov.pl, accessed: 06.08.2015]. Such a broad scope of activities of volunteer fire departments resulted in including them in the present study on par with the State Fire Service.

2. Materials and research methods

To accomplish the methodological and cognitive aims of the research, it was necessary to include in the analysis the data illustrating land development in Łódź, and showing the local structure of fire service operations. The analysis includes, therefore, the vector data illustrating the distribution of land development as well as road, tram and rail infrastructure together with the distribution of forests, reservoirs, and watercourses in Łódź and within the 20-kilometre buffer around the city. This allowed us to avoid the impact of the boundary on the accessibility of a fire department situated in the area

of a neighbouring municipality even if it is located near this boundary [Anselin 1988; Guagliardo 2004], and the boundary alone does not represent a barrier and has only an administrative nature. Such a research variant dismisses the unrealistic assumption of border impenetrability (e.g. in the case of municipality borders). Researching accessibility of fire services to each of the above-mentioned elements was supposed to specify the overall effectiveness of the functioning of this service in the most comprehensive manner possible. Data on their distribution, surface, or course were imported from the database of topographical objects showing the current situation as of the end of 2014.

The research also included all State and volunteer fire departments situated within the adopted spatial scope of the analysis, which were listed in the register of departments co-operating with the system of Emergency Medical Services in the Operating Plan of Emergency Medical Services for the Łódź province as of June, 2015. Operation of fire services on the analysed area is based on 11 fire and rescue departments in Łódź (city headquarters), district headquarters in towns of the Łódź agglomeration, and numerous fire stations of the volunteer fire service. Fire departments were classified according to the number of professional and volunteer fire fighters serving in them.

On the basis of the input data collected in this way, it was possible to accomplish the subsequent research assumptions. The analysis was commenced by including vector data, showing the road network of the area in question, in the research. Each network segment was characterized by means of such features as class, category, length, maximum speed (in accordance with traffic regulations), journey time (assuming that journeys were made at maximum speed) and possible one-way traffic. Individual attributes of the database were obtained from the Emapa Transport + Europe application (application dedicated to the service of transport companies). The Network Dataset was created on the basis of the database developed in this way. Then the New Service Area (tool for determining the course of isolines, e.g. travel time isochrones) from the Network Analyst (tool package in ArcMap program, primarily designed for the analysis of transport) was used. It was necessary to introduce vector data concerning the location of fire departments additionally characterized by the number of fire fighters serving in the given fire station. The New Service Area tool was calibrated, pointing to subsequent isochrones of maximum fire engine arrival time (up to half an hour in 5-minute intervals) and excluding limitations resulting from one-way roads, which do not concern emergency vehicles. As a result, surface vector data were obtained representing joined areas marked by the isochrones of identical arrival time to every fire department (joined rings of identical time values) (see Figure 1).

The next stage of the study, which consisted of defining the elements of built structures within the city, considering their location in individual fire service arrival time zones, required the introduction of vector data concerning road, train and tram networks, built-up areas as well as watercourses and forests. In addition, point data concerning the location of crossroads were introduced, as in accordance with the Police Accident and Collision Register System these are precisely the spots where road events with fire service intervention tend to occur. Each object from the abovementioned thematic layers was given an attribute of belonging to a relevant fire service arrival time

scope. This allowed us to sum up the objects in the same zones, and to specify what percentage they constitute in the total number of objects (see Table 1).

Spatial adjustment of fire department distribution to the distribution of potential fire service intervention spots was analysed for the city's built environment and its road network. Databases of the provincial headquarters in Łódź indicated that a clear majority of fire service activities on urban areas consisted in road accident rescue in places where roads cross, or in various types of interventions in buildings. The New Service Area tool of the Network Analyst package was employed at this stage. This time, however, polygons marking areas of fire service arrival time were generated individually for each fire department. The subsequent steps in this part of the research were the result of using the *two-step floating catchment area* method (2SFCA) [Albert and Butar 2005; Langford and Higgs 2006; Cervigni et al. 2008]. Spatial accessibility defined by using this method refers both to the factor of supply (size of the given fire department) and demand (surface of buildings or number of crossroads). This method was first used in the analysis of spatial accessibility of labour market in the USA [Peng 1997].

In the first stage of the 2SFCA, the activity area of each fire department was defined, assuming the borderline value of arrival time. Then the individual indicator R_j was calculated, being the quotient of weight (number of fire fighters) of individual departments and the Volunteer Fire Service to the surface of buildings or the number of the city's crossroads in the area designated by the given isochrones of fire fighters' arrival from the particular department:

$$R_j = \frac{S_j}{\sum_{i \in \{d_{pj} \leq d_{max}\}} \frac{P_{pi}}{\sum P_{pi}}} \quad (1)$$

where:

- S_j – weight (number of fire fighters) in the fire department j
- P_{pi} – surface of building/crossroads p in the studied polygon i
- d_{pj} – arrival time between fire department j and building/crossroads p
- d_{max} – isochrone marking the maximum arrival time of a fire engine for individual research variants

The distance between each analysed fire department and individual city infrastructure elements was expressed in time units of fire engine arrival to the intervention spot. It was assumed that changes in vehicle speed during intervention were affected solely by traffic regulations concerning maximum allowed speeds. Despite the fact that speed limits do not concern emergency vehicles, it may be assumed that design speeds determine the maximum speed, which allows the vehicle to reach the intervention spot safely. As a result, all other factors, such as congestion or weather conditions, were excluded from the study. It was assumed arbitrarily that the speed of arrival during intervention has values higher by $20 \text{ km} \cdot \text{h}^{-1}$ than those allowed on the given road section. The fire engine travels on the shortest travel route between the two points.

Thus, calculations were made concerning the theoretical load of individual fire departments with potential interventions in relation to built structures and road traffic. This was a particularly important stage of the study, as it should be assumed that fire fighters intervening in one place are excluded from effective rescue operations in other areas, which naturally decreases safety levels of the population living there. Consequently, the coordination between neighbouring units seems to be of key importance.

In the second stage of the two-step floating catchment area method, the attention shifts to the area of the city within which built structures and road network are located. Hence it is necessary to introduce the basic unit into the research. The arbitrary use of a figure grid (e.g. hexagons) or districts and sub-districts is artificial, and it may considerably distort the real spatial relations [Benenson et al. 2011; Vale et al. 2016], which is why primary fields, which tend to be more “natural” for the researched phenomenon, were introduced. They were formed by “cutting” the city surface and the 20-kilometre buffer with a grid of isochrones of access to individual fire departments. This allowed us to observe the extent to which the distribution of fire stations corresponded to the factual distribution of buildings and crossroads in individual primary units. This is particularly important in situations when analyses are based on data aggregated to large space units in which fire stations are located on the peripheries rather than in the centre [Geronimus et al. 1996]. The results of the conducted analyses were strongly affected by the choice of primary units for the analysis, the so-called MAUP phenomenon or *Modifiable Areal Unit Problem* [Anselin 1988; Fortney et al. 2000; Martin et al. 2002]. According to Openshaw and Taylor [1981], the MAUP issue consists of two dimensions, which have an impact on research results: arbitrary boundary delineation (*zoning dimension*) and the choice of scale (size) of the primary unit of the analysis (*scale dimension*). In the case of the adopted solution, both dimensions of the MAUP phenomenon do not represent a threat to the correct interpretation of the results obtained.

The superimposition of subsequent areas of fire service arrival on the studied area resulted in polygons covered by a different number of fire departments. Each such polygon was given an individual number.

Then an area was delineated for each polygon (individual number) within the boundaries of the analysed area, as in the first stage of the study, using the adopted border value of fire engine arrival time. Subsequently, for each polygon, the author calculated the accessibility indicator A_i , which is the sum of the value $R_j(1)$ obtained for all fire departments distributed within the area of the individual polygon i :

$$A_i = \sum_{j \in \{d_{pj} \leq d_{max}\}} R_j \quad (2)$$

The last stage of the research focused on specifying the minimum number of fire departments from the analysed area, which are necessary to ensure theoretical safety with the assumption of different time scopes of arrival for intervention. This fire station effectiveness test was carried out in relation to the accessibility to the given area's built

environment. Centroids were generated for every fire department and every building, which may require intervention. Subsequently, a matrix of fire engine arrival time for all possible relations between the fire station and the building was generated, using the New OD Cost Matrix tool (a tool to generate the connection matrix between the identified starting points and end-point) of the Network Analyst package. This, in turn, made it possible to use the New Location-Allocation tool (a tool for determining the optimal location of objects on the basis of the input spatial data analysis), which – based on the previously formulated matrix – chose such a set of fire stations whence the arrival time to the buildings did not exceed the adopted value of the maximum isochrones, and at the same time the accumulated journey time of this group was the smallest. This tool selected the minimum number of fire stations necessary to cover all or the largest value of the demand below the adopted border values of fire engine arrival time to the place of intervention.

3. Results

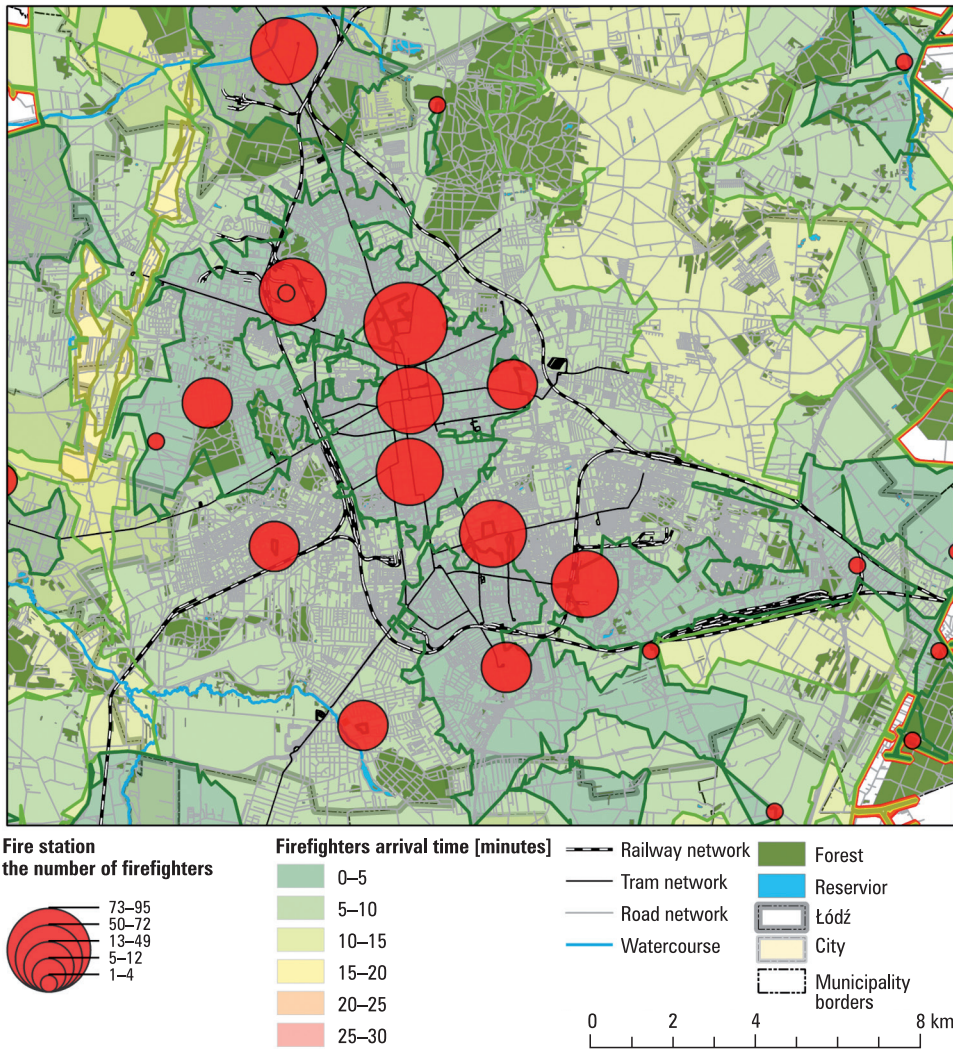
The methodological approach presented above was tested on the example of Łódź. Delineating isochrones of access to fire station network of the analysed area (Figure 1) made it possible to subsequently specify the structure of the city's spatial development elements according to the arrival time of fire fighters (1) (Table 1).

The satisfactory level of fire service time accessibility to the individual elements of the city's built infrastructure is represented by an almost negligible share of those elements, in the case of which arrival time is longer than 15 minutes.

Table 1. Structure of spatial development elements in the city of Łódź according to fire service arrival time

	Fire service arrival at:	Fire service arrival time [min]			
		0–5	5–10	10–15	15–20
Share of elements in time zones of fire service arrival	Built environment [number of buildings]	34%	53%	13%	0%
	Built environment [surface of buildings]	48%	48%	5%	0%
	Road network	38%	54%	8%	1%
	Crossroads	42%	55%	3%	0%
	Train network	35%	60%	4%	0%
	Tram network	65%	35%	0%	0%
	Watercourses	27%	58%	13%	1%
	Forests	3%	39%	58%	0%
	City surface [area of land within the administrative borders of Łódź]	29%	50%	20%	1%

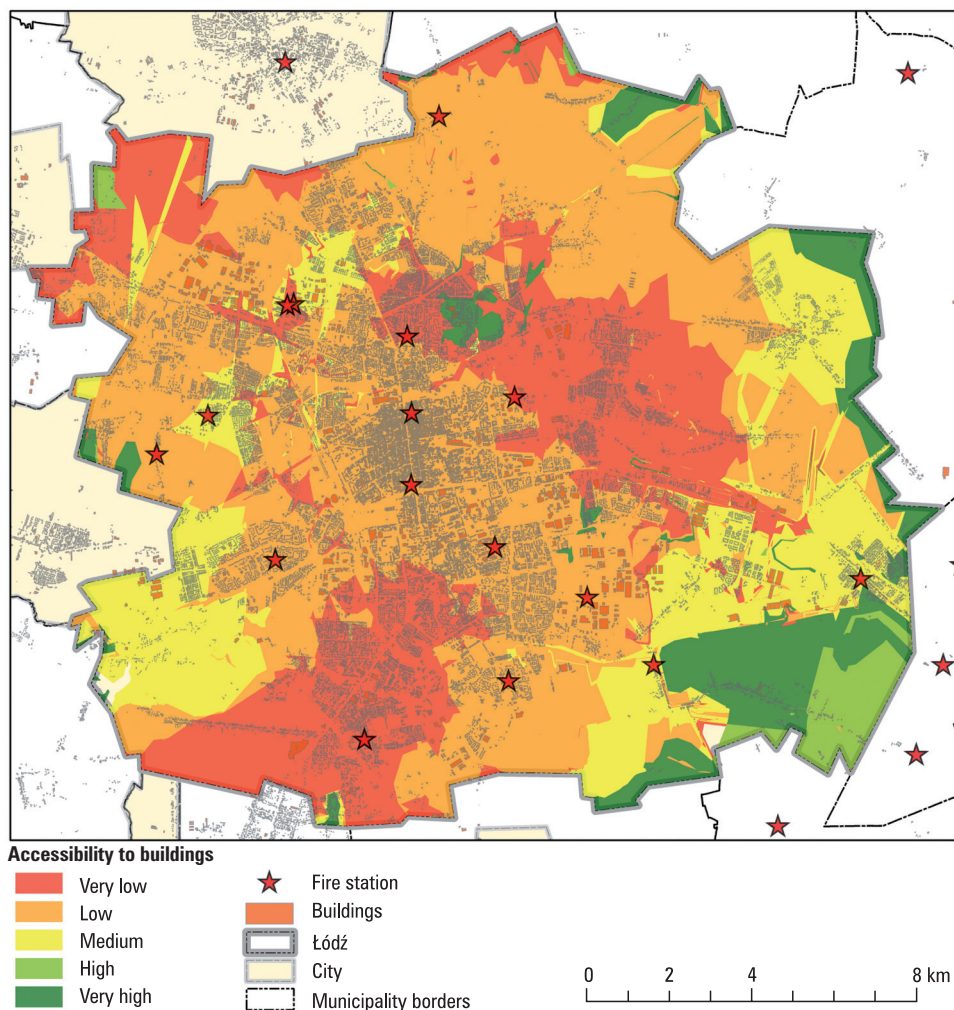
Source: author's study



Source: author's study

Fig. 1. Spatial differentiation of fire service time accessibility in Łódź

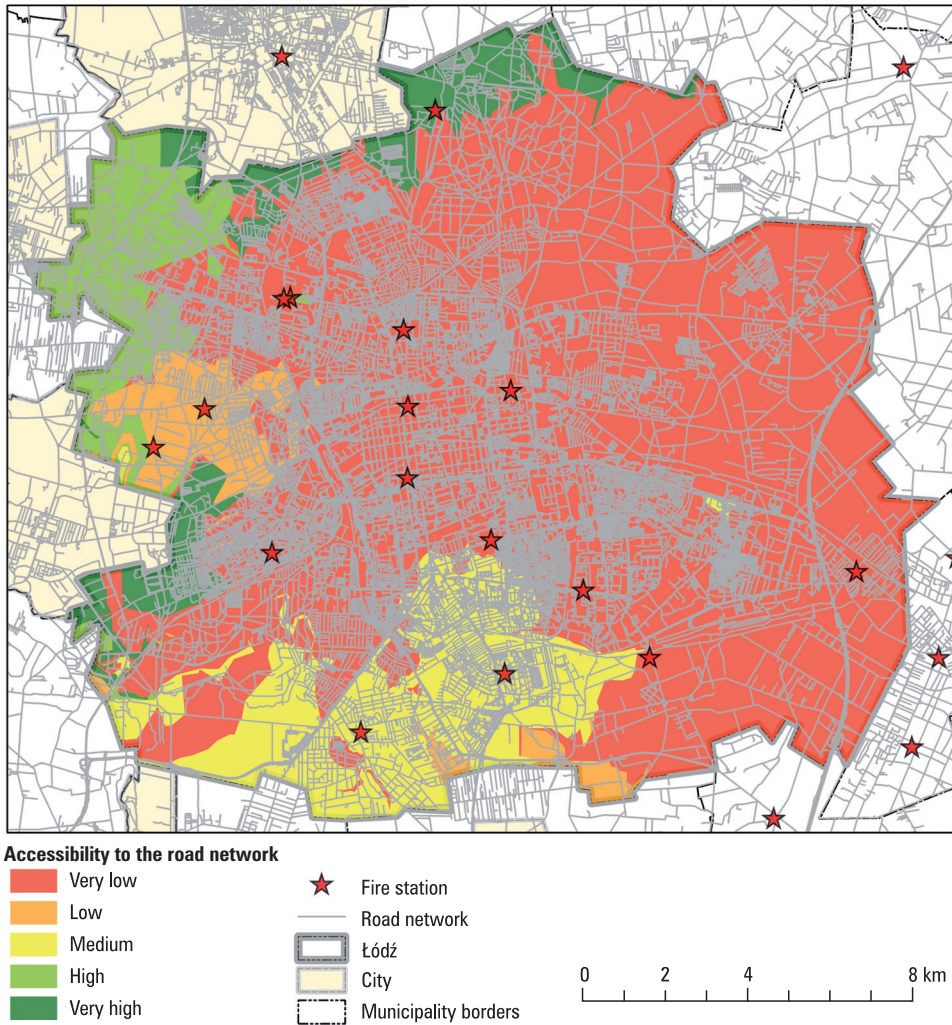
Such consistently good results are not obtained from analysing the adjustment in the distribution and number of fire fighters from individual fire departments to the distribution of built environment (Figure 2) and road network crossroads (Figure 3). Areas of particularly low adjustment levels were revealed in the course of the research (2). Considering the results presented earlier, it seems justified to increase the staffing of these departments from which arrival time to objects in the problematic areas is the shortest.



Source: author's study

Fig. 2. Spatial differentiation of fire service accessibility to spots of potential intervention in relation to built environment

The study assumed that the fire departments, which are involved in rescue action, have sufficient quantities of extinguishing agent (e.g. water). Implementation of the survey data on the distribution of fire hydrants increases the accuracy of the analysis. However, it was assumed that in urban areas, access to water supply was not a problem.



Source: author's study

Fig. 3. Spatial differentiation of fire service accessibility to spots of potential intervention in relation to road events

Analysis aimed at establishing the minimum number and location of fire stations (Figure 4) confirms the indispensability of all the existing departments. It also shows that, in theory, the fire departments in Łódź are incapable of providing adequate safety levels. In order to ensure protection, it is necessary to include also the departments from the neighbouring municipalities.

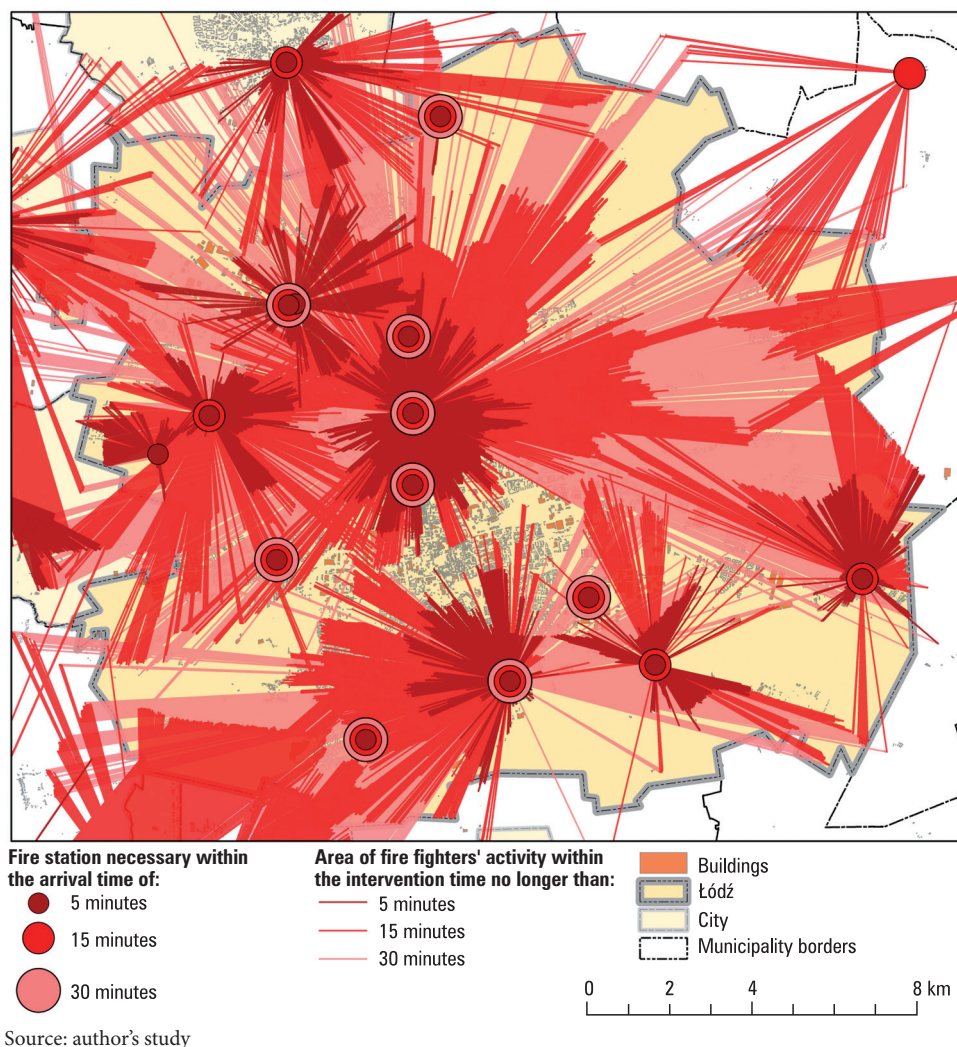


Fig. 4. Minimum number of fire departments necessary to ensure potential safety of Łódź built environment in the individual ranges of arrival time for intervention

4. Conclusions

The research we have conducted allowed us to accomplish the two aims, which were established initially. In the cognitive scope, the analysis indicated satisfactory effectiveness levels of the fire service operations in the city of Łódź (see: Table 1). It must be said that the existing system of fire rescue is efficient as far as the number of departments is concerned (see: Figure 4). Nevertheless, in order to increase the level of adjustment to spatial differentiation of potential hazard supply spots, consideration must be given to the

development of these departments, which provide services to the city's space on a particularly low level – predominantly in the eastern part of the city (see: Figure 3). From the methodological perspective, in turn, the research confirms the relevance of combining spatial information system tools with methods of spatial statistics. High calculating capacity, together with logical and theoretically-rooted gravitation model (which is used by the New Location-Allocation tool), brings results which are easy to interpret and free from distortions arising from artificial boundaries of the primary field.

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