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# Vehicle routing problem as urban public transport optimization tool

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This article presents possibilities of using one of network analysis tools for public transport optimization. The work focuses on presenting the transport system as a research polygon for analysis of its geographical information system (GIS). The article covers both a cognitive and methodological application approach. The first is achieved on a wider scope through discussing research regarding public transport in the GIS environment and in a narrower focus on the methodology where the vehicle routing problem (VRP) tool is referred to in detail. The city of Łódź, Poland and its system of night bus connections were used as a case study to illustrate how GIS solutions may be used to manage public transport. The simulation using the VRP tool conducted on a large urban center meets the work's methodological assumptions and may present an indication for local transport managers of how the spatial information systems can boost their organizational operations.

**Keywords:** vehicle routing problem, network analyst, accessibility, public transport, city.

## 1. Introduction

It must be clearly stressed that the *sine qua non* of assuring transport accessibility to the city's inhabitants consists in organizing adequate access to infrastructure elements as well as to carrier services. These two elements are closely connected with each other since using transport services is not possible without appropriately problem-free access to its infrastructure. On the other hand, even relatively easy and general access to it does not guarantee transport accessibility of a desired level. The maximum level of access availability to disparate places, goods, services or persons, which are often at a considerable distance from one another, is determined, apart from the accessibility to transport alone, by existence of other elements (e.g., financial means) that contribute to the ability to reach such places, services or persons [1]. Transport only enables us to get to the destination, but it does not focus on the use of the goods, services, work places or education centers available at the destinations [2].

Public transport plays an extremely important role in the structure of passenger services in the majority of countries [3], both in developing countries characterized by low rate of motorization and more highly developed countries where public transport is competitive both financially and time wise and provides a viable substitute to individual transport [4].

Calibration of a public transport system is highly complicated since it requires taking into consideration an extremely diverse number of factors of supply and demand for transport services as well as the environmental conditions in which services of this kind are to be provided [5]. Therefore it is necessary to focus, among other things, on the transport postulates of potential users, their number, age structure, distribution of traffic generators, road network condition, congestion levels, daily and weekly fluctuations of traffic volume, available rolling stock as well as the spatial and functional structure of the area within which transport is intended to function [6]. These are only a few factors that outline the complexity of the problem of organizing public transport [7].

Numerous examples show that this task may be fulfilled with varying success [8]. Different spatial scales (from international to local) as well as specific characteristics of public transport users show that whereas there is a list of certain constant elements which should undoubtedly be taken into account while planning public transport operations, still the hierarchy of their importance and groups of unique factors are considerable enough so that it is necessary to support the decision-making procedure with tools which are able to take into consideration the largest possible group of variables and produce results that are easy to interpret [9].

Of course, managers of public transport systems have at their disposal a broad choice of software dedicated strictly to transport solutions [10, 11]. The specificity of such software results from the fact that it can be used in a narrow scope. As a result, applications using the geographical information systems (GIS) environment seem to be of particularly great value. Although the formation and initial growth of these tools were not directly connected with research into transport, their dynamic evolution eventually led to a situation when researchers have specially dedicated GIS transport solutions at their disposal [12]. The competitiveness of these tools resides in being able to include in the research the elements of spatial development of the analyzed areas which do not directly form part of the transport system but which play a vital role in its effectiveness and, in particular, in interpretation of results, as such systems may work flawlessly in a virtual environment but their superimposition on geographical space with all its natural and anthropogenic elements may turn out to be disappointing [13].

Research works dedicated to planning, implementing, functioning and optimizing transport systems using GIS are deeply rooted in literature on the subject [14, 15]. Authors present studies, in which GIS is either a tool to accomplish the adopted aim or represents an aim in itself once the possibilities it offers in the field of transport research are demonstrated [16]. This article corresponds with both research trends since it presents the possibilities of using the network analysis tools available in the ArcMap application for public transport optimization. This work concentrates on presenting the transport system as a research polygon for analyses of spatial information of geographical systems.

Transport accessibility may be analyzed with different methods and tools. The primary problem of all methods in question is a lack of data which does not allow for accurate measurement of many variables. Therefore, it is so vital to use modern information technologies that allow the gathering large amounts of real data without the need of conducting extremely time-consuming measurements on a large scale [17]. By using GIS tools it is possible to virtually carry out analyses of accessibility to public transport [18].

The growing interest in sustainable development stresses the importance of accessibility as a key indicator of assessment of transport investments in cities. Due to the tools available in ArcMap, one may compare area accessibility for both private and public transport, which is of considerable importance [19]. Travelling by public transport not only involves the journey by bus or tram but also the time of reaching the stop, waiting for the given transport to arrive, as well as possible changing and repeating this process to arrive at one's final destination.

It is absolutely necessary to analyze all journey stages to obtain a full picture of time accessibility for any given destination. GIS tools are necessary for this purpose, not only for calculations but also for presentation of research results. Efficient public transport accessibility carries great social significance. It also is, or at least should be, competitive to succeed, as this is one of the most important elements of influencing transport behavior of a city's inhabitants [20, 21].

In addition, GIS tools make it possible to generate isochrones for journeys by public transport [14]. They can also calculate the number of buildings or inhabitants in any delineated accessibility zones [22]. ArcMap makes it is possible, to conduct more simplified accessibility analyses through delineating buffers or more advanced ones using network analysis.

Due to the dynamic development of spatial information systems, entities responsible for public transport can obtain and process information necessary for managing transport networks easier and faster. Spatial information systems are the most suitable tools of obtaining information on accessibility of public transport systems as GIS serves as a database, rather than simple being a ‘map in the computer’. Therefore, possibilities of GIS tools are not merely limited to a cartographic presentation of data but these tools can be used to conduct spatial analyses in the environment of raster and vector data as well [23].

As mentioned, this article aims to analyze both the cognitive as well as methodological applications of these phenomena. The first is realized on a wider scope through discussion of public transport in the GIS environment and the second in a focused way in which the vehicle routing problem (VRP) is analyzed in depth. The city of Łódź and its system of night bus connections were used as a case study based on how GIS solutions may be used for public transport management. Simulations using VRP conducted on a large urban center correspond to the methodological assumption of the work and may give guidelines for local transport managers on how spatial information systems may boost their organizational operations.

## 2. Public transport in the GIS environment

As stated earlier, research conducted at the interface of transport geography and spatial analyses using GIS tools finds its reflection in numerous scientific publications [18, 24, 25] as well as in professional evaluations completed for the purposes of local governments [26] or transport managers.

Research into transport carried out using GIS tools tends to focus on one of three trends: infrastructure [27–31], individual transport [32, 33] or public transport [34, 35]. Multidimensional research is conducted far less frequently, which, most likely results from the vastness of threads created for each trend.

The very broad application of GIS toolbox allows researching every single element comprising the transport system [37]. This may be achieved both with the use of universal tools to conduct spatial analyses and those dedicated solely to transport issues.

The vector image of reality in which individual elements are presented by means of point, linear or spatial objects are ideal for transferring individual transport system elements existing in real life into the analytical space of GIS programs [38]. Nevertheless, on any departure from the supply side, the number, distribution and features of potential public transport passengers must be specified. This may be represented from a point perspective, where an attribute is assigned to every point in the form of information on a given person or group of people living in a given locale. Another approach is analysis based on transport regions – polygons whose attribute table includes data on the population inhabiting the given region [39].

Some research methods (e.g., methods based on potential) demand to designate a point representative (e.g., centroid) for a given region, which on the principle of spatial connection takes over, to some extent, the attributes of the whole polygon [40]. The information on spatial distribution of potential public transport users may represent a base for research proceedings by using spatial analysis tools. An introduction of structuring of different kinds (e.g., sex, age, level of education, earnings, etc.) of potential users enables a dynamic increase in analysis directions, for instance in the search for regularities in distribution such as spatial autocorrelation. When researching public transport, bus stops are the best representatives of a given analyzed area. The way in which this area is defined will be discussed later in this article since bus stops represent places where a potential passenger may join a network of connections. Assuming that from the point perspective it is possible to present the distribution of potential public transport passengers, by defining stops as places where a passenger’s journey begins and ends, it becomes also possible to present the traffic generator from this perspective. The density of traffic generators and the potency with which they generate this traffic should be considered as a stimulant for transport development. Point elements in GIS analyses may also perform the function of representing an inhibitor or barrier to public transport operations. These types of points introduced to network analyses may reflect, for instance, temporary exclusion of crossroads from traffic as a result of road works or car accident.

The linear object is a natural presentation of connections between the journey's source and its destination. Regardless of the type of public transport which the researcher studies, the connections of individual travel points of means of transport take a linear form, which may reflect differently understood distances (time, cost etc.), and have a different course (physical etc.). In this way, lines in the GIS environment will present a displacement vector, either in the form of a road infrastructure along which transport moves or a graph showing routes of public transport vehicles in a simplified manner.

In the analyses devoted to public transport systems it is justified to include a broader scope of infrastructure network than that necessary for connections of existing means of transport since it is extremely rare to come across a situation where a passenger gets on and off public transport at precisely her/his planned initial and final point of the journey [41] as public transport by definition does not provide door to door connections. This is why it is necessary to include research of pedestrian paths or driveways along which potential passengers may travel from stops or to change vehicles.

There are different definitions of spatial scope of the network remaining within the reach of pedestrians. Different values of isochrones or equidistances are adopted depending on the means of transport, land development or the characteristics of a pedestrian to represent the border of acceptable distance to be covered on foot. As in the case of point elements, also linear objects may be described as barriers to public transport. Linear natural (e.g., watercourses) or anthropogenic objects (e.g., railway lines, motorways) may, on a local scale, constitute objects which force public transport operators to considerably extend routes and relocate the network of stops.

A set of data containing the abovementioned elements allows to create a package of network data by which it is possible to initiate network analyses. Of course, the larger the attribute description of each element introduced into the research the wider the spectrum of output analyses which may be obtained.

## 3. VRP in public transport management

Although this article pays special attention to analysis of VRP, network analyses available in the ArcMap application also include five other tools, all of which can be applied to research into public transport. Tools such as New Route, New Service Area, New Closest Facility, New OD Cost Matrix or New Location-Allocation meet analytical needs of almost every element and process which public transport systems contain. Consequently, it may be said that these tools are complementary in character in relation to the VRP, providing diagnostic material specifying the optimum distribution of stops which have to be subsequently connected in the most effective possible manner. If the analysis comprises information on distribution of the population of a given area, the abovementioned tools provide invaluable information on the potential load of individual transport network points, and this provides information on how many passengers public transport vehicles have to carry between individual traffic generators.

If we assume that the researcher has access to comprehensive data on population distribution of a given area together with its basic features, such as passenger's age, the course of individual elements of the area's transport network and distribution of stops, the first step of analysis is to build a set of network data on the basis of a linear dimension illustrating the area's transport network.

Assuming that the transport will be intermodal, by combining, for instance, pedestrian paths, bus services and a tram network, it is therefore necessary to configure each of the three networks. Each of them shows a way of travelling within its boundaries using numerical attributes expressing length (distance, time) of the section as well as logical attributes (one-way roads, exclusion from traffic). Combining the networks into a whole will allow to conduct door to door analyses. The target analysis of public transport routes should be preceded by an analysis of stop distribution validity and its potential load. It is possible to commence the target research after establishing the final list of points and giving them attributes, which specify the number of potential passengers (Fig. 1).

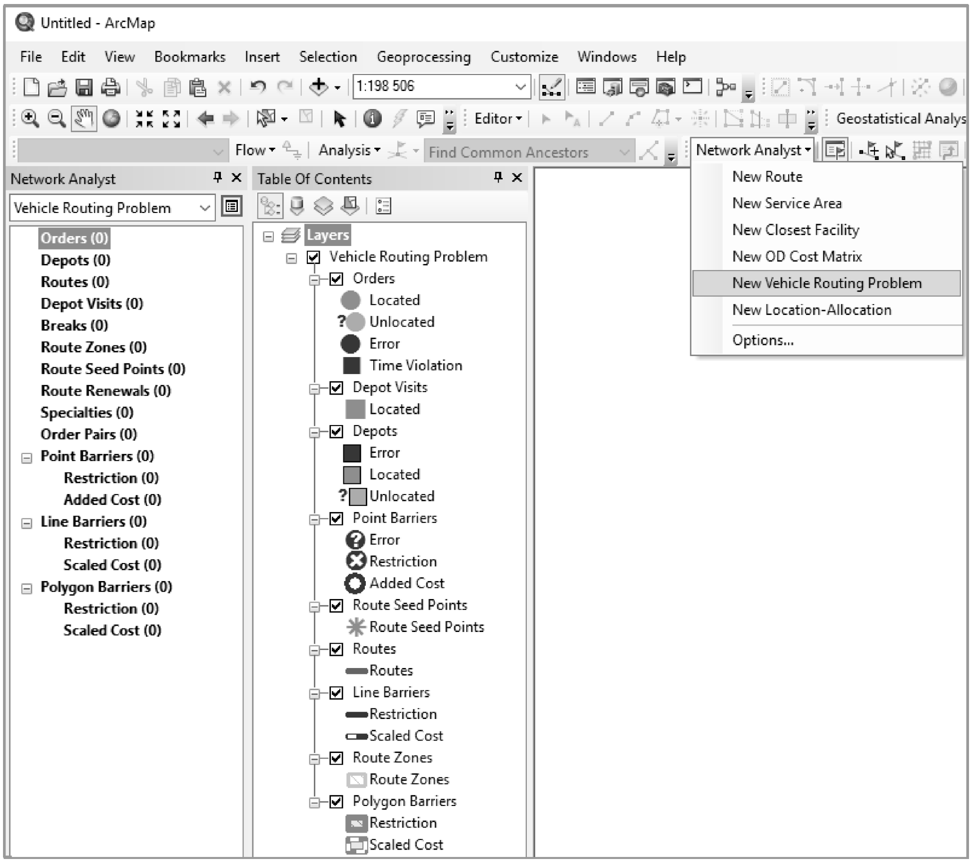


**Fig. 1.** ArcMap with the New Vehicle Routing Problem tool launched (source: own work).

The first step consists of entering all necessary elements for the analysis. As VRP is dedicated to analysis of logistics performance, which is usually based on vehicle fleet management to process orders, at first glance, the terminology used in the analysis does not seem to correspond to public transport management. However, when individual categories of objects are translated into facilities functioning in the public transport system they appear to exhaust the list of necessary features. Therefore, orders should be identified with stops. Each stop (Name) may be characterized by many features which differentiate the service effectiveness of individual points. This is the time at which the stop is serviced (ServiceTime), where means of transport can be found at the given point so that passengers may enter or depart the vehicle. This may assume a fixed value or be the function of the number of potential passengers.

The 'Enter Stop Wizard' also enables to indicate time scopes (TimeWindow) in which the given stop must be serviced by a vehicle. This allows considering changes in the demand for transport services and account for variations such as peak hours. Spatial differentiation of individual time scopes may correspond with daily changes in fluctuations in transport directions from work places and educational institutions to places of residence. In the same manner, it is also possible to specify acceptable delay times of arrival of a means of transport to a given point by entering stop locations during the slowest hours (MaxViolation).

From the numerous characteristics which may describe every entered stop it is worth stressing the importance of variables specifying the number of potential passengers who should be serviced by means of transport at a given stop (DeliveryQuantities and PickupQuantities). In turn, depots together with transfer hubs follow, where modal shifts take place. Each of them (Name) may also be described by the time scope (TimeWindow) in which vehicles should reach it. In the case of public transport organization based on transfer centres, the time windows in which hubs of different gradation transport lines should also be changed.

While planning service of concrete traffic generators (e.g., public utility facilities, mass events) depots may be treated as these objects. Additionally, routes reflect individual public transport lines. This is an element of analysis which is the most extensive as far as the number of attributes is concerned. For every line (Name) it is necessary to specify both the starting (StartDepotName) and ending (EndDepotName) points between which the means of transport will move. The choice should be made from the scope of hubs named beforehand (Depots).

The possibility of specifying the time scope of waiting for a given line's vehicles at a specific transfer hub seems to be an invaluable tool for designing the transfer system (StartDepotServiceTime and EndDepotServiceTime). Therefore, the analysis takes into consideration the time between arrival of the means of transport and its departure to the next loop. The two following variables refer to the time scope within which the first and the last service may take place on a given line (EarliestStartTime and LatestStartTime). This function seems particularly useful when there is more than one form of organized public transport in a given area. A good example of this is a day-time system based on many transfer hubs and night public transport where all lines meet at one main transfer hub. A smooth transition from one system to another excludes decreases in accessibility levels during the time scope when these two systems overlap.

Characteristics of individual lines also account for the capacity of public transport vehicles (Capacities). This allows to differentiate vehicles in the network, considering the time of day and traffic volume changeability which accompanies it as well as the demand for transport services or the functional and spatial structure of the area where the given line operates. Transport needs of single-family housing areas are completely different than those of densely populated inner city built-up areas or districts with blocks of apartments. Establishing the capacity of vehicles will translate directly into frequency of connections if servicing potential passengers is considered the system's priority.

VRP also allows to take cost analysis into account. Movement of vehicles on a given line may be burdened with two categories of costs – fixed (FixedCost) and variable costs depending on work time and/or the distance covered by the given vehicle (CostPerUnitTime and CostPerUnitDistance) just as it happens in the economic reality. Of course, cost may be understood in the strictly economic sense but also as any variable whose growth may accompany the provision of transport services and be of interest to the researcher. A good example is provided by the different kinds of environmental costs connected with mobility.

The last group of variables refers to functioning of individual lines that are borderline values up to which a given line can operate on a continual basis. These variables allow to take into account, for instance, safety rules connected with vehicle operation or maximum work time of drivers. The first variable permits to reduce the number of places where public transport vehicles stop (MaxOrderCount). The following three (MaxTotalTime, MaxTotalTravelTime and MaxTotalDistance) allow to establish time or distance values which may not be exceeded while planning operation work of a means of transport [42].

The objects described so far form indispensable elements for conducting any VRP analysis. However, network analyses for determining journey routes account for a much wider scope of variables. Due to the fact that drivers of public transport vehicles may work only for a precisely defined amount of time without an adequately long break, it is recommended to define 'breaks' while optimizing public transport operations with vehicle routes delineation. For every work break that vehicle drivers are entitled to, it is also possible to define not only its duration (ServiceTime) but also, for instance, the maximum time of work between breaks (MaxTravelTimeBetweenBreaks) and non-extendible accumulated time period which a given driver has spent at work after which there must be a break (MaxCumulWorkTime). The tool makes it possible to specify in a logical way (true/false) if the time spent on the work break should be added to the paid hours of the driver's work or not.

The ‘Route Zones’ should be employed if the designed public transport system assumes the zone variant where individual lines cater to specific areas (districts, suburbs) assigned from a wider area. They define the boundaries of an area in the scope of which the given line will operate. The software also gives access to optional settings such as Route Seed Points, Route Renewals, Specialties and Order Pairs, yet these are all variables which do not have to be considered in research aimed at optimizing public transport.

The ‘Depot Visits’ are the last element included in the Network Analyst Window characteristic of the VRP tool. However, this element displays values only after simulations are conducted. Therefore, it is one of the features characterizing the final suggested solution to the problem of determining a public transport system’s vehicle routes. In a thematic scope, the variable informs about the frequency of connections on a given line which, depending on the adopted analysis parametres, which is necessary to cater to potential passengers or possible to be implemented with restrictions regarding work time of drivers or length of the concrete line.

After defining all these variables, which are to be included in modelling of public transport operations for a given area it is still necessary to specify the properties of the thematic dimension. Only two tabs require attention in the case of the VRP tool. These are the Analysis Settings and Advanced Settings. In the first setting it should be pointed out in what time and distance units all analyses have to be conducted, whether the designed solution is supposed to refer to a given time frame on a daily or weekly scale and what kind of restrictions in road traffic organization refer to drivers of public transport vehicles.

Here, it is also necessary to mention Capacity Count. This refers to the number of elements which in analyses are to be treated as the subject of transport. Taking into account that public transport concentrates exclusively on passenger transport, one should leave the default value set to 1. In the advanced settings it is necessary to define weight (low/medium/high) for violation of a time window and for exceeding transit time. The greater the preference for meeting time windows, the more emphasis in the result is placed on solutions which minimize exceeding time windows at the expense of increasing the total result cost. And the greater the preference for the minimization of exceeding transit time windows, the more emphasis in the result is placed on solutions with shorter transit time between a pair of orders at the expense of increasing the total result cost.

## 4. The use of VRP to improve night public transport in Łódź

To illustrate the above mentioned use of the VRP tool it was decided that the process of public transport optimization would be carried out in the city of Łódź. This is a city inhabited by approximately 700 000 people with a surface area of 293.25 km$^2$, which gives an average population density of 2397.9 people/km$^2$. In order to simplify the research, the analysis was conducted on night public transport organization in the city as night public transport in Łódź consists of seven bus lines (N1–N7) as opposed to the day system which is based on several dozen bus and tram lines. An approach based on the day transport system in Łódź would involve an analysis exceeding the limits of this article format, and its results would be difficult to synthetize in an easily comprehensible manner. First of all, night transport analysis was undertaken because of its organization in Łódź. It takes the form of an interchange in which all bus lines “meet” in one place at thirty-minute and one-hour intervals. This form of organization is very well grounded in the available VRP functionality. The day-time public transport system takes a hybrid form, which could significantly complicate the analysis. Three of Łódź’s night lines (N1, N4, N6) extend beyond the city’s boundaries. All night lines have one central connecting point in Łódź where it is possible to change. On weekdays, this “meeting” takes place every hour, while on weekends – every 30 minutes. Within the city there are 578 stops operated by night public transport (Fig. 2).

Therefore, this part of the article focuses on designing night public transport operations in Łódź as effectively as possible with the VRP tool, and assuming that it must cater for passengers at

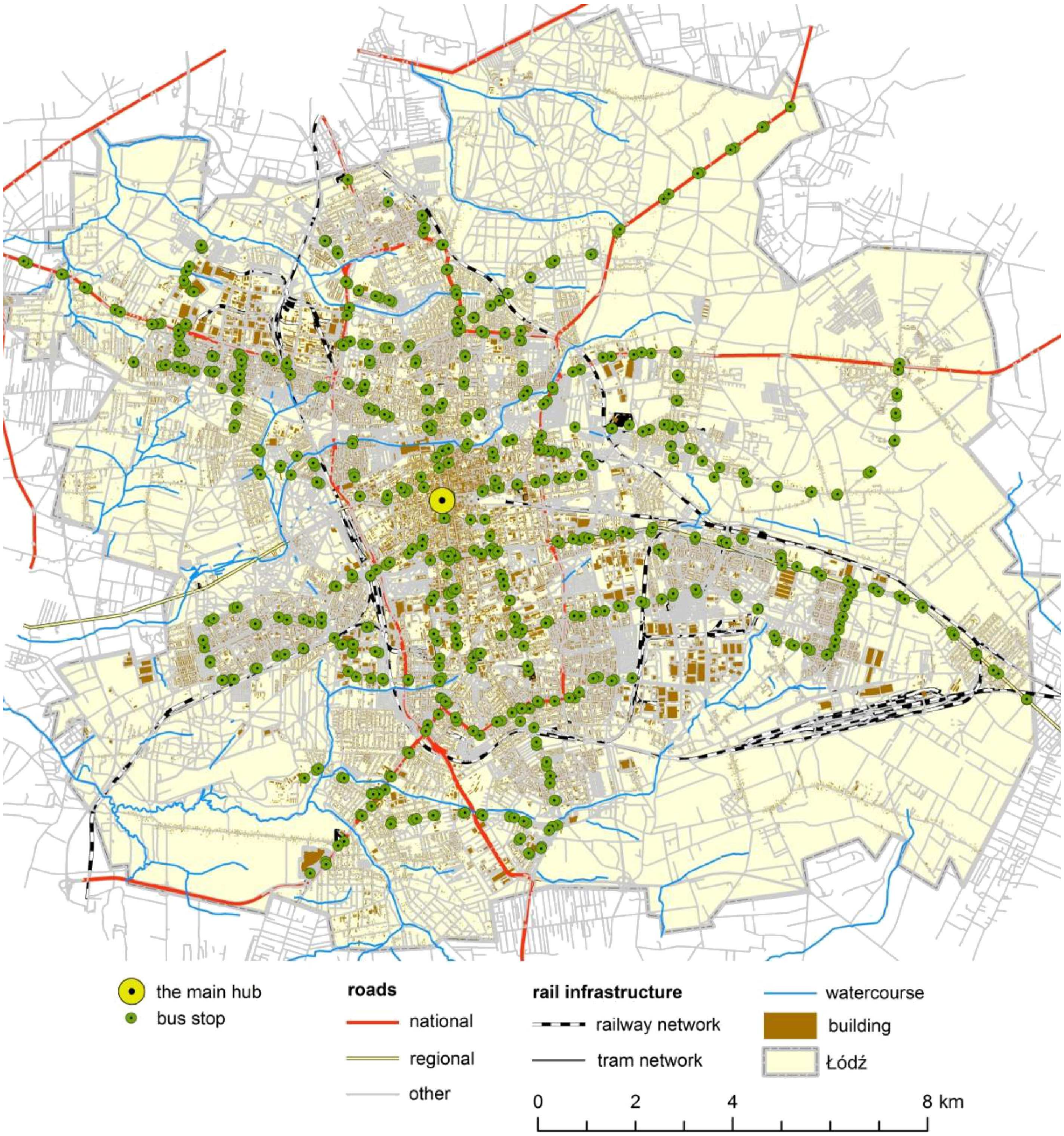


**Fig. 2.** Distribution of night public transport in Łódź (source: own work).

a specified distance from the nominated 578 stops with the use of no more than seven bus lines intersecting at one main transfer hub.

To achieve the adopted aim, it was necessary to gather source materials concerning the distribution of stops serviced by night bus lines as well as information on the distribution and age structure of Łódź inhabitants.

The location of each of the 578 stops was taken from the databases of the Road and Transportation Authority in Łódź. Data on the city's demographic potential (registered permanent and temporary residents of the city) were obtained from the City Strategy Bureau of the City of Łódź Office.

In accordance with the algorithm presented above, the analysis was commenced by calculating the number of potential night transport passengers. As for research methods the authors employed accessibility analyses that are commonly used in research devoted to public transport: cumulative accessibility and accessibility measured by distances [43, 44]. The first is also known as isochrone accessibility. This type of accessibility is measured by estimating a collection of destinations available at a given time along/together with the specified journey cost or effort [45–47].

In this research, calculations concerned Łódź inhabitants whose physical distance of access on foot to individual night public transport stops did not exceed 1 km and was delineated into 250 m intervals. The courses of isolines with identical lowest possible values were joined after drawing equidistances of access on foot to individual stops within the boundaries of Łódź. This permitted to mark the spatial differentiation of accessibility within the city's boundaries A central point was generated for every building (address) within the city's boundaries and the number of inhabitants was ascribed to it in accordance with the data from the City of Łódź Office as of January 1st, 2016.

In Poland, it is customarily assumed that the zone of impact of public transport stops occupies an area of a radius ranging from 500 m to 1 km. This means that inhabitants should be able to reach the stop on foot from 6 to 12 minutes assuming that the pedestrian's average speed is 5 km/h [48]. However, this model does not reflect the possibilities of generating demand for a stop for public transport services even if they are provided in all possible directions and with maximum frequency. This results from the fact that each inhabitant may have a different border distance which makes them to decline from using the stop. Additionally, the hypothetical public transport user may consider other factors, besides distance, such as possible facilities which make the access to the stop easier or barriers hindering access to it. The influence of these factors is different for every inhabitant and tends to be heavily determined by individual features of each user, such as age, health condition, sex, place of residence etc. [49, 50].

Generally, in the literature there are methodological problems connected with the border distance for different means of transport. In Great Britain, an equidistance of 640 m is considered the maximum distance of access to a bus stop in town, whereas in the case of regional rail or underground it is 960 m [48]. German urbanists, in turn, assume that the maximum distance of accessing a bus stop is 300 m, 400 m for a tram stop and for regional rail it is 500 m [51]. Differences in determining border distances in relation to means of transport result from a number of key issues. Greater distances from a tram stop as compared to a bus stop are decreased by the capital expenditure incurred by the construction of new tram lines with the simultaneous assumption that inhabitants can go farther to the stop if they can reach their destination quicker and under more comfortable conditions.

Consequently, this research adopted a few variants of border distance, which the potential passenger must cover on foot to get to the stop. The Manhattan distance metric was adopted to establish these distances. If using the distances of 250–500 m in the research is justified in the literature on the subject, the introduction of larger distances may seem contentious. It was decided to introduce into the research isolines of the value of 750 m and 1000 m due to character of transport services at night. It should be assumed that potential passengers are willing to cover a greater distance to the nearest stop, firstly because of lack of an alternative means of public transport and secondly due to the organization of night transport which due to the transfer point enables to reach any place covered by night transport with only one change. The third argument which may justify extending the research area is an individual's sense of security while moving around the city at night. It should be assumed that travelling by bus gives a feeling of greater comfort and safety than covering the same given distance on foot. Consequently, it was assumed that at night inhabitants will prefer using public transport instead of covering the given distance on foot, even if during the day they would be ready to do so. In this respect, the distribution of night public transport stops and main generators of night traffic is of utmost importance.

Bus journey times between individual stops according to the carrier's timetable were adopted to assess time accessibility of the city's inhabitants to specific transfer points by night local public transport. Subsequently, following the methodology presented above, the authors calculated the number of potential passengers who live in the given equidistance to a concrete stop along with the assigned access time to the transfer hub.

The presented research proceedings allowed to define spatial differentiation of pedestrian availability for night public transport stops (Fig. 3). A superficial analysis shows that the distribution

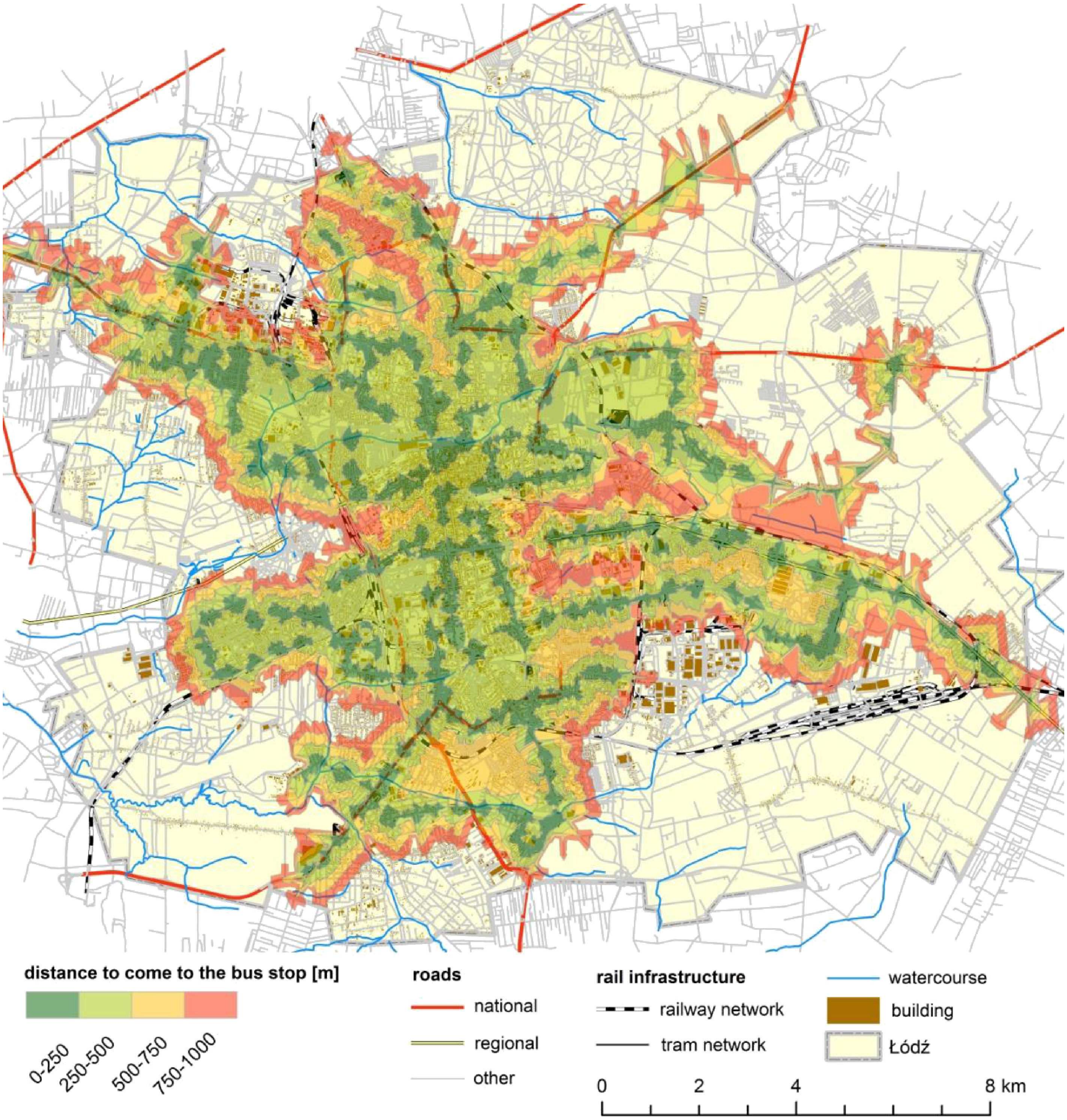


**Fig. 3.** Accessibility on foot to night public transport stops in Łódź (source: own work).

of night public transport stops is highly satisfactory since the area limited by equidistances covers half the area of the whole city.

Nevertheless, almost half of this zone comprises areas from which potential passengers would be forced to cover a distance ranging from 500 to 1000 m to reach to their nearest stop (Fig. 3). However, effectiveness of public transport should be related to the distribution of the population. From this perspective, the outlook seems even more upbeat. The walking distance to night public transport does not exceed 500 m for three of every four inhabitants of Łódź (Fig. 3). This type of reflections make sense only in the case of such transport organization in which there is a transfer point where all lines meet and the waiting time allows time to change the bus. Otherwise, availability to public transport assessed in terms of accessibility to the bus stop is highly theoretical as it does not take into account the place which may be reached by the passenger from the given stop and to what extent this corresponds to transport needs of inhabitants even if they are only theoretical.

The age structure of the population that is living in the areas delineated by equidistances of access to the bus stop does not differ considerably from the characteristic structure of the whole city where the population's pre-working age represents 14%, working age is 64%, and post-working age 22%. Assuming that night journeys of the city's inhabitants are mostly connected with travelling to work on weekdays while at weekends they also include journeys to places connected with leisure and social meetings, the age group that markedly dominates such journeys is the working age population.

Having assumed the distance and age criterion, the authors established the potential load of individual stops. In this way, all the variables necessary for the VRP analysis were prepared. The location of 578 bus stops was entered as Orders and subsequently all their obligatory and optional parameters, including load, service time or maximum delay, were determined (Fig. 4).

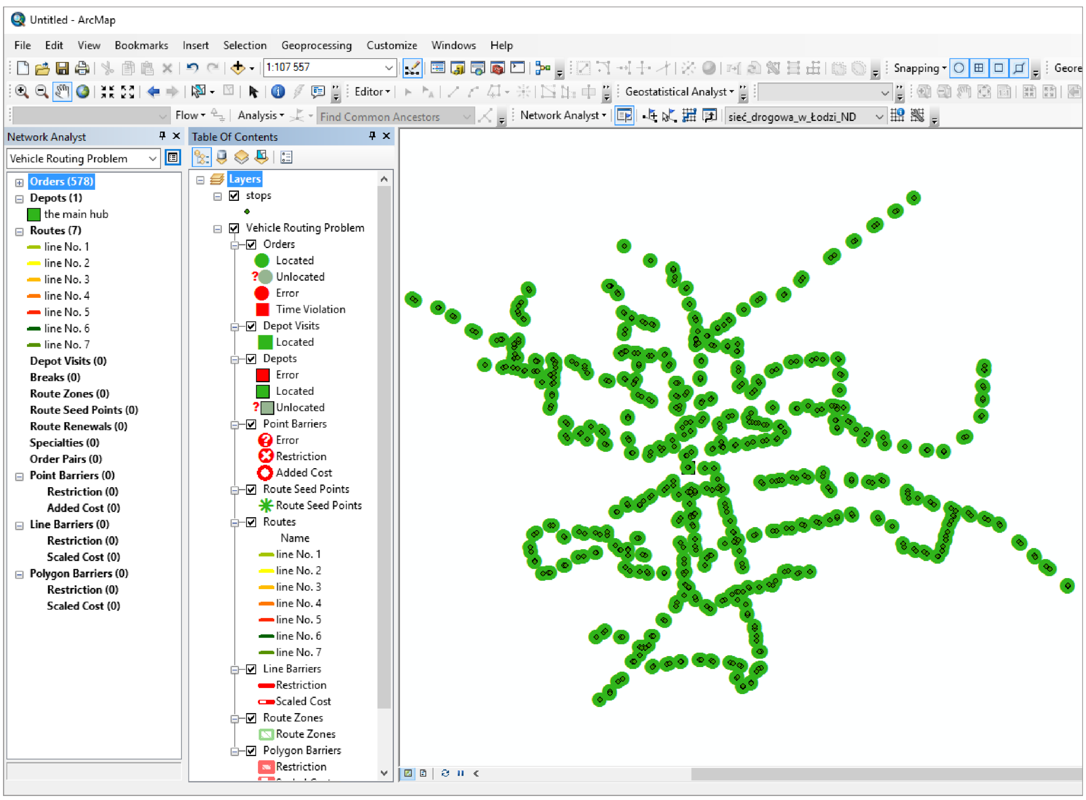


**Fig. 4.** New VRP with entered analysis variables (source: own work).

Moreover, the location of the main transfer hub was established and the time scope in which night transport functions was specified (from 10 p.m. to 6 a.m.). The subsequent step involved introducing the seven bus lines. Each of them was defined in terms of, among other things, the total time it takes for a bus to cover the entire route to be on a level of one hour so that all lines could meet at the transfer center. It was also pointed out that public transport vehicles should wait for five minutes upon reaching the hub and vehicle capacity was established at a level of 200 seats.

An analysis was launched upon introduction of the aforementioned changes. Its results pinpointed routes for each of the seven night lines (Fig. 5) as well as the number of connections necessary to cater for potential passengers.

Each bus line was designated according to a rule that minimizes total transit time. Since service times for each stop are fixed values, the decisive factor that determines selection of the path is the time taken to cover each of the road network segments. This, however, was conditioned primarily by the permissible speed of the road and the technical parameters of the road infrastructure. Of course, the results of the analysis can be further refined. One of the possibilities of a large group is to prohibit a return in the space of one intersection. In fact, this will help to avoid problems when the vehicle is moving while turning the width of an intersection.

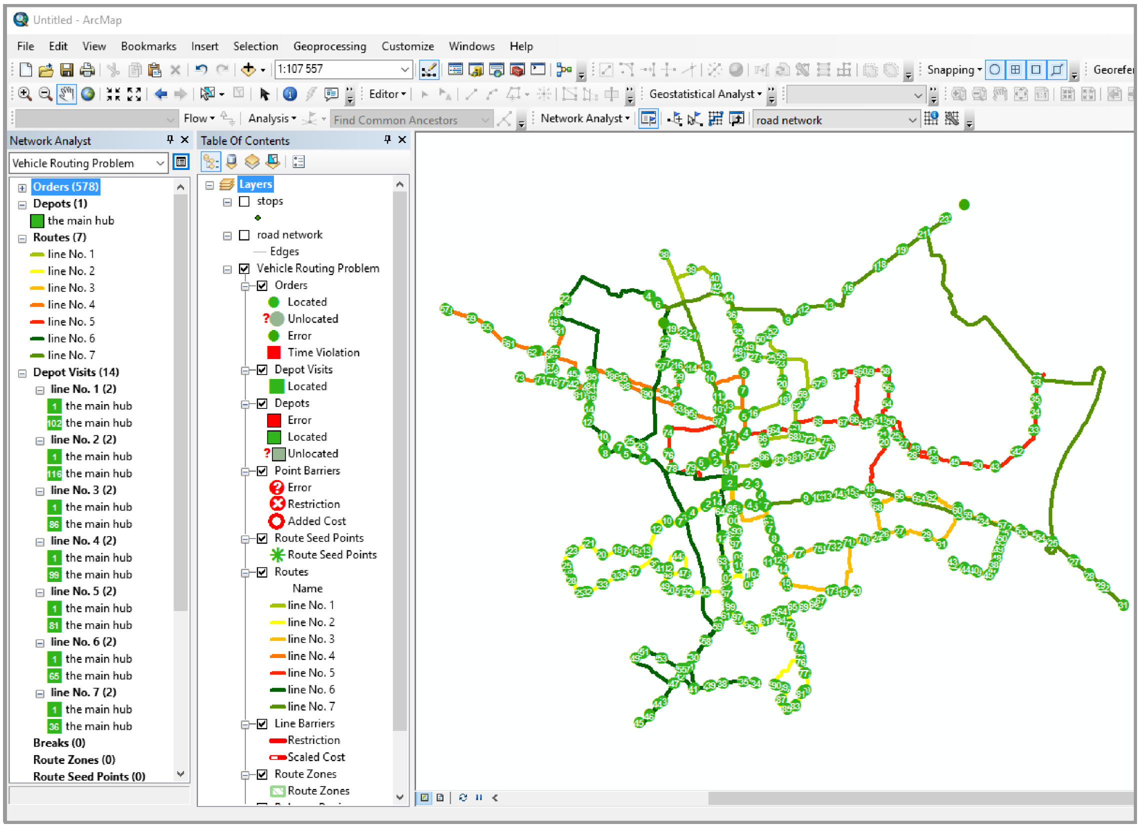


**Fig. 5.** Results of analysis into VRP for night public transport system in Łódź (source: own work).

Figure 5 shows sections of several lines (e.g., lines no. 6 and 7), which are devoid of any stop for a significant length of the route. They are certainly the most beneficial routes in terms of travel time. However, the time gain may be so insignificant that we can route the line through other points supported by a very slight loss of time. The flexibility of the entire network is therefore increased for potential users. There is also a disproportion in the number of stops and the length of routes served by individual lines. In economic practice, this situation can affect the cost of operating a vehicle and the efficiency of managing the driver's working time. Even a longer route but without many detentions, exploits the vehicle much less and causes less wear and potential damage to the bus. The results of the VRP tool testing can be interpreted for various research problems. The software can be useful for planning and managing the operation of city transport, transport infrastructure planning, human capital management of a transport company, investment policy of a company for the purchase of new vehicles, and stimulating spatial development of a city by increasing its spatial accessibility.

Research into night public transport calibrated in this way, in the scope of connection speed offered by its lines, allows to draw a conclusion that if a journey is commenced at any transfer point the passenger will not have to devote more than 50–55 minutes to reach the most distant bus stops (Fig. 6).

If it is assumed that a potential passenger decides to end a journey commenced in the transfer point at the bus stop located closest to his or her place of residence, then almost every fourth Łódź inhabitant who must cover a maximum distance of 1 km to the bus stop will travel no longer than 15 minutes. In turn, a 30-minute bus journey should allow for as many as 80% of Łódź inhabitants to reach their place of residence. Analysis of population age covered by individual isochrones of access from the transfer point corresponds in its majority directly to the age structure of Łódź inhabitants. This regularity is not followed by the group of people who spend between 25 to 30 minutes on a bus. This is highly numerous group of inhabitants, which is why their situation should

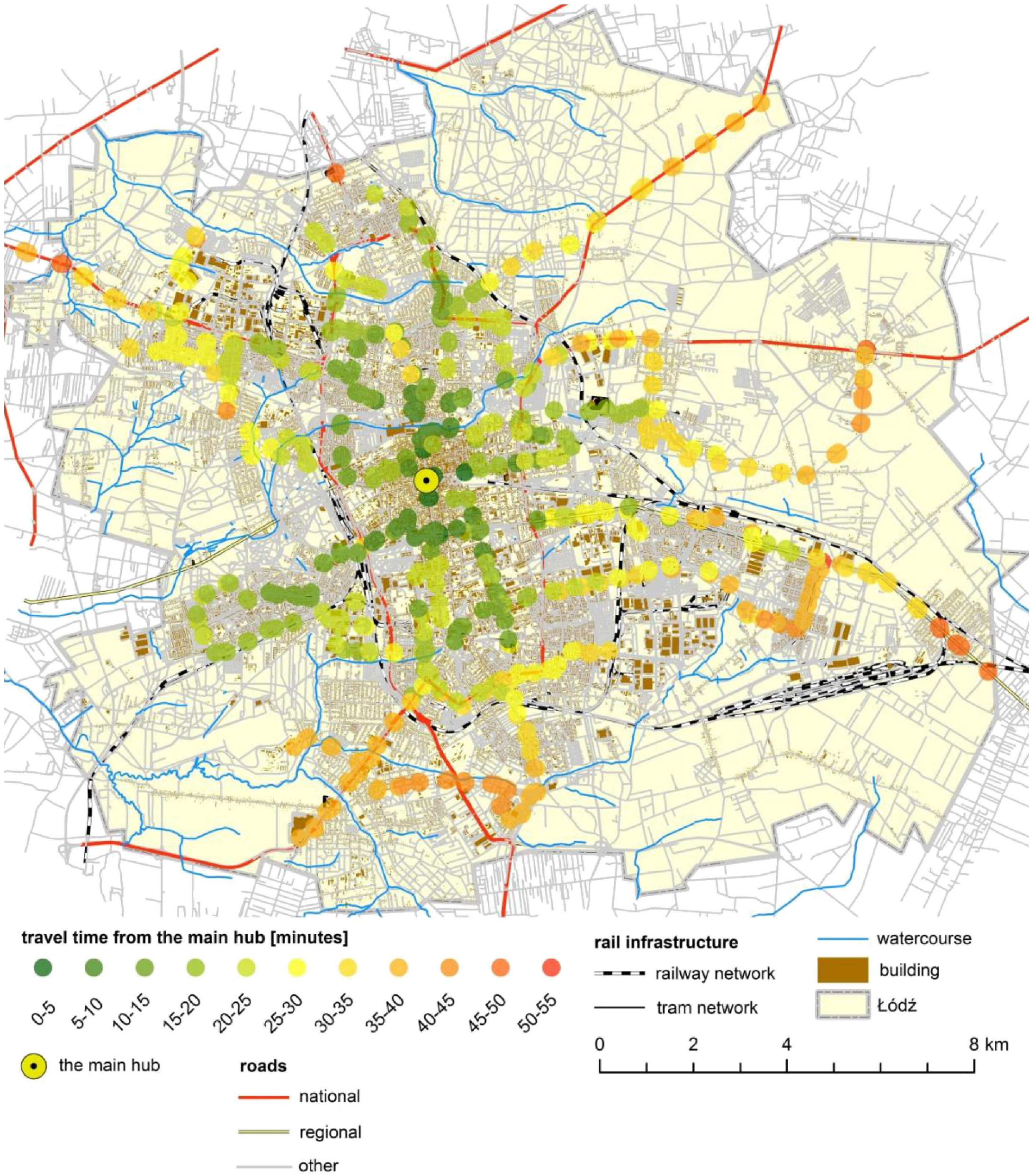


**Fig. 6.** Time accessibility of night public transport transfer point in Łódź (source: own work).

be of particular importance for local transport managers. It is recommended that in-depth research should be conducted on these sections of nigh bus routes.

Generally speaking, the performance of Łódź's night public transport should be deemed effective, taking into account its features scrutinized in this research. Buses are capable of catering to 75% of the city's population with the commonly accepted walking distance to the stop (up to 500 m) with seven operating lines and nearly 600 stops. Moreover, 80% of the city's population (with the adopted border distance of walking to the bus stop) is able to go through almost the whole city passing through the transfer point within just one hour. One should naturally bear in mind that the presented results assume that the potential passenger will be willing to change the bus at the transfer point.

The high effectiveness of the system designed in this way seems to justify the designed network of transfer hubs in a new model of public transport for Łódź, which takes for granted that individual bus and tram lines will "meet" at transfer hubs of different degrees of importance, from either local or regional ones located in different parts of the city. Conclusions arising from how night transport functions should provide guidelines to designers of a day-time public transport system since if transfer system implementation has some universal stages and features, still every city in the area of which it is about to be introduced has its individual characteristics, such as demographic potential distribution, which make transport solutions unique.

## 5. Conclusions

All passengers using public transport tend to be interested in a high reliability of services denoting the degree to which means of public transport provide their services on time. On the other hand, deficiency of vehicles constitutes an everyday problem for many public transport companies worldwide. Negative consequences of a lack of buses may include, for instance, cancellation of some scheduled services, which entails depriving a certain number of passengers transport and/or increasing the average waiting time.

In many instances, dispatchers responsible for traffic operations tend to use their own experience and intuition when allocating the available means of transport to the scheduled lines. Dispatchers are often unable to define optimum or near optimum solutions concerning the combinatorial nature of the problem. Hence, the main aim of public transport operators' job should be increasing the number of passengers who trust in public transport services.

The proposed method of allocating available transport for bus routes ensures minimizing total waiting time, while simultaneously servicing the passengers using the service. The presented method was put forward based on the VRP technique. Part of the model is based on the route selection model which assumes that the passenger chooses their route based on his or her preferential path as compared to features of alternative routes. The proposed reasoning algorithm calculates percentages of passengers on individual paths. The obtained analysis time is quite promising and enables application of the method in real life. Data processing time in the VRP analysis is short enough to enable the dispatcher to interactively work on changing input data.

In addition, the dispatcher may relaunch the computer application by inserting new data attributes of individual analysis elements if the solution already in use is not satisfactory. In this way, the computer application makes it possible for dispatchers to have a very active role in choosing the final solution. The proposed model generates high quality solutions and could contribute greatly to boosting traffic management and decision-making processes in situations where there are disruptions in the scheduled operations.

In future research, it is necessary to study frequently experienced occurrences such as when bus lines or parts of lines are shortened due to a lack of vehicles. It is of vital importance to scrutinize possibilities of easing disruptions according to the schedule with simultaneous relocation of available means of transport and changing the typology of the public transport network.

This work presents basic tools to simulate traffic for an entire road network. These tools can also be used not only to foresee the consequences of work on an existing infra- or suprastructure, but also of taking decisions of whether to invest in this type of solutions or not. This work concentrates on the use of the VRP tool as a model of mobility and demographic availability to assess the effectiveness of public transport systems.

The research results show that the VRP tool, which is based on accomplishment of needs concerning journey analyses, proves extremely useful in transport planning as well as spatial strategy development and setting policies in general. Apart from forecasting estimations in the scope of economic and environmental costs caused by road traffic, the presented methodology may be used for purposes of promoting public transport within a single traffic management system. The VRP tool was elaborated for urban transport and may ensure estimations of consequences resulting from the adopted traffic principles. GIS-based tools include a representation of real multimodal transport networks and effective implementation of solutions for the sake of network balance. Problems connected with the use of the tool for urban transport principles were also taken into account when considering the case study which showed the effectiveness of the proposed approach for the city of Łódź.

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