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THE METHOD FOR EVALUATION OF EFFICIENCY OF THE CONCEPT OF CENTRALLY MANAGED DISTRIBUTION IN CITIES

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Abstract. The paper describes proecological solution dedicated for organizing logistics services in urban areas. Proposed solution is based on cross-docking processes combined with consolidation centres. Authors proposed new method of estimating economic and social benefits from implementing centrally managed cooperation of logistics operators using common city consolidation hubs. Developed mathematical model bases on Vehicle Routing Problem (VRP) with vehicles of different types, limited loading capacities and multiply depots characterized by limited throughput. Proposed approach was supported by case study of integration of distribution processes in Warsaw (Poland) performed by three medium-size logistics operators. The central management of distribution was investigated in variants assuming using existing warehouses and with new configuration of logistics network developed with using SIMMAG 3D tools. As it was proved for analysed case, total costs of distribution in the city after implementation of centrally managed distribution were reduced by 8.1% for variant with current depots and by 26.5% for variant with new logistics network, while emission of carbon monoxide (CO) was reduced respectively by 7.8 and 16.7%.

Keywords: urban logistics; optimization of distribution; delivery problem; vehicle routing problem; city hub; central management of distribution; SIMMAG 3D.

Introduction

Highly urbanized areas are characterized by a large number of senders and recipients with a diverse transportation needs gathered on the relatively small area of the city. The area is then laden by a high number of transport tasks related to the movement of small quantities of goods. Freight traffic overlaps the passenger traffic carried out by private and public transport. Consequently, citizens face the problems of traffic congestion in selected locations and times of day. These blockages cause a significant loss of time in transport system on one hand and heighten negative impact of transport on the environment and people's lives on the other. This is why the freight transport in urban areas must be carefully organized, vehicles utilization must be increased and empty runs should be eliminated.

Over the years the following solutions reducing environmental burdens from goods distribution in urban areas have been proposed (the driving technique is not without significance; that problem was analysed, among others, by Shafaghat *et al.* (2016)):

- night deliveries, including the ongoing rail transport (freight trams, metro in Japan);
- underground supply network;
- entry control and limited time windows for freight vehicles serving specified areas;
- multi-purpose road lanes with functions shifting depending on the time of day;
- limited entry to the specified areas during certain hours;
- limited tonnage for trucks entering streets and areas with limited access;
- limited emission from vehicles entering areas with limited and/or paid access;
- entry fees in crucial areas;
- parking fees;
- emission-free and low-emission vehicles (electric, gas fuelled and other clean technologies);
- restricted authorised stopping time in dedicated loading/unloading bays or outside these places lowering traffic obstruction;
- home shopping mechanisms switching series of single transports made by consumers to the shopping places to one delivery route carried out by the supplier;
- new solutions for 'last mile' deliveries to reduce traffic (e.g. parcel lockers);
- specialized distribution infrastructure placed within the city – urban consolidation centres.

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The reduction of freight transport burdens in urban areas is conditioned by access to the complex and actual information about logistics situation in the area. It is primarily about identifying supply needs and capabilities of logistics operators. Such information provides a basis for optimizing logistics chains in the city with regard to their nuisance for residents, it is also the first step to implement the concept of urban consolidation hubs.

It should be emphasized that the best results can be achieved by combining described solutions. However, the authors' opinion is that the idea of implementing common urban consolidation hubs and central planning mechanisms remains the key element of that system. In practice, the idea faces many barriers, the most important of which are the economic one.

Given the above, the method for identification of economic and social advantages of implementing central management of freight distribution in cities was proposed.

1. The Idea of Urban Consolidation Hubs

Urbanized area gathers a number of logistics companies of different specializations competing to provide wide range of logistics services for business entities and individual recipients expecting high quality and reliable service. Logistics companies trying to minimize operational costs make efforts to optimize transport by shortening distances, ensuring highest possible utilization of loading capacities and taking into account traffic situation in particular periods of the day. Often it is associated with planning combined transport cycles for better use of both, the mileage of vehicles, as well as their capacity. Combined multi-stop transport routes predestine high capacious heavy vehicles. In fact, the limited transportation abilities (the ability of logistics system was defined by Wasiak (2011) as resources of that system, relations between those resources and work organization mechanisms, which allow realization of specified operations on loadings and accompanying information) of forwarders and logistics operators are a significant limitation for increase in transport efficiency. Other limitations are: scale of realized transport tasks and specific (different depending on the location) set of restrictions for freight traffic in the city.

Transport ability depends on the number and type of used transport and handling devices, number of workers and work organization (Wasiak 2011). Thus, the optimization effect in the field of transport is strongly associated with the scale of the task (e.g. number of vehicles taken into consideration).

It is easy to notice that aforementioned restrictions are less severe in case of a pooled analysis of all transport tasks identified for the site and transport abilities of all companies that carry out these tasks. This pattern is discernible in complex optimization rule, according to which optimizing individual subsystems does not guarantee optimum functioning of the entire system. This way of optimizing presupposes the existence of single entities for which the individual result may be less favourable, but the result for all stakeholders in general is favourable.

Joint processing of resources and tasks performed by various operators requires the assumption that all operators are obliged by legal standards to cooperate, or will take tangible benefits from this cooperation. Both conditions can be obtained through restricted access to particular zones for vehicles owned by specified carriers and paid access for other vehicles. It should be noted that some additional economic incentives can be introduced in that way. The benefit achieved for the entire system, less the costs associated with common management can be shared on the participants in the system.

City hubs are difficult to define because differences between them and other forms of logistics facilities like express parcels hubs, collection points for home deliveries, intermodal terminals or retail distribution centres are blurred. Urban consolidation hub or urban consolidation centre is best described as (Allen *et al.* 2007): 'A logistics facility situated in relatively close proximity to the geographic area that it serves (be that a city centre, an entire town or a specific site such as a shopping centre), to which many logistics companies deliver goods destined for the area, from which consolidated deliveries are carried out within that area, in which a range of other value-added logistics and retail services can be provided'.

Urban consolidation hub offers transport companies a possibility to provide goods destined for recipients located in the city to specialized facility without entering crowded and busy city centre. Goods from hub will be supplied to final recipients collectively instead of direct and independent actions. Urban consolidation centres can handle both – retail or industry products (e.g. supply for construction sites).

From a commercial perspective experiences with publicly operated hubs have been mostly negative (Allen *et al.* 2007). Many hubs are subsequently closed due to low volumes of throughput, ongoing requests for financial support from regional government, and dissatisfaction with service levels. Since 2000, most of new hubs were led by commercial enterprises for their own purposes (such as BAA at Heathrow Airport, London and Shopping Centre Operators) which recognized the benefits of controlling their logistics operations.

Different financing arrangements are applied for urban consolidation hubs. Some facilities are paid from central, regional or local public funding (e.g. La Rochelle, Amsterdam and Monaco). Some hubs are financed from EU projects (e.g. La Rochelle, Nuremberg or Bristol). Other are partially or fully financed by central operators, recipients and operators delivering goods to the hubs.

Significant barriers for implementing city consolidation hubs, except institutional barriers, are expenditures for new logistics facilities and less use of existing ones. To avoid that a new distribution system in the city can be constructed on the base of existing objects.

Additional interesting aspect of centrally managed network of city hubs is the need for existence of a central body – integrator, which controls and shapes the network in a multifaceted way taking into account needs of different users. Such integrator can be compared to 4PL integrators in logistics networks who coordinate many supply chains of different companies to gain global benefit or even to 5PL integrators who are able to influence law regulations and rates.

2. State of the Art

Discussed problem touches two areas of research: modelling freight transport in cities and vehicle routing. Usually traffic modelling in cities is confined to individual cars or public transport services (Karoń, Żochowska 2015) or it is considered in total (Álvarez-Herranz, Martínez-Ruiz 2012). Freight traffic is rarely discussed, but present in current literature (Nuzzolo *et al.* 2009; Jacyna *et al.* 2016). Attempts undertaken in that areas cover mapping traffic distribution and traffic analysis with respect to environment pollution (Jacyna, Wasiak 2014; Jacyna-Gołda *et al.* 2014; Jacyna *et al.* 2015). These researches are the base to evaluate the impact of changes in freight distribution in cities on congestion and environment. While it is possible to consider different organizational solutions for the distribution of goods, routing of vehicles is overlooked. Therefore, it must be solved before.

Planning goods distribution under central management is correlated with Vehicle Routing Problem (VRP). VRP is a family of problems and their mathematic formulations differentiated according to basic assumptions and complexity. Significant number of examples and variants of VRP have been presented by Caceres-Cruz *et al.* (2015). Complex VRP problems with strong assumptions mapping real distribution systems are called Real-world VRP. The most popular types of discussed issues, associated with this paper are:

- CVRP (Capacitated VRP) – the most popular approach in which limited capacity is a basic constrain. This version of the problem is primal for all other versions of VRP (Laporte *et al.* 1985; Toth and Vigo 2002);
- HVRP (Heterogeneous fleet VRP) – group of problems based on the assumption that transport is implemented by vehicles of different characteristics, typically different loading capacities. In classic HVRP number of vehicles is limited but in its modification Fleet Size and Mix VRP (FSMVRP) no such restriction exists. However, some studies present HVRP with unlimited vehicles (Brandão 2011; Li *et al.* 2010). The problem can be extended to serve particular recipients only by specified types of vehicles Site-Dependent VRP (DSVRP) or can use limitations of infrastructure Road-Dependent VRP (DRVRP). It is also possible to allow using specified vehicles to perform a few routes. In that case the problem is defined as Heterogeneous fleet VRP multitrips (HVRPM). It results directly from real distribution problems since forwarders often dispose differential vehicle stock. HVRP is commonly discussed in the literature (Baldacci *et al.* 2008; Dell'Amico *et al.* 2007; Gendreau *et al.* 1999; Paraskevopoulos *et al.* 2008);
- MDVRP (Multiple Depots VRP) – is a version of VRP in which supplies are performed from more than one warehouse. It is often combined with HVRP and in that form is a base of the model presented in next section. Literature review reveals variety of types and approaches towards this problem (Baldacci, Mingozzi 2009; Crevier *et al.* 2007);
- SDVRP (Split Delivery VRP) – is an important group of problems in which single delivery to the client can be split into few routes, if it is economically viable. This is especially important when demand reported by client exceeds the capacity of a vehicle. Often SDVRP is an addition to the other problems like HVRP, or MDVRP (Archetti, Speranza 2012; Chen *et al.* 2007; Dror *et al.* 1994);
- MOVRP (multiobjective VRP) – is a type of problems in which different criteria are taken into account at the same time. This approach requires applying multicriteria optimization methods, which make searching for solutions very difficult. Problems of this type allow for including different points of view and interests of different participants of distribution process. MOVRP are regular and important part of real VRP. Modifications and improvements of that problem include different aspects of randomness of model parameters or diversified vehicle stock. The literature in this area is differentiated, so many competing approaches can be indicated (Ghannadpour *et al.* 2014; Heng *et al.* 2015; Jiang *et al.* 2014; Jozefowiez *et al.* 2002);
- GVRP (Green VRP) is a quite new group of VRP including ecological criteria in planning distribution. A comprehensive review of that problems was presented by Demir *et al.* (2014). They reveal a variety of models (like COPERT or CMEM) accounting for fuel consumption or emission of harmful components of exhaust gases in relations to different parameters of vehicles and routes. The high degree of diversity of assumptions is noted for VRP, CVRP through VRPTW, SVRP and MOVRP. Incorporating several criteria is especially important in searching for compromise between used vehicles and payed costs. The single-criterion problems commonly base on fuel consumption minimization and the fuel cost itself. The authors discussing these problems are represented by Felipe *et al.* (2014), Jacyna, Szczepański (2013), Juan *et al.* (2014), Lewczuk *et al.* (2013), Schneider *et al.* (2014).

Apart from the problems mentioned above the VRP with Time Windows (VRPTW) are considered as significant in goods distribution. VRPTW assume limited serving time in delivery points or in main depot (Hu *et al.* 2016; Szczepański *et al.* 2014). The approach formulated in next section omits this limitation since it appears that time windows can be fitted to the delivery plan.

Literature review highlights the need for multiaspectual thinking about goods distribution. This is important for sustained development and eliminating negative environmental impact of transport. Different studies show that cost minimization as a base criteria function is often supplemented by environmental criteria (Molina *et al.* 2014; Salimifard, Raeesi 2014). The routing problems are commonly included into single or multistage localization problems (Szczepański *et al.* 2014)

In view of the above, the multicriteria optimization problem of goods distribution in the area of the city was formulated to map real urban transport system. The main purpose is to investigate potential effects of applying central management of distribution processes and possible better usage of disposed resources. The expected benefits from proposed method are reduced performed tonne-kilometres within the city, lowered distribution costs and emission of pollutants. Formulated problem belongs to the family of VRPs and is based on assumptions of VRP versions discussed above. It can be also included into so called Real-world problems.

3. The Formulation of a Problem

For mathematical formulation of the problem, where logistics operators serving selected area do not cooperate, the following assumptions are made:

- planning period covers one work-day;
- the area is served by multiple logistics operators using own resources (warehouses, transportation abilities);
- operators distribute known amounts of goods to the known recipients within the planning period;
- operators can have more than one warehouse (depot);
- logistics operators use vehicles of different types which differ in respect of loading capacities and exploitation, economic and ecological characteristics;
- features of delivered materials allow transporting them in the same vehicle;
- supplies can be performed at any time within planning period (time windows for supplies are not considered);
- ordered amounts of materials don't exceed loading capacities of vehicles;
- all demand reported by customers must be satisfied;
- drivers' working time and driving time are constrained by law regulations;
- particular logistics operators maximize their individual benefit.

In accordance with above list of assumptions the problem is based on VRP with multiple types of vehicles of limited capacities and multiple depots controlled by individual operators. The research is based on the classical approach to the problem formulated by Dantzig and Ramser (1959) with additional modifications on the types of vehicles and their capacities (HVRP) and multiply depots (MDVRP), as well as daily drivers' working time proposed by Pyza and Wasiak (2012). Proposed optimization task takes the following form:

Having regard to:

$\boldsymbol{W}$ – set of nodes of transport network identified within specified area, $\boldsymbol{W} = \{1, \ldots, w, \ldots, W\}$;

$\boldsymbol{L}$ – set of direct road connections between selected transport nodes within the area, $\boldsymbol{L} = \{(w, w'): \lambda_{w,w'} = 1, w, w' \in \boldsymbol{W}\}$, where $\lambda_{w,w'} = 1$ if nodes w, w' are directly connected and 0 otherwise;

$d_{w,w'}$ – length of the connection (w, w') where $(w, w') \in \boldsymbol{L}$;

$\boldsymbol{S}$ – set of types of vehicles used in specified area, $\boldsymbol{S} = \{1, \ldots, s, \ldots, S\}$;

$\boldsymbol{SC}$ – set of types of vehicles used in specified area for which GVM exceeds 3.5 tonnes, $\boldsymbol{SC} = \{s : \pi^s = 1, s \in \boldsymbol{S}\}$, where $\pi^s = 1$ if s-th type vehicle has GVM greater than 3.5 tonnes and 0 otherwise, $\boldsymbol{SC} \subseteq \boldsymbol{S}$;

$\boldsymbol{H}$ – set of types of pollutants emitted by vehicles, $\boldsymbol{H} = \{1, \ldots, h, \ldots, H\}$;

q^s – loading capacity of s-th type vehicle expressed in unified units, $s \in \boldsymbol{S}$;

ku^s – fixed cost of ownership and preparing for operation the s-th type vehicle in planning period expressed in currency units, $s \in \boldsymbol{S}$;

k^s – distance dependent unit cost of transport for s-th type vehicles expressed in currency units referred to distance units, $s \in \boldsymbol{S}$;

$e^{s,h}$ – specific emission of h-th type pollutant from the vehicle of s-th type related to the distance units, $s \in \boldsymbol{S}$, $h \in \boldsymbol{H}$;

$tj^s_{w,w'}$ – time of travelling distance (w, w') by vehicle of s-th type, $w, w') \in \boldsymbol{L}$, $s \in \boldsymbol{S}$;

$\boldsymbol{O}$ – set of logistics operators serving specified area, $\boldsymbol{O} = \{1, \ldots, o, \ldots, O\}$;

$\boldsymbol{N}^s_o$ – set of numbers of s-th type vehicles owned by o-th logistics operator, $\boldsymbol{N}^s_o = \{1, \ldots, n^s_o \ldots, N^s_o\}$;

$\boldsymbol{M}_o$ – set of numbers of depots used by o-th logistics operator, $\boldsymbol{M}_o = \{w : \mu_{w,o} = 1, w \in \boldsymbol{W}, o \in \boldsymbol{O}\}$, where $\mu_{w,o} = 1$ if o-th operator owns depot localized in w-th node and 0 otherwise, $\boldsymbol{M}_o \subseteq \boldsymbol{W}$;

$P_{w,o}$ – capacity of depot owned by o-th logistics operator and localized in w-th transport node, $w \in \boldsymbol{M}_o$, $o \in \boldsymbol{O}$;

$cu_{w,o}$ – fixed cost of maintenance of depot owned by o-th logistics operator and localized in w-th transport node, $w \in \boldsymbol{M}_o$, $o \in \boldsymbol{O}$;

$c_{w,o}$ – specific material handling cost in depot owned by o-th logistics operator and localized in w-th transport node, $w \in \boldsymbol{M}_o$, $o \in \boldsymbol{O}$;

$\boldsymbol{K}_o$ – set of clients served by o-th logistics operator, $\boldsymbol{K}_o = \{w : \kappa_{w,o} = 1, w \in \boldsymbol{W}, o \in \boldsymbol{O}\}$, where $\kappa_{w,o} = 1$ if o-th operator serves the client localized in w-th node and 0 otherwise, $\boldsymbol{K}_o \subseteq \boldsymbol{W}$;

$p_{w,o}$ – demand reported by client localized in w-th transport node satisfied by o-th logistics operator expressed in unified units, $w \in \boldsymbol{K}_o$, $o \in \boldsymbol{O}$;

$t_{w,o}$ – vehicle stopping time in w-th transport node resulting from serving client localized in that node by o-th logistics operator, $w \in \boldsymbol{K}_o$, $o \in \boldsymbol{O}$;

TP – maximal daily drivers' working time in Poland after deduction of so called 'sandwich brakes' equal to 7 hours and 45 minutes for a basic system of work time and 11 hours and 45 minutes for equivalent system of working time (Kancelaria Sejmu 2004);

TJ – maximal daily drivers' driving time equal in whole European Union to 10 hours (EC 2006),

one should find the values of decision variables:

$x^{s,n_o^s}_{w,w',o}$ – equal to 1 if connection (w, w') is charged by n_o^s-th vehicle of s-th type owned by o-th logistics operator and 0 otherwise,

$y^s_{w,o}$ – number of vehicles of s-th type that should be used by o-th operator to perform transportation tasks within planning period from w-th depot,

$z_{w,o}$ – equal to 1, if the depot localized in w-th transport node owned by o-th logistics operator is used in planning period,

Q_o^{s,n_o^s} – number of units of material moved in planning period by n_o^s-th vehicle of s-th type owned by o-th logistics operator,

which minimize the following criteria functions:

$$f_1 = \sum_{s\in \boldsymbol{S}} k^s \sum_{o\in \boldsymbol{O}} \sum_{n_o^s\in \boldsymbol{N}_o^s} \sum_{(w,w')\in \boldsymbol{L}} d_{w,w'} \cdot x^{s,n_o^s}_{w,w',o} + \sum_{s\in \boldsymbol{S}} ku^s \sum_{o\in \boldsymbol{O}} \sum_{w\in \boldsymbol{M}_o} y^s_{w,o} + \sum_{s\in \boldsymbol{S}} \sum_{o\in \boldsymbol{O}} \sum_{n_o^s\in \boldsymbol{N}_o^s} Q_o^{s,n_o^s} \sum_{w'\in \boldsymbol{M}_o} c_{w',o} \sum_{w\in \boldsymbol{W}:\lambda_{w,w'}=1} x^{s,n_o^s}_{w,w',o} + \sum_{o\in \boldsymbol{O}} \sum_{w\in \boldsymbol{M}_o} cu_{w,o} \cdot z_{w,o}; \quad (1)$$

$$f_2^h = \sum_{s\in \boldsymbol{S}} e^{s,h} \sum_{o\in \boldsymbol{O}} \sum_{n_o^s\in \boldsymbol{N}_o^s} \sum_{(w,w')\in \boldsymbol{L}} d_{w,w'} \cdot x^{s,n_o^s}_{w,w',o} \quad (2)$$

with the constrains:

$$\sum_{w\in \boldsymbol{W}:\lambda_{w,w'}=1} \sum_{s\in \boldsymbol{S}} \sum_{n_o^s\in \boldsymbol{N}_o^s} x^{s,n_o^s}_{w,w',o} = 1, \quad \forall o \in \boldsymbol{O},\ \forall w' \in \boldsymbol{K}_o; \quad (3)$$

$$\sum_{w'\in \boldsymbol{W}\setminus \boldsymbol{M}_o:\lambda_{w,w'}=1} \sum_{n_o^s\in \boldsymbol{N}_o^s} x^{s,n_o^s}_{w,w',o} = y^s_{w,o}, \quad \forall o \in \boldsymbol{O},\ \forall w \in \boldsymbol{M}_o,\ \forall s \in \boldsymbol{S}; \quad (4)$$

$$\sum_{w\in \boldsymbol{W}:\lambda_{w,w'}=1} x^{s,n_o^s}_{w,w',o} = \sum_{w\in \boldsymbol{W}:\lambda_{w',w}=1} x^{s,n_o^s}_{w',w,o}, \quad \forall o \in \boldsymbol{O},\ \forall w' \in \boldsymbol{W},\ \forall s \in \boldsymbol{S},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (5)$$

$$Q_o^{s,n_o^s} = \sum_{w'\in \boldsymbol{K}_o} p_{w',o} \sum_{w\in \boldsymbol{W}:\lambda_{w,w'}=1} x^{s,n_o^s}_{w,w',o}, \quad \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{S},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (6)$$

$$Q_o^{s,n_o^s} \le q^s, \ \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{S},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (7)$$

$$\sum_{w\in \boldsymbol{M}_o} y^s_{w,o} \le N_o^s, \ \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{S}; \quad (8)$$

$$\sum_{s\in \boldsymbol{S}} \sum_{n_o^s\in \boldsymbol{N}_o^s} Q_o^{s,n_o^s} \sum_{w'\in \boldsymbol{W}\setminus \boldsymbol{M}_o:\lambda_{w',w}=1} x^{s,n_o^s}_{w',w,o} \le P_{w,o} \cdot z_{w,o}, \quad \forall o \in \boldsymbol{O},\ \forall w \in \boldsymbol{M}_o; \quad (9)$$

$$\sum_{w'\in \boldsymbol{K}_o} t_{w',o} \sum_{w\in \boldsymbol{W}:\lambda_{w,w'}=1} x^{s,n_o^s}_{w,w',o} + \sum_{(w,w')\in \boldsymbol{L}} tj^s_{w,w'} \cdot x^{s,n_o^s}_{w,w',o} \le TP, \quad \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{S},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (10)$$

$$\sum_{(w,w')\in \boldsymbol{L}} tj^s_{w,w'} \cdot x^{s,n_o^s}_{w,w',o} \le TJ, \quad \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{SC},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (11)$$

$$\sum_{s\in \boldsymbol{SC}} \sum_{n_o^s\in \boldsymbol{N}_o^s} \left(\frac{1}{540} \cdot \sum_{(w,w')\in \boldsymbol{L}} tj^s_{w,w'} \cdot x^{s,n_o^s}_{w,w',o} \right) \le 1.4 \cdot \sum_{s\in \boldsymbol{SC}} \sum_{w\in \boldsymbol{M}_o} y^s_{w,o}, \ \forall o \in \boldsymbol{O}; \quad (12)$$

$$ST_{w,o} - ST_{w',o} + |\boldsymbol{W}| \sum_{s\in \boldsymbol{S}} \sum_{n_o^s\in \boldsymbol{N}_o^s} x^{s,n_o^s}_{w,w',o} \le |\boldsymbol{W}| - 1, \quad \forall o \in \boldsymbol{O},\ \forall (w,w') \in \boldsymbol{L},\ ST_{w,o} \in \mathcal{R}^+; \quad (13)$$

$$x^{s,n_o^s}_{w,w',o} \in \{0, 1\},\ \forall (w,w') \in \boldsymbol{L}, \quad \forall o \in \boldsymbol{O},\ \forall s \in \boldsymbol{S},\ \forall n_o^s \in \boldsymbol{N}_o^s; \quad (14)$$

$$\forall o \in \boldsymbol{O},\ \forall w \in \boldsymbol{M}_o,\ \forall s \in \boldsymbol{S},\ y^s_{w,o} \in \mathcal{N}. \quad (15)$$

Constrains (3) and (5) ensure that each client served by particular logistics operator will be visited by only one vehicle and, after serving time, that vehicle will follow to the next point in transport network. Constrains (4) and (5) ensure that depots of particular operators dispatch the number of vehicles equal to the number of vehicles used in distribution. The aforesaid vehicles go back to the depots from which they have started. Constrain (6) allows determining workload on specific vehicles. Another, (7) constrain guarantees that loading capacity of vehicles is not exceeded. Loading capacity can be expressed by the number of loading units (e.g. palletized units) or units of weight. The constrain for number of disposed vehicles is described by formula (8). Condition (9) constrains using capacity of depots and at the same time constrain for using depots within planning period.

Another constrains result from drivers' work time regulations. They are formulated finding that distribution plan is set for a single workday. In this light, if time windows are disregarded, the regulations about rest periods, breaks from work and weekly working time are irrelevant. On the contrary the constrains of daily work time (10), daily driving time (11) – important for vehicles of GVM exceeding 3.5 tonnes, and optional constrain for daily work time but weekly administrated (12)[1], are included.

Constrain (13) eliminates inadmissible transportation cycles, while last two ((14) and (15)) are applied to the decision variables. Symbol $\mathcal{R}^+$ used in formulas marks the set of positive real numbers, symbol $\mathcal{N}$ – set of natural numbers with zero, and $ST_{w,o}$ is a fixed parameter of large value.

It is easy to see that resources of particular operators are not shared and not used for joint-services in a version of the problem formulated above. To identify potential benefits from central management of distribution processes in urban area, proposed problem was reformulated and modified by excluding existing allocation of resources and transport tasks to logistics operators. For that purpose, constrains (3), (8) and (12) are replaced by the following:

$$\sum_{w \in \boldsymbol{W}: \lambda_{w,w'}=1} \sum_{s \in \boldsymbol{S}} \sum_{o \in \boldsymbol{O}} \sum_{n_o^s \in \boldsymbol{N}_o^s} x_{w,w',o}^{s,n_o^s} = 1, \ \forall w' \in \bigcup_{o \in \boldsymbol{O}} \boldsymbol{K}_o; \quad (16)$$

$$\sum_{o \in \boldsymbol{O}} \sum_{w \in \boldsymbol{M}_o} y_{w,o}^s \le \sum_{o \in \boldsymbol{O}} N_o^s, \ \forall s \in \boldsymbol{S}; \quad (17)$$

$$\sum_{s \in \boldsymbol{SC}} \sum_{o \in \boldsymbol{O}} \sum_{n_o^s \in \boldsymbol{N}_o^s} \left(\frac{1}{540} \cdot \sum_{(w,w') \in \boldsymbol{L}} tj_{w,w'}^s \cdot x_{w,w',o}^{s,n_o^s} \right) \le$$
$$1.4 \cdot \sum_{s \in \boldsymbol{SC}} \sum_{o \in \boldsymbol{O}} \sum_{w \in \boldsymbol{M}_o} y_{w,o}^s. \quad (18)$$

Under presented constrains, economic and social benefits from central management of goods distribution in cities can be identified through solving presented optimization task before and after modification. The economic or emission benefits resulting from the difference between both solutions must be corrected by deducting costs of central management.

Proposed optimization task of transport services in urban area is a further development of VRP, for which first solving algorithm was presented in 1932 – more than 50 years' after it was firstly drawn. Research on a new, more effective algorithms, are still continued (Wasiak 2011).

To solve formulated task a dedicated metaheuristic algorithm was developed and implemented in computer application. Algorithm bases on SPEA2 method (Zitzler *et al.* 2001).

4. Case Study

Research on reorganization of distribution of goods in urban areas originates from the need to reduce transport work-load in highly urbanized areas and thus to improve quality of transport services in cities and reduce negative impact of transport on environment. Integration through cooperation between logistics operators is considered as effective way of serving recipients. To prove the quality of presented approach the cost-benefit analyses were carried out for integration of three logistics operators serving Warsaw (Poland). The map with markings representing receiving points and depots is shown in Fig. 1.

Distribution plan was developed in three variants:

- ***variant 1:*** 3 logistics operators, each operator performs individually own transport tasks, three depots are used (Operator 1 – HUB1, Operator 2 – HUB2, Operator 3 – HUB3);
- ***variant 2:*** central planning engages three operators, but all transport tasks and depots (HUB1, HUB2, HUB3) are considered as common;
- ***variant 3:*** new depot – city consolidation hub is introduced (HUB4) while not economically feasible depots (HUB2 and HUB3) are eliminated. For the purposes of this analysis, the methodology developed in SIMMAG 3D project was applied to localize new facility and organize supply chain by SIMMAG 3D software. Used methods are described in (Izdebski *et al.* 2016; Jacyna-Gołda *et al.* 2016) and other studies. Furthermore, visualization and simulation tool developed in the framework of SIMMAG 3D was used to prepare technological concept of HUB3 facility.

For a real network of roads, the following assumptions are given:

- distances between nodes correspond to the actual distances in the city;
- basic loading unit for all clients is a palletized unit;
- operators can use three types of vehicles carrying 7, 12 or 18 palletized units, all vehicles meet the EURO 5 standard;
- demand and localization of recipients is the same in all three variants of organization;
- planning period covers one day;
- total daily demand requested by recipients is 351 palletized units;
- routes are generated upon metaheuristic algorithm SPEA2 under multicriteria optimization, where first criteria function describes costs, while the second function describes emission of carbon monoxide (CO);
- 100 recipients are served in total by three operators (each operator serves 30 recipients exclusively, whilst 10 recipients is common to all operators;
- estimation of pollutant emission (CO) is based on COPERT 4 (Tier 3) model, including cold start.

Calculations undertaken for implemented multicriteria method, have led to setting distribution plans for each variant. Gained results are gathered in Table. In addition, Figs 2–4 show city maps with indicative routes travelled in variants 1–3. Green colour marks routes served by 7-pallet vehicles, red colour marks routes served by 12-pallet vehicles and blue is for 18-pallet vehicles.

[1] Daily driving time can be extended to more than 9 hours (540 minutes) only 2 times a week; hence, assuming 5 working days in a week, averagely working time can be exceeded maximally on 40% of daily routes (this condition is relevant only when all drivers work for full 5 days, that is for basic system of work time).

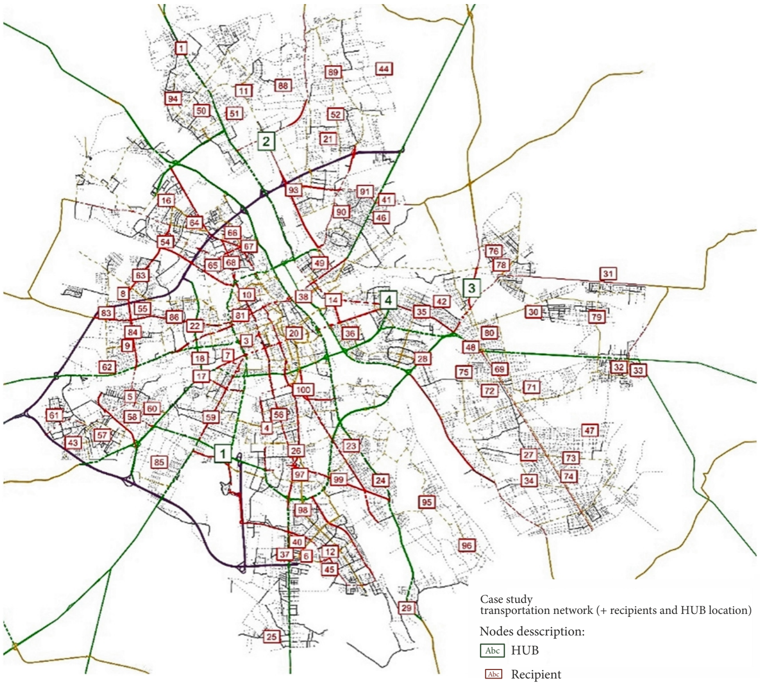

Fig. 1. Transport network, localization of depots and recipients

Table. Calculation results sheet for organizational variants

	Variant 1				Variant 2				Variant 3		
	HUB1	HUB2	HUB3	Sum	HUB1	HUB2	HUB3	Sum	HUB1	HUB4	Sum
Costs of distribution [EUR]	3239.72	3119.78	2395.87	8755.38	2881.15	2479.00	2682.49	8042.64	3431.71	3008.23	6439.95
CO emission [g]	247.78	274.64	237.37	759.78	240.88	206.79	237.19	684.86	314.94	255.79	570.73
Total travelling time [h]	18.94	16.81	17.18	52.92	16.60	14.51	16.91	48.03	22.33	20.12	42.45
Number of routes	10	8	9	27	12	10	8	30	16	14	30
Routes length [km]	706.90	623.96	579.36	1910.22	603.76	554.00	603.90	1761.65	808.78	711.78	1520.56
Volumes supplied [palletized units]	128	110	113	351	134	119	98	351	195	156	351

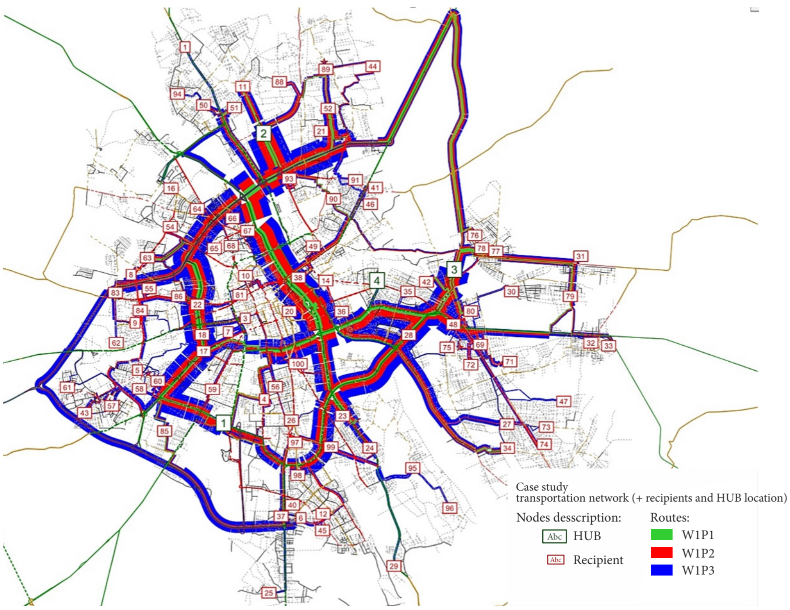

Fig. 2. Routes in variant 1

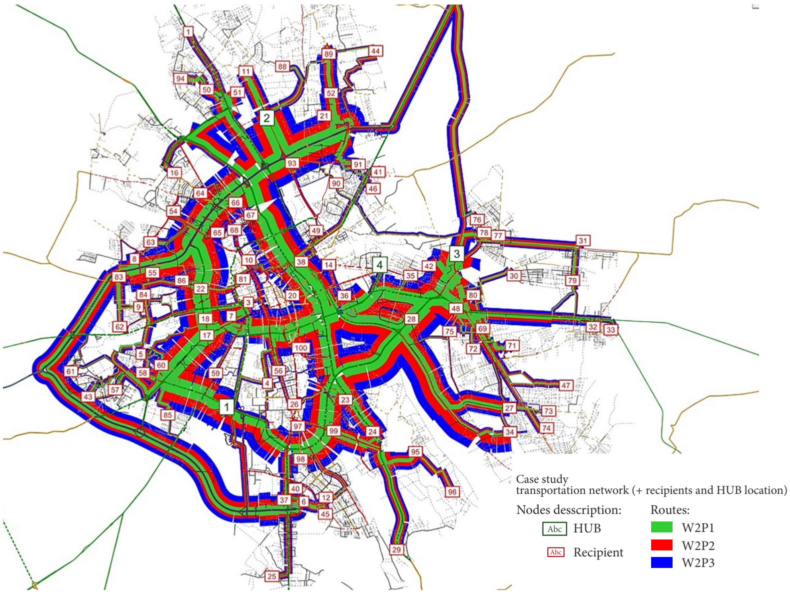

Fig. 3. Routes in variant 2

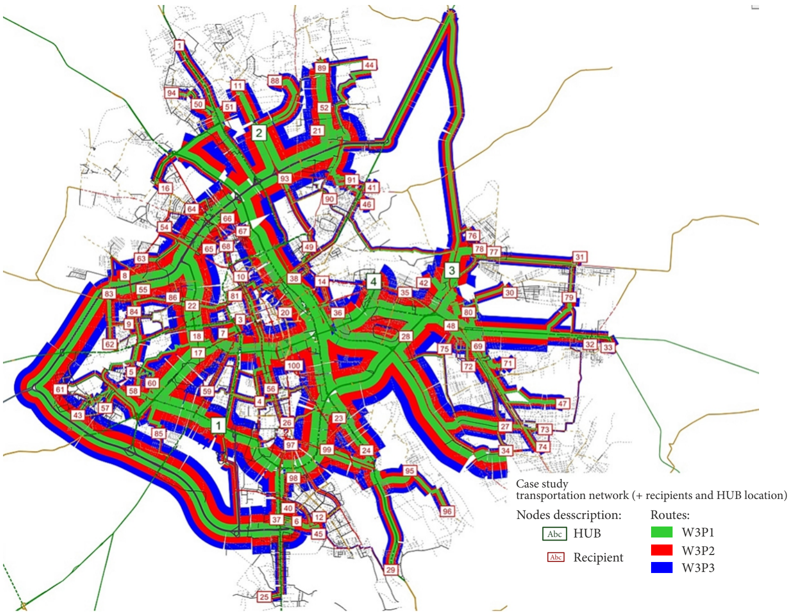

Fig. 4. Routes in variant 3

The example does not provide detailed data and calculations because of their immensity. The purpose of the example was to point the differences and overall advantages to be gained from new organization of goods distribution in the city. The most favourable is variant 3 in which organization through central management was supported by new investment in logistics facility and eliminating two existing, but inefficient ones. Just implementing the central planning brings significant savings and efficiency growth for 8% in relation to 1 variant. It is also non-invasion and does not require any additional investment expenditures but allows logistics operators to decrease number of engaged vehicles and reduce transport costs. It should be therefore made clear that this form of distribution in urban areas is difficult to implement because of other factors (e.g. necessary cooperation between different entities that compete in normal conditions).

Conclusions

In the face of growing communication problems in many cities, searching for new solutions organizing transport processes is necessary. While passenger traffic is improved by increasing the share of public transport (especially railway) in total traffic and limiting car traffic, the freight transport has no other alternative than road transport. Except for the low-emission technologies, the most promising methods of reducing negative impact of heavy traffic in cities are proposed in this paper organizational methods.

Sharing logistics resources and joint services for clients by many logistics operators introduces economy of scale and synergy effects. Central management of goods distribution in the city combined with city consolidation hubs allows for connecting supplies from many origins destined for a single recipient. Therefore, the vehicles capacity utilization grows while total distance travelled, including empty mileage, is reduced. It is clear that these changes cause less pollutant emission and noise, as well as congestion.

Proved social advantages are not sufficient grounds for business entities to persuade the centralized management, whilst potential economic benefits from implementing proposed solutions are not recognized. Proposed method allows for identification of both – social and economic benefits, which are possible to get through central management of distribution in the city. The method compares optimal, for given conditions, distribution realized by independent logistics operators and distribution planned centrally. What is important, additional administrative constrains, like limited access or access fees, can be taken into account in that method for comparison purposes. Therefore, such a method allows not only for estimation of economic benefits from central management of distribution in the city in present state, but also allows for identification of additional administrative and financial solutions, which ensure sufficient level of benefit for logistics operators after implementing central management of distribution.

Because of diversity of city transport systems and their traffic-loads it is difficult to point universal estimation of economic and social advantages. Especially as the solutions for goods distribution and scale of those processes are different in particular areas. However, significant benefits are expected and are essential for rational satisfying of transport needs within passenger transport (due to expected traffic on the roads). According to analyses provided in the paper, integration of three medium-size logistics companies disposing own warehouses (depots) and serving known clients in the area of Warsaw produces economic benefits of 8.1% and reduces emission of carbon monoxide (CO) for about 7.8%. Additionally, reengineering of logistics system of these companies will bring another 19.9% reduction of costs and 16.7% reduction of harmful emission. These are therefore significant advantages, which must be considered sufficient without introducing any additional financial and administrative incentives.

Summing up, presented approach is a tool supporting the development of eco-friendly solutions for the distribution of goods in cities. This tool can be used both by local and national authorities as well as by research and development units involved in solving problems in the field of urban logistics.

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