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Optimisation Of Road Transport Performed By Empty Vehicles: A Case Study From Poland - Part 2

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Abstract

Road transport performed by empty runs both in the EU and in Poland constitute a significant percentage of unprofitable transport, and they arise as a result of the lack of balance between demand and supply observed on the market of transport services. This publication consists of two parts, in the first one the phenomenon of road transport performed by empty runs has been outlined, the assumptions and methodology of the procedure are defined, while in the second practical part the mentioned methodology has been illustrated with a numerical example. Empty runs are not only a financial loss for the company, but also have ecological significance. In practice, this problem cannot be eliminated, it is and will always be a problem for people involved in planning transport routes. In this work, the authors took up a single-criteria optimization problem, for which a commonly available MS Excel spreadsheet with the Solver was used.

Keywords: road transport, empty runs, optimisation, transportation network

1. Introduction

Optimisation of transport tasks leads to an increase in the efficiency of transport companies' operations. In practice, the efficiency of a road transport company has various dimensions, which can be related to a number of operational aspects. Their set may include the issues related to the management of empty containers in conditions of risk and uncertainty (Nikfarjam and Moosavi, 2020; Stawowy et al., 2023), forecasting the traffic flow distribution within the transport network (Ziółkowski et al., 2019), and optimisation of the life cycle (Zhu et al., 2023), delivery time for perishable products (Małachowski et al., 2020), vehicle speeds (Mandal et al., 2020), fuel reduction (Rosero et al., 2021; Ziółkowski et al., 2022), costs of road transport companies (Sendek-Matysiak et al., 2022; Ziółkowski and Borucka, 2016) or carbon dioxide emissions (Liu et al., 2023). One of the main aspects of sustainable mobility (Torbacki, 2021) is to fully utilise the load capacity of transport vehicles and minimise the empty runs (Ziółkowski and Lęgas, 2018). The problem of minimising the empty runs is related to the development of an optimal transport plan within a given network. The word optimal transport means the transport for which the number of vehicle-kilometres of empty trucks will be minimal. Additionally, the constraints on the use of supply and demand of empty means of transport within the network under consideration must be met.

According to Eurostat data (Road freight transport by journey characteristics - Statistics Explained (europa.eu, 2023)) in 2022, on average, over 20% of transport operations in the European Union were empty runs. In practice, empty runs are difficult to eliminate, and in some types and directions of transport their percentage may be significant. Moreover, they often depend on the specific requirements of the client and the specific requirements of a given order or contract.

Fig. 1 presents statistical data on empty runs in selected European Union countries (Road freight transport by journey characteristics - Statistics Explained (europa.eu, 2023)).

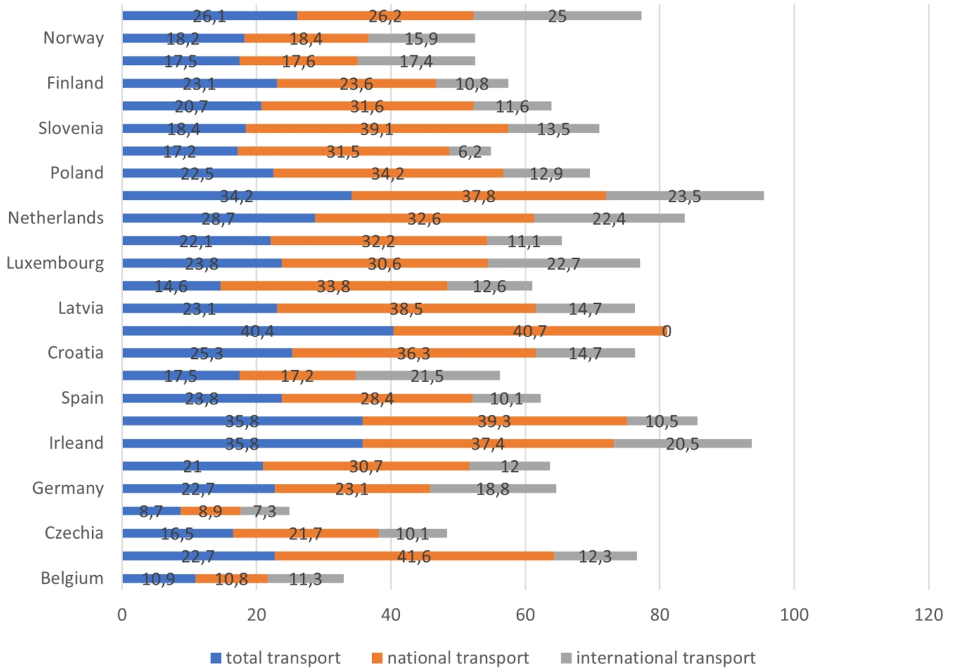

Fig. 1. Road transport performed by empty vehicles by type of operation, 2022 [% share in vehicle-km].

Polish carriers cope quite well with empty runs, especially those operating internationally. Taking into account all transport operations in 2022, the empty runs amounted to 22.5% of vehicle-kilometres (Fig. 1). There is a constant disproportion between domestic and international transport in this respect.

The domestic direction is definitely less effective with empty run rate of 34.2%. International carriers reduced this problem more effectively by searching for additional loads on freight exchanges, which resulted in the empty run rate at the level of 12.9%. Polish companies also have much better results in international transport than their competitors from other countries. For example, German companies' rate of empty runs in vehicle-kilometres amounted to 18.8%, French companies to 21%, and Dutch companies to 22.4%. Of the larger EU member states, only Spain achieved 10.1%, which is a better rate than the Polish 12.9% (Fig. 1).

2. Methodology - assumptions regarding the transport network

The present study analyses a problem related to a courier company that has branches in eight Polish cities. They act as a transport base and a consolidation centre (combining several smaller shipments from different deliveries, going in the same direction, to the same recipient) and deconsolidation of shipments (dividing the delivery into smaller batches) brought to these points by couriers from the covered area and also delivered from these points to recipients located within the covered area. The company noticed that some of the long-distance transport operations between its branches there are empty runs, which understandably negatively affects the company's financial results. Due to the high level of customer service maintained by the company, it cannot introduce higher prices for the services offered as such action would reduce its competitiveness. In turn, extending the delivery time of parcels in order to make better use of trucks would reduce the customer service quality level. The analysed company has branches in the following eight Polish cities: Warsaw, Krakow, Wroclaw, Poznan, Szczecin, Bydgoszcz, Bialystok, Zielona Gora (Figure 2). The graph symbolizing the structure of the network reflecting all possible variants of transport is shown in Figure 3.

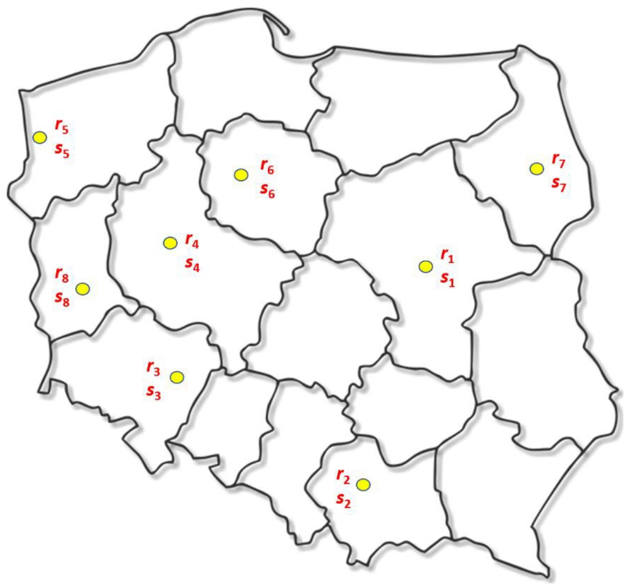

Fig. 2. Locations of suppliers and recipients (*r* – recipient, *s* – supplier).

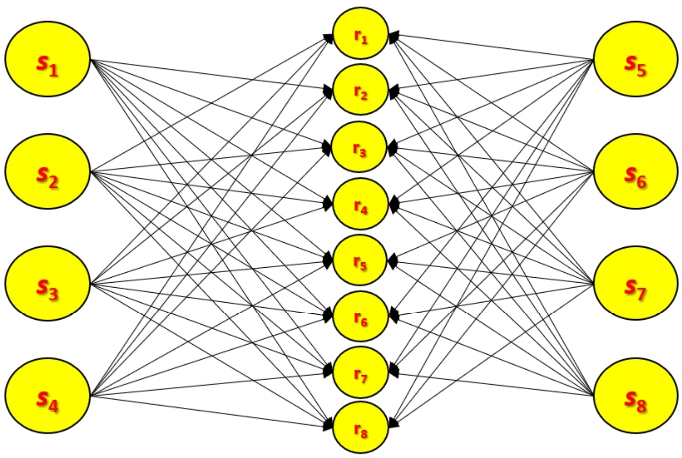

Fig. 3. Network structure of the transportation problem ($s_i \neq r_i$).

Table 1 shows the distance between nodes of the distribution network.

Table 1. Distance between nodes of the distribution network [km].

ij	Warsaw	Krakow	Wroclaw	Poznan	Szczecin	Bydgoszcz	Bialystok	Zielona Gora
Warsaw	0	310	362	313	571	306	208	460
Krakow		0	291	457	652	485	600	444
Wroclaw			0	169	362	279	556	153
Poznan				0	266	142	512	155
Szczecin					0	259	770	218
Bydgoszcz						0	505	288
Bialystok							0	658
Zielona Gora								0

Table 2 presents the monthly demand for transport between branches, expressed in the number of full means of transport, and the balance of the value of inbound and outbound transport for each branch.

Table 2. Shipments and inbound and outbound transport values for each branch [trucks].

ij	Warsaw	Krakow	Wroclaw	Poznan	Szczecin	Bydgoszcz	Bialystok	Zielona Gora	outbound transport e_i
Warsaw	0	23	7	5	17	25	15	18	110
Krakow	6	0	8	18	11	10	23	21	97
Wroclaw	11	13	0	15	6	7	12	20	84
Poznan	12	9	17	0	16	19	9	17	99
Szczecin	16	19	12	14	0	9	22	21	113
Bydgoszcz	22	12	29	14	18	0	14	19	128
Bialystok	10	5	11	16	15	18	0	12	87
Zielona Gora	18	21	10	13	12	19	14	0	107
inbound transport i_i	95	102	94	95	95	107	109	128	

As shown in the data presented in Table 2, the demand for transport on individual routes varies significantly. This is due both to the size of a given centre and the region covered by a given branch, as well as the level of economic development of network nodes located in various locations in the country. This, in turn, translates into the number of supported business entities constituting the basic group of customers and their activity, as well as the number of households supported (increase in demand for courier services resulting from the increase in e-commerce transactions). Therefore, the amount of the inbound and outbound transport operations executed by a given branch (node) of the analysed network may also vary.

3. A Case Study from Poland

Table 3 presents the calculations of supply and demand values for empty means of transport in each branch.

Table 3. Balance of demand and supply for empty means of transport for each branch [trucks].

i	Warsaw	Krakow	Wroclaw	Poznan	Szczecin	Bydgoszcz	Bialystok	Zielona Gora
i_i	95	102	94	95	95	107	109	128
e_i	110	97	84	99	113	128	87	107
$i_i - e_i$	-15	5	10	-4	-18	-21	22	21

According to the data presented in Table 3, four branches (marked in yellow) that have a positive balance are suppliers of empty means of transport, i.e.:

- Krakow with a surplus of 5 trucks;
- Wroclaw with a surplus of 10 trucks;

- Bialystok with a surplus of 22 trucks;
- Zielona Gora with a surplus of 21 trucks;

while four branches (marked in green) are recipients of empty means of transport, i.e.:

- Warsaw with a shortage of 15 trucks;
- Poznan with a shortage of 4 trucks;
- Szczecin with a shortage of 18 trucks;
- Bydgoszcz with a shortage of 21 trucks.

In the analysed case, the optimisation problem has a size of 4 x 4, hence the next two tables will not be completely populated with data. Table 4a summarises the distances between suppliers and recipients of empty vehicles and Table 4b the obtained demand and supply values for the empty means of transport. Formulas for the left sides of limiting conditions have also been defined. The empty runs providers are marked with a letter a along with an appropriate index, while the empty runs recipients with a letter b (also with an appropriate index). In the cells indicating the number of empty runs (decision variables) in a given relation (see: the "Transport" column - Table 4a) and the left sides of the limiting conditions (see: the "Limiting conditions" - Table 4b) before starting the *Solver* add-on "0" value should be entered.

Table 4a. Transport data summary – distances between suppliers and recipients of empty vehicles.

Supplier	Recipient	Distance [km]	Transport [trucks]
Krakow	Warsaw	310	0
Krakow	Poznan	457	0
Krakow	Szczecin	652	0
Krakow	Bydgoszcz	485	0
Wroclaw	Warsaw	362	0
Wroclaw	Poznan	169	0
Wroclaw	Szczecin	362	0
Wroclaw	Bydgoszcz	279	0
Bialystok	Warsaw	208	0
Bialystok	Poznan	512	0
Bialystok	Szczecin	770	0
Bialystok	Bydgoszcz	505	0
Zielona Gora	Warsaw	460	0
Zielona Gora	Poznan	155	0
Zielona Gora	Szczecin	218	0
Zielona Gora	Bydgoszcz	288	0
		Total mileage of empty means of transport	0

Table 4b. Transport data summary – demand and supply values for the empty means of transport [trucks].

Transport point	Limiting conditions	Supply	Demand
Krakow	0	5	
Wroclaw	0	10	
Bialystok	0	22	
Zielona Gora	0	21	
Warsaw	0		15
Poznan	0		4
Szczecin	0		18
Bydgoszcz	0		21

The decision variables (Table 4a – the "Transport" column) were defined as the number of runs performed by empty vehicles between the branches with a surplus of empty trucks and the branches with a shortage of empty trucks. Their detailed interpretation is as follows:

- x_{21} – means the number of runs performed by empty vehicles from Krakow to Warsaw;
- x_{24} – means the number of runs performed by empty vehicles from Krakow to Poznan;
- x_{25} – means the number of runs performed by empty vehicles from Krakow to Szczecin;

- x_{26} – means the number of runs performed by empty vehicles from Krakow to Bydgoszcz;
- x_{31} – means the number of runs performed by empty vehicles from Wroclaw to Warsaw;
- x_{34} – means the number of runs performed by empty vehicles from Wroclaw to Poznan;
- x_{35} – means the number of runs performed by empty vehicles from Wroclaw to Szczecin;
- x_{36} – means the number of runs performed by empty vehicles from Wroclaw to Bydgoszcz;
- x_{71} – means the number of runs performed by empty vehicles from Bialystok to Warsaw;
- x_{74} – means the number of runs performed by empty vehicles from Bialystok to Poznan;
- x_{75} – means the number of runs performed by empty vehicles from Bialystok to Szczecin;
- x_{76} – means the number of runs performed by empty vehicles from Bialystok to Bydgoszcz;
- x_{81} – means the number of runs performed by empty vehicles from Zielona Gora to Warsaw;
- x_{84} – means the number of runs performed by empty vehicles from Zielona Gora to Poznan;
- x_{85} – means the number of runs performed by empty vehicles from Zielona Gora to Szczecin;
- x_{86} – means the number of runs performed by empty vehicles from Zielona Gora to Bydgoszcz.

The objective function is aimed at minimisation and takes the following form:

$$f(x_{21}, x_{24}, x_{25}, x_{26}, x_{31}, x_{34}, x_{35}, x_{36}, x_{71}, x_{74}, x_{75}, x_{76}, x_{81}, x_{84}, x_{85}, x_{86}) = \\ = 310x_{21} + 457x_{24} + 652x_{25} + 485x_{26} + 362x_{31} + 169x_{34} + 362x_{35} + 279x_{36} + 208x_{71} + 512x_{74} + 770x_{75} + 505x_{76} + 460x_{81} + 155x_{84} + 218x_{85} + 288x_{86} \rightarrow \min. \quad (10)$$

In addition, limiting conditions had to be specified:

a) for suppliers:

- Krakow: $x_{21} + x_{24} + x_{25} + x_{26} = 5;$ (11)
- Wroclaw: $x_{31} + x_{34} + x_{35} + x_{36} = 10;$ (12)
- Bialystok: $x_{71} + x_{74} + x_{75} + x_{76} = 22;$ (13)
- Zielona Gora: $x_{81} + x_{84} + x_{85} + x_{86} = 21;$ (14)

b) for recipients:

- Warsaw: $x_{21} + x_{31} + x_{71} + x_{81} = 29;$ (15)
- Poznan: $x_{24} + x_{34} + x_{74} + x_{84} = 37;$ (16)
- Szczecin: $x_{25} + x_{35} + x_{75} + x_{85} = 37;$ (17)
- Bydgoszcz: $x_{26} + x_{36} + x_{76} + x_{86} = 37;$ (18)

and an additional condition of non-negativity of the decision variables, formulated as:

$$x_{21}, x_{24}, x_{25}, x_{26}, x_{31}, x_{34}, x_{35}, x_{36}, x_{71}, x_{74}, x_{75}, x_{76}, x_{81}, x_{84}, x_{85}, x_{86} \geq 0. \quad (19)$$

The *Solver* add-on was used to find the solution. After starting the program, in the dialogue box, enter the address of the objective function and the addresses of the decision variables, limiting conditions and the type of optimisation. Using the "Options" button, open an additional dialogue box in which you must select the type of linear model and the non-negativity of the decision variables. Then, in the dialogue box, select the "Solve" command.

As a result, the dotted fields in the "Calculations" sheet are also filled. From Table 5a you can read the optimal solution, which is the value of the objective function. Finally, the transport tables take the form shown in Tables 5a-5b.

Table 5a. Transport table with the optimal solution after running the *Solver* add-on – minimisation.

Supplier	Recipient	Distance [km]	Transport [trucks]
Krakow	Warsaw	310	0
Krakow	Poznan	457	0
Krakow	Szczecin	652	0
Krakow	Bydgoszcz	485	5
Wroclaw	Warsaw	362	0
Wroclaw	Poznan	169	1
Wroclaw	Szczecin	362	0
Wroclaw	Bydgoszcz	279	9
Bialystok	Warsaw	208	15
Bialystok	Poznan	512	0
Bialystok	Szczecin	770	0
Bialystok	Bydgoszcz	505	7
Zielona Gora	Warsaw	460	0
Zielona Gora	Poznan	155	3
Zielona Gora	Szczecin	218	18
Zielona Gora	Bydgoszcz	288	0
		Total mileage of empty means of transport	16149 [km]

Table 5b. Transport table after running the *Solver* add-on – minimization [trucks].

Transport point	Limiting conditions	Supply	Demand
Krakow	5	5	
Wroclaw	10	10	
Bialystok	22	22	
Zielona Gora	21	21	
Warsaw	15		15
Poznan	4		4
Szczecin	18		18
Bydgoszcz	21		21

Later in this study, the direction of optimisation was changed. Maximising empty runs in transport involves determining the optimal travel plan for empty means of transport (from suppliers to recipients) in the transport network, but also the maximum number of “empty” vehicle-kilometres. In this case, the mathematical notation takes the following form:

$$\sum_{n=1}^{n}\sum_{j=1}^{n} d_{ij}x_{ij} \quad \rightarrow \max. \qquad (20)$$

and the objective function in full form was written as:

$$f(x_{21}, x_{24}, x_{25}, x_{26}, x_{31}, x_{34}, x_{35}, x_{36}, x_{71}, x_{74}, x_{75}, x_{76}, x_{81}, x_{84}, x_{85}, x_{86}) =$$
$$= 310x_{21} + 457x_{24} + 652x_{25} + 485x_{26} + 362x_{31} + 169x_{34} + 362x_{35} + 279x_{36} + 208x_{71} + 512x_{74} + 770x_{75} + 505x_{76}$$
$$+ 460x_{81} + 155x_{84} + 218x_{85} + 288x_{86} \rightarrow \max. \qquad (21)$$

To maximise the empty runs in transport, in the *Solver* dialogue box change the direction of optimisation.

As a result of the calculations, the optimal solution determining the value of the objective function was obtained. The value of the objective function for maximising empty runs in transport is presented in Tables 6a-6b.

Table 6a. Transport table with the optimal solution after running the *Solver* add-on – maximisation.

Supplier	Recipient	Distance [km]	Transport [trucks]
Krakow	Warsaw	310	0
Krakow	Poznan	457	0
Krakow	Szczecin	652	0
Krakow	Bydgoszcz	485	5
Wroclaw	Warsaw	362	0
Wroclaw	Poznan	169	0
Wroclaw	Szczecin	362	0
Wroclaw	Bydgoszcz	279	10
Bialystok	Warsaw	208	0
Bialystok	Poznan	512	4
Bialystok	Szczecin	770	18
Bialystok	Bydgoszcz	505	0
Zielona Gora	Warsaw	460	15
Zielona Gora	Poznan	155	0
Zielona Gora	Szczecin	218	0
Zielona Gora	Bydgoszcz	288	6
		Total mileage of empty means of transport	29751 [km]

Table 6b. Transport table after running the *Solver* add-on – maximization [trucks].

Transport point	Limiting conditions	Supply	Demand
Krakow	5	5	
Wroclaw	10	10	
Bialystok	22	22	
Zielona Gora	21	21	
Warsaw	15		15
Poznan	4		4
Szczecin	18		18
Bydgoszcz	21		21

4. Summary

1. In the problem considered, the optimal monthly plan includes:
   - 5 runs performed by empty vehicles from Krakow to Bydgoszcz;
   - 1 run performed by empty vehicles from Wroclaw to Poznan;
   - 9 runs performed by empty vehicles from Wroclaw to Bydgoszcz;
   - 15 runs performed by empty vehicles from Bialystok to Warsaw;
   - 7 runs performed by empty vehicles from Bialystok to Bydgoszcz;
   - 3 runs performed by empty vehicles from Zielona Gora to Poznan;
   - 18 runs performed by empty vehicles from Zielona Gora to Szczecin.

   The above plan guarantees a minimum number of empty runs of 16149 [VKM].
2. If the objective function is focused on maximisation, the optimal plan is as follows:
   - 5 runs performed by empty vehicles from Krakow to Bydgoszcz;
   - 10 runs performed by empty vehicles from Wroclaw to Bydgoszcz;
   - 4 runs performed by empty vehicles from Bialystok to Poznan;
   - 18 runs performed by empty vehicles from Bialystok to Szczecin;
   - 15 runs performed by empty vehicles from Zielona Gora to Warsaw;
   - 6 runs performed by empty vehicles from Zielona Gora to Bydgoszcz.

   The above plan guarantees a maximum number of empty runs of 29751 [VKM].
3. To summarise the above, the optimal plan ensures the minimum number of empty runs of 16149 [VKM]. Changing the direction of optimisation from min. to max., the objective function amounted to 29751 [VKM].

Minimising empty runs in transport is aimed at reducing fuel expenses (economic effect); the max.-min. difference was 13602 [VKM].
4. An additional, purely environmental argument, is the reduction of CO_2 emissions (ecological effect). Assuming any type of means of transport, the burden on the natural environment can be easily calculated.

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