Advanced Logistic Systems – Theory and Practice, Vol. 17, No. 4 (2023), pp. 64-70.
https://doi.org/10.32971/als.2023.032

VACCINE DISTRIBUTION NETWORK OPPORTUNITIES ON A NATIONAL SCALE

KITTI SEPRÉNYI[1] - PÉTER VERES[2] - ÁKOS CSERVENÁK[3]

Abstract: *Building an effective distribution network is a significant advantage for any company. This is especially true for easily damaged or perishable items, where the length and speed of the transport, as well as the loading time, play a major role in maintaining quality. In this article, we examined the transport/distribution options for the creation of a vaccine distribution network in Hungary, which can meet strict rules. We took into account the driver's working hours, the maximum delivery time of the vaccine, the storage options of the county seats, and as a result we got the most efficient distribution plan of Hungary. To solve the problem, we use conventional-, greedy-, and heuristic algorithms, which were compiled by Excel and its SOLVER extension. This research was born from a TDK research and a continuation of a publication.*

Keywords: *multi route planning, cold-chain, Solver, vehicle routing problem*

1. Introduction of vaccines and the bases of Travelling Salesman Problems

Vaccines are the best tools to prevent viral outbreaks according to the current state of science [1]. The development of vaccines to protect against the global pandemic of Covid-19 was the fastest in the history of medicine. However, the distribution of these vaccines was initially a serious challenge for humanity, as many aspects had to be taken into account during storage, packaging and transportation. The entire pandemic raised many new logistical problems, of which distribution with route planning played a particularly significant role. The Vehicle Routing Problem (VRP) is one of the most common optimization problems in logistics. Since they are perishable products, in addition to the working hours of the person carrying out the road transport activity, the various packaging, storage and transport needs of the vaccines must also be taken into account, so the establishment of a distribution network is a rather complex task, even in the case of a small country. In this article we will also present the packaging, storage and transport properties of vaccines, since each vaccine has different needs depending on the type of vaccine. In order to be able to carry out the vaccination on time, planning a distribution network is a very important process. Within the framework of this publication, we will deal with the distribution of vaccines among county seats with the aid of multiple algorithms and Excel. Our goal is to create a distribution network within which vaccines can be delivered cost-effectively and quickly from the national distribution centre to the regional distribution centres.

[1] BSc student, University of Miskolc, Institute of Logistics, Hungary
seprenyi.kitti@gmail.com
[2] Senior lecturer, University of Miskolc, Institute of Logistics, Hungary
peter.veres@uni-miskolc.hu
[3] Senior lecturer, University of Miskolc, Institute of Logistics, Hungary
akos.cservenak@uni-miskolc.hu

1.1. Cold chains and COVID-19 vaccines

Having examined the cold chain from several perspectives, we would like to summarize what we know about vaccine packaging, storage, transport and distribution. Primary packaging materials include glass vials and syringes, as well as stoppers and seals. Secondary and tertiary packaging is very important for distribution. Secondary packaging helps to reduce volume, save costs, minimize logistical burdens and reduce carbon footprint. Tertiary packaging plays an important role in transportation, as it serves to protect both the product and the packaging underneath when it is transported from one destination to another [2]. Each manufacturer has its own concept, system and regulations for how long and how it can be stored. Comirnaty, the Pfizer-BioNTech vaccine, was one of the most popular and the most attention-grabbing vaccines, so we use this as a basis for flight planning. In a special refrigerator with dry ice on top, the vaccine can last up to 12 hours without deterioration below -60^{o}C. After this time, since most transport vehicles are not special refrigerated vans that cannot maintain temperatures between -60 and -90^{o}C, the integrity of the vaccines cannot be guaranteed. Regarding storage, we have prepared a summary table (Table I).

Table I.

Packaging, storage and delivery of Covid-19 vaccines [2]

Condition of vaccine	Storage and transport temperature	Recommended storage duration
Diluent	Store at room temperature. During the vaccination, store at+2°C to +8°C	Until expiration date
Diluted vaccine	+2°C to +8°C	6 hours after first puncture
Unopened thawed vial	+2°C to +8°C (can't be refreeze)	1 month
Unopened frozen vial	-90°C to -60°C	9 months after time of manufacturing or until expiry date
	-25°C to -15°C	Up to 2 weeks for a single period within the vaccine's 9 months

As it can be seen in Table I. the setup and operation of some cold chains depends on what we ship. After all, each cargo unit to be transported has different requirements in terms of stress, cargo and the integrity of the transport.

1.2. The traveling salesman problem

When planning a vaccine distribution network, many aspects must be taken into account in order to ensure that the vaccine is not damaged and that it can be used effectively. In this subchapter, we would like to summarize in general what we know about route planning, what aspects must be taken into account, and what steps we must go through.

Route planning is generally the process of planning schedules and routes for means of transportation such as vehicles, airplanes, trains, ships. Route planning takes into account traffic needs, capacity, weather and other factors, such as:

- Route planning: Planning the route of the transport vehicle in order to arrive at the destination at the right time and in the right place.
- Timetable: Planning the timetables that determine the departure and arrival of vehicles at each station and/or stop.
- Capacity: Planning the capacity of the routes in order to transport the necessary passengers/cargo comfortably and safely.
- Available resources: Route planning must take into account the available vehicles and personnel and the fueling, maintenance and other necessary resources of the vehicles.

In the case of vaccines, in addition to the aspects mentioned above, I had to pay special attention to whether the different types of vaccines have any special transport requirements, for example in what form they can be transported, in what storage device, how long they can be kept under non-ULT (ultra-low temperature) conditions.

The traveling salesman problem (TSP), which is the basic problem of route planning, tries to find the answer to one question: "Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once, and return to the starting city?" [3]. This is an NP-hard problem in combinatorial optimization, but it is also important in operations research and theoretical informatics. This problem was first formulated in 1930 and has been one of the most intensively studied problems of optimization ever since. Many heuristic and exact algorithms are known to solve this problem, so some instances containing tens of thousands of cities can be completely solved, and even problems containing millions of cities can be approached within a fraction of 1% [4].

In the meantime, countless algorithms have been developed to solve vehicle scheduling tasks, most of which use heuristics. The Vehicle Routing Problem (VRP) deals with finding the optimal route for multiple vehicles, each of which starts from a warehouse, visits a set of customers and returns to the warehouse, with all the customers visited by the vehicles, subject to various constraints such as vehicle capacity and time window constraints [5].

2. BASIC DATA AND INITIAL STEPS FOR THE DISTRIBUTION PROBLEM

This research was born from a continuous TDK research and partly contains elements of a previous publication from a year ago with the name *“Developing a vaccine distribution network between county towns”* [6]. For our route planning, we first established that the main centre where the vaccines arrive. This will be in our capital, Budapest, while the other 18 county seats are the regional distribution centres. Truck and lorry drivers can drive for 9 hours every day in two instalments according to European Union and Hungarian rules and can be increased to 10 hours twice a week. Among the storage options, we would use passive crates, as they do not require a special vehicle, they only need to be refilled with dry ice. Vaccines can be delivered frozen for up to 120 hours, and thawed for up to 12 hours. The loading time between +15 and +25°C can be a maximum of 1 minute, the vaccines must be immediately placed in the ULT freezer. Based on these, we took the loading time as 1 minute in the task as well. The distances between the county seats were obtained by querying an online dataset, which stores the data based on cartographic data (Table II). From these distances, we calculate the time travelled at an average speed of 70 km/h. This is the accepted speed in practice. Taking all aspects into account, flight planning was carried out in Excel using the SOLVER add-on with sometimes surprising results.

Table II.

Distance matrix between county seats (km) [6]

Distance between settlements by road (km)	Budapest	Békéscsaba	Debrecen	Eger	Győr	Kaposvár	Kecskemét	Miskolc	Nyíregyháza	Pécs	Salgótarján	Szeged	Székesfehérvár	Szekszárd	Szolnok	Szombathely	Tatabánya	Veszprém	Zalaegerszeg
Budapest		216	231	158	126	189	81	177	234	205	109	165	67	153	108	231	62	111	233
Békéscsaba	216		137	200	340	323	136	235	187	285	260	103	278	241	119	442	276	322	443
Debrecen	231	137		136	354	417	182	108	49	353	189	227	295	301	132	459	290	338	460
Eger	158	200	136		280	344	171	71	139	359	107	257	221	307	137	385	217	265	387
Győr	126	340	354	280		203	205	299	356	301	231	288	88	248	232	121	66	81	155
Kaposvár	189	323	417	344	203		188	362	419	64	295	219	127	91	292	175	189	123	124
Kecskemét	81	136	182	171	205	188		190	232	171	179	86	142	118	57	306	140	186	307
Miskolc	177	235	108	71	299	362	190		111	378	119	276	240	326	156	404	235	284	406
Nyíregyháza	234	187	49	139	356	419	232	111		435	191	277	297	383	182	461	293	341	0
Pécs	205	285	353	359	301	64	171	378	435		311	182	158	61	228	238	237	154	186
Salgótarján	109	260	189	107	231	295	179	119	191	311		263	172	258	148	337	168	216	338
Szeged	165	103	227	257	288	219	86	276	277	182	263		226	139	122	390	225	270	391
Székesfehérvár	67	278	295	221	88	127	142	240	297	158	172	226		107	170	165	62	45	170
Szekszárd	153	241	301	307	248	91	118	326	383	61	258	139	107		176	245	184	125	214
Szolnok	108	119	132	137	232	292	57	156	182	228	148	122	170	176		334	168	214	335
Szombathely	231	442	459	385	121	175	306	404	461	238	337	390	165	245	334		172	121	67
Tatabánya	62	276	290	217	66	189	140	235	293	237	168	225	62	184	168	172		102	206
Veszprém	111	322	338	265	81	123	186	284	341	154	216	270	45	125	214	121	102		126
Zalaegerszeg	233	443	460	387	155	124	307	406	463	186	338	391	170	214	335	67	206	126	

First, we arranged the settlements in one route in order to find out what is the best distance and time that can be reached and to get a framework that can be used as minimum and maximum for multi-route planning with the Excel SOLVER help based on the distance matrix.

Generated	Order	City	Lng	Lat	Distance
	1	Budapest	19,0408	47,4983	109
10	11	Salgótarján	19,7867	48,0853	107
3	4	Eger	20,3747	47,8989	71
7	8	Miskolc	20,7833	48,1	111
8	9	Nyíregyháza	21,7167	47,95	49
2	3	Debrecen	21,6392	47,53	137
1	2	Békéscsaba	21,0833	46,6833	103
11	12	Szeged	20,1667	46,25	122
14	15	Szolnok	20,1764	47,1747	57
6	7	Kecskemét	19,6917	46,9074	118
13	14	Szekszárd	18,7039	46,3558	61
9	10	Pécs	18,2331	46,0708	64
5	6	Kaposvár	17,7833	46,3667	124
18	19	Zalaegerszeg	16,8511	46,8392	67
15	16	Szombathely	16,6333	47,2333	121
4	5	Győr	17,6344	47,6842	81
17	18	Veszprém	17,9167	47,1	45
12	13	Székesfehérvár	18,4167	47,2	62
16	17	Tatabánya	18,3949	47,5862	62
	1	Budapest	19,0408	47,4983	

Total Distance:	1671
Speed:	70
Time:	23,87142857

Figure 1. Arrangement of county seats in an optimal route [6]

As you can see in Fig. 1, with a total distance of 1671 km and about a day it is theoretically possible to visit all the county seats in Hungary. Mostly the problem there is time, as the vaccines will go bad in 12 hours and the driver can work for a maximum of 9+2 hours in one seating. In this case, either the driver would break the rules, or/and the vaccines would heat up so much, that they would be useless For this reason, more vehicles and more routes need to introduce in the distribution system [6].

At first we would think, that 4-5 vehicles would be enough to cover the whole area. But this cannot be achieved with such a large number of vehicles and routes. The best allocation we found is 7 routes with the two extended period of 10 hours. This is created by the Solver add-on from multiple running. The result is shown in Fig. 2, with 3442km [6].

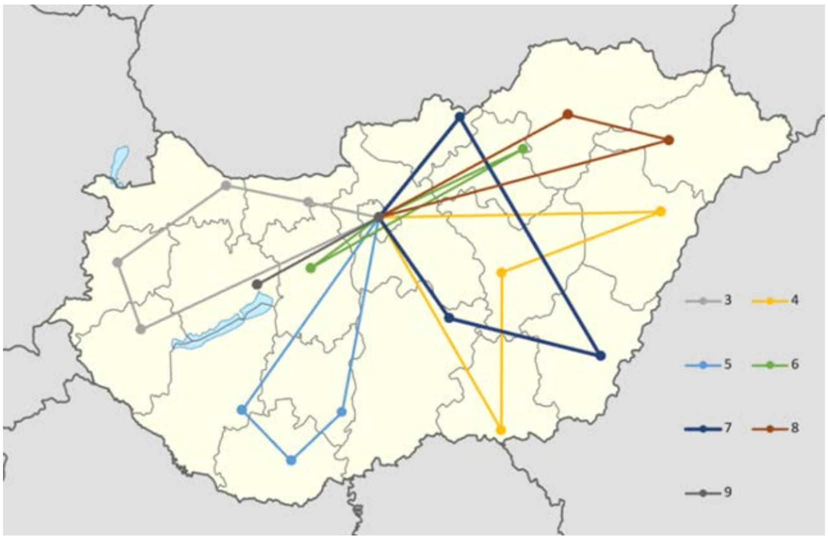

Figure 2. Best routes started from Budapest [6]

The optimization would end here if not all county seats were equipped with ULT storage. This means it is possible to transport and store vaccines to some county seats and at some point distribute vaccines from here. The question is, which cities should be these distribution centres also.

3. SELECTION OF A DISTRIBUTION CENTRE WITH CLUSTERING

We used the K-means method to determine the centres. This method is a prototype-based clustering procedure where one-level partitioning of data objects can be produced. This K-means method selects a centre point for the prototype, which is generated from the average of a group of given points and can typically only be applied to continuous points located in n-dimensional space. In this task, these points were by definition the county seats and their coordinates, with the exception of Budapest. As a first step, we wanted to find out whether 2 centres are sufficient to cover the country. To create the clusters, the centres were generated in Excel with the random function. Then we assigned each city to the centre closest to it, and the groups thus formed became the starting clusters. From there, the centre of each cluster was updated based on the points assigned to the cluster until the centres remained the same.

In the end, we needed 4 centre points and we got a result where the total distance was 2730 km, which is 712 km less than the previous solution, and the times of the groups were within 9 hours. So it became a much better solution. After that, we did another test, in which we also allowed the 10-hour work schedule, as well as applying the objective functions of clustering and flight planning at the same time. Using the general problem-solving Excel add-in, SOLVER, and the currently available data and constraints, we first built the model with a strong bias. The algorithm could work with ten optional group options, and then the Solver chooses for itself which groups it wants to use. Budapest was repeatedly removed from the list, but a separate column had to be prepared, which contains the distance of the given city from Budapest. The individual groups were created in such a way that, from the cities assigned to the given group generated by the system, and select the one that is closest to Budapest and choose this as the centre. We have calculated the total distance for each group with the average speed of 70 km/h, and a loading/unloading time of 1 minute for time measurement. After that, we summed up all the paths of the 8 groups and Solver minimized this value. As a limiting condition, we added that the time of each group cannot exceed 8 hours. The Solver used only five groups, all of which are within 8 hours and there is absolutely no danger of exceeding it, even with a loading time of a few minutes. The best solution here is 2730 km with 39 hours of travel time.

After this solution we recognise, that we can arrange the direct paths to local distribution centres into a distribution route. This is shown as two pink route in Fig. 3. The total distance with this improvement was 2,656 km, which can be covered in 30,73 hours with several vehicles, and compared to the 2,730 km solution, which takes 39 hours, the result obtained during automation is 74 km and 8.27 hours more favourable, so this final solution to the problem at the centre of the research.

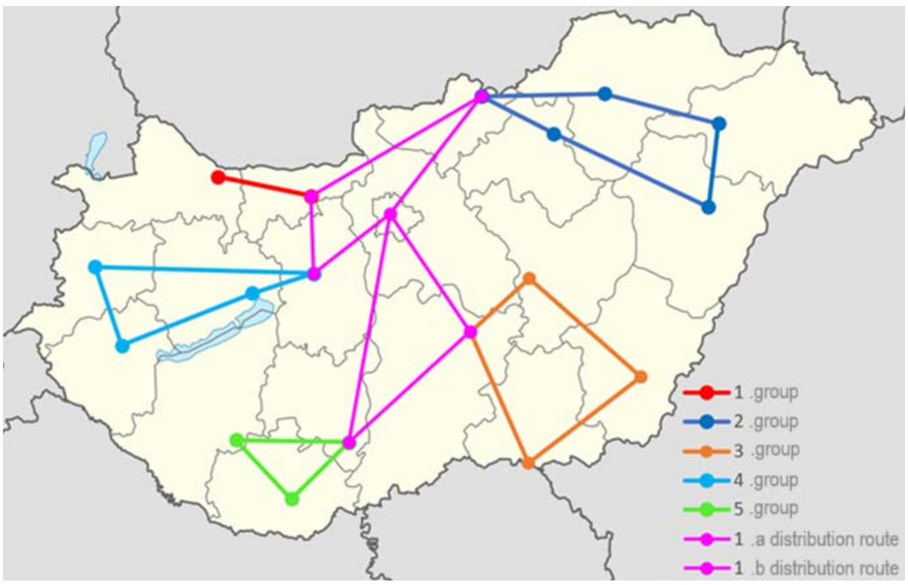

Figure 3. Best routes with local distribution centres

4. Conclusions

In the article, we dealt with the vaccines that play a major role in overcoming the Covid-19 pandemic and the related cold chain processes. First, we conducted an in-depth literature research on the topic so that all information would be available to me when we start working on route planning. We also discussed the simplified requirements of vaccines, which used for limitations in our optimisation. Within the route planning, we defined the important parameters and the rules affecting the task. We have presented the travel agent problem (TSP) with its principles and solution options. After all important information was available, we prepared the routes between the counties with the MS-Excel Solver, which provided the basis for the subsequent multi-flight planning, in which all parameters were taken into account. We examined many different cases calculated by different algorithms, from which we selected the most cost-effective and fastest option. This combined task was automated, where the total road length was 2656km and the times of the groups were within 9 hours of working time.

Acknowledgements

„Supported by the ÚNKP-22-1 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund."

The research work described in this article was carried out in the framework of the project "Talent management and professional community building in the Terplán Zénó Szakkollégium", NTP-SZKOLL-22-0023, with the support of the Ministry of Culture and Innovation and the Human Resources Support Fund.

References

[1] Anne, S. (2011). Human Vaccines and Their Importance to Public Health. *Procedia in Vaccinology* **5**, 120-126. https://doi.org/10.1016/j.provac.2011.10.008

[2] Andrew, K.: *The evolution of cold supply chain in the wake of covid-19*. Retrieved from https://www.contractpharma.com/contents/view_experts-opinion/2021-10-21/the-evolution-of-cold-supply-chains-in-the-wake-of-covid-19 (accessed: 21 October 2021)

[3] Zirour, M. (2008). Vehicle routing problem: models and solutions. *Journal of Quality Measurement and Analysis JQMA*, **4**(1), 205-218.

[4] Mathumalar, L. F. et all. (2022). Management of COVID-19 vaccines cold chain logistics. *Journal of Pharmaceutical Policy and Practice*, **15**, No. 16, https://doi.org/10.1186/s40545-022-00411-5

[5] *Training on handling, storing and transporting Pfizer BioNTech COVID-19 Vaccine COMIRNATY®*. Retrieved from https://www.who.int/publications/m/item/training-on-handling--storing-and-transporting-pfizer-biontech-covid-19-mrna-vaccine-comirnaty (accessed: 28 May 2023)

[6] Seprényi, K., Veres, P. & Cservenák, Á. (2023). Developing a vaccine distribution network between county towns. *Advanced Logistic Systems - Theory And Practice* **17**(2), 14-22, https://doi.org/10.32971/als.2023.012