Advanced Logistic Systems – Theory and Practice, Vol. 17, No. 2 (2023), pp. 14-22.
https://doi.org/10.32971/als.2023.012

DEVELOPING A VACCINE DISTRIBUTION NETWORK BETWEEN COUNTY TOWNS

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

Abstract: *Without the cold-chain network, it would be impossible in today's world to transport large quantities of perishable goods, primarily food and medicine, over long distances, but it is still very important that the necessary materials reach their destination on time and with adequate cooling. This is absolutely true for the vaccines created to stop the Covid-19 pandemic, which had to be distributed quickly and at certain storage temperatures to all parts of the world. This is a rather difficult task with NP-hard complexity. In this research, we are investigating the optimal way to get from a distribution center in Budapest to the county towns with transport vehicles, so that neither the vaccines deteriorate, nor we violate regulations. For this, we used vehicle route planning principles and Excel-Solver software.*

Keywords*: multi route planning, cold-chain, Solver, VRP*

1. INTRODUCTION

The development of vaccines to protect against the global pandemic Covid-19 was the fastest in the history of medicine. However, the commercialization of these vaccines was initially a major challenge for mankind, as many aspects had to be taken into account during storage, packaging, and transport. The whole pandemic raised many new logistical problems, of which route planning was a particularly important one. The Vehicle Routing Problem (VRP) is one of the most frequently encountered optimization problem in logistics. As the products are perishable, the different packaging, storage and transport needs of the vaccines have to be taken into account in addition to the working time of the road transport operator, making the design of the distribution network a rather complex task, even for a small country. In this article, we will describe the basics and principles of chilled goods and the cold chain through a literature review. Subsequently, we will also discuss the packaging, storage, and transport characteristics of vaccines, since depending on the type of vaccine, different vaccines have different requirements. In order to ensure timely vaccination, the design of a distribution network is a very important process. In the framework of this publication, the distribution of vaccines between the duchies will be addressed. we will solve the complex route planning problem using several methods within Excel. The aim is to create a distribution network within which vaccines can be transported 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] PhD., University of Miskolc, Institute of Logistics, Hungary
peter.veres@uni-miskolc.hu
[3] PhD., University of Miskolc, Institute of Logistics, Hungary
akos.cservenak@uni-miskolc.hu

2. EVOLUTION OF THE COLD CHAIN AND COOLED GOODS

Thanks to globalization, we are now in a position where we can deliver products to all parts of the world. However, the greater the physical distance that has to be covered during transport, the greater the risk of damage to the product. To be efficient, transport requires time and coordination, and delays can have negative consequences. This is particularly true for food, pharmaceutical and medical products, so these businesses are increasingly relying on cold chain processes.

Cold chain refers to the transportation of temperature-sensitive products in the supply chain using thermal and refrigerated packaging methods, and also includes logistics planning to protect the integrity of these shipments [1].

Thanks to the emergence of cold chain processes, many companies no longer rely only on well-known suppliers such as FEDEX or United Parcel Service (UPS), but also on those specialized in the transport of temperature-sensitive products (Maersk, Patheon). These suppliers are familiar with customs duties, local regulations, environmental conditions, know which route is the most appropriate and have become very important factors in global trade. The cold chain allows many developing countries to participate in the global market for perishable goods, thus contributing to economic development. At global level, the cold chain has an impact on the specialization of agricultural functions that allow the transport of temperature-sensitive foods to distant markets, as well as the distribution of vaccines and other pharmaceutical or biological products [1].

The cold chain and cold chain trucks have undergone many changes. Advances in technology have enabled a high level of control over every aspect of the cold chain. The cold chain industry contributed 56 billion USD to the US gross domestic product and supported 67 000 jobs in 49 states in 2012. As the United States is a world leader in the development of efficient cold chain technologies and management processes, cold chain now covers almost the entire world [2]. The temperature-controlled transport of medicines and medical products is a much more modern idea than the transport of chilled or frozen food. From the 1950s onwards, third-party logistics (3PL) companies began to emerge, introducing new ways to successfully transport these global commodities. Before their emergence, cold chain processes were mostly managed in-house by the manufacturer. In the United States, restrictions imposed by the Food and Drug Administration on cold chain stability and other measures have encouraged many companies to rely on specialized courier services rather than completely transforming their supply chains. Thus this specialized industry was born. Cold chain processes for the preservation of expensive vaccines and medical supplies only began to be recognized when these logistics providers emerged. As awareness began to grow, so did the need for effective cold chain management, especially during the Covid-19 pandemic [2].

Temperature control of food transport is one of the elements of the industry whose need is constantly increasing with international trade. As food and produce production is at the heart of the export economies of more and more countries, it has become increasingly important to keep these products fresh for longer [1].

One of the key issues in cold chain processes is to ensure a temperature-controlled environment. Depending on what product is being shipped, different temperature levels need to be maintained to ensure a healthy arrival. The most common temperature standards include 'banana' (13°C), 'chill' (2°C), 'frozen' (-18°C) and 'deep-frozen' (-29°C). Staying within temperature limits is vital to the integrity of the shipment in the supply chain and any deviation can cause irreversible and costly damage; whereby the product can simply lose its market or use value [1].

Keeping the cargo in one temperature range for a longer period is only possible with a suitable container. As manual temperature recording is unreliable beyond a certain point, innovative solutions were needed. These began to gain momentum in the 1970s and 80s when Electrolux Luxembourg, working with a wooden refrigerated box from a laboratory in Sweden in 1974, created an easily transportable vaccine storage container. The Luxembourg cold box was successfully tested in Ghana and became a widely used model for manufacturers. In 1976, the WHO (World Health Organization) developed a strategy to address critical problems in vaccine distribution, including temperature control systems during transport, lack of storage facilities and inadequate training of staff. In 1977, after the invention of the refrigerated box, a US-based portable container company collaborated with the Pan American Health Organization (PAHO) to create a vaccine container that is now used worldwide. In the late 1970s, PATH also began working with the WHO and various technology partners to better assess whether vaccines were exposed to heat. A big step forward was the development in the early 1980s by PATH and Temptime Corporation of temperature-sensitive VVM (Vaccine Vial Monitor) stickers that change colour when it gets too hot, meaning that the vaccine they are attached to has become ineffective. These VVM stickers have also been used for polio vaccines since 1996 and are now required by the WHO for all vaccines provided by the United Nations International Children's Emergency Fund (UNICEF). The cold chain monitor (CCM) was also created in the 1980s by companies in the United States and Switzerland. It was an innovation to reliably monitor vaccine warehouses from the manufacturer to delivery sites in different countries [4].

In order to know what kind of packaging is needed, it is important to know the size of the shipment, the duration of the transport and the ambient or external temperature. These can range from small, insulated boxes requiring dry ice or gel packs, to rolling containers, to refrigerated containers several meters long with their own motorized refrigeration unit. The main cold chain technologies include [1]. The major developments in the evolution of the cold chain are shown in Fig. 1.

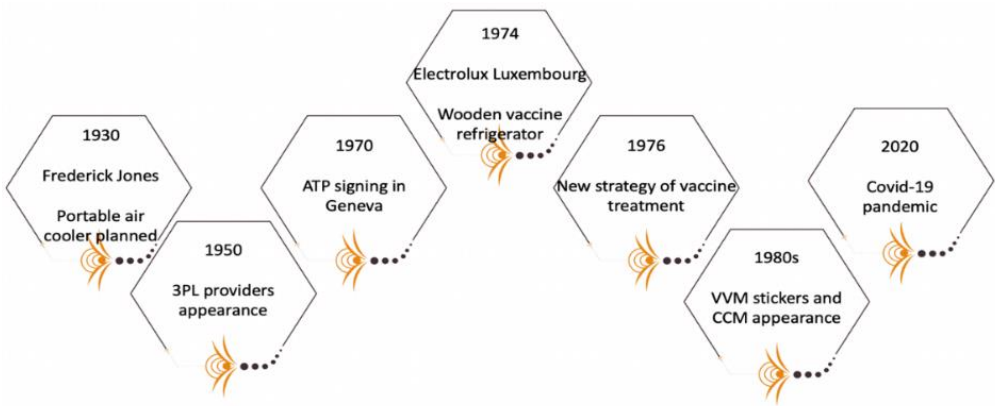

Figure 1. Major development in the evolution of cold chain (own made)

The "Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for such Carriage" (ATP) was signed in Geneva in September 1970. The regulations define how perishable foodstuffs are to be transported, the requirements for special vehicles and the control procedures to ensure compliance. The aim is to guarantee to the final consumer that the food arrives in the right conditions. As of 2016, it is in force in 50 countries, most of which are in Europe or Central Asia [3].

The purpose of the cooling units in refrigerated trucks is to keep the temperature within a predetermined range, not to cool it! In other words, before you load a consignment into a refrigerated truck, it must be brought to the desired temperature. Of course, this requires special loading, unloading and storage solutions. Nowadays, refrigerated trucks are also becoming increasingly modern, equipped with sensors that monitor the temperature and shut down the refrigeration system if necessary. This makes it possible to improve the reliability of temperature control and extend the autonomy of the refrigerated truck [1].

The movement of a consignment through the supply chain requires the development of a comprehensive logistics process involving several phases, from the preparation of the consignment to the final check of the integrity of the consignment at the point of delivery:

- Preparation of the shipment,
- Selection of the mode of transport,
- Individual procedures,
- The "last mile”,
- Integrity and quality assurance.

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

3. Packaging, storage and transport of Covid-19 vaccines

Having looked at the cold chain from several angles, we would like to summarize what we know about the packaging, storage, transport and distribution of vaccines. WE would then like to describe the most common vaccines that have very specific packaging requirements, both for storage and transport. Primary packaging materials include glass vials and syringes, as well as stoppers and seals. For distribution, secondary and tertiary packaging is very important. Secondary packaging helps to reduce volume, save costs, minimize logistical burdens and reduce the 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 [5].

For storage, we have prepared a summary chart in the Table I.

Each manufacturer has its own ideas, systems and specifications on how long and how it can be stored. Comirnaty, Pfizer- BioNTech's vaccine, was one of the most popular and most carefully managed vaccines and we use this as a basis for our route planning. In a special refrigerated box with dry ice on top, the vaccine will last up to 12 hours without spoilage at -60°C. With this time deposit, since most transport vehicles are not special refrigerated vehicles that cannot keep between -60 and -90°C, no guarantee can be made for the integrity of the vaccines.

Table I.

Storing requirements for different type of vaccines

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
Unopend 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

4. RULES AND PRINCIPLES OF ROUTE PLANNING

When designing a vaccine distribution network, many considerations must be taken under consideration to ensure that vaccines are not damaged and can be used efficiently. In this chapter, we want to summarise in general terms what we know about route planning, what aspects need to be taken into account and what steps need to be followed.

Route planning is generally a process of planning schedules and routes for transport vehicles such as vehicles, planes, trains, ships, e.g. in municipal waste collection [8] or efficiency optimization with considering IoT [10]. In route planning transport needs, capacity, weather and other factors are really important. Route planning usually includes several aspects such as:

- Route planning: planning the route of flights in order to reach the destination at the right time and place.
- Timetable: the planning of timetables that determine the departure and arrival of vehicles at each station and/or stop.
- Capacity: planning the capacity of the routes to ensure that the required passengers/cargo can be transported comfortably and safely.
- Available resources: Route planning should consider available vehicles and staff, as well as vehicle fuelling, maintenance and other necessary resources.

For vaccines, in addition to the above-mentioned considerations, particular attention had to be paid to whether different types of vaccines have any specific transport requirements, such as the bulk condition in which they can be transported, the type of container in which they can be stored, and the length of time they can be kept in non-ULT (ultra-low temperature) conditions.

The travelling salesman problem (TSP), which is the basic problem of route planning, tries to answer a 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 returns to the city of origin?". This is an NP-hard problem in combinatorial optimization, but it is also important in operations research and theoretical computer science. This problem was first formulated in 1930 and has been one of the most intensively studied problems in optimization ever since. Many heuristic and exact algorithms are known to solve this problem, so that some instances with tens of thousands of cities can be completely solved, and even problems with millions of cities can be approximated within a fraction of 1% [6].

Numerous algorithms have been developed to solve vehicle scheduling problems, most of which use heuristics. One problem deals with finding the optimal route of several vehicles, each of which starts from a warehouse, visits a set of customers and then returns to the warehouse with all the customers visited by the vehicles, under various constraints such as vehicle capacity and time window constraints [7].

5. ESTABLISHING A DISTRIBUTION NETWORK BETWEEN THE COUNTY TOWNS

Using distribution model or network is well wide used, for instance, for layout optimization [9].

The first step in the route planning was to establish that the main centre of vaccine delivery, i. e. our national distribution centre, would be our capital city, Budapest, while the other 18 county towns would be the regional distribution centres. Truck and lorry drivers will be allowed to drive 9 hours each day in two parts according to EU and Hungarian rules and have an extra 2 hours per week in case of emergency. Among the storage options, passive boxes would be used, as they do not require a special vehicle but only need to be refilled with dry ice. Frozen vaccines can be transported for 120 hours and thawed for 12 hours. The loading time between +15 and +25°C should be up to 1 minute and the vaccines should be placed immediately in a ULT freezer. Based on these data, the loading time was assumed to be 1 minute in this exercise. The distances between the counties were obtained by mapping an online dataset that stores data based on cartographic data (Fig. 2). From these distances we calculate the travel time for an average speed of 70km/h. This is the accepted speed in practice.

	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	463
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	

Figure 2. Municipal network matrix (own made)

Taking all aspects into account, the route planning was carried out in Excel using the SOLVER extension with surprising results.

We made one route for all the cities first to find out the best distance and time that can be reached and to get a framework that can be used as a minimum and maximum for multi-flight planning.

Figure 3. 1st solution for the problem – map (own made)

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 4. 1st solution for the problem –calculation (own made)

At first glance, many would think that 3 or 4 vehicles would be enough to cover the whole area. But this is not true with such a large number of vehicles. The best allocation was found by allowing 10 flights for SOLVER's algorithm and setting a maximum time of 10 hours. Of these, the algorithm used 7 routes and twice exceeded 9 hours. The result is shown in Figure 5, where different colours denote the route IDs.

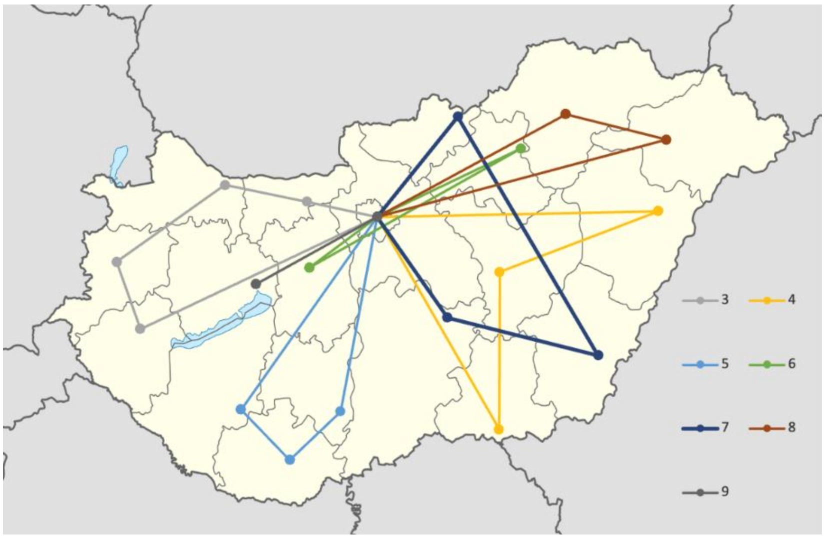

Figure 5. Best and final solution for the problem (own made)

6. SUMMARY

In this article, we have discussed the vaccines that play a major role in the fight against the Covid-19 pandemic and the related cold chain processes. First of all, we conducted a short literature search on the topic so that WE have all the information at my disposal when I start working on flight planning. This led to an introduction to the cold chain, including the simplified requirements for vaccines. Within route planning, we have defined the important parameters and the rules that apply to the task. We presented the traveling salesman problem (TSP) with its principles and possible solutions. Once all relevant information was available, we prepared the inter-county route using MS-Excel Solver, which was the basis for the subsequent multi-county route design, in which all parameters were considered. In the research different cases were examined, from which the most cost-effective and fastest option was selected, but in this paper it was not detailed. Contrary to our original idea, we ended up with 7 trucks capable of fulfilling the problem at the heart of this publication with 9+1 shift hours.

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] Rodrigue, J.-P. & Notteboom, T. (2020). *The Geography of Transport Systems*, Routledge publisher, ISBN 9780367364632

[2] Cargo Data's official website, *The Evolution and The History of the Cold Chain*, Retrieved from https://cargodatacorp.com/the-evolution-and-history-of-the-cold-chain/, downloaded: 2023. 04. 28.

[3] RFL Cargo's official website, *The different types of vehicles in the cold chain*, Retrieved from https://rflcargo.com/en/the-different-types-of-vehicles-in-the-cold-chain/

[4] Osigwe, T.-A. (2021). *Keeping vaccines cool with cold chain*, Retrieved from: https://www.gavi.org/vaccineswork/keeping-vaccines-cool-cold-chain

[5] Fahrni, M. L., Ismail, I. A.-N., Ref, D. M., Almeman, A., Yaakob, N. C., Saman, K. M., Mansor, N. F., Noordin, N. & Babar, Z.-U.-D. (2022). Management of COVID-19 vaccines cold chain logistics, *Journal of Pharmaceutical Policy and Practice*, **15**, Article number: 16 https://doi.org/10.1186/s40545-022-00411-5

[6] Cummings, N. (2000). *A brief history of the travelling salesman problem*, The operational research society, Retrieved from https://www.theorsociety.com/about-or/or-methods/heuristics/a-brief-history-of-the-travelling-salesman-problem/

[7] Chang, Z. (2022). *Models and algorithms for route planning of freight buses*, HAL open science, Retrieved from https://theses.hal.science/tel-03621433/file/Zheng_Chang_2019TROY0022.pdf

[8] Akkad, M. Z., Rajab, Y. & Bányai, T. (2023). Vehicle Routing for Municipal Waste Collection Systems: Analysis, Comparison and Application of Heuristic Methods, *LECTURE NOTES IN MECHANICAL ENGINEERING Vehicle and Automotive Engineering* **4,** 694-708. https://doi.org/10.1007/978-3-031-15211-5_58

[9] Veres, P. & Bányai, T. (2023). Layout optimization of a multi-centre distribution model, *Advanced Logistic Systems - Theory and Practice* **17**(1), 5-20, https://doi.org/10.32971/als.2023.001

[10] Zaher, A. M., Sameh, H., Rana, R. & Bányai, T. (2022). Efficiency optimization of vehicle routing problem with considering IoT - a case study in Slovakia, In: *2022 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies* (3ICT), IEEE, pp. 372-379, https://doi.org/10.1109/3ICT56508.2022.9990687