LUT Scientific and Expertise Publications

Pekka Neittaanmäki, Kirill Akimov, Veronika Akimova, and Ronja Tuovinen

Challenges and Current Solutions of Refrigerated Transportation

LUT University

Challenges and Current Solutions of Refrigerated Transportation

Pekka Neittaanmäki[1], Kirill Akimov[2], Veronika Akimova[3], and Ronja Tuovinen[4]

[1]LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland, pekka.neittaanmaki@jyu.fi

[2]University of Helsinki, Yliopistonkatu 3, 00014 University of Helsinki, Finland, kirill.akimov@helsinki.fi

[3]University of Helsinki, Yliopistonkatu 3, 00014 University of Helsinki, Finland, veronika.akimova@helsinki.fi

[4]LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland, ronja.tuovinen@gmail.fi

Autumn 2023

Abstract

This paper addresses issues arising from cold chain logistics with primary focus on its environmental impact. In particular, the sources of emissions, including carbon dioxide (CO_2) and other serious pollutants contributing to global warming, are considered. We overview methods for reducing these emissions, specifically the methods that can be integrated without drastically altering existing temperature-controlled transport systems. We discuss strategies for both completely and partially mitigating emissions associated with on-road refrigeration. These strategies include the use of passively refrigerated transport packaging to eliminate the need for active refrigeration and the enhancement of current refrigeration methods with phase change materials. Moreover, we present an approach to minimise the emissions that may arise from inadequate logistics management delving into the principle behind the CO_2-based optimisation of distribution routes. Additionally, we overview mathematical optimisation techniques used in identifying environmentally

preferable solutions in managing temperature-sensitive logistics. We also note a potential area where artificial intelligence could be applied to enhance the optimisation of cold chain logistics.

1   Introduction

As the world becomes more interconnected so does the transportation of food, medicine, and everyday goods. As a result, one can receive a vaccine that was produced in Germany, buy bananas that were grown in Philippines and cook fish that was imported from Norway. None of this would be possible if refrigerated transportation did not keep these items cool all throughout the journey. This so-called cold chain accounts for all the actions taken to maintain a certain stable temperature no matter what weather conditions are faced outside in order to keep the products safe for consumption.

This article examines the current state of cold chain logistics with an emphasis on environmental concerns. It also provides insights into the practical implementation of temperature-controlled distribution in Finland. It identifies the origins of the emissions associated with cold chain transport. The discussion includes an analysis of methods aimed at reducing emissions, highlighting a novel approach to ensure transportation temperature that does not require an additional energy supply and underscores the importance of monitoring temperature compliance.

Furthermore, the article presents various strategies to minimize emissions in cold chain logistics. One such strategy involves optimizing the sequence of delivery stops to reduce emissions effectively. The review extends to scholarly investigations into this concept within the domain of temperature-controlled transportation. The focus is to determine which optimization methods have been extensively researched and which may possess untapped potential for enhancing the sustainability of the cold chain.

The article is organised as follows: Section 2 presents an overview of a cold chain logistics. Section 3 specifies the emission sources in cold chain transportation. Section 4 demonstrates the ways of minimisation of refrigeration-related emissions. In Section 6, the minimisation of mismanagement-related emissions is discussed. Finally, the conclusion and a short discussion of this article are provided in Section 7.
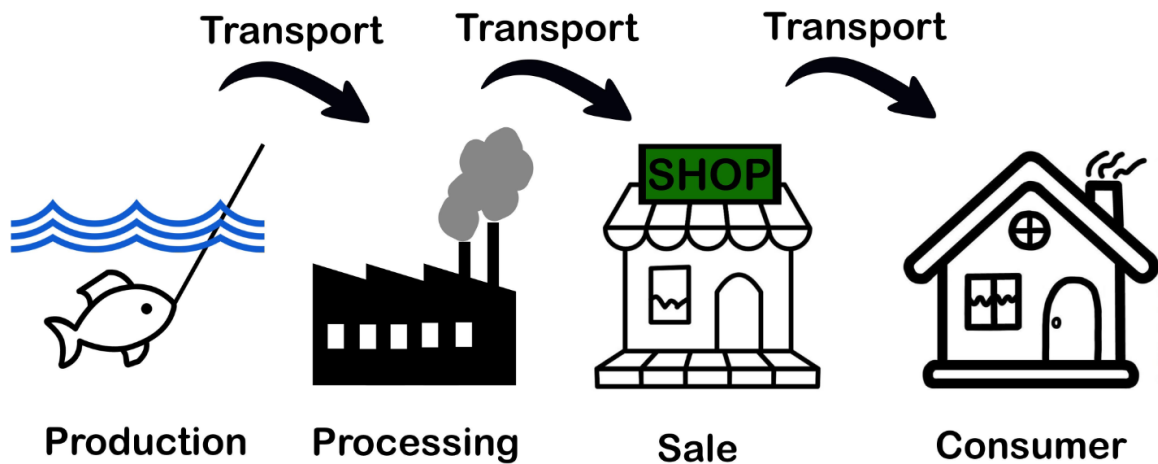
Figure 1: Different parts of cold chain. The example is about the cold chain of fish.

2   Cold Chain

Cold chain is the actions taken to maintain a product at a certain temperature through the journey from producer to the consumer. The cold chain consists of five parts, like shown in Figure 1.

In this article we will focus mainly on the problems caused by transportation. However since transportation and storage face some similar obstacles, we will discuss the solutions for both parts, when relevant.

We reached out to a distributor[1], who distributes temperature-controlled products. He has experience of distributing from the storage facility to shops and restaurants in cities as well as in smaller villages. The car can handle a few different temperatures at once by locating the products on different places. The refrigeration is on from the moment the driver fetches the vehicle until the moment when the last product has been distributed. The driver is responsible for the temperature and is required to inform the customer in case the temperature has risen above a certain limit, meaning that the produce is not safe anymore. The products are often distributed in boxes, platforms or carriages with wheels. They often need to be transported back once the products have been loaded off them, which takes room in the truck.

It is important to have an unbroken cold chain since products that have gotten warmer or colder than the wanted temperature might not be safe for consumption any longer. This is especially important when transporting medicine or easily perishable products like meat or fish. This cold

---

[1]Artturi Neittaanmäki

chain can be created in many ways that vary from passive cooling (e.g. insulating cold boxes) to active cooling (e.g. VCR, or vapor compression refrigeration).

2.1 Environmental Impact

Cold chain has a huge impact on the environment and economy. This is why regulations for different parts of it are getting stricter. It is estimated that Vapor Compression Refrigeration systems cause approximately 10% of greenhouse gas emissions and consumes 15% of the electrical energy. It holds about 80% of the market share for refrigeration (both commercial and industrial) and air conditioning systems [35]. According to a report made by Food and Agriculture Organization of the United Nations in 2017, approximately one third of the food is wasted during the production, processing, transportation and consumption. Majority of it is wasted during production and post-harvest, especially in the developing countries or by the consumer, especially in Europe and North America and East Asia. On average 4% is lost during distribution [10]. However the number lost due to transportation (any time the food is moved from place to place) can be larger, since the products need to be transported from producer to processing facilities, from there to storage facilities and only from there to distribution.

On top of the emissions, refrigerated transportation is a big source of noise pollution. This is a problem especially in proximity to cities and villages, since noise pollution has been linked to increased stress levels, disturbed sleep and cardiovascular diseases [42]. Some of the cold transportation happens during night when there is the least amount of traffic. This however leads to the engine running loudly during offload and that can disturb the sleep of people living nearby.

Because of climate change many organizations want to reduce the emissions they or their members produce. For cold transportation this means either reducing the number of products that are transported across the globe or reducing emissions caused by this transportation. Since the first option is highly unlikely if we look at trends in globalization, the reduced emissions of transportation methods are the way to go. For example, EU set a regulation that by 2030 new trucks need to reduce emissions by 45% compared to 2019 [8].

A recent climate conference held by the United Nations, COP28, agreed that the whole world will start phasing out of fossil fuels [28]. This would mean that all the countries need to start taking urgent action to shift from fossil fuels to other sources of energy. Passive cooling options are perfect aid for that, since they don't need an external energy source.

2.2 Economical impact

Cold chains are not ideal for economics either. Loss of products is not good for the producer, because they need to work extra to cover for the percentage that gets lost. The cold chain is also expensive to maintain. Equipment for the cold chain is more expensive than their non-temperature-controlled counterparts and often requires installation right into the van, truck or storage room. This brings up costs to the final product that is sold to the consumer. The transportation is also inefficient, since in most systems one cannot transport products that require a vastly different temperature. This means that multiple trucks can be driving nearly the same route half-empty because they are transporting things that cannot be stored together in the same temperature. Most of the systems release gas as a side product of the refrigeration systems and thus are not suitable for air transportation in large quantities. [30]

2.3 Vapor Compression Refrigeration

Vapor compression refrigeration is the most commonly used method in refrigeration, cooling or air conditioning. It accounts for approximately 80% of the market share [35]. This is due to the the variety of different power supply methods, e. g. taking the power straight from different parts of the engine or from a separate generator. The VCR cycle looks something like this [23]:

1. Evaporator: evaporates refrigerant by absorbing thermal energy from the environment. The evaporator is located in the are which is cooled by the cooling effect of the absorption.

2. Compressor: compresses the refrigerant to the maximum pressure of the cycle. This happens by absorbing energy from an external source (e. g. the engine)

3. Condenser: Allows the refrigerant to condense from gas to liquid by releasing thermal energy in the environment. The condenser is usually located outside the area which is being cooled (e. g. outside the truck)

4. Expansion device: Drops the pressure of the refrigerant, which cools it down. This Low-pressure and low-temperature refrigerant is directed back to the evaporator and the cycle starts over again.

There are a few things we should consider regarding VRC systems. First issue is the refrigerant. Study estimated that around 5-25% of the annual charge per year of refrigerant in vapor compression transportation refrigeration units get leaked [32]. Refrigerants are often hydrofluorocarbon refrigerants with high Global Warming Potentials [32]. EU has set legislation to

phase out from using these refrigerants, which leads to growing market for alternatives [9]. The second thing to consider is efficiency. This is especially visible when the systems is closely linked to the engine. One of the weakest points for VCR systems is on and off loading of the truck. During on and off loading the doors to the cooled area will be open for longer periods of time and thus the cooled air mixes with the warmer air from the outside. The truck needs to stay running to counter-power the mixing and keep products from spoiling [25]. Similar efficiency problem arises when the load is not full. The system still needs to keep the entire truck cold, even though it is only half full. The efficiency of the engine drops to 1-10% in these two cases [25].

3   Emission Sources in Cold Chain Transportation

In cold chain transportation, most CO2 emissions arise from fuel combustion inside internal combustion engines. This type of engines is widely used in refrigerated transport as main engines to propel trucks and as auxiliary engines to ensure the refrigeration. The purpose of the internal combustion engine is to convert the chemical energy of the fuel into more convenient mechanical energy [13], which can directly be used by:

- the powertrain to rotate the wheels

- a generator to produce electric current for an electric refrigeration unit

- the compressor of the refrigeration unit.

The energy conversion is carried out as ignition (reduction-oxidation reaction), in which most carbon of the fuel compounds forms CO2 while some carbon forms compounds that will eventually transform to CO2 [13].

The amount of CO2 emissions released from the main or an auxiliary engine depends on the fuel composition and the amount of combusted fuel [13]. This amount depends on the energy content of the fuel [13], efficiency of the engine [27], and desired power output [3].

- In case of the main engine, the desired power output is mainly determined by needs of the powertrain, which consumes energy to accelerate or compensate speed losses caused by air resistance, tire rolling resistance, and gravity (when travelling uphills) [3].

- In case of the auxiliary engine, the desired power output is mainly determined by needs of the refrigeration unit, which consumes energy to lower the temperature of the freight

compartment and compensate temperature rises caused by heat transfer from the environment to cargo area (due to inefficient thermal insulation) and warm air flows inside the freight compartment during unloading [29].

In addition to the fuel combustion, the refrigeration is a source of emissions in the cold chain transportation. Most refrigerated systems are based on heat absorption (endothermicity) of evaporation and heat emission (exothermicity) of condensation [7]. In order for the refrigerant to condense at an outside temperature that is usually much higher than its dew point [6], the dew point is raised by increasing the pressure [7]. However, high pressure causes leakages of the refrigerant that is most commonly R-404A or R-452A in the refrigerated road transport [33]. These substances are mixtures of different refrigerants that are chemically pure hydrofluorocarbons. These compounds are considered greenhouse gases [24]. For a more detailed description of the formulations of R-404A and R-452A refer to Figures 2a and 2c.

The amount of leaked refrigerant may be converted to the corresponding amount of CO2 emissions based on the climatic impact of the refrigerant when released into the atmosphere (see Figure 2). The conversion factor may be defined as a ratio of the respective effects on the amount of energy trapped in the atmosphere. This rate is called global warming potential (GWP) and is commonly used in policies [4], particularly in the context of refrigerant. However, greenhouse gases do not influence global warming instantly after their emission and the GWP value varies with respect to the interval under consideration [4]. Commonly, the accumulated global warming effect over the following time horizons is considered: 20 years (GWP-20), 100 years (GWP-100) and 500 years (GWP-500) [11].

In addition to the primary emissions that are directly emitted during cold chain transportation, there are secondary emissions. These arise from the carbon footprint of the products that are lost due to inadequate temperature-controlled transportation. Namely, flawed cold chain logistics force production to produce more products and emit more CO2 in order for production to not only meet consumer demand but also a certain percentage of transportation losses. The losses may occur due to a complete absence of refrigeration during transport, which is more relevant to developing countries, or due to malfunctions in refrigeration units, breakdowns of refrigerated trucks, and traffic accidents, which is more relevant to developed countries [17].

4 Minimisation of Refrigeration-Related Emissions

Due to the high demand on more efficient and environmentally friendly solutions related to refrigerated transportation and cold chains there has been an increase in new innovation and
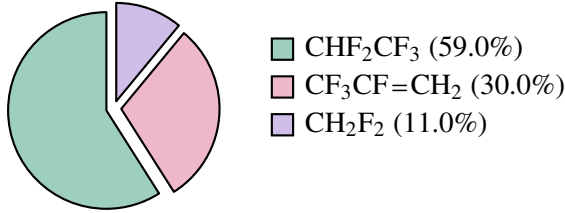
(a) Mass share of the constituents of R-404A

☐ CH$_3$CF$_3$ (52.0%)
☐ CHF$_2$CF$_3$ (44.0%)
☐ CH$_2$FCF$_3$ (4.0%)
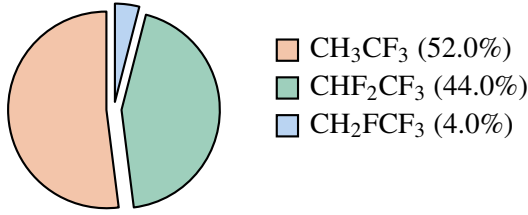
(b) GWP values of R-404A

Constituent	GWP-20	GWP-100	GWP-500
CH$_3$CF$_3$	7840	5810	1940
CHF$_2$CF$_3$	6740	3740	1110
CH$_2$FCF$_3$	4140	1530	436
R-404A mixture:	≈ **7210**	≈ **4730**	≈ **1510**

(c) Mass share of the constituents of R-452A

☐ CHF$_2$CF$_3$ (59.0%)
☐ CF$_3$CF=CH$_2$ (30.0%)
☐ CH$_2$F$_2$ (11.0%)

(d) GWP values of R-452A

Constituent	GWP-20	GWP-100	GWP-500
CHF$_2$CF$_3$	6740	3740	1110
CF$_3$CF=CH$_2$	1.81	0.501	0.143
CH$_2$F$_2$	2690	771	220
R-452A mixture:	≈ **4270**	≈ **2290**	≈ **680**

Figure 2: Global warming potentials over 20 years (GWP-20), 100 years (GWP-100) and 500 years (GWP-500) for R-404A and R-452A, expressed in CO2 equivalents. Calculations are based on the composition of each refrigerant [6] and the GWP-20 values of their respective compounds [36]. Constituents are color-coded for convenience.

research on the topic. In this section we will discuss some of them.

4.1 Passive Cooling

Well-insulated box with a cold gel mat inside it (see Figure 3), presents a considerable solution for temperature controlled transportation [30]. The box ensures that the cooling provided by the cold gel mat wont mix with the air outside box, giving a perfect solution for on and off loading. The insulation would also allow the transportation of multiple products that require different temperatures from each other. This would drastically reduce the used energy and thus lower the emissions. The box would also include a sensor that can collect and share data and keep track of the temperature. The downside of the box is that it needs to be transported back instead of simply recycling like cardboard boxes it at the final destination. Some solutions include a box that can be disassembled for the journey back, when it would take less space. However, the box is very energy-efficient transportation method.

4.2 Phase Change Materials

Phase change materials absorb thermal energy by changing the phase from solid to liquid or liquid to gas and thus keep the products at a wanted temperature. There are a few different

Figure 3: Example of a cold box according to the new patent [30]

PCMs types to choose from:

- Organic: Paraffin or non paraffin

- Inorganic: metals or salt hydrates

- Eutectic solutions: combinations of multiple materials [23]

Phase change materials can often be used alongside VCR systems. This means that the cooling effect is given by both, PCM and VCR. A study showed that when the car was moving at a low speed or stationary the energy consumption was reduced by 17% due to the PCM [34]. The cold packs or tubes that have PCM within are generally easy to use and don't require a lot of installation.

The PCM materials do have some downsides to them as well. The containers are often not optimized to be used in refrigerated transport and thus it can be hard to place the PCM into the box evenly [23]. The biggest issue however comes from having only one possible temperature, the melting or vaporizing point of the material, and only one duration, the time it takes for the material to melt. This limits the range of temperatures as well as the range of materials that can be used.

5 Minimisation of Transportation-Related Emissions

The International Energy Agency (IEA) [18] expects that replacement of internal combustion engine trucks with those powered with electric batteries and hydrogen fuel cells will signif-

icantly reduce emissions by 2050. The IEA notes that the battery power is more promising for medium-duty trucks taking shorter and regular routes while the hydrogen power is more promising for heavy-duty trucks taking long-haul routes. To achieve reasonable results in emission reduction, the IEA estimates that trucks should be electrified faster. In 2022 only 1.2% of trucks sold worldwide were electric. However, the sale share of electric trucks should increase to 33% by 2030, according to the IEA.

The passive cooling concept described in Section 4.1 holds the potential to lower emissions from cold chain logistics by integrating intermodal transportation. The IEA [1] asserts that transferring freight from road to rail not only improves energy efficiency of transportation but also lowers its emissions. The IEA underscored by the fact that rail transport is uniquely characterised by its extensive electrification, with up to 50% of rail freight transport being electrically powered. Furthermore, the IEA regards trains as the only viable alternative to trucks for land-based transportation. However, refrigerated freight cars are no longer being manufactured in Europe [33], which may significantly hinder the adoption of rail transport in cold chain logistics. The use of cold boxes, as described in Section 4.1, may enable the transportation of perishable products at ambient temperature in conventional cars, including alongside other types of freight.

6   Minimisation of Mismanagement-Related Emissions

Mismanagement of cold chain logistics may lead to inefficient fuel consumption and consequently to higher CO2 emissions. A rough example of poor management may be distributing products one by one. Obviously, it is more efficient to deliver the whole order at once. A similar conclusion may be drawn at the order level: delivering several orders at a time is more efficient than delivering them separately. However, making further decisions might not be that straightforward. For instance, it could be challenging to determine which locations to visit at a time and, more crucially, to decide the sequence in which to tour them. These questions are dealt with in the vehicle routing problem (VRP).

6.1   Modelling the Vehicle Routing Problem for Emission Minimisation

The VRP is thought to be first presented by G. B. Dantzig and J. H. Ramser in 1959 [21], and it is originally formulated as the problem of lessening the total length of distribution routes in a petrol supply network [5]. Namely, the authors suggest an approach to allocate refuelling stations to tankers in accordance with the ability of the tankers to hold demands of the stations.
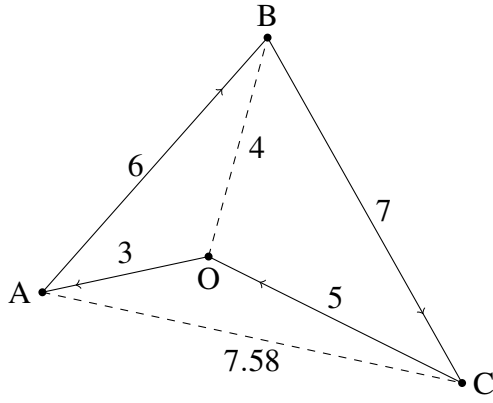
(a) When all customers can be served at a time, the route $O \rightarrow A \rightarrow B \rightarrow C \rightarrow O$ is the shortest one with its length 21. Other routes visiting each location once have lengths 21.58 and 22.58
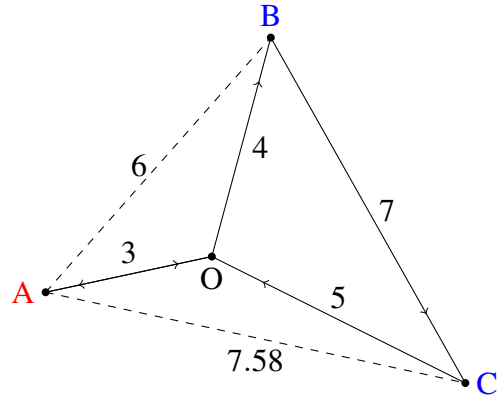
(b) When two customers at most can be served at a time, the route $O \rightarrow A \rightarrow O \rightarrow B \rightarrow C \rightarrow O$ is the shortest one. Its length is 22. Other routes visiting each customer once have lengths 23, 23.58, and 24.

Figure 4: Visual illustrations of the TSP (left) and VRP (right). O represents a distribution centre. A, B, and C represent customers.

Subsequently, they apply the travelling salesman problem (TSP) to each tanker — in other words, rearrange the stations in the visiting order that minimises the length of the tour.

Both TSP and VRP may be represented visually as problems of joining up dots on the paper (see Figure 4). In the TSP the challenge is to loop the dots together such that the length of the loop is a minimum. In contrast, the VRP is a more challenging problem of minimising the total length of loops constructed as follows: First, the points representing customers are identified and labeled with numbers in order to represent their demands. Then, the labeled points are painted with different colours so that the sum of the labeled numbers does not exceed a limit (truck capacity) within any group of dots sharing the same color. Finally, the dot representing the distribution center is looped with each group of points.

The VRP may be reformulated into the problem of minimising CO_2 emissions in a temperature-controlled distribution network when the amount of CO_2 emitted on a route is considered instead of the length of the route [3]. However, this approach complicates the problem due to the following fact: while the shortest path between any two locations is a constant that can be found beforehand, and moreover, is assumed to be known in the original VRP, the minimum amount of CO_2 emitted during a conveyance depends on several factors and cannot be determined with certainty in advance. Some of the challenges are listed below.

- *Load-dependence*: The heavier the freight is the more fuel is consumed for its transportation and consequently more CO_2 emitted [27, 3]. Consequently, the amount of CO_2 being emitted on the path to the customer depends on the order of the customer in the distribution sequence.

- *Vehicle-dependence*: Heterogeneous fleets are originally considered in the context of different capacities of trucks [15]. However, the fuel efficiencies of the trucks may differ as well [27], which may result in different amounts of fuel consumed and CO_2 emitted by different trucks under equal conditions [3].

- *Road-dependence*: The steepness of the road may result in higher fuel consumption and higher emissions [3].

- *Speed-dependence*: Every vehicle has an optimum driving mode that minimises fuel consumption. Inevitable deviations from this during the delivery process increase the amount of emissions per unit of travel. The impact of speed limits on emissions is discussed in [3].

- *Driver-dependence*: Speed fluctuation, especially rapid accelerations and decelerations, may result in higher fuel consumption (emissions) compared to moderate driving [27].

- *Time-dependence*: Travelling during rush hours can significantly affect the speed of the truck resulting in inefficient fuel consumption and higher emissions compared to deliveries during off-peak hours [12].

Many realities further increase the level of complexity of the routing optimisation. For example, limitation of truck drivers' working hours may impose *time windows* – in other words, constraints on delivery times [20]. That is why the most CO_2-efficient routing strategy may prove inappropriate for a practical application and either increasing vehicle speeds or involving more vehicles may be needed.

6.2 Solving the CO2-Oriented Vehicle Routing Problem for Cold Chain Logistics

The CO_2-oriented VRP in temperature-controlled logistics is most commonly solved by means of mathematical optimisation, where the optimisation problem is represented in the form of one or more objective functions and constraints. Consequently, the objective of the problem becomes to either maximise the value of the function (in case of profit) or minimise it (in case of environmental impact), subject to the given constraints. For that purpose, appropriate values are sought for the variables, commonly referred to as decision variables.

The decision variables denote decisions affecting the final characteristics of the model, such as economic, environmental and social impact. In the context of optimizing temperature-controlled transportation with respect to CO_2 emissions, it is common to simultaneously search

for optimal routing, location-allocation, and inventory. These three elements are interconnected so to optimize the model as a whole it is important to look for values of decision variables within a single problem rather then subsequently solve the vehicle routing problem, location-allocation problem, and inventory problem. For example, routing decisions may impact inventory levels, and the placement of facilities (location-allocation) can affect both routing and inventory decisions.

In the field of cold chain logistics, the desired values of the decision variables are most commonly sought using various optimisation techniques, including exact [37, 16, 19], metaheuristic [31, 40, 22, 47, 45, 46, 41, 14], and a combination of both, referred to as hybrid methods [39, 2, 43, 38]. For more details see Table 1. Recent research advancements show a trend towards solving VRPs by means of artificial intelligence, particularly using deep reinforcement learning [26, 44]. However, to the best of our knowledge, this trend has not yet been extensively applied in optimising logistics for temperature-sensitive goods.

7 Conclusion

In this article we showed how the cold chain is a crucial part of today's world and what are it's weak points. However, refrigerated transportation has a considerable impact on the environment and that the current systems need to improve in order to meet the growing needs to reduce emissions while the needs for transportation are growing.

The majority of the systems used currently are Vapour Compression Refrigeration (or VCR) systems. Other common systems is the use of Phase Change Materials, especially when combined with a VCR system to provide extra help. There are also some newer solutions, one of them being well-insulated cold box with a cold-gel mat and a sensor inside. These new innovations and solutions could provide the much needed help to reduce the emissions of cold transportation.

We discussed the optimization of cold transportation by using the Vehicle Routing Problem. The biggest issue with this optimization was that CO2 emissions are not a constant, but depend on the traffic situation and can be drastically changed with an external influence. One of the answers to that problem was to use real-time data about traffic to solve and update the route.

We have shown that the refrigerated transportation is a complex system. It can provide us with a lot of valuable data, that can be used to analyze and optimize the cold chain and refrigerated transport. In the future, it will be vital to use this data to train AI methods, that could be used to further reduce emissions. This will be the next step in our research regarding this topic.

Table 1: A classification of solution approaches used to solve the VRP with respect to CO2 emissions in temperature-controlled transportation.

Applied Method	Method Type			Reference
	Exact	**Metaheuristic**	**Hybrid**	
ε-constraint method	✓			[37, 16]
Revised multi-choice goal programming method	✓			[19]
Cycle evolutionary genetic algorithm		✓		[31, 40]
Particle swarm optimization (standard and modified)		✓		[22]
Many-objective gradient evolution algorithm		✓		[47]
The ribonucleic acid ant colony optimization algorithm		✓		[45]
An improved ant colony algorithm with a multi-objective heuristic function		✓		[46]
An adaptive genetic algorithm		✓		[41]
Non-dominated sorting genetic algorithm II		✓		[14]
Hybrid genetic algorithm (with heuristic rules)			✓	[39]
A matheuristic algorithm based on the iterated local search algorithm and a mixed integer programming			✓	[2]
A variable neighborhood search combined with the non-dominated sorting genetic algorithm II and techniques for order preference by similarity to an ideal solution			✓	[43]
Hybrid solution technique (based on possibilistic linear programming and fuzzy weighted goal programming approach)			✓	[38]

8 Acknowlegements

Appendix A

Let us represent the truck as a multi-body system and consider its kinetic energy as a function of time $K(t)$. Then by examining the system over a time period $[t_0; t_1]$ we can establish the

following relation between the magnitudes $K(t_0)$ and $K(t_1)$, based on the work-kinetic energy theorem:

$$K(t_0) + W = K(t_1) \tag{1}$$

where W is the net work done on the system during the time period $[t_0, t_1]$ under review.

To specify $K(t)$ we can go through all the components of the truck (down to the bolts and nuts), determine each one's kinetic energy and sum the values. With this approach, all of the kinetic energy of the truck will be accounted for if none of the details are missed. Thus, having identified a total of n individual parts of the truck, we may define the kinetic energy of our system as follows:

$$K(t) = \sum_{i=1}^{n} K_i(t),$$

where $K_i(t)$ is a function of time denoting the kinetic energy of ith object.

Now, to calculate $K_i(t)$, we may disregard the elasticity of each object and consider its motion in the way suggested by Chasles' theorem: as a combination of translation of the centre of mass and rotation about an axis passing through the centre of mass. This approach allows us to represent $K_i(t)$ mathematically as a sum of translational and rotational kinetic energies:

$$K_i(t) = \frac{1}{2}m_i v_i^2(t) + \frac{1}{2}I_i \omega_i^2(t),$$

where m_i and I_i are the mass and moment of inertia of ith object, respectively, while $v_i(t)$ and $\omega_i(t)$ are functions of time denoting the translational and angular velocities of ith object, respectively.

To specify W of the Equation 1, we first need to dissect the physical nature of our system. Notably, our system incorporates a heat engine that represents the internal combustion engine of the truck. By definition, a heat engine converts heat into mechanical energy with a certain loss. In our case, this mechanical energy is transferred to our system in the form of work. However, the kinetic energy that the system might acquire as a result of the work is partially lost in the form of heat as a result of internal friction. The loss is difficult to estimate computationally, so we will not consider the work of the motor and that of the internal friction separately. Instead, we will consider the whole powertrain as a heat engine doing work W_p on our system.

15
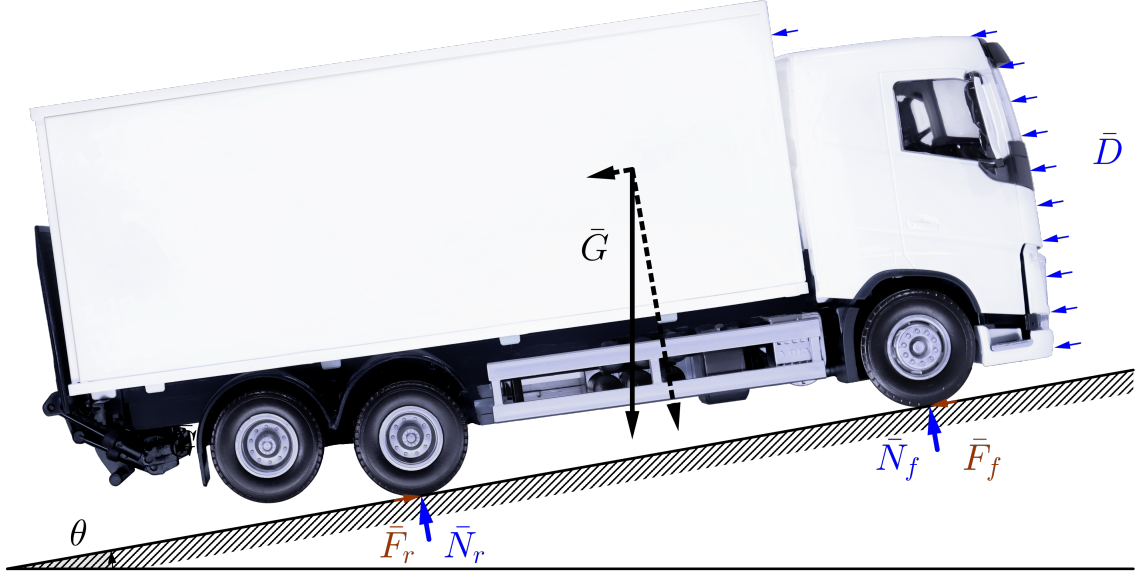
Figure 5: A simplified free-body diagram of a truck accelerating uphills. $\bar{G}$ is the gravity, $\bar{D}$ is the total air drag, $\bar{N}_f$ and $\bar{F}_f$ are the normal reaction force and rolling friction exerting on the right front wheel, $\bar{N}_r$ and $\bar{F}_r$ are the normal reaction force and rolling friction exerting on the right rear wheel, and θ is the angle of inclination of the road.

The rest of the work done on our system may be defined by examining the work done by the forces highlighted in Figure 5:

- W_g due to gravity $\bar{G}$

- W_n due to normal (reaction) force $\bar{N}$

- W_d due to air drag $\bar{D}$

- W_f due to rolling friction (resistance) $\bar{F}$

We note that $W_n = 0$ because the normal reaction force is exerting perpendicularly to the displacement (see Fig. 5). Additionally, since gravity is a conservative force, its work can be written in terms of the corresponding potential energy, gravitational energy:

$$W_g = mg(h(t_0) - h(t_1))$$

where m is the mass of our system, g is the gravitational constant, and $h(t)$ is a function of time denoting the height of the system in relation to a selected potential reference point.

Now we can write down the formula for W (Eq. 1):

$$W = mg\left(h(t_0) - h(t_1)\right) + W_p + W_d + W_f$$

Substituting the formulae of $K(t_0)$, W, and $K(t_1)$ into the equation 1, we obtain:

$$\sum_{i=1}^{n}\left(\frac{1}{2}m_i v_i^2(t_0) + \frac{1}{2}I_i\omega_i^2(t_0)\right) + mg(h(t_0) - h(t_1)) + W_p + W_d + W_f$$
$$= \sum_{i=1}^{n}\left(\frac{1}{2}m_i v_i^2(t_1) + \frac{1}{2}I_i\omega_i^2(t_1)\right)$$

Now we can express from this equation the mechanical energy (work) required from the powertrain:

$$W_p = \sum_{i=1}^{n}\left(\frac{1}{2}m_i(v_i^2(t_1) - v_i^2(t_0))\right) + \sum_{i=1}^{n}\left(\frac{1}{2}I_i(\omega_i^2(t_1) - \omega_i^2(t_0))\right) + mg(h(t_1) - h(t_0)) - W_d - W_f$$

Appendix B

Both TSP and VRP may be formulated in terms of graph theory. Then TSP becomes the problem of defining the Hamiltonian cycle in an arc-weighted graph such that the sum of arc weights in the cycle is a minimum. In contrast, the VRP becomes the problem of partitioning a mixed-weighted[2] complete graph into induced subgraphs[3] and defining in each subgraph a Hamiltonian cycle in the following manner: one vertex (bulk terminal) is common to all subgraphs and yet no other vertex (filling station) is present in more than one subgraph, the total sum of edge weights (mileage) of the cycles is a minimum, and the sum of vertex weights (demands) of each subgraph does not exceed a constant (tanker capacity).

Another challenge of minimising CO2 emissions, as opposed to merely lessening the length of the routes, is the directional aspect of road travel, as illustrated in Figure 6. For route length minimisation, the direction a truck takes on a road does not matter, as the length of the road is invariant to the direction of travel. However, when focusing on CO2 emission minimisation, any substantial altitude differential between two points can significantly influence fuel consumption and, consequently, emission levels. Specifically, the energy consumption surges when ascend-

---

[2]both arc-weighed and vertex-weighed at the same time
[3]to be Hamiltonian as the original graph is complete
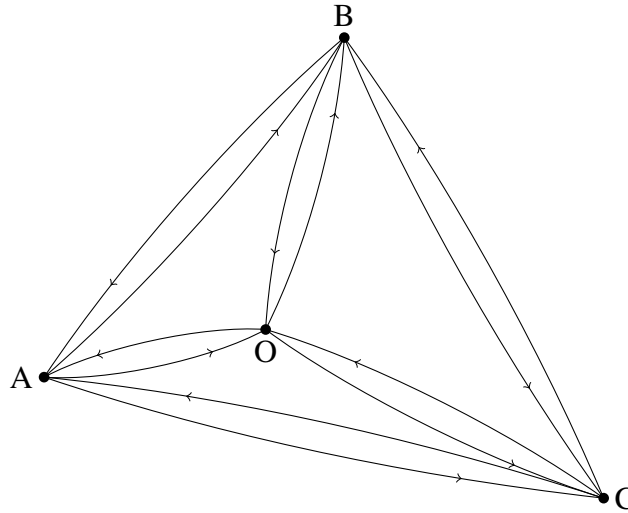
Figure 6: Each arc of the original graph is split into two directed ones.

ing and decreases by the same amount, when descending an incline. This is in contrast to energy consumption on a completely horizontal road.

Another conclusion based on Appendix A is the importance of considering heterogeneous fleets. In the original VRP, the minimisable parameter, the total length of distribution routes, does not depend on the choice of vehicle on the route. Thus, in the original VRP fleet is homogeneous: it is assumed that all tankers have the same capacity, although the case where tankers have different capacities is debated [5]. In contrast, the amount of CO_2 emissions emitted by a carrier on a distribution route is influenced by characteristics of the vehicle such as air dynamics, tire rolling resistance, the efficiency of the drive train and engine and the energy content of the fuel.

To avoid obtaining a trivial solution in which the lowest-emission representative of the fleet is assigned to all distribution routes, the original VRP requires a further complication. Namely, the number of distribution tours that can be assigned to a carrier must be limited. The most reasonable format for the restriction seems to be setting deadlines for the delivery times. Then the lowest-emission truck will be unable to distribute all the orders (commodities) and the other vehicles should be engaged.

When the VRP is solved and trucks are dispatched to their routes, the initial model parameters can change significantly. For example, on the way from one customer to another, there might be a car accident creating a bottleneck effect and reducing the throughput capacity of the road. In such a case, due to the detour around the congested road segment, the initial client visitation plan might become suboptimal. In case of delivering specific orders, the TSP might optimally be re-solved for a particular truck. In case of distributing a singular product to different locations, the VRP may be re-solved in its entirety (see Figure 7b). Here, re-solving the TSP means changing the order of visiting customers by a specific truck, while re-solving the VRP also
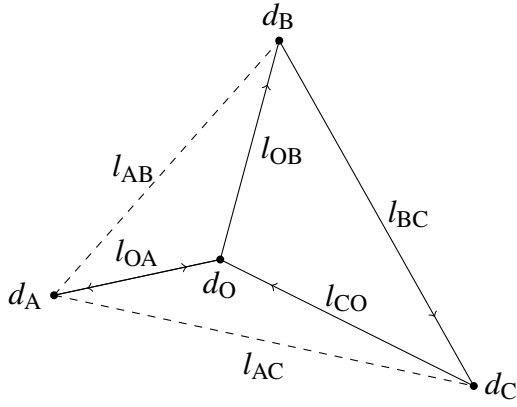
(a) Initial solution of the VRP. The customer C is scheduled to be visited after A.
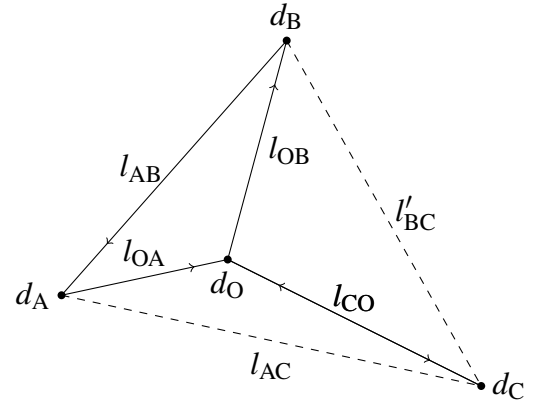
(b) After visiting customer *B*, the VRP is re-solved due to a significant change $l_{BC} \to l'_{BC}$

Figure 7: Geometrical illustration of the real-time routing optimisation.

means changing the distribution of clients among trucks.

References

[1] International Energy Agency. *The Future of Rail*. 2019, p. 175. URL: https://www.oecd-ilibrary.org/content/publication/9789264312821-en.

[2] Mahla Babagolzadeh et al. "Sustainable cold supply chain management under demand uncertainty and carbon tax regulation". In: *Transportation Research Part D-transport and Environment* (2020). DOI: 10.1016/J.TRD.2020.102245.

[3] Tolga Bektaş and Gilbert Laporte. "The Pollution-Routing Problem". In: *Transportation Research Part B: Methodological* 45.8 (2011), pp. 1232–1250. ISSN: 0191-2615. DOI: https://doi.org/10.1016/j.trb.2011.02.004.

[4] Intergovernmental Panel on Climate Change (IPCC). "Anthropogenic and Natural Radiative Forcing". In: *Climate Change 2013 – The Physical Science Basis : Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2014, pp. 659–740. DOI: 10.1017/CBO9781107415324.018.

[5] G. B. Dantzig and J. H. Ramser. "The Truck Dispatching Problem". In: *Management Science* 6.1 (1959), pp. 80–91. DOI: 10.1287/mnsc.6.1.80.

[6] *Designation and Safety Classification of Refrigerants*. ANSI/ASHRAE 34. ISSN: 1041-2336. American National Standards Institute / American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2022.

[7]   Ibrahim Dinçer. *Refrigeration Systems and Applications*. English. 3rd ed. John Wiley & Sons, Incorporated, 2017. ISBN: 9781119230755.

[8]   European Commission. *Reducing CO2 emissions from heavy-duty vehicles*. `https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en`. Accessed: 2023-10-04. 2022.

[9]   European Union. *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 Text with EEA relevance*. Official Journal of the European Union. Retrieved from EUR-Lex. May 2014. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014R0517`.

[10]   Food and Agriculture Organization of the United Nations. *The Future of Food and Agriculture: Trends and Challenges*. Rome, Italy, 2017. ISBN: 978-92-5-109551-5. URL: `https://www.fao.org/agrifood-economics/publications/detail/en/c/471795/`.

[11]   P. Forster et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity". In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by V. Masson-Delmotte et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021, pp. 923–1054. DOI: `10.1017/9781009157896.009`.

[12]   Anna Franceschetti et al. "The time-dependent pollution-routing problem". In: *Transportation Research Part B: Methodological* 56 (2013), pp. 265–293. ISSN: 0191-2615. DOI: `https://doi.org/10.1016/j.trb.2013.08.008`.

[13]   Amit Garg, Kazunari Kainou, and Tinus Pulles. "Chapter 1: Introduction". In: *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Ed. by H.S. Eggleston et al. Vol. 2. Energy. Japan: IGES, 2006.

[14]   Amin Gharehyakheh et al. "A multi-objective model for sustainable perishable food distribution considering the impact of temperature on vehicle emissions and product shelf life". In: *Sustainability (Switzerland)* 12.16 (2020). DOI: `10.3390/su12166668`.

[15]   Bruce Golden et al. "The fleet size and mix vehicle routing problem". In: *Computers and Operations Research* 11.1 (1984), pp. 49–66. DOI: `10.1016/0305-0548(84)90007-8`.

[16]   Maryam Golestani et al. "A Multi-Objective Green Hub Location Problem with Multi Item-Multi Temperature Joint Distribution for Perishable Products in Cold Supply Chain". In: *Sustainable Production and Consumption* 27 (2021), pp. 1183–1194. DOI: `10.1016/j.spc.2021.02.026`.

[17] High Level Panel of Experts on Food Security and Nutrition. *Food losses and waste in the context of sustainable food systems*. Report. Rome: Committee on World Food Security, 2014.

[18] International Energy Agency (IEA). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.* `https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach`. License: CC BY 4.0. Paris, 2023.

[19] Javid Jouzdani and Kannan Govindan. "On the sustainable perishable food supply chain network design:A dairy products case to achieve sustainable development goals". In: *Journal of Cleaner Production* (2021). DOI: `10.1016/J.JCLEPRO.2020.123060`.

[20] A. L. Kok et al. "A Dynamic Programming Heuristic for the Vehicle Routing Problem with Time Windows and European Community Social Legislation". In: *Transportation Science* 44.4 (2010), pp. 442–454. DOI: `10.1287/trsc.1100.0331`.

[21] Gilbert Laporte. "Fifty Years of Vehicle Routing". In: *Transportation Science* 43.4 (2009), pp. 408–416. DOI: `10.1287/trsc.1090.0301`.

[22] Yan Li, M. Lim, and M. Tseng. "A green vehicle routing model based on modified particle swarm optimization for cold chain logistics". In: *Ind. Manag. Data Syst.* (2019). DOI: `10.1108/IMDS-07-2018-0314`.

[23] Angelo Maiorino, Fabio Petruzziello, and Ciro Aprea. "Refrigerated transport: State of the art, technical issues, innovations and challenges for sustainability". In: *Energies* 14.21 (2021). DOI: `10.3390/en14217237`.

[24] J.B.R. Matthews et al. "Annex VII: Glossary". In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by V. Masson-Delmotte et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021, pp. 2215–2256. DOI: `10.1017/9781009157896.022`.

[25] Soheil Mohagheghi Fard and Amir Khajepour. "An optimal power management system for a regenerative auxiliary power system for delivery refrigerator trucks". In: *Applied Energy* 169 (2016), pp. 748–756. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2016.02.078`.

[26] Taukekhan Mustakhov, Yernar Akhmetbek, and Aigerim Bogyrbayeva. "Deep Reinforcement Learning for Stochastic Dynamic Vehicle Routing Problem". In: 2023. DOI: `10.1109/ICECCO58239.2023.10147154`.

[27] National Research Council. *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*. Washington, DC: The National Academies Press, 2010. DOI: `10.17226/12845`. URL: `http://nap.nationalacademies.org/12845`.

[28] The United Nations. URL: https://news.un.org/en/story/2023/12/1144742.

[29] Agnes Poks et al. "Wholistic simulation of an all-electric refrigerated delivery vehicle". In: 2020, pp. 1–6. DOI: 10.23919/SICEISCS48470.2020.9083498.

[30] Jukka Proskin. *Method for temperature controlled transport*. EP 2 494 293 B1. European Patent Office. Oct. 2020.

[31] Gaoyuan Qin, Fengming Tao, and Lixia Li. "A Vehicle Routing Optimization Problem for Cold Chain Logistics Considering Customer Satisfaction and Carbon Emissions." In: *International Journal of Environmental Research and Public Health* (2019). DOI: 10.3390/IJERPH16040576.

[32] Ashika Rai and Savvas A. Tassou. "Environmental impacts of vapour compression and cryogenic transport refrigeration technologies for temperature controlled food distribution". In: *Energy Conversion and Management* 150 (2017), pp. 914–923. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2017.05.024.

[33] Air Conditioning Refrigeration and Heat Pumps Technical Options Committee (RTOC). "Transport refrigeration". In: *2022 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee: 2022 Assessment*. United Nations Environment Programme, 2022, pp. 125–136. ISBN: 978-9914-733-93-8. URL: https://ozone.unep.org/system/files/documents/RTOC-assessment%20-report-2022.pdf.

[34] Seyed Ehsan Shafiei and Andrew Alleyne. "Model predictive control of hybrid thermal energy systems in transport refrigeration". In: *Applied Thermal Engineering* 82 (2015), pp. 264–280. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.2015.02.053.

[35] Xiaohui She et al. "Energy-efficient and -economic technologies for air conditioning with vapor compression refrigeration: A comprehensive review". In: *Applied Energy* 232 (2018), pp. 157–186. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2018.09.067. URL: https://www.sciencedirect.com/science/article/pii/S0306261918313734.

[36] C. Smith et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material". In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by V. Masson-Delmotte et al. Intergovernmental Panel on Climate Change, 2021. URL: https://www.ipcc.ch/.

[37] Mehmet Soysal, Jacqueline M. Bloemhof-Ruwaard, and J.G.A.J. van der Vorst. "Modelling food logistics networks with emission considerations: The case of an international beef supply chain". In: *International Journal of Production Economics* (2014). DOI: 10.1016/J.IJPE.2013.12.012.

[38] Erfan Babaee Tirkolaee and Nadi Serhan Aydın. "Integrated design of sustainable supply chain and transportation network using a fuzzy bi-level decision support system for perishable products". In: (2022). DOI: 10.1016/J.ESWA.2022.116628.

[39] Songyi Wang, Fengming Tao, and Yuhe Shi. "Optimization of Location-Routing Problem for Cold Chain Logistics Considering Carbon Footprint." In: *International Journal of Environmental Research and Public Health* (2018). DOI: 10.3390/IJERPH15010086.

[40] Songyi Wang et al. "Optimization of Vehicle Routing Problem with Time Windows for Cold Chain Logistics Based on Carbon Tax". In: (2017). DOI: 10.3390/SU9050694.

[41] Ziqi Wang and P. Wen. "Optimization of a Low-Carbon Two-Echelon Heterogeneous-Fleet Vehicle Routing for Cold Chain Logistics under Mixed Time Window". In: *Sustainability* (2020). DOI: 10.3390/SU12051967.

[42] World Health Organization. *Burden of disease from environmental noise – Quantification of healthy life years lost in Europe*. 2011. URL: https://www.who.int/publications/i/item/9789289002295.

[43] Daqing Wu et al. "Research on the Time-Dependent Split Delivery Green Vehicle Routing Problem for Fresh Agricultural Products with Multiple Time Windows". In: (2022). DOI: 10.3390/AGRICULTURE12060793.

[44] James J. Q. Yu, Wen Yu, and Jiatao Gu. "Online Vehicle Routing with Neural Combinatorial Optimization and Deep Reinforcement Learning". In: *IEEE Transactions on Intelligent Transportation Systems* 20.10 (2019), pp. 3806–3817. DOI: 10.1109/TITS.2019.2909109.

[45] Li-Yi Zhang et al. "Low-carbon cold chain logistics using ribonucleic acid-ant colony optimization algorithm". In: *Journal of Cleaner Production* (2019). DOI: 10.1016/J.JCLEPRO.2019.05.306.

[46] Banglei Zhao et al. "Cold Chain Logistics Path Optimization via Improved Multi-Objective Ant Colony Algorithm". In: *IEEE Access* (2020). DOI: 10.1109/ACCESS.2020.3013951.

[47] Ferani E. Zulvia, Ren-Jieh Kuo, and Dwiyanti Y. Nugroho. "A many-objective gradient evolution algorithm for solving a green vehicle routing problem with time windows and time dependency for perishable products". In: *Journal of Cleaner Production* (2020). DOI: 10.1016/J.JCLEPRO.2019.118428.