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Review

The Current State and Future of the Urban Cold Chain: A Review of Algorithms for Environmental Optimization

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Abstract: Cold chains are essential in providing people with food and medicine across the globe. As the global environmental crisis poses an existential threat to humanity and societies strive for more sustainable ways of life, these critically important systems need to adapt to the needs of a new era. As it is, the transportation sector as a whole accounts for a fifth of global emissions, with the cold chain being embedded in this old fossil-fuel-dependent infrastructure. With the EU is passing regulations and legislation to cut down on emissions and phase out polluting technologies like combustion engine vehicles, the next couple of decades in Europe will be defined by rapid infrastructural change. For logistics and cold transportation, this shift presents many opportunities but also highlights the need for innovation and new research. In this literature review, we identify pressing issues with the current urban cold chain, review the recent research around environmental optimization in urban logistics, and give a cross-section of the field: what the trending research topics in urban logistics optimization across the globe are, and what kind of blind spots are identifiable in the body of research, as well as changes arising with future green logistics infrastructure. We approach the issues discussed specifically from the point of view of refrigerated urban transportation, though many issues extend beyond it to transportation infrastructure at large.

Keywords: cold chains; environment; transportation; refrigerated transportation; optimization; algorithms; literary review

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1. Introduction

Food and medicine are vital to humans everywhere on the planet. However, their transportation is not easy, since most food and medicine spoil or degrade quickly if not refrigerated, with medicine often requiring very specific storing temperatures. This continuous chain from production to the consumer in a controlled temperature environment is called the cold chain. The cold chain is often difficult to maintain, requiring storage, transfer, and delivery, with the minimal or zero exposure of products to warmth. This logistics chain currently requires a lot of energy and resources, a lot of which are wasted in the process. Trucks that are specifically made to accommodate these refrigerated products are generally inefficient with their energy use, emitting significantly more greenhouse gases and air pollutants than their non-refrigerated counterparts. Some further issues associated with road-based cold transport vehicles' poor environmental performance are noise pollution, air pollution, tire microplastics, and the refrigerants used in the cooling process, which all contribute to adverse health effects for both humans and natural ecosystems. On top of that, they are often dependent on the traffic conditions of the local environment, which can be highly unpredictable due to car accidents, road works, and weather conditions. These problems are especially present in cities with much traffic and unoptimized transportation planning. Urban cold chains not only can, but must, be made more efficient. This shift in both will and need is evidenced by the EU instatement of a ban on all but zero-emission road vehicles by 2035 [1] and demanding increasing cuts to emissions across all sectors of society [2].

In this literature review, we summarize the current state of urban cold transportation from the perspective of environmental performance and efficiency, review the current optimization methods found in the literature and outline future directions for urban cold transportation research. Section 2 discusses the current shortcomings of, and problems within, the cold chain, putting into numbers the economic and environmental damage caused by cold chain failures, as well as the level of pollution in the current cold chain. In Section 3, we identify aspects of the cold chain that can be optimized to decrease its environmental impact and discuss different methods of, and approaches to, optimization. In Section 4, we discuss the future of urban infrastructure and how the phasing out of urban automobility affects the planning and optimization of logistics and cold transportation. Conclusions are drawn in Section 5, followed by a list of references.

2. Shortcomings of Urban Cold Transportation

As it is, road transportation is responsible for 15% of global greenhouse gas (GHG) emissions, with road freight accounting for nearly 6% of global GHG emissions; this is more than the emissions produced by all aviation, shipping, and rail traffic combined, which amount to around 4.6% of global emissions [3]. There is a lack of literature estimating the GHG emissions of refrigerated transportation specifically, as required environmental data on companies' operations is scarce, though some sources mention figures: the US government [4], for example, estimates that cold transport vehicles consume around 20% more fuel than standard road vehicles, and a literature review on cold chain management [5] asserts that cold transport accounts for around 1% of global GHG emissions, noting that in developed countries, the share is even higher; for the United Kingdom, the figure is 3.5%. Though various figures are thrown around, there is a consensus in the field that refrigerated vehicles, still mostly relying on diesel engines to power their refrigerated units (RU), consume significantly more fuel than their non-refrigerated counterparts. Increased fuel consumption means that inefficiencies in urban road traffic—mainly congestion and idling in traffic—are also worse when it comes to refrigerated transportation. Similarly, the noise and air pollution caused by refrigerated transportation in urban areas can be greater than for other traffic, as the added fuel consumption leads to more exhaust fumes and the generators often used to power RUs are very loud. Also problematic from an optimization point of view is that nighttime is often the most fuel-efficient time of day to make deliveries as traffic is low; however, noise pollution at this time is at its most harmful as it can negatively impact people's sleep quality.

In addition to the vehicles themselves, there are some other environmental considerations to make relating to refrigeration within the cold chain. A Chinese research paper [6] modeling different scenarios regarding the development of GHG emissions in the Chinese cold chain found that, in all scenarios, warehousing accounted for over 85% of cold chain operations' emissions due to the high energy consumption of refrigerated storage. This notion makes clear that it is also essential to consider the wider energy infrastructure surrounding cold transportation, as switching to renewable energy alone could eliminate most of the emissions of cold chain operations. Refrigeration in cold transport vehicles could also be improved significantly regarding sustainability. The refrigerants used in cold transport RUs often have high global warming potential (GWP), which means their lifetime environmental impact is high even though their in-use impact might be low. Additionally, as the cargo space of a cold transport vehicle is often just a single cooled space, loading and unloading can waste significant amounts of energy in repeatedly exposing the cooled space to warm outside air.

Exposure to outside temperatures, as well as the breakdown or malfunction of a cold transport vehicle or its RU, cause quality degradation or the spoilage of the perishable goods being transported. Today, 13% of all globally produced food or about 720 million tons is lost during transportation each year [7]. In 2018, the production of this lost food alone was responsible for nearly 4% of global GHG emissions [8]. A 2021 study [9] found that studies and data collection about food loss during supply chains are still somewhat underdeveloped. It is thus difficult to estimate how much food is lost during cold transportation specifically, but a wider estimate states that more than a fifth of all food wastage can be attributed to loss due to failures in, or the lack of, cold chains [10]. Medicines similarly degrade and spoil in the absence of proper refrigeration, but they often have significantly higher production costs than food, and their wastage can deprive people of healthcare. It is, again, difficult to find any statistics on wasted or lost medicine, and some figures have turned out to be unreliable. Still, medicine waste during cold transportation is bound to be similar or greater than that of food, as the temperature requirements of different medicines are often precise or extreme, making successful cold delivery significantly more challenging. It needs to be said that the degree of refrigeration during cold transport can also be excessive; that is, a product's quality is maintained as well or better with less cooling. This wastes energy and, similarly to inadequate refrigeration, can lead to product degradation.

3. Solutions for Different Points of Optimization in Urban Cold Transportation

As evidenced by Section 2, cold transportation has many shortcomings. Building on the noted issues, this section identifies the different facets of environmental and performance optimization in urban cold transportation and examines the spectrum of optimization solutions appearing in the current logistics and cold transportation research literature.

3.1. Points of Optimization

Most research on environmental optimization in the urban cold chain fundamentally focuses on GHG emissions. The main emissions from urban cold transportation can be divided into fuel/energy emissions, food and medicine waste emissions, and equipment lifetime emissions. Although equipment and fuel consumption are closely associated, it is easier from an optimization perspective to consider fuel and energy emissions as equipment-specific optimizations and emission reductions caused by, for example, switching the delivery vehicle from an ICEV to an EV, as affecting equipment lifetime emissions.

There are different kinds of algorithmic optimization methods for each of these emission categories. For the fuel or energy consumption of operations, the most significant algorithmic optimizations have to do with routing. Emissions in the form of degraded and discarded goods need to be tackled from multiple angles, as product degradation can arise both when hardware is working as intended and when breakdown occurs. In the former case, algorithms are needed for modeling the behavior of perishable goods in different conditions to improve current cooling technology. As for the breakdown or malfunction of devices, predictive algorithms can be utilized to both predict when the cooling device will need maintenance and to minimize the damage when equipment failure does occur by detecting it early. Life cycle assessment typically does not involve algorithms but, when in possession of these lifetime emission estimates, algorithms can be used to analyze the data to find the optimal measures to enhance the environmental performance of a given fleet in a given economic frame.

Lastly, the degree of resource utilization of a cold transport operation can also significantly affect its final emissions. It is a common problem for trucks to be driven half empty due to the temperature constraints of products, combined with a limited demand for one type of product; this means that transport potential is left unused, leading to greater emissions. Although the equipment in use can also significantly affect the degree of utilization, packing problems are an algorithmic way to optimize the contents of each truck to achieve a higher degree of resource utilization.

Additionally, it is important to note that urban logistics and cold transportation exist within the wider urban transportation network. Congestion is a ubiquitous problem in these urban traffic environments, and logistics and cold transportation—which often have tight delivery schedules—are not immune to these challenging traffic conditions, with unpredictable changes caused by traffic accidents and construction. Traffic prediction using real-time data can be added to routing algorithms to make them more accurately reflect travel times in the dynamic traffic system. Congestion can be alleviated with improvements to general traffic infrastructure, which can algorithmically be achieved by, for example, introducing smart traffic fees for the use of specific roads or parking, or smart traffic lights.

3.2. Overview of Solutions Found in Current Logistics Literature

Topical logistics and cold transportation research present a variety of technical as well as algorithmic solutions. The most researched types of algorithmic solutions relevant to the optimization of urban cold transportation are route optimization and traffic prediction.

Routing optimization is carried out using different variations of the Vehicle Routing Problem. Most solutions to different VRPs relevant to urban logistics are different variations and combinations of the annealing algorithm, variable neighborhood search and genetic algorithms. Most of the algorithms include some variation of variable neighborhood search. Below is Table 1, in which solutions to relevant variations of the VRP found in the current literature are presented. We can see that variations of Green VRP are quite well covered in the research.

Table 1. Different algorithms proposed as solutions to different variations of VRP and relevant to the maintenance of the cold chain in urban areas while reducing emissions.

Proposed Algorithm	**Variable of VRP Present in the Problem**					
	Green	**Multi-Depot**	**Time-Dependent**	**Split Delivery**	**Multiple Time Windows**	**Other**
Hybrid simulated annealing and tempering algorithm [11]	X	-	X	-	-	-
Simulated annealing algorithm with a joint distribution model [12]	X	-	-	-	-	Joint Distribution
Genetic algorithm [13]	X	X	-	X	-	Multi-Tour
General Variable Neighborhood Search method/Tabu Search [14]	X	X	-	-	-	-
Variable neighborhood search combined with a non-dominated sorting genetic algorithm II [15]	X	-	X	X	X	-
Hybrid Butterfly Optimization Algorithm [16]	X	-	-	-	-	-
Hybrid Evolutionary Algorithm [17]	X	X	-	-	-	-
Hybrid adaptive large neighborhood search with tabu search [18]	-	-	X	-	X	Duration-minimizing
Adaptive large neighborhood search combined with variable neighborhood descent [19]	-	-	X	-	X	Multi-Trip
Ant Colony Optimizer [20]	-	-	-	-	-	Drones

The complement to route optimization is traffic prediction and control, which can be applied in the whole of urban transportation. In Table 2, different solutions to traffic prediction and traffic control are presented. The solutions remain in many cases quite theoretical, as the implementation of these methods is not discussed in most papers.

Table 2. Different algorithms proposed as solutions to predict or control traffic and how they would be applied.

Proposed Algorithm	Traffic Prediction	Traffic Control	Where/How Is It Applied?
Stacked Autoencoder [21]	X		
DNN-BTF [22]	X		
Ant Colony Optimizer [23,24]		X	Via Internet of Vehicles
Bee Colony Optimizer [25,26]		X	
Adaptive algorithm in a smart traffic light [27]		X	In the traffic light
Two-stage hybrid algorithm [28]	X		When the refrigerated truck is finding the optimal route

In the other optimization areas identified, algorithmic solutions specifically for the optimization of environmental performance are significantly fewer in number. Table 3 contains examples of such current algorithms, but many more gaps are identified.

The economic effects of the degradation of goods during cold transport have been modeled by first using a set of first-order linear differential delay equations to model the development of the degradation process and then by adding a feedback control to represent the slowing of degradation by cooling, and finally by finding the optimal case for a set financial criterion, such as minimal costs [29]. To the authors' knowledge, this method has not been implemented in environmental optimization, although algorithms for preventing degradation do exist.

Considering the urban freight fleet composition problem, green variants that reduce the life cycle emissions of fleets do not presently exist, though the data and methodologies are available. However, some algorithmic solutions to reducing the environmental impact of urban freight fleets do exist, examples of which are presented below.

Notably, we were unable to find research combining route and load optimization for freight fleets. The optimization of fleet-wide operations should be investigated further in the future.

Table 3. Different solutions for minimizing the emissions of refrigerated transport in urban areas.

Solution	Type of Solution	Problem
Extended load-dependent vehicle routing problem [30]	New type of model for solving VRP	VRP that specifically includes refrigeration-related emissions
Random forest regressor and decision tree regressor [31]	Machine learning algorithms used to optimize vehicle characteristics based on temperature and humidity in time to reduce product degradation.	The humidity and temperature fluctuate in cold transport vehicles, causing perishable goods to spoil.
Multi-vehicle cooperative bin packing problem [32]	Determines packing order of goods between multiple vehicles to increase space utilization.	Vehicles are not packed optimally, resulting in less efficient operations and more emissions.
Real-time anomaly detection [33]	Sends out an alert if the perishable goods in transport are in danger of spoiling due to temperature fluctuations.	The temperature fluctuates in cold transport vehicles, causing perishable goods to spoil
Anomaly prediction using big data [34]	Algorithmic data analysis to identify and predict reasons for the spoilage of goods	A variety of reasons can cause the temperature of a refrigerated vehicle to diverge from the required bounds, leading to the spoilage of goods.

Table 3. *Cont.*

Solution	Type of Solution	Problem
Truck utilization rate evaluation based on agent modeling [35]	Simulation of freight operations and regression analysis of the data to find conditions of maximum fleet utilization.	A fleet may collectively spend a big percentage of its life cycle parked rather than in operation, meaning that the whole fleet is not needed.
Integrated mixed vehicle routing problem with time window and fleet replacement model [36]	A set of various algorithmic methods to aid in the planning of an urban freight fleet containing both EVs and ICEVs.	Replacing ICE delivery vehicles with more environmentally friendly electric delivery vehicles is often complicated, requiring significant upfront investment and routing considerations.
Predictive maintenance algorithms [37]	Algorithms to predict the need for maintenance	A refrigerated vehicle or its RU breaking down can result in the whole cargo perishing. It cannot be assumed that the optimal time interval between maintenance remains constant.
Artificial bee colony optimizer [38]	Route optimization with variables for food degradation	The degradation of perishable products during transportation
Sustainable inventory model [39]	A mathematical model that includes the decay of the products as a main factor	The degradation of perishable products during transportation

Aside from the identified optimization areas, it is relevant to note that the global market environment affects the capacity of a company to execute its operations efficiently and reliably, meaning that the environmental performance of a cold chain operation is also significantly affected by the markets surrounding them. While the resilience of cold chains has been studied in both business-as-usual [40] as well as exceptional [41] circumstances, the goal of these studies has historically been primarily to identify ways to prevent operation disruptions and economic losses. A literature review of cold chain management [5] found that while food cold chains are globally trending towards adopting sustainable practices, this is mostly taking place in developed countries. Research is needed on the resilience of sustainable cold chain operations, that is, the ability of a company to keep up their operations not only without disruptions but also while fulfilling sustainability requirements, as well as on making the sustainable technologies used in cold transportation more accessible to developing nations.

4. Logistics and Cold Transportation in Future Green Cities

Most optimization solutions presented so far in this paper presume a car-based infrastructure, as that is the prevalent state of transportation infrastructure today. This will not likely remain so: by now, it has been widely proven that automobility and car-based infrastructure is harming humanity across multiple different facets of health and wellbeing [42]. Rail transport on the other hand is tremendously clean compared to road transport and more efficient at transporting large numbers of people than cars. Despite this, the transition away from car-based infrastructure is posing to be a great challenge. In addition to the costs of encouraging a massively car-dependent infrastructure network to rely on other modes of transport, the car industry has significant power over transportation politics and has managed to create a cultural significance around automobility [43]. Although any significant modal shift is being stifled by car industry lobbying, interest towards, and demand for, alternative methods of transportation is increasing. The EU transport sustainability goals include shifting to cleaner modes of transportation such as rail and inland waterways. Many European cities are improving public transportation and promoting active forms of mobility such as cycling and walking through better infrastructure [44]. Many European cities have also declared car-free zones independent of EU targets [45–47] as a response to the demand for cleaner, quieter, pedestrian and biker-friendly urbanity.

It needs to be said that although the EU has set ambitious targets for increasing the modal share of rail transportation in freight and passenger transport—such as the tripling of European high-speed rail by 2030 [48]—it is not on path to meet those targets. A significant majority of European states have had their rail networks shrink within the last few decades, many losing a quarter or more of their operating rail routes since 1950 [49]. Between 1996 and 2016, the modal distribution of passenger and freight traffic saw practically no change but for a slight increase in the share of road transportation [49]. Significantly greater investment in rail infrastructure is needed to increase the modal share of rail in freight, though the difficulty of procuring this investment is unsurprising when we take into consideration the car industry's grip on politics and our society [43]. This barrier may well be overcome in the coming years, as science has already unequivocally shown automobility's harmfulness to human health and wellbeing, as well as the environment [42].

Although the bulk of our transportation infrastructure may stay car-dependent for decades to come, cities are the forerunners in future green mobility solutions. As urban transportation infrastructure pivots away from automobility, the optimization methods and solutions for road-based logistics and cold transportation will inevitably be suboptimal for modeling the new system. If last-mile delivery in city areas free of passenger car traffic continues to be carried out by, say, electric road vehicles, many of the optimization methods presented in Section 3 will remain relevant, but require readjusting to new modes and networks of traffic—likely more predictable ones—if dominated by public transportation. However, if urban logistics and cold transport are to shift to reduced or zero car dependency in some urban areas, a whole new approach to optimizing urban transportation is needed.

Underground and Co-Modal Urban Logistics Systems

In areas of great population growth and high demand for new living space, whole new cities and urban areas are being built from scratch. While old cities of the world are universally vexed by the planning constraints placed on them by infrastructure and zoning made for a bygone era, a modern, newly built city has no such constraints. In China, as new cities are being built, we are seeing a shift in research towards underground logistics systems (ULSs) [50]. The excavation of predominant ULS pathways—to act as a city's veins and arteries for goods—is significantly easier and less costly when there is not yet above-ground or other below-ground infrastructure impeding the construction. The shape of the new city can be planned to support the ULS, meaning systems like this, although still challenging to implement, become more viable economically. Although the interest in and demand for ULSs is growing, planning and constructing them still poses a great challenge, and there is little data on their implementation [50].

An especially promising type of ULS for future green cities is the metro-based ULS (M-ULS), which is also a promising form of co-modal—that is, passenger combined with freight—urban transport. In a M-ULS, the underground infrastructure is predominantly rail—as opposed to, for example, road traffic tunnels—and works to synergistically transport both passengers and goods within the city. Not only has this metro system been shown to have high potential for freight, but a modern M-ULS system would aid a city in all areas of sustainability—economic, social, and environmental [51]. An existing city's metro network can also be transformed into a M-ULS, but the network will need to be expanded in order to guarantee that it acts as a functional hybrid transportation system [51].

Systems like M-ULS need custom optimization methods. As M-ULS infrastructure is being built and expanded, ways to calculate the best shape and structure for the network are needed. One method for M-ULS planning first evaluates the underground freight volume, calculates the optimal location–allocation of nodes, and lastly utilizes a hybrid of E-TOPSIS, the exact algorithm, and the heuristic algorithm to achieve the final result [52]. Another study uses a M-ULS network location–allocation-routing fuzzy random programming model with a crisp linearization method and carries out combinatorial optimization utilizing a discrete binary chaos particle swarm optimization–genetic algorithm in conjunction with exact algorithms [49]. A metro-based last-mile delivery system was also proposed by

Galbiati [53] using multiple unnamed custom algorithms, a genetic TSP algorithm, and a courier management algorithm. This shows that although research on M-ULS optimization exists, it is still scarce and dominated by Chinese research. A Chinese literature review [54] on the topic also found that, as it is, ULS and M-ULS research is still on a highly theoretical level, and rarely discusses aspects of engineering and application.

Other types of co-modal urban transportation systems are also being researched, but they do not have nearly as much research effort being put into them as M-ULS, with both their variety and volume being quite low. For example, all short-haul co-modal transportation projects—the ones most relevant to urban transportation—ongoing in 2023 were tram projects [55]. Although the number of papers on co-modal tram transport is quite low, optimization and modeling frameworks for this form of operation still exist [56,57].

Though the implementation of urban co-modal transportation systems is not without difficulty, a literary review of urban co-modality studies found that co-modality is held as a promising way to reduce congestion and pollution in city centers, and that it could synergistically benefit both freight and passenger transport, if done correctly [55]. Organizational and institutional challenges were seen as a greater obstacle to implementing co-modal urban transportation than technical challenges [55]. Co-modal urban transportation is still clearly in its infancy, and there are many unknowns. This area of research holds much future promise, especially as the European Commission is funding research into affordable freight decarbonization [58].

5. Conclusions

The decarbonization of cold transportation is likely to pick up speed in the coming years as the EU decarbonizes its traffic infrastructure. Though in its current loosely regulated state cold transportation is still a significant contributor to urban air and noise pollution, as well as to global warming, this review shows that wide range of research is aiming to improve the efficiency and reduce the emissions of logistics and cold transport operations. Notably, a significant number of green logistics solutions remain theoretical—for green logistics systems in many cases are also highly particular and non-generalizable—and require further research and data collection to create standards for implementation.

Of the optimization methods available in the current green logistics literature, routing algorithms are by far the most common. The application of algorithmic solutions in traffic control and prediction—a tightly related area of research—also appear abundantly in green mobility papers. The individual problems associated with environmental optimization within cold transportation are in themselves often very intensive computationally, which is likely why there is practically no research investigating the optimization of a local urban cold transportation system as a whole. Such a piece of research would need to apply routing problems solved on the level of individual vehicles to a whole fleet of cold transport vehicles, finding the optimal routes and the optimal packing of goods between those trucks so that the best routes can be used. Any solution like this would likely not be practical for rapidly changing delivery conditions—like the contents and scheduling of deliveries—as the computation would be too slow; however, for more static operations, this kind of research could mark a shift to system-scale problem solving. Other system-level problem solving, like optimizing the quality and environmental impact of equipment while maintaining the medium- and long-term profitability of operations, will likely become a greater trend in the future too.

As for the future of urban logistics, there are two competing paths before us. The automobile industry has enormous political and societal sway over the decisions being made about the future of transportation infrastructure. The EU has also stated that the future of green mobility lies in electric vehicles. Despite this, many European cities have become, to some degree, disillusioned with automobility and are restricting personal car use in favor of better public transportation and active mobility infrastructure, such as that for cycling and walking. In China, we can see a strong trend towards automobile-free infrastructure in the form of ULS research, with co-modal M-ULS often being highlighted as a potential sustainable and efficient solution for both urban logistics and passenger mobility. Elsewhere in the world, short-haul co-modal freight is, for now, completely limited to tram projects, of which most have only been trials. It is evident that the barriers to co-modal urban transportation are political and bureaucratic in nature, not technological. As much of ULS and co-modal urban freight research remains theoretical, with very few successful implementations and a lack of real-world data, trials and public investment are needed to fully realize the potential of future green logistics research.

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