MIT Center for
Transportation &
Logistics

Operational and tactical levers to reduce carbon emissions in temperature-sensitive freight transportation for pharmaceuticals

Jonas Lehmann, Matthias Winkenbach, Milena Janjevic
MIT Center for Transportation and Logistics

August 2023

Contact

MIT Center for Transportation and Logistics
MIT E40, Floor 2
1 Amherst Street
Cambridge, MA 02142
ctl.mit.edu

Acknowledgement

MIT CTL thanks SkyCell AG for their support in creating this report.

Summary

Carbon emissions are surging worldwide, with mounting political targets and shareholder pressure driving decarbonization efforts across all sectors. The temperature-sensitive pharmaceutical industry is particularly carbon-intensive, partly due to its reliance on carbon-intensive air transport. As pharmaceutical companies predominantly outsource transportation services, they have become increasingly interested in understanding how to minimize emissions from shipping their goods. Consequently, we introduce a carbon estimation and allocation tool tailored to cold-chain logistics for pharmaceuticals, addressing several unique aspects not considered in previous studies, such as incorporating network-level emissions for cooling container provision and a more granular approach for estimating transportation emissions. Applying the tool to a series of case studies, we discover that cooling containers with a lower weight and a higher ratio of usable interior volume to outer container volume have a lower carbon footprint, primarily due to reduced emissions from airfreight. In addition, the optimal container choice depends on the shipment size to maximize the container fill rate. Moreover, the provisioning of cooling containers to alleviate network imbalances via maritime or airfreight should be thoroughly assessed, as it may significantly increase a shipment's carbon emissions.

1 Introduction

End of March 2023, the Intergovernmental Panel on Climate Change (IPCC) issued another dire outlook on irreversible losses and damages to nature and people caused by human-induced climate change (Lee et al., 2023). The IPCC report reiterates the importance of immediate action to limit global warming to close to 1.5 °C in the near-term to substantially reduce projected losses and damages related to climate change. As a result, carbon emissions need to be curbed across all industries and sectors.

One sector that has received relatively little attention on curbing carbon emissions, is the pharmaceutical sector (Belkhir and Elmeligi, 2019). The healthcare and pharmaceutical sectors are corner stones for the well-being of modern societies, and inhibit a high carbon emissions footprint. Karliner et al. (2019) estimate the health care's climate footprint to be around two gigatons of CO_2-equivalent, representing 4.4% of global net emissions. Of these, around 200 megatons of CO_2-equivalent, are estimated to be assigned to the global biotechnology and pharmaceutical industry (Connelly et al., 2021), which as a result has a $>$50% higher carbon intensity than the automotive industry (in 2015) (Belkhir and Elmeligi, 2019). Moreover, Belkhir and Elmeligi (2019) suggest a disparate set of environmental practices within the industry as the Top-15 pharmaceutical companies have a greater variability than the compared Top-10 automotive companies. At the same time, the pharmaceutical sector is predicted to grow rapidly over the next decade, with growth rates of over 10% per year (Grand View Research, 2021).

This high carbon intensity paired with the rapid and ongoing growth of the pharmaceutical and biotechnology sector calls for increased efforts to reduce emissions (Milanesi, Runfola, and Guercini, 2020), in particular since the majority of companies within the biotechnology and pharmaceutical industry do not have climate commitments aligned with a 1.5 Celsius world (Connelly et al., 2021). The predominant source of emissions in the biotechnology and pharmaceutical industry of their emissions come from Scope 3 (in particular purchased goods and services as well as the use of sold goods), which are nearly five times larger than Scope 1 and 2 emissions combined (Connelly et al., 2021). As a result, pharmaceutical companies are trying to reduce their Scope 3 emissions throughout, which includes investigating the transportation of goods from centralized manufacturing sites to global distribution centers. In particular the amount of temperature-sensitive pharmaceuticals (such as vaccines, cancer medicine, and blood plasma) needed to be transported by carbon-intensive air freight are rising.

Consequentially, pharmaceutical companies aim to reduce their emissions by improving processes and products as well as choosing carriers and Logistics Service Providers (LSPs) with reduced climate impact. We aim to support and guide this decision-making process by providing a tool that map the door-to-door emissions of transporting temperature-sensitive pharmaceuticals. First, we provide a tool that extends previous work on estimating and allocating carbon emissions from logistics by tailoring it to the specific case of temperature-sensitive pharmaceuticals using air-freight. We integrate sector-specific product-level and network-level characteristics like calculating emissions from reverse logistics of cooling containers or accounting for the volume constraints of airfreight. Second, we use the tool to generate a series of case-studies to highlight the trade-offs and implications for the transportation of temperature-sensitive goods.

The remainder of the paper is structured as follows. Section 2 provides an overview of the existing work on measuring and reporting carbon emissions from transportation services. Section 3 introduces our proposed tools for analysing the footprint of cold-chain logistics for pharmaceuticals. A set of detailed case-study on levers to reduce carbon emissions follow in Section 4. We conclude with summarizing our work and proposing future research directions in Section 5.

2 Existing Work

This section reviews the existing work on estimating and allocating carbon emissions in transportation and supply chains. In Section 2.1 we briefly introduce the background and main concepts on estimating and measuring any carbon footprint, and in Section 2.2 we summarize the main sources of emission in logistics. We then review existing frameworks and standards for emissions reporting and allocation in logistics in Section 2.3 before presenting current work specific for the context of cold-chain logistics in Section 2.4. In Section 2.5 we highlight the main research gaps addressed by our work.

2.1 Methodologies for measuring the carbon footprint of products and processes

This section provides a general overview of carbon footprinting methodologies in supply chains. It is based primarily on Boukherroub et al. (2017). A carbon footprint can be measured on three dimensions: an organization, a value chain, or a product. The organizational carbon footprint accounts for emissions from all activities undertaken by the organization, such as energy use in buildings, industrial processes, and company vehicles. On the other hand, the value chain carbon footprint includes emissions from both upstream and downstream activities, such as those from suppliers and consumers, and it takes into account the entire life cycle of the product. Lastly, the product carbon footprint measures the emissions generated over the entire life cycle of a single unit of product and are typically evaluated through a life-cycle assessment (LCA). The main framework and seminal concept for accounting for carbon emissions is the Greenhouse Gas Protocol (GHGP). It is composed of seven standards, of which two are directly related to supply chains: the corporate standard (Scope 1 and 2) and corporate value chain standard (Scope 3 standard). There are various methods for measuring carbon emissions: 1) direct measurement, 2) energy-based calculations, 3) activity-based calculations, 4) economic input-output life-cycle assessment (EIO-LCA).

1) direct measurement has the lowest level of extrapolation and is mostly applied to production sites subject to environmental regulations and using continuous emission monitoring systems. Emissions recorded from direct measurement are generally only applicable for a share of Scope 1 emissions. In 2) energy-based calculations, the carbon emissions are based on mass balance or theoretical combustion specific to a facility or a process. It mainly applies to fuel consumption and is generally available for a share of Scope 1 and Scope 2 emissions. It is the most accurate and desired way of calculating carbon emissions from freight transportation, yet requires specific access to fuel consumption data. 3) activity-based calculations aims to derive emissions from activity information by using conversion factors. It is the most common approach used to calculate carbon emissions because of its simplicity and the implementations differ by granularity of the data. Last, 4) EIO-LCA aims to convert the expenditures by a company in a given industry sector into an average amount of carbon emissions. While simple to apply, it may show high fluctuation depending on the economic situation and may only account for "cradle-to-gate" upstream emissions. The four approaches above differ by level of extrapolation involved, and therefore by accuracy, scope and simplicity. More accurate estimation techniques like 1) direct measurement and 2) energy-based calculations are usually more favourable. However, the necessary data might not be available or too expensive to acquire. As a result, a simpler approach for the benefit of broader scope may be chosen, as has often been observed in logistics services (see following Section 2.2).

2.2 Greenhouse Gas Emissions in Logistics

This section provides a brief review on carbon emissions in logistic processes and is mostly based on Blanco and Sheffi (2017). Emissions from logistics are predominantly related to the combustion of fuels during freight transportation and may be complemented by indirect emissions from cooling of goods or operating logistics facilities. The most reliable approach to measure primary greenhouse gases from transportation is energy-based calculation by determining emissions based on the types and volumes of fuels consumed. However, despite being the most accurate methodology, energy-based calculation is often not feasible due to lack of the appropriate data. Fuel purchasing data may be available to individual truck owners, but it is often not accessible to third-party logistics providers, manufacturers or retailers who make logistics decisions. Moreover, logistics decisions are made at the shipment level (e.g., box, container, carton, pallet) or at another planning metric (e.g., kilogram, cubic feet, or tonne), and not at the conveyance level (e.g., truck, plane, vessel). The most widely used method for estimating carbon emissions from logistics is the use of activity-based calculations. They are leveraged using "emission factors", which convert an activity into Greenhouse Gas (GHG) emissions. They are simple to use, and sensitive to the choice of fuel emissions factors. The two most widely used activity-based methods in logistics processes are distance-based and weight-distance-based. Distance-based emission estimation is the most simple method but inadequate when using shared modes of transportation, thus the emissions related to a specific amount of goods shipped. Weight-distance based methods are expressed in ton-miles/ton-kilometres and are useful when comparing different modes and the efficiency of goods moved. However, weight-based emissions factors may be not well suited for low-density goods or modes with tighter volume than weight constraints, as they ignore the volume dimension and therefore may underestimate emissions. One of the main complexities in estimating and allocating carbon emission from freight transportation is the distinction between individual lanes and an entire network. Logistics service providers, decide on their lanes based on aggregated demand dynamics to optimize the flow in the whole network. When outsourcing shipments to a LSP and aiming to incorporate their emissions into the decision-making, looking at individual lanes or shipments could therefore be inaccurate and it may be more insightful to look at the emissions of a carrier's entire network.

2.3 The path to a unified standard for emissions reporting and allocation in freight transportation and logistics

The need for carbon estimation and allocation frameworks for transportation and logistics has arisen due to the sector's inherent emissions intensity and its projected growth. However, accurately measuring the emissions for the logistics sector is complex, as the sector is highly fragmented, in-transparent, and technologically diverse. As a result, manifold carbon estimation and allocation frameworks have emerged to address the complexities of the logistics sector in the last decade. The myriad of methods have called for a stronger harmonization of logistics and supply chain emission estimation methods (Davydenko et al., 2014; Wild, 2021), which ultimately led to the creation of a new global standard ISO 14083:2023 by the International Organization for Standardization (ISO) for quantifying and reporting greenhouse gas emissions arising from transport chain operations (ISO, 2023). In a 2021 review on carbon estimation and allocation frameworks for the logistics sector then, Wild (2021) presents eighteen standards and frameworks that are commonly used, of which we will briefly introduce the most relevant.

The US Environmental Protection Agency (EPA) introduced the SmartWay Transport program in 2004 for tracking, documenting and sharing information about fuel use and freight emissions across supply chains. The predominant goal of the program is to help companies identify and select more efficient freight carriers, transport modes and operational strategies to lower the environmental footprint. It mainly focuses on North America. The European Standard EN-16258 (CEN, 2012) has been the first international and multimodal emissions calculation standard. It provides a common methodology for energy consumption and GHG emissions to passenger and freight transport services. The Carbon Footprint of Freight Transport (COFRET) project, partially-funded by the European Commission, provides a comparison of then-existing methods and standards to remove uncertainty over calculating carbon footprint for freight transport (COFRET, 2014). It also served as basis for the International Workshop Agreement (IWA) 16:2015 (ISO, 2015), which provides a framework for coherent quantification of CO_2 emissions of freight transport on the level of operation of transport chain element, the level of network including company level and the level of cargo. In addition, the Smart Freight Centre has led the formation of the Global Logistics Emissions Council (GLEC), a consortium of academia, companies and associations. They published the GLEC framework for Logistics Emissions Accounting and Reporting (Smart Freight Centre, 2019). The framework leverages and partially harmonizes existing methods like EN16258 or SmartWay and aligns with global reporting protocals like the GHG Protocol or the Carbon Disclosure Project (CDP). Due to its simplicity and the broad support from industry, it has now been one of the most widely used reporting standards in logistics. Moreover, GLEC and IWA 16:2015 form the basis of the newly introduced ISO 14083:2023 standard for carbon emissions in logistics. ISO 14083:2023 has become the new de-facto standard for the quantification and reporting of GHG emissions for transport chains for passengers and freight. It aggregates and synthesizes the accumulated knowledge of over a decade of estimation and reporting standards for carbon emissions in logistics. To account for the manifold logistics operations, from multinational organizations leveraging multiple transport modes to ship goods globally, through local carriers delivering a simple service to a single user, it has been designed to ensure broad applicability (ISO, 2023).

2.4 Extant work on cold-chain logistics from practitioners

Concurrently to the development of general carbon estimation frameworks in transportation and logistics, a handful of studies investigated in more detail the emissions of cold-chain logistics for pharmaceuticals and in particular the role of the cooling containers used. myclimate (2018a), myclimate (2018b), and myclimate (2022) provide carbon footprint analyses for several cooling containers leveraged for transporting temperature-sensitive pharmaceuticals, commissioned by the company SkyCell. They leverage a LCA approach to determine the emissions of a cooling container from fixed manufacturing and end-of-life emissions as well as variable preconditioning and transportation emissions. They compare the different cooling containers by normalizing the emissions over the usable volume of each container to account for different product densities as well as the durability of the container to account for their potential reusability. They calculate the emissions of the container components as well as the transport assuming long-distance air travel via standardized emissions databases. Wildhaber and Stoelzle (2020) leverage a different approach for estimating carbon emissions from transport. They use a volume-weight ratio to calculate the marginal emissions per payload tonne. The authors calculate the total emissions for a plane flight and assume the plane to be filled with only one container type. They then divide these emissions by the total amount of the weight or volume transported. They compare nine different container types by their economic viability as well as their CO_2 footprint. Fixed product emissions are taken from myclimate (2018a) and myclimate (2018b). Peli BioThermal (2021) builds on top of the results from Goellner and Sparrow (2014) and compares the emissions of single-use vs. reusable containers. They perform their own LCA for product-level emissions and calculate the average emissions based on thousands of shipments for clinical trials. Last, va-Q-tec (2021) introduce a framework to calculate the life-cycle emissions of thermal packaging solutions. They base their method off the GHGP and define emissions based on the different scopes. Moreover, they separate emissions into fixed (product related) and variable (use-phase related) emissions. Contrary to most other studies, they use pure distance-based emissions factors for calculating emissions from transportation. In addition, they include a distinction in the carbon footprint method of two business models that incorporate reverse logistics: a) monthly rentals of cooling units (relocation via plane) and b) One-way trip rental (relocation via Ship).

2.5 Research gap

There has been a growing body on estimating and allocating carbon emissions from logistics processes for increased transparency and easier reporting. The newly published ISO 14083:2023, as new de-facto method, provides a general standard to calculate and report carbon emissions for any transportation operation. However, the high level of aggregation of versatile standards may provide limitations for identifying tactical and operational levers to reduce carbon emissions. For example, calculating transport emissions solely via emissions factors based on tonne-kilometres transported may ignore product- and network-level characteristics that reduce the number of vessels needed and thus the total emissions of a system. Moreover, there have been a handful of studies that focus on the specifications of the transport of temperature-sensitive pharmaceuticals. However, they lack an overarching analysis on which container, network or carrier characteristic to focus on when facing the decision of how to transport temperature-sensitive goods based on their carbon footprint. Moreover, the methods applied make simplified assumption about the transportation process and ignore network effects for the container re-balancing.

This research aims to complement existing work on estimating and allocating carbon emissions for the transportation of temperature-sensitive pharmaceuticals by providing a tool that aims to guide and inform the decision-making process of any shipper. More specifically, we provide a tool that specifically addresses the practitioners' need for a decision-support tool in multiple ways:

- we provide a door-to-door carbon emission estimation and allocation tool that helps shippers decide on which transportation service to choose for their pharmaceutical products
- we address emissions from container positioning flows on the network level. While some studies have incorporated emissions from repositioning containers from the des-

tination point to the origin point, container flows often happen throughout the network and may not therefore be simply assumed to have the same return way. We therefore introduce the concept of provisioning emissions, that indicate the emissions associated with providing a container from the origin point in the first place

- we account for product-level features like the temperature excursion rate to accurately account for the longevity of product emissions for reusable containers throughout their lifetime

This research is not intended to introduce yet another allocation standard or framework, even less so as a global ISO standard for reporting carbon emissions from logistics operations has just been released. We instead intend to provide complementary intuition and a first of many decision-support tools that go beyond the first step of aggregated emissions reporting and aim to inform how tactical and operational decisions may reduce an operation's carbon footprint.

3 Methodology

This Section introduces the methodology for estimating and allocating carbon emissions in the door-to-door transport of temperature-sensitive pharmaceuticals. The main components for calculating the emissions of a specific shipment are based on two components. First, the fixed emissions of the packaging solution. Second, the variable emissions during the transport. The following Sections provide an overview of each component, Section 3.1 introducing the fixed emissions, mostly product-related, and Section 3.2 covering the variable emissions, mostly transport-related. Section 3.3 combines the two component into an overall function to calculate the emissions.

3.1 Fixed emissions

The fixed emissions component for the transport of pharmaceuticals is primarily the carbon footprint of the containers used to transport the temperature-sensitive products. Three types of packaging solutions are most commonly used, differentiated by their cooling technology: active, passive and hybrid containers. Active containers use an active cooling technology such as electrical cooling systems or cooling with dry ice. They tend to have an active temperature control, that adjusts the temperature inside the container for a specified temperature range. They are primarily reusable, as they have costly battery components and electronics to operate the cooling. Passive containers, primarily cool their products by water-filled components, dry-ice, phase change material (PCM) as well as additional insulation. They are available in disposable and reusable forms. Hybrid containers are a combination of active and passive and can be used multiple times. They do not have an active cooling unit, and keep the temperature steady through a combination of insulation and PCM. They are called hybrid since they may re-charge in ambient temperatures.

We assume a cradle-to-grave consideration for the system boundaries of calculating the carbon emissions and thus calculate the carbon footprint of the packaging solution from the emissions of raw materials extraction, the production as well as the end-of-life processes. Emissions from the use-phase are covered in Section 3.2. Going into detail of the components of the LCA for the fixed emissions is outside of the scope of this document. In a first step, we therefore require the fixed emissions to be available for each packaging solution based on external audits complying with ISO 14040:2006. In a second step, we normalize the fixed product-level emissions based on their expected lifetime. As we estimate the emissions for one specific shipment, the fixed emissions for a container ought to be divided by the number of expected shipments per lifecycle. For single-use containers, the fixed emissions are therefore attributed completely to one shipment, as they are being disposed of at the end of the shipment. The emissions of multi-use containers, however, are distributed among their lifecycle. We summarize the fixed emissions based on Equation 1:

$$\text{Fixed Emissions} = \frac{\text{CO}_2 \text{ emissions from extraction of raw materials, production, and end-of-life}}{\text{Number of shipments per lifecycle}} \tag{1}$$

3.2 Variable emissions

We define the variable emissions component as the emissions associated to the transportation of the containers as well as the preconditioning of the containers (see Equation 2).

$$\text{Variable Emissions} = \text{CO}_2 \text{ emissions from transportation} + \text{CO}_2 \text{ emissions from pre-conditioning} \tag{2}$$

The pre-conditioning of containers varies depending of the technology used, as active containers use the cooling technology in the container, while passive and hybrid containers are cooled in a cold storage. The emissions therefore stem in both cases from the electricity of the local grid. The preconditioning emissions are therefore part of the variable emissions, as they depend on the temperature range associated with a specific transport as well as the origin location where the electricity originates from. Similar to the fixed product emissions in Section 3.1, the exact calculation of the preconditioning emissions lies outside of the scope of this project. As an example, however, myclimate (2018a) determine the power consumption needed to precondition active and hybrid containers for a given temperature range and estimate the emissions based on emission factors for power mixes in countries of origin. The variable emissions stemming from the transport of the pharmaceuticals represent the largest share of emissions (c.f., myclimate (2018a), myclimate (2018b), and va-Q-tec (2021)). The high share of emissions from transport can be assigned to using airfreight as primary mode of intercontinental transport, as the temperature-sensitive goods are highly valuable and vulnerable to spoilage based on temperature excursion and should therefore only be transported as short as possible. In this study, we investigate the door-to-door transport chain of a pharmaceutical as depicted in Figure 1 with seven nodes and four main legs:

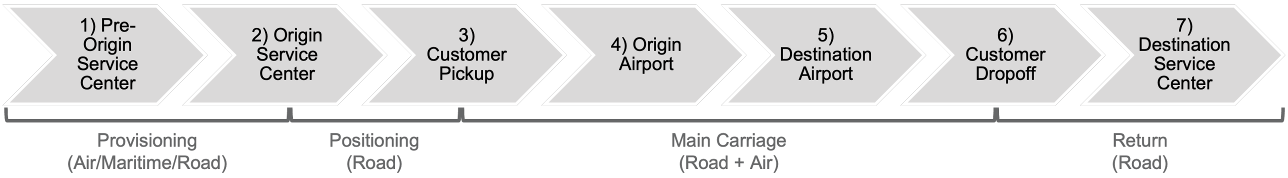


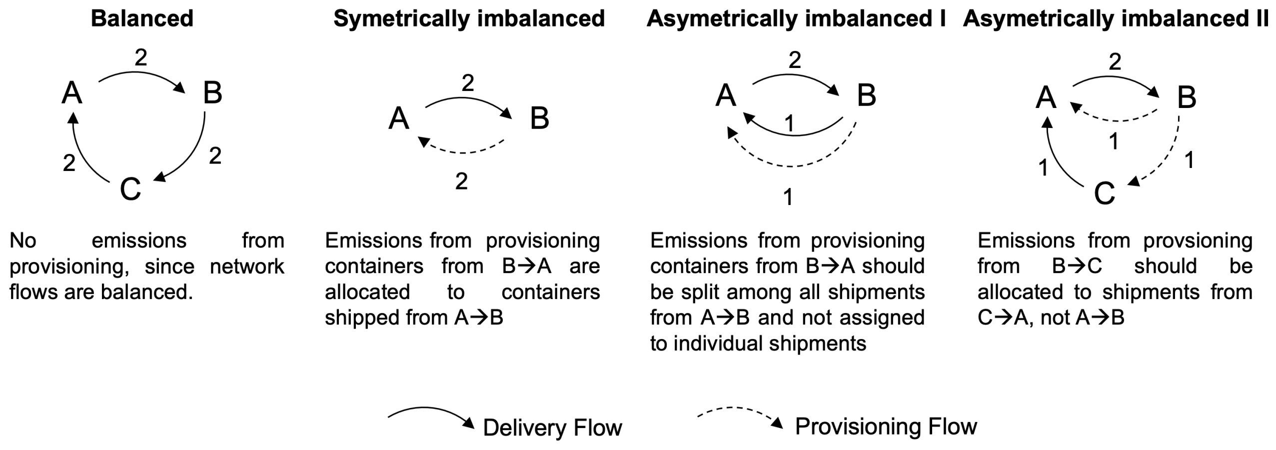
Figure 1: Illustration of the transportation chain for temperature-sensitive pharmaceuticals

Subsection 3.2.1 describes how to conceptualize the emissions from provisioning as first leg, while Subsection 3.2.1 presents the positioning, main carriage and the return. Subsection 3.2.3 describes how we calculate the emissions per transport mode in each of the legs.

3.2.1 Emissions from provisioning emissions

The provisioning of a container describes the process of providing a container to the origin service center. In the case of single-use containers, this may involve the transportation of the containers from the production facility to the storage center. In the case of multi-use containers this may involve the shipment of empty containers across a network of service centers. We conceptualize the emissions from provisioning in the context of reverse logistics and differ in two ways from the existing work on allocating emissions to reverse logistics. First, we allocate emissions from reverse logistics based on the origin service center, and not based on the destination service center. This is different from other studies, who account the reverse logistics to occur at the end of a shipment. va-Q-tec (2021), for example, calculate the reverse logistics from the repositioning of the customer drop-off back to the origin service center. They thus assume that when shipping a container from Frankfurt to Los Angeles, that same container will be returned from Los Angeles to Frankfurt. This may be the case for centralized networks with one global service center, where all containers are pooled. However, in many cases, the containers are part of a dynamic network. In this network of service centers, containers are shipped throughout the network and may only be relocated to another service center if the network flows are imbalanced and more containers need to be provisioned at specific service centers. Contrary to previous studies, we therefore do not allocate the emissions from reverse logistics based on the hypothetical return of a container from the destination service center to the origin service center, but purely on the network flows of containers at the origin center. Therefore, the provisioning emissions are based on the net inflow/outflow at each service center. Second, we determine that allocating the emissions from reverse logistics should therefore be aggregated and shared among all outgoing flows at each service center. Third, the emissions from reverse logistics should be forward-looking and under the expectation of including a load into the network (c.f. COFRET (2014)). The company providing the cooling containers should therefore not provide emissions based on the current network balances, but assuming the new container flows in the network.

Figure 2 provides four cases of network imbalances that indicate potential scenarios for emissions from reverse logistics by exemplarily routing containers across a network of two to three service centers. The 'Balanced' scenario has no provisioning logistics, as the demand flows are balanced and thus no containers need to be provisioned but can be reused at the destination anew. There are no emissions from reverse logistics. The 'Symmetrically imbalanced' scenario reflects the incumbent conceptualization of reverse logistics, i.e. empty containers are returned from the destination service center B to the origin service center A. Assuming a steady network imbalance, this is the same as allocating the emissions based on the provisioning flow from B to A in the first place. In both methods, accounting for emissions from reverse logistics are the same. This changes conceptually for Scenarios 'Asymmetrically imbalanced I' and 'Asymmetrically imbalanced II'. In the former, only one of the two outgoing containers need to be provided because of flow imbalance. Allocating the emissions from the provisioning flows to either of them is, however, arbitrary. As a result, the emissions from provisioning one container from B to A should be distributed among both outgoing containers from A to B. The last scenario inhibits the largest conceptual difference. It shows two provisioning flows, one from B to A and one from B to C. Allocating the emissions based on the origin service center and the net container flows in each node accurately maps the emissions to the nodes which cause the provisioning flows in the first place. In this case, the shipment from C to A needs to account for the provisioning flow from B to C.



Balanced

No emissions from provisioning, since network flows are balanced.

Symetrically imbalanced

Emissions from provisioning containers from B→A are allocated to containers shipped from A→B

Asymetrically imbalanced I

Emissions from provisioning containers from B→A should be split among all shipments from A→B and not assigned to individual shipments

Asymetrically imbalanced II

Emissions from provsioning from B→C should be allocated to shipments from C→A, not A→B

Figure 2: Scenarios of network imbalances. Numbers indicate example container flows per lane.

The emissions from provisioning therefore need to be estimated at each service center. If the net inflow/inventory of containers is non-negative (i.e., less than or equal number of containers outgoing than incoming), the provisioning emissions are zero. In the case of negative inflow and subsequent provisioning flows, the emissions based on the provisioning flows need to be distributed across all outgoing containers. In the scenario Asymmetrically imbalanced I' in Figure 2, for example, we assume the one provisioning shipment from B to A to cause η kg-CO_2. As a result, the provisioning emissions for each of the two shipments from A to B is $\frac{\eta}{2}$kg-CO_2. This method of calculating emissions of reverse logistics is more accurate than the existing methods, but requires two implementation details. First, the data on the network flows of containers including the transportation modes need to be available to accurately compute the emissions from provisioning. Second, it assumes a time component to accurately compute the net flows per service center, which needs to be calibrated.

3.2.2 Emissions from positioning, main carriage and return

The legs of positioning, main carriage, and return cover the transportation of the cooling container from the origin service center to the destination service center. Positioning and return describe the transport of empty containers to and from the customer-specific locations. Based on industry discussions we assume the two legs to mostly occur via road as primary mode of transportation. The main carriage refers to the transport of the customer pickup location, to the origin airport, on to the destination airport and last to the customer dropoff location. The transport to and from the airport is assumed to happen via road freight, with the main distance of the entire container transport happening via airfreight between the airports.

3.2.3 Emissions calculation per mode

This Subsection describes the calculation of the transportation emissions by mode. Naturally, an energy-based calculation of transportation emissions is most favourable, yet as previously discussed often unavailable. We therefore use activity-based calculation of carbon emissions per mode. In particular, the emissions were calculated using the NTM methodology by the Network of Transport Measures (NTM, 2023), which has dedicated calculation methods for air, maritime, rail and road transportation. The NTM methdology works with emissions factors based on the weight of the freight and the distance traveled. However, the emission factors are based on additional input on the vehicle characteristics and fill-rates, which heavily impact the emissions calculated. The emissions e_{ij} for shipping good i with mode j follow the following general equation:

$$e_{ij} = w_i * (f_j + v_j * d_{ij}) \tag{3}$$

where f_j and v_j are emission constants specific to the mode and vehicle characteristics (e.g., fill rate) chosen. f_j is the fixed emissions factor associated with the generated emissions during start and end of a trip. v_j represent the variable emissions factor based on the distance traveled. Correspondingly, d_{ij} is the distance good i traveled with mode j. Last, w_i represents the weight of the shipment to allocate the emissions.

For road freight transportation, we set w_i as the actual weight of the shipment, assuming that the weight is the constraining factor for road transport. d_ij is the distance traveled on an actual road network.

For air freight transportation, we use the volumetric weight for the emissions calculation. The volumetric weight $\hat{w}_i$ is determined by the following formula:

$$\hat{w}_i = \max\{w_i, v * \rho\} \tag{4}$$

where v is the volume of the shipment and ρ is the minimum density for air freight specified by the LSP. We use the volumetric weight to allocate the emissions for air freight to account for the fact that airplanes are in practice often volume restricted. In addition, the volumetric weight allows for better product-level comparison for low vs. high-density cooling containers. Also, using volumetric weight resembles the current practice on how LSPs charge customers for airfreight. The distance d_ij is calculated by the great circle distance plus a constant factor representing detours for additional maneuvering and taxiing. In addition, we multiply the emissions of air freight associated with the burning of jet fuel by a radiative forcing index (RFI). A RFI may be included, since aircraft operating in high altitudes may alter the atmospheric concentration and therefore have higher climate change contributions than based on the pure release of CO_2 via burning fuel (Cox and Althaus, 2019).

For maritime freight transportation, we use the actual shipment weight as w_i to calculate the emissions. In addition, d_ij is the actual travel distance across the seas.

3.3 Total emissions

We define the total emissions from the transport of temperature-sensitive pharmaceuticals in Equation 5 as the sum of the fixed and variable emissions normalized by a factor on the safety of the cooling chain.

$$\text{Total Emissions} = \frac{\text{Fixed Emissions + Variable Emissions}}{\text{Shipment success rate}} \tag{5}$$

We include a normalization factor to account for the risks and costs of a failed transport of the temperature-sensitive products. The complex multi-step process of the transportation chain involving multiple stakeholders, such as consignors, freight forwarders, or ground handling agents, pose significant risks for temperature excursion or other damages to the shipments (Coles and Long Alastair, 2020). We therefore include a factor based on the risk of temperature excursion by the cooling container, that reflects the risk of spoilage of goods on average. Besides higher costs for additional shipments and wasted materials, the need for re-sending the pharmaceuticals will result in additional carbon emissions.

4 Analysis

This Section presents the analysis on operational and tactical levers to reduce carbon emissions in temperature-sensitive freight transport for pharmaceuticals. Section 4.1 describes the implementation of the emissions calculator and the parameters chosen. Section 4.2 analyses the impact of different packaging materials used and Section 4.3 analyses the effect of different network structures on the emissions from provisioning.

4.1 Implementation and parameters

We implemented the methodology to calculate the emissions for temperature-sensitive pharmaceuticals as described in Section 3 in Python and Excel. The interested reader and practitioner may freely use our implementation for their own analysis via:
https://github.com/MIT-MLL/co2-estimator-cold-chain-logistics.

We leverage the API integration of the NTMCalc Advanced 4.0 for estimating the emissions per shipment (NTM, 2023). We calculate the distance for road freight transport leveraging the Google Maps Distance Matrix API (Google Maps, 2023). The distance for air freight transport is calculated via the grand circle distance formula and a detour factor of 95 km in line with the GLEC framework is applied (Smart Freight Centre, 2019). In addition, we apply a RFI of 2 to account for non-CO_2 effects of air travel to global warming. The maritime distance for any shipment is calculated via the Python package 'searoute' (Halili, 2023). For all road transportation, we assume using a 6 t Diesel B7 truck with Euro 6 norm on roads of average road quality. We further investigate the case for pure-freight aircrafts and choose to use a Boeing 747-400F for emissions calculation. We only present the results for full-freight aircrafts, since the results are directionlly the same when using Belly-freight aircrafts, the only difference being that full-freight aircrafts generally show lower emissions per m^3 or kg freight transported than Belly-freight aircrafts (e.g., c.f. EN16258 emissions factors for medium and long-haul transport). For maritime transportation, we assume an ocean carrier with 40.000 dwt capacity. All load factors are taken from the default NTM parameters: for road transport a weight load factor of 40%; for airfreight a weight load factor of 65%; for maritime we set a weight load factor of 70%. Moreover, we assume the default density for the volumetric weight of ρ=167 kg/m^3.

We investigate the case of two shipment decisions for a hypothetical pharmaceutical company with a distribution center in Philadelphia (Pennsylvania, USA). First, we investigate the case of a medium-haul shipment from a production facility in San Juan (Puerto Rico, USA) to Philadelphia via San Juan and Philadelphia Airports. Second, we investigate a long-haul shipment from a production site near Frankfurt (Germany) to Philadelphia via Frankfurt and Philadelphia Airports. In both cases we assume a service center for the different packaging material containers to be located in close proximity to the respective production facilities and distribution centers as well as the airport used, which can be serviced by road.

4.2 The impact of the cooling container and packaging material

This section analyses the impact of choosing a packaging material or cooling container on the carbon footprint of a pharmaceutical shipment. We include containers for each of the in Subsection 3.1 introduced container types, namely active, passive and hybrid. We use three example containers for this analysis: the Envirotainer RKN e1 (active cooling), the Taracell TC432 (passive cooling) and the SkyCell 1500X (hybrid). The RKN e1 and 1500X are reusable containers, while the TC432 is a single-use container. All fixed product-level carbon emissions and technical specifications are taken from myclimate (2018a), myclimate (2018b), myclimate (2022), SkyCell (2023), and Envirotainer (2023). The technical dimensions of the containers can be found in Table 1. For the following numerical analyses, we assume that the entire internal volume of a cooling container can be loaded with goods and is therefore usable volume. In the majority of real-world shipments, however, goods are shipped on standardized pallets (most commonly EU or US pallets), for which a container's actual internal volume used is determined by the dimensions of the pallet. Moreover, we assume a success-rate of 99.9% for all container types and Moreover, we use a lower-bound estimate that assumes an average of one hundred shipments per life-cycle for the exemplary active and hybrid containers. In a first step, we assume the shipment of 1m^3 of pharmaceuticals weighing 250kg. Furthermore, we set the emissions from reverse logistics to zero as we assume a balanced network for the reusable containers 1500X and

RKN e1. Last, we assume the customer destination distribution center to be the last stop for the single-use container, such that there are no emissions from transporting them onward to the container company's distribution center.

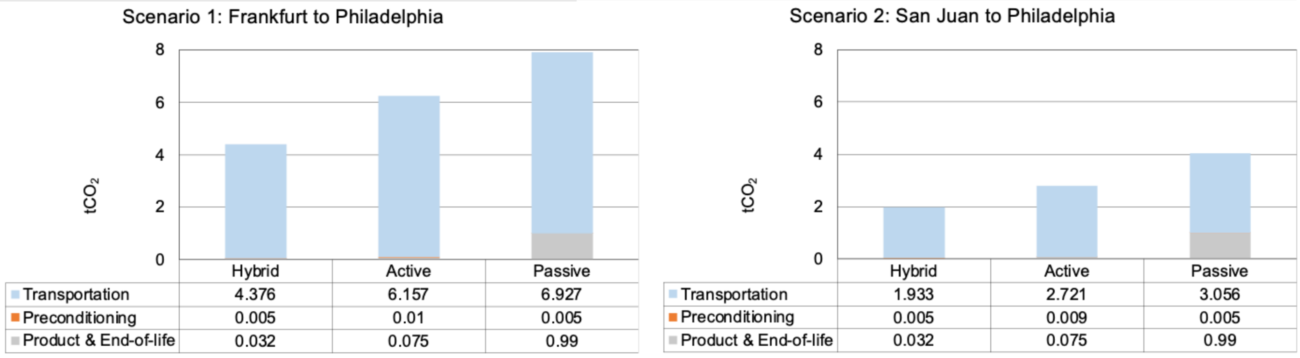
Container	**Hybrid** **(Skycell 1500X)**	**Active** **(Envirotainer RKN e1)**	**Passive** **(Taracell TC432)**
Exterior vol. [m3]	2.70	4.80	1.70
Usable interior vol. [m3]	1.66	2.30	0.43
Unladen weight [kg]	379.00	635.00	249.00
US/EU pallet capacity	1.00	1.00	0.00

Table 1: Technical dimensions of the example cooling containers by cooling technology

Figure 3 presents the CO_2 emissions for the shipment scenarios for each of the three sample containers. The emissions per shipment are split up into the footprint components, namely the transportation, the preconditioning and the fixed product-level emissions (from product manufacturing and end-of-life). We find that transportation, most notably the airfreight transportation, is causing the majority of emissions for all three containers in both Scenarios. For the multi-use hybrid and active containers, the emissions from transportation are in fact responsible for over 97% of the total emissions. For the passive container, the emissions from transportation are responsible for 87% for the long-haul and 75% for the medium-haul transport scenario. The second-largest share of emissions are coming from the fixed product side. While neglectible in share on total emissions for the active and hybrid containers, the fixed product emissions can be attributed to 12-24% of emissions for the passive product. This is because the passive container is a single-use container, such that all emissions from material extraction, production and end-of-life are attributed to a single shipment. For the multi-use containers, the fixed product emissions are distributed over the assumed one hundred usages and therefore significantly lower per shipment.

Moreover, we find that the emissions from transportation are heavily influenced by the density of the products. First, it should be noted that shipping $1m^3$ of goods fits well into both sample hybrid and active containers. For the passive solution, however, three containers are needed to transport $1m^3$ of goods (assuming the goods can be split arbitrarily to fit into any container shape). As a result, the hybrid container represents the container with the lowest total volume and weight when shipping $1m^3$ and therefore also has the lowest transportation and overall emissions. The active container follows due to higher transportation emissions based on higher weight and volume of the cooling container.

The choice of the cooling container should be based on the shipment volume itself in addition to the characteristics of the container types. Figure 4 presents the total emissions per shipment (left) as well as the relative emissions per m^3 shipped (right) for three container types for different volumes shipped. The emissions are calculated for the Frankfurt-Philadelphia shipment scenario and we assume a linear $1m^3$:250kg ratio to scale the weight based on the shipments' volume. The total emissions per shipment follow a quasi-step function. The slope is determined by the weight of container and shipment and the step-changes in the emissions are based on the number of containers needed and the associated increase in fixed and transportation-related emissions. We find that the optimal container



Scenario 1: Frankfurt to Philadelphia

	Hybrid	Active	Passive
▨ Transportation	4.376	6.157	6.927
▨ Preconditioning	0.005	0.01	0.005
▨ Product & End-of-life	0.032	0.075	0.99

Scenario 2: San Juan to Philadelphia

	Hybrid	Active	Passive
▨ Transportation	1.933	2.721	3.056
▨ Preconditioning	0.005	0.009	0.005
▨ Product & End-of-life	0.032	0.075	0.99

Figure 3: Comparison of emissions for the three example container types in two scenarios

choice depends primarily on the utilization rate of a container based on the shipments' size and a container's usable interior volume, since the container's volume is the constraining dimensions for the assumed shipment product density of 250kg/m^3. For small shipments, the example passive container shows the lowest overall and relative footprints. This is because only one passive container parcel is needed to transport the shipment, which itself has lower weight and volume than a single active or hybrid container. We find that for larger shipments cooling containers with higher usable inner volume per outer volume ratio and lower weight show the lowest absolute and relative footprint.

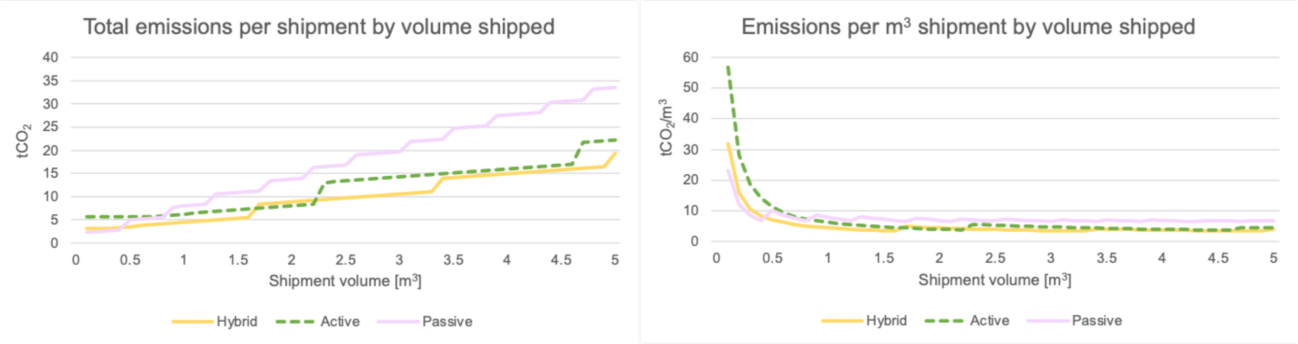


Figure 4: Comparison of emissions by volume for the Frankfurt-Philadelphia scenario

4.3 The impact of the network on emissions from provisioning and reverse logistics

In addition to cooling container and shipment-level characteristics, the carbon footprint of a shipment of temperature-sensitive pharmaceuticals may also depend on the network balance and provisioning of cooling containers. For this analysis, we analyse five container network scenarios. The first scenario assumes a perfectly balanced network as in the analyses before, such that there are no emissions from provisioning. For the other four network scenarios, we assume an imbalanced network, such that there is a net negative container inventory at the origin service center, which needs to be offset by sending containers from other parts of the network. Two scenarios assume a 50% provisioning: the service center has twice as many outgoing containers than incoming, therefore, half of the outgoing containers need to be provided. Two additional scenarios assume a 100% provisioning, i.e. all containers used need to provided from other parts of the network. For two of the scenarios we assume the containers to be shipped via maritime to the service center, in the other two via air freight. Last, we compare the emissions against a case of no provisioning emissions by using the single-use passive container.

We compare it based on a shipment of 2.5m^3 of 625kg payload from Frankfurt to Philadelphia for all example cooling containers. For each container analysis, we assume the provisioning shipments to be evenly split via company locations in Philadelphia and Bogotá (Colombia). We calculate the maritime return routes via the ports of New Jersey/New York for Philadelphia and Cartagena for Bogotá, as well as the port of Rotterdam (Netherlands) for the service center in Frankfurt. For the air freight provisioning, we assume the containers from Bogotá to be shipped via Bogotá International Airport. Since we use a single-use product as passive container in our analysis, the emissions for the passive container are the same independent of the scenario used. Figure 5 provides the estimated emissions per m^3 shipment for each scenario.

We find that maritime as network re-balancing mode is vastly more carbon efficient compared to air freight. Even at 100% provisioning and a very imbalanced network, the additional emissions based on maritime relocation of containers is only 3-4%. As a comparison, assuming a 50% (100%) provisioning via air freight increases the emissions per m^3 shipment by 39-50% (78-100%). This highlights the importance of balanced network flows and the choice of transportation mode for rebalancing containers throughout the global network of service centers. In addition, we find that single-use containers may in fact have a lower carbon footprint than a reusable container depending on the share of air freight returns. This highlights the pivotal role of air freight in the emissions estimation of temperature-sensitive shipments.

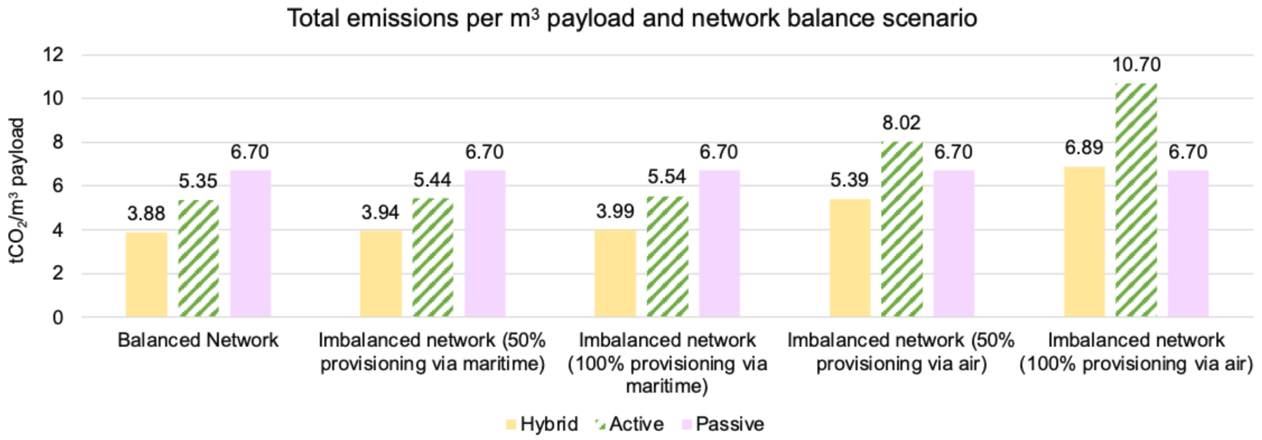


Figure 5: Comparison of emissions per m^3 payload for the sample containers based on five different network balance scenarios for a 2.5 m^3 Frankfurt-Philadelphia shipment

5 Conclusion

In this study we investigate the operational and tactical levers to reduce carbon emissions for temperature-sensitive cold-chain logistics. First, we provide a door-to-door carbon emission estimation and allocation tool for temperature-sensitive shipments using airfreight as primary mode of transportation. The tool addresses multiple domain- and product-specific aspects, such as temperature excursion rate to accurately account for the estimated loss of products via spoilage. In addition, we estimate the emissions from container positioning flows in imbalanced container networks. This is of particular importance as supply (production facilities) and demand (customer locations) nodes may not be evenly distributed globally. Moreover, we implement a volumetric-weight carbon emissions allocation for airfreight to resemble airfreight pricing and account for the impact of cooling container densities.

We compare a set of representative active, passive and hybrid cooling containers under a set of scenarios. First, we find that airfreight emissions are the single biggest source of emissions for all types of containers. Especially for reusable containers, the share of airfreight transportation emissions may easily be above 95%. As a result, the weight and volume of cooling containers and packaging materials in combination with their usable interior volume are among the most important characteristics for reducing the carbon emissions. Second, we find that the relative emissions per m^3 shipment is also contingent on the usable interior volume and the number of containers needed for a given shipment. Since airfreight emissions represent the largest share of emissions of a shipment, achieving a high fill-rate within a container solution is desirable. The specific container solution should therefore be chosen based on the specific volume of the shipment, since this is usually the constraining dimension. Third, the emissions of positioning flows of cooling containers should be considered carefully, as the impact of sending empty containers across the network may be substantial. We find that an imbalance in container flows across the network may be of limited impact if containers are re-balanced via maritime, which has a low carbon footprint. Sending empty containers across the network via airfreight, however, has the potential to massively increase the carbon footprint of a shipment. As a result, containers with more balanced networks should be favoured over networks with less balanced networks, while the primary mode for relocating containers through the network should also be taken into consideration. Moreover, the emissions from network balancing implies in which single-use containers may be favoured over multi-use containers if there is a large network imbalance and the re-balancing happens primarily via airfreight.

This study may be expanded along multiple dimensions. First, this tool primarily describes the carbon footprint for different cold-chain solutions under a range of scenarios to investigate general dynamics and identify levers for reducing the carbon footprint. In a next step, it can be integrated in a prescriptive framework to suggest the carbon footprint optimal temperature-sensitive transportation solution available. Second, the impact of container inventory and provisioning across the network should be further investigated. While we find, that an imbalanced network leads to higher emissions due to additional re-balancing flows, the cost and emissions of a more balanced network is not considered. For example, a higher container network balance may be achieved due to higher inventory of containers throughout the network, which in return however, may lead to higher capital commitment and product-level emissions. In addition, re-balancing flows via maritime follow different lead times than airfreight, such that a pure maritime-based re-balancing strategy may require substantially higher container inventories. As result, we suggest future research on the implications of network design and reverse flows on economic viability and the carbon footprint of cold-chain solutions.

References

[1] Lotfi Belkhir and Ahmed Elmeligi. “Carbon footprint of the global pharmaceutical industry and relative impact of its major players”. In: *Journal of Cleaner Production* 214 (Mar. 2019), pp. 185–194. ISSN: 09596526. DOI: `10.1016/j.jclepro.2018.11.204`.

[2] Edgar Blanco and Yossi Sheffi. “Green Logistics”. In: *Sustainable Supply Chains*. Ed. by Yann Bouchery et al. Vol. 38. Springer Series in Supply Chain Management 4, 2017. Chap. 7, pp. 147–187.

[3] Tasseda Boukherroub et al. “Carbon Footprinting in Supply Chains”. In: *Sustainable Supply Chains*. Ed. by Yann Bouchery et al. Springer Series in Supply Chain Management 4, 2017. Chap. 3, pp. 43–64.

[4] CEN. *EN 16258 :: Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)*. Tech. rep. 2012.

[5] COFRET. *COFRET: Results Report*. Tech. rep. 2014. URL: `https://cordis.europa.eu/project/id/265879`.

[6] Peter Coles and Long Alastair. *Handling Air Pharma*. 2020. URL: `https://www.clydeco.com/en/insights/2020/12/air-pharma`.

[7] James Connelly et al. *The Carbon Impact of Biotech & Pharma : A roadmap to 1.5°C*. Tech. rep. 2021. URL: `https://www.mygreenlab.org/uploads/2/1/9/4/21945752/the_carbon_impact_of_biotech___pharma-_final.pdf`.

[8] Brian Cox and Hans-Jörg Althaus. *How to include non-CO2 climate change contributions of air travel at ETH Zurich*. Tech. rep. ETH Zurich, June 2019. URL: `www.infras.ch`.

[9] Igor Davydenko et al. “Towards a global CO2 calculation standard for supply chains: Suggestions for methodological improvements”. In: *Transportation Research Part D: Transport and Environment* 32 (Oct. 2014), pp. 362–372. ISSN: 13619209. DOI: `10.1016/j.trd.2014.08.023`.

[10] Envirotainer. *Envirotainer RKN e1 Technical Specifications*. Tech. rep. 2023. URL: `https://www.envirotainer.com/492c32/siteassets/documents/envirotainer-rkn-e1-container-tech-specs-2020.pdf`.

[11] Kai N. Goellner and Eph Sparrow. “An environmental impact comparison of single-use and reusable thermally controlled shipping containers”. In: *International Journal of Life Cycle Assessment* 19.3 (Mar. 2014), pp. 611–619. ISSN: 16147502. DOI: `10.1007/s11367-013-0668-z`.

[12] Google Maps. *Distance Matrix API*. 2023. URL: `https://developers.google.com/maps/documentation/distance-matrix/overview`.

[13] Grand View Research. *Pharmaceutical Manufacturing Market Size, Share & Trends Analysis Report*. 2021. URL: `https://www.grandviewresearch.com/industry-analysis/pharmaceutical-manufacturing-market`.

[14] Gent Halili. *Searoute py 1.0.9*. 2023. URL: `https://pypi.org/project/searoute/`.

[15] ISO. *ISO 14083:2023 Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations*. Mar. 2023.

[16] ISO. *IWA 16:2015: International harmonized method(s) for a coherent quantification of CO2e emissions of freight transport*. 2015. URL: `https://www.iso.org/standard/67844.html`.

[17] Josh Karliner et al. *Health Care's Climate Footprint : How the health sector contributes to the global climate crisis and opportunities for action*. Tech. rep. 2019.

[18] Hoesung Lee et al. *Synthesis Report of the IPCC Sixth Assessment Report (AR6)*. Tech. rep. Intergovernmental Panel on Climate Change (IPCC), 2023.

[19] Matilde Milanesi, Andrea Runfola, and Simone Guercini. *Pharmaceutical industry riding the wave of sustainability: Review and opportunities for future research*. July 2020. DOI: `10.1016/j.jclepro.2020.121204`.

[20] myclimate. *SkyCell-Carbon Footprint*. Tech. rep. Zurich: myclimate, 2022. URL: `www.myclimate.org`.

[21] myclimate. *SkyCell-Carbon Footprint compared with Envirotainer*. Tech. rep. Zurich: myclimate, 2018. URL: `www.myclimate.org`.

[22] myclimate. *SkyCell-Carbon Footprint compared with Taracell*. Tech. rep. Zurich: myclimate, 2018. URL: `www.myclimate.org`.

[23] Network for Transport Measures NTM. *NTMCalc Advanced 4.0*. 2023. URL: `https://www.transportmeasures.org/ntmcalc/v4/advanced/#/`.

[24] Peli BioThermal. *An environmental impact comparison of packaging methods in the cold-chain industry*. Tech. rep. 2021.

[25] SkyCell. *SkyCell 1500X Technical Specifications*. 2023. URL: `https://www.skycell.ch/1500X/`.

[26] Smart Freight Centre. *Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting Smart Freight Centre*. Tech. rep. 2019.

[27] va-Q-tec. *An Industry Initiative: Transparent CO2 Calculation of thermal Packaging*. Tech. rep. 2021.

[28] Peter Wild. "Recommendations for a future global CO2-calculation standard for transport and logistics". In: *Transportation Research Part D: Transport and Environment* 100 (Nov. 2021). ISSN: 13619209. DOI: `10.1016/j.trd.2021.103024`.

[29] Victor Wildhaber and Wolfgang Stoelzle. *Performance comparison of pharmaceutical airfreight containers*. Tech. rep. 2020.