Measuring Emissions of Time and Temperature Sensitive Pharmaceutical Shipments

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Executive summary

Pharmaceutical companies need to be equipped with the appropriate tools to carefully assess the performance of isothermal packaging solutions for their time and temperature sensitive shipments. We contribute to this objective by providing a methodology for measuring emissions for non-reusable and reusable isothermal packaging solutions.

We complement existing methodologies to account for three specific features. First, existing studies assume a return rate of 100% for reusable packaging. We notice that this assumption does not apply to all solutions in practice, and we account for the possibility of a lower return rate. Second, we acknowledge that some reusable packaging solutions are foldable, and this affects packaging density in case of repositioning. Third, we supplement existing methodologies to better account for repositioning emissions.

We conducted an in-depth study of two representative cases of pharmaceutical shipments, and we compare emissions for five packaging options for both cases. Our results highlight that emissions vary greatly depending on the packaging solution chosen. The worst packaging solution considered generates 2.8 times more emissions than the best packaging solution under study. Our results show that a pharmaceutical company that is willing to reduce greenhouse gas emissions from time and temperature sensitive shipments should select a packaging solution provider that ensures three key features: lightweight, reusability, and repositioning via maritime transport.

As the weight performance of the packaging might be challenging to compare between different packaging solutions, we introduce an easy to compute indicator, the *standardized weight factor*, that allows companies to easily compare the performance of several packaging solutions.

1 Introduction

Global access to vital medicines is of crucial importance. These pharmaceutical products require appropriate management to be delivered at the right place, at the right time, and in the right quantities to meet patients' needs. This raises multiple logistics challenges. We are particularly interested in specific pharmaceutical products that require being kept within a specific temperature range to protect their physical properties. This includes vaccines, biologics, and certain medications. Rodrigue and Notteboom (2014) highlight that according to the Healthcare Distribution Management Association, temperature sensitive drugs represent 10% of the 200 billion dollars pharmaceutical distribution market. If kept in inappropriate conditions, these pharmaceutical products can become ineffective, and they can even become dangerous for patients. Therefore, these medicines require appropriate temperature management through their entire journey from production to the consumption sites. This is the objective of the cold chain, a supply chain that uses a mix of refrigeration and insulation to guaranty that the cargo stays in a temperature-controlled environment through its entire journey. The cold chain is a very complex system that requires careful attention. Numerous related challenges have been tackled to provide a reliable cold chain with a worldwide footprint. However, the cold chain is constantly facing the risk of unexpected disruptions. They include natural disasters, failures, human errors or logistical delays. Therefore, pharmaceutical companies need to choose the most appropriate isothermal packaging solution for safe delivery of their temperature sensitive products.

In the meanwhile, pharmaceutical companies are becoming more and more committed to improving their sustainability performance. Sustainability is multifaceted and cannot be reduced to a single dimension. Therefore, improving the sustainability of pharmaceutical supply chains requires a holistic approach. Reducing greenhouse gas emissions, that are responsible for global warming, is among the key priorities for many pharmaceutical companies. Therefore, they need to be able to accurately measure the greenhouse gas emissions of their activities as a pivotal part of their holistic sustainability strategy. The GHG protocol (www.ghgprotocol.org/) classifies greenhouse gas emissions into three categories. Scope 1 emissions correspond to direct emissions from the activities of a company. Scope 2 emissions relate to indirect emissions from the generation of the energy purchased by the company. Finally, Scope 3 emissions correspond to all other indirect emissions. They are generated by other entities in the supply chain. They include both upstream (e.g., raw material, inbound transportation) and downstream (e.g., emissions from the later stages in the product life cycle) emissions. While many companies focus mainly on Scope 1 and 2 emissions, they often represent just a fraction of their total emissions. For instance, CDP (2021) estimated that Scope 3 emissions are on average 11 times higher than Scope 1 and 2 emissions combined. Therefore, companies which aim at getting a clear view of their greenhouse gas emissions should not neglect Scope 3.

Greenhouse gas emissions from the shipment of temperature sensitive pharmaceutical products fall into Scope 3 emissions for pharmaceutical companies, and the choice of the isothermal packaging solution can heavily influence these emissions. Pharmaceutical companies have multiple packaging options available, ranging from active to passive technologies. These packaging solutions fall into the class of tertiary packaging (see e.g. Mahmoudi and Parviziomran (2020) for a definition of tertiary packaging), also referred to as logistics packaging. A noticeable trend is the extensive use of reusable logistics packaging solutions, also referred to as returnable transport items. This trend also applies to isothermal packaging solutions for the shipment of temperature sensitive pharmaceutical products as we can witness more and more reusable packaging solutions available on the market. While measuring greenhouse gas emissions for a temperature sensitive pharmaceutical shipment with a non-reusable packaging solution is already quite challenging, measuring emissions for the use of reusable packaging solutions creates an additional level of complexity.

Pharmaceutical companies need to be equipped with the appropriate tools to carefully assess the performance of isothermal packaging solutions for temperature sensitive shipments in terms of safety, costs, and greenhouse gas emissions. While safety and cost assessments have been heavily documented, there is a need for refined emission measurement methodologies. We contribute to this objective, and we specifically focus on time and temperature sensitive pharmaceutical products in the pre-distribution stage. This stage corresponds to the transport of the pharmaceutical products from the production facility to the distribution center. This often represents the longest leg in the distribution chain and air transport is used to meet the tight time constraints of time sensitive products. Air transport is by far the most impactful mode in terms of greenhouse gas emissions. For instance, air transport generates 27 times more emissions than train transport according to the GLEC V3.0 framework (Ehrler et al., 2023).

We complement existing methodologies to account for three specific features. First, we focus on non-reusable and reusable packaging solutions. For this later category, existing studies assume a return rate of 100%. We notice that this assumption does not apply to all reusable packaging solutions in practice, and we account for the possibility of a lower return rate. Second, we acknowledge that some reusable packaging solutions are foldable and this affects packaging density. Indeed, although packaging weight remains unchanged, exterior volume is reduced in case the packaging is folded. Third, we integrate the impact of reusable packaging repositioning. The related provisioning emissions are challenging to measure. We complement the methodology for measuring provisioning emissions proposed by Lehmann et al. (2023) and we provide a formal definition of the *provisioning rate*.

We apply our methodology to two cases that are representative of classical shipments for temperature and time sensitive pharmaceuticals, and we compare the performance of five packaging options in terms of greenhouse gas emissions. Our results show that emissions vary greatly depending on the packaging solution chosen. The worst packaging solution considered generates 2.8 times more emissions than the best packaging solution under study. We conducted a sensitivity analysis on key parameters for the two cases and we show that the best packaging solutions in terms of emissions are lightweight, reusable, and repositioned via maritime transportation. We conclude that a pharmaceutical company that is willing to reduce greenhouse gas emissions from time and temperature sensitive shipments should select a packaging solution provider that ensures three key features: reusability, lightweight, and repositioning via maritime transport. As the weight performance of the packaging might be challenging to compare between different packaging solutions, we introduce an easy to compute indicator, the *standardized weight factor*, that allows companies to easily compare the performance of several packaging solutions.

The rest of the report is organized as follows. We review the related literature in Section 2. Section 3 is devoted to our methodological developments. We present two applications in Section 4. Finally, Section 5 is devoted to the conclusion.

2 Existing work

2.1 The cold chain

The cold chain is a specific type of supply chain with many challenges. Rodrigue and Notteboom (2014) define the cold chain as “the transportation of temperature sensitive products along a supply chain through thermal and refrigerated packaging methods and the logistical planning to protect the integrity of these shipments”. They highlight that the type of packaging and the refrigeration method are the two key components in the cold chain. They ensure that the shipment will remain within a temperature range for an extended period of time. The cold chain is useful for several types of cargo ranging from fresh and frozen food to pharmaceuticals. Bishara (2006) investigates the specificity of the cold chain for pharmaceutical products. Demir et al. (2021) focus on cold chain logistics for airlines vaccine distribution. They identify three core capabilities for cold chain logistics service providers: on-time delivery, special storage and transport equipment, and process monitoring ability. Ren et al. (2022) provide an overview of some cold chain shipping solutions. Turan and Ozturkoglu (2022) identify the most important challenges that affect the performance of the cold chain in the pharmaceutical industry. They highlight that packaging, transportation, storage specifications and handling practices are the most influencing factors. Both Ren et al. (2022) and Turan and Ozturkoglu (2022) highlight that packaging is among the most important factors driving overall cold chain efficiency. This is the key focus of our study.

2.2 Reusable packaging solutions and reverse logistics

Packaging used for the shipment of time and temperature sensitive pharmaceutical products are either disposable or reusable. For this later category, reverse logistics is often needed to guarantee proper reuse. We refer to De Brito and Dekker (2004) for an overview of the driving forces behind reverse logistics. The authors additionally discuss the reverse logistics processes, the types and characteristics of returned products, and the actors of reverse logistics. Besides, Roy et al. (2006) discuss the governance structures of reverse logistics networks. Reverse logistics encompasses different types of flow. Goudenege et al. (2013) focus on reverse logistics management for reusable containers. They develop a generic optimization model, and they present an industrial application. Carrasco Gallego (2010) distinguishes between returnable transport items, reusable packaging materials and reusable products. This typology is further detailed in Carrasco-Gallego et al. (2012). The authors additionally discuss six cases, and they identify related challenges. Readers can refer to Transchel et al. (2024) for an overview of reusable packaging material solutions.

Returnable transport items have deserved a lot of attention in the academic literature. We refer to Glock (2017), Mahmoudi and Parviziomran (2020), and Katsanakis et al. (2023) for in-depth literature reviews. The management of returnable transport items induces some key operations management challenges. These include fleet size dimensioning, cycle time and rotation optimization, return and replacement management, scheduling of reconditioning and refurbishing activities and inventory balancing between depots (Carrasco Gallego, 2010). For instance, Hellström and Johansson (2010) highlight that the choice of the control strategy has a significant impact on investment and operating costs for returnable transport items. The authors study three of these strategies, namely a switch-pool system, a transfer system and a depot system, and they develop a simulation-based method for optimizing the fleet size required for these three control strategies. Cobb (2016) highlights how RFID can be leveraged to estimate cycle time and return rates for returnable transport items. The author additionally develops a method for forecasting returns.

2.3 Measuring greenhouse gas emissions

In this study, we are particularly interested in estimating the greenhouse gas emissions of time and temperature sensitive pharmaceutical shipments. In line with the literature, we refer to the quantity of greenhouse gas emissions released as the carbon footprint. We refer to Boukherroub et al. (2024) for more details about the measurement, reporting and disclosure of carbon emissions in supply chains. Koomen et al. (2023) highlight the importance of accounting for supply chain carbon emissions, also referred to as Scope 3 emissions, and they provide an evaluation method to identify the most promising carbon-reduction projects along the supply chain. Besides, Blanco and Sheffi (2024) provide an in-depth analysis on methods to measure carbon emissions from logistics activities. Some additional contributions specifically focus on carbon emissions from reverse logistics activities (see e.g., Okudan Kremer et al., 2013).

An important stream of literature evaluates carbon emissions for reusable packaging solutions in comparison to disposable ones. We refer to Coelho et al. (2020) and to Pålsson and Olsson (2023) for in-depth reviews. While focusing on disposable versus reusable packaging for food, beverages and e-commerce, Pålsson and Olsson (2023) highlight that the transport setting (that is the distance and transportation mode) as well as the number of reuse cycles are the key drivers of the carbon footprint for reusable packaging solutions. Some academic contributions additionally focus on evaluating carbon emissions from transportation in the cold chain context. Du Plessis et al. (2023) analyze data from 147 long distance truck shipments for temperature sensitive cargo. They develop a novel fuel calculation method based on the data analyzed. This method allows for identifying the emission factors related to refrigerated truck shipment. Habibur Rahman et al. (2023) develop a model for calculating fuel consumption for a cold chain. Some contributions additionally focus on mode and route selection decisions to optimize carbon emissions for the cold chain. For instance, Zhang et al. (2020) propose an optimization model that determines shipment quantities, ship deployment, and sailing speeds for perishable cargo in a multi-period context. They focus on reefer bulk and reefer container shipping solutions.

While the articles listed above provide some strong foundations for our study, they do not allow for a joint evaluation of the carbon emissions of the cargo and the packaging solution for a time and temperature sensitive shipment. Indeed, some studies focus specifically on packaging, while some others focus more on cargo and do not necessarily put much emphasis on the packaging solution and its implications. We are aware of two contributions that provide specific methodologies for measuring carbon emissions for cold chain packaging solutions. Meng et al. (2023) apply life cycle assessment to compare the environmental performance of a reusable and a disposable packaging solution for food cold chain express deliveries. The disposable packaging solution is lighter and has a simple material composition while the reusable packaging solution can be utilized up to 180 times. The findings highlight that the reusable packaging solution outperforms the disposable solution in terms of environmental impact for the settings considered. The results are driven by the better insulation provided by the reusable packaging solution. Lehmann et al. (2023) is the study that is the most closely related to our objective. The authors analyze the carbon emissions of several packaging solutions for the shipment of time and temperature sensitive pharmaceuticals. They provide a carbon emission estimation and allocation tool that helps shippers to select the most appropriate transport service and packaging solution. They provide a notable contribution to the estimation of the network effect from repositioning operations for reusable packaging. Note that interested readers can also refer to references cited by Lehmann et al. (2023) for an in-depth description of some early developments in measuring emissions from different packaging solutions for pharmaceutical shipments. These methods are based on simplifying assumptions that do not properly address the specificities of isothermal reusable packaging solutions for pharmaceutical shipment.

2.4 Our contribution

We described above the extent literature that inspired our study. There is considerable knowledge related to carbon emissions measurement in a cold chain context. Besides, many academic articles focus on carbon emissions measurement of packaging solutions. However, reusable isothermal packaging solutions stand at the intersection of these two streams of literature, and they share some specificities that are not appropriately handled by the models described above.

We contribute to this research gap by proposing three main improvements to existing methodologies for measuring emissions of time and temperature sensitive pharmaceutical shipments. At first, we acknowledge that all existing studies about the carbon footprint of isothermal packaging solutions in a cold chain context assume a return rate of 100% for reusable packaging solutions. This does not always apply in practice, and this might lead to a biased evaluation of their carbon footprint. Second, in case of maritime repositioning, isothermal packaging solutions are containerized. The GLEC V3.0 framework (Ehrler et al., 2023) is the main methodology to measure emissions from freight transportation. In this methodology, carbon emissions from containerized maritime transport are expressed per maritime container (per TEU, 20ft. equivalent unit). This implies that shippers need to be able to evaluate the number of packaging to be loaded into a container in case of maritime repositioning. This heavily depends on whether reusable isothermal packaging solutions can be folded when emptied. This feature has never been taken into account in previous studies. Finally, we acknowledge the pivotal contribution of Lehmann et al. (2023) for measuring carbon emissions from packaging repositioning operations. The authors define the corresponding provisioning emissions, and they account for the network effect of repositioning by computing the net inflow/outflow at each service center. We extend the concept by additionally accounting for distances and we express provisioning as a percentage of the distance traveled for the loaded leg of packaging transport. This allows us to provide a formal calculation method for this *provisioning ratio*.

Overall, we propose an improved methodology to measure carbon emissions of time and temperature pharmaceutical shipments. We apply this methodology to two cases, and we derive managerial insights that help pharmaceutical companies to select a packaging solution provider.

3 Methodology

We propose a methodology to measure carbon emissions of time and temperature sensitive pharmaceutical shipments. We follow the principles of life cycle assessment (Guinée & Heijungs, 2024) and we perform a cradle-to-grave analysis that focuses on global warming measured in carbon dioxide equivalent (CO_{2e}). We define the function as "shipping a given load of temperature and time sensitive pharmaceutical products from origin to destination while preventing temperature excursion" and the functional unit as the given weight of the cargo to transport from a given origin to a given destination. For instance, we can define the functional unit as 250kg of a given temperature and time sensitive pharmaceutical product to transport from origin A to destination B. We aim at comparing different isothermal packaging technologies for the shipment under consideration. In what follows, the *shipment* refers to the combination of the cargo and the packaging. We focus specifically on active, hybrid and passive technologies. Active packaging systems have an active temperature control that ensures that the temperature inside the packaging is kept within a specified range. They require electricity and they often include a battery to ensure that electric cooling is maintained while unplugged. Passive technologies store water or Phase Change Material (PCM) cooling elements and control temperature through insulation. Hybrid technologies are containers that are not plugged and need to be preconditioned before use. They include a PCM bunker that cannot be separated from the rest of the packaging.

We classify emissions into 3 categories that we discuss below. Besides, we provide additional assumptions that allow us to simplify the calculations of emissions.

Category 1: Fixed emissions relate to emissions from packaging raw material extraction, production, pre-positioning to the service center and end-of-life management. These emissions are independent of the number of packaging uses (that is why they are referred to as fixed emissions). Therefore, they will be divided by the average number of times the packaging is used throughout its lifetime to obtain fixed emissions associated with one functional unit. We discuss further how to compute the average number of times the packaging is used in subsection 3.1.

Category 2: Variable packaging emissions relate to the carbon emissions generated by the use of the packaging to achieve one functional unit. Variable emissions include emissions from provisioning the packaging to the service center, emissions from positioning the packaging from the service center to the customer's origin location, emissions from pre-conditioning, emissions from transporting the packaging from origin A to destination B (often including carriage and long-haul transportation), emissions from returning the packaging from the customer's destination to the service center or to the waste facility, and emissions from refurbishing operations. Note that pre-conditioning emissions relate to energy consumption associated with cooling down the shipment to the required temperature. These emissions also include energy consumption from battery charging for active packaging technologies. Besides, refurbishment emissions correspond to the emissions from the refurbishment activities. This includes energy consumption as well as the emissions associated with the replacement of some parts of the packaging. Emissions from provisioning the packaging relate to the emissions generated in case of packaging repositioning for future use. In accordance with Lehmann et al. (2023), we measure these emissions prior to the use of the packaging, and we refer to them as provisioning emissions accordingly. Note that we neglect emissions generated by energy consumption in the use phase for active technologies.

Category 3: Product emissions account for the cradle-to-grave emissions of the pharmaceutical product under study. They are measured for the weight associated with the definition of the functional unit. They can be decomposed into cradle-to-gate emissions, pre-distribution emissions, distribution emissions, use related emissions and end of life emissions. In this study, we focus on the pre-distribution stage, in which pharmaceutical products are transported from the production facility to the distribution center. We assume that more downstream emissions (distribution emissions, use related emissions and end of life emissions) are not affected by the packaging system used for pre-distribution and therefore, we omit these emissions in our analysis. Besides, we assume that the success rate of pre-distribution is similar for all packaging solutions under study. Therefore, cradle-to-gate product emissions are not affected by the packaging system used for pre-distribution. We consequently omit these emissions in our analysis. We can observe from the discussion above that product-related emissions solely consist of pre-distribution emissions in our analysis. Therefore, we combine them with emissions from transporting the packaging from origin A to destination B in our analysis.

Total emissions are obtained by summing up fixed, variable and product related emissions and by dividing them by the shipment success rate.

3.1 Trippage number and fixed emissions per functional unit

The average number of times the packaging is used throughout its lifetime is of paramount importance when measuring the carbon footprint of reusable packaging solutions. This indicator that we denote as U is usually referred to as the *trippage number* in the academic literature (Bojkow, 1991; Glock, 2017). The trippage number should not be confused with the maximum number of time a packaging can be used, also referred to as *packaging durability*, denoted n in what follows. It corresponds to the technical capabilities of the packaging. For instance, $n=100$ according to Lehmann et al. (2023) for reusable active packaging. Packaging of *age 1* and n are the newest and oldest, respectively. There are two main reasons for U to differ from n in practice. First, the customer can be unwilling or unable to return the packaging and if not returned, the packaging cannot be reused. We refer to ω as the return rate of the packaging, that is the probability that the packaging is returned by the customer. We assume that the age of the packaging has no influence on the return rate. Second, the packaging can be damaged due to inadequate usage, and this might lead to replacing the packaging before the end of its expected lifetime. We refer to ψ as the damage probability and we assume that ψ is independent of the packaging age. Note that we distinguish between the packaging that are damaged and the packaging that are not returned by the customer as in the former case, the packaging is returned to the destination service center and this affects transport emissions. When returned at a service center, packaging gets inspected to ascertain whether it can be reused again; any packaging that reaches the end of its life cycle n or that has been too damaged to be repaired is disposed of. Figure 1 provides an illustration for a reusable packaging solution, assuming a closed loop in which the packaging is reused from the same origin A to the same destination B.

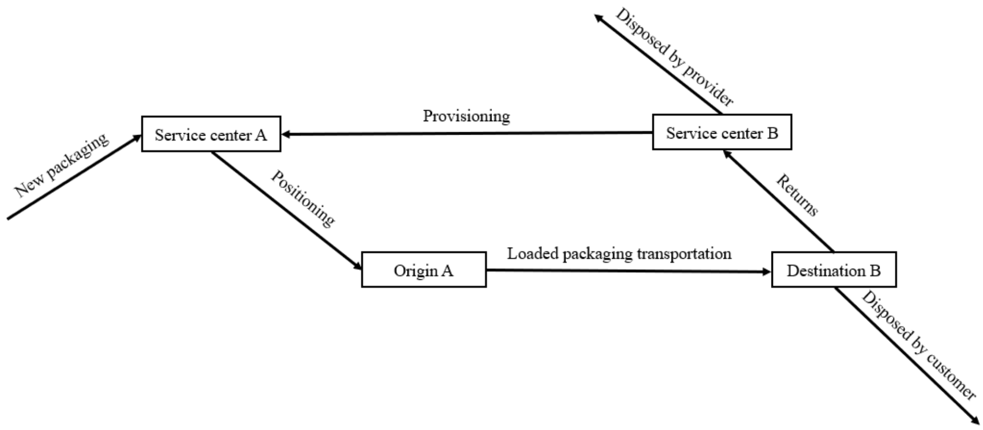

Figure 1: Packaging flow in a closed loop with provisioning

In this setting, provisioning is necessary from service center B to service center A. Note also that we refer to the service center associated to origin A as service center A and to the service center associated to destination B as service center B in what follows. We discuss provisioning further in subsection 3.3.

The assumptions above allow us to estimate U as a function of n, ω and ψ. Formula 1 below is a direct extension of the mean trippage number after n uses as derived in Bojkow (1991) that account for damage probability ψ:

$$U = \frac{1-((1-\psi)\omega)^n}{1-(1-\psi)\omega}\text{, if } (1-\psi)\omega < 1,$$
$$U = \text{n otherwise.} \tag{1}$$

As an illustrative example, assume that $n=100$, $\omega=0.95$ (that is a return rate of 95%) and $\psi=0.01$ (that is a damage rate of 1%), then, we obtain that $U=16.8$. This example shows that relying solely on packaging durability can be misleading in practice as there is a significant difference between U and n for the setting considered.

The fixed emissions associated with one functional unit are obtained by dividing the fixed emissions for the packaging (category 1) by U.

3.2 Transport emissions

Transportation is the main focus of this study that investigates emissions for a time and temperature sensitive pharmaceutical shipment in the pre-distribution phase from origin A to destination B. We model several transport activities. First, the packaging has to be made available at service center A. For the first use of the packaging, emissions from pre-positioning are already accounted into fixed emissions. In case the packaging is reused, it can require being transferred to another service center after refurbishment (see Figure 1 for an example of provisioning from service center B to service center A). We account for provisioning either via air or maritime transportation and we provide more details in subsection 3.3. The packaging is then sent by truck from service center A to origin where it is loaded with the pharmaceutical product. We then account for transport emissions from origin A to destination B for the packaging and the cargo jointly. We assume that air transport is used for long-haul transport as we focus on time sensitive pharmaceutical shipment, in accordance with practice. We also account for carriage by truck from origin A to the airport of origin and from the airport of destination to destination B. After the packaging is unloaded at destination, it is either returned by truck to service center B or kept by the customer. We assume that the packaging is sent to the waste facility by truck in case the packaging is not returned. Besides, shipment from the service center to the waste facility in case the packaging has reached its end of life is accounted for into fixed emissions.

We model emissions from transportation through activity-based calculations (Boukherroub et al., 2024) and we make use of the GLEC V3.0 framework (Ehrler et al., 2023). The Global Logistics Emissions Council (GLEC) is a universal method for logistics emissions accounting that serves as a basis for ISO 14083. We refer to Lewis (2016) for more details about its underlying principles and its inception. The overall idea of activity-based calculation consists in multiplying activity data (distance and weight or a proxy) by a mode-dependent emission factor. Note that we account for well-to-wheel (WtW) emission factors, that is, we measure emissions through the entire life cycle of the mode of transport. We detail how emissions are modeled for truck, for air and for maritime transport below.

3.2.1 Truck transport

In case of road transport by truck, emission factors (also referred to as emission intensity in the GLEC framework) are expressed in g CO_{2e}/t-km. One t-km relates to the transport of one ton over one kilometer. Consequently, the weight of the shipment (in ton) is multiplied by the distance (in kilometer) and by the emission factor that corresponds to the type of truck used in each geographic area to obtain related truck transport emissions.

3.2.2 Maritime transport

Maritime transportation can be used for empty packaging repositioning. We assume that containerized maritime transport is used, in accordance with practice. In the GLEC framework, emission factors for containerized maritime shipments are expressed in g CO_{2e}/TEU-km. TEU stands for twenty-foot equivalent unit, and this corresponds to the dimensions of 1 twenty-foot container. Therefore, we multiply the distance (in kilometer) by the emission factor of the corresponding maritime lane, and we divide by the number of packaging that can be loaded into a twenty-foot container. The capacity of a twenty-foot container depends on packaging exterior volume as well as foldability. Indeed, some reusable packaging solutions can be folded when transported empty. This does not impact packaging weight, so it has no impact on truck transport emissions. However, it influences maritime container capacity. We define the *folding ratio* as the exterior volume of an unfolded packaging divided by the exterior volume of a folded packaging. The number of folded packaging that can be loaded into a twenty-foot container can be obtained by multiplying the number of unfolded packaging that can be loaded into the container by the folding ratio.

3.2.3 Air transport

In the GLEC framework, air transport emissions are measured in g CO2e/t-km. There is an ongoing debate in the packaging industry about measuring carbon emissions from air transport. Some advocate that carbon emissions from air transport are mainly driven by shipment weight, and that the standard weight (that is, the real weight of the shipment) should be accounted for when measuring carbon emissions. Some others advocate that carbon emissions should replicate the cost structure of air transportation. This one is characterized by using volumetric weight instead of standard weight. Volumetric weight ensures that shipments with a low density will be charged based on volume utilization instead of weight utilization. Let ρ be the default density, let S_v be the shipment volume and let S_w be the shipment standard weight. Then, volumetric weight is obtained as:

$$\widehat{S_w} = \max(S_W, \rho S_v). \tag{2}$$

The default density is usually taken as ρ=0.167 t/m^3. Our methodology enables accounting for either standard weight or volumetric weight depending on the user's perspective. While we present the results computed with standard weight in Section 4, we additionally study the impact of using volumetric weight in subsection 4.5. Besides, we present all results in case of volumetric weight in the appendix. Air transport emissions are obtained by multiplying the distance (in kilometer) by the weight or volumetric weight (in ton) by the WtW emission factor of air transport provided by the GLEC framework. Note also that the folding ratio could impact volumetric weight in case of empty return via air transport.

3.3 Provisioning emissions

Reusable packaging solution providers usually operate a network of service centers and movements of empty packaging between these centers are sometimes necessary. Indeed, flow imbalance is very difficult to avoid. Empty packaging movements are responsible for carbon emissions referred to as provisioning emissions. Estimating provisioning emissions is quite challenging and, from our knowledge, Lehmann et al. (2023) provide the most accurate methodology to account for these emissions. The authors propose to measure provisioning based on the net inflow and outflow at each service center and they allocate provisioning emissions based on the origin service center. We complement the methodology of

Lehmann et al. (2023) and we formally define the *provisioning rate*. Note that Lehmann et al. (2023) mention a percentage of provisioning, but they did not provide any formal definition.

In what follows, we exclude from the analysis new packaging injected into the network as well as old packaging disposed of at a service center (as the impact is accounted for into fixed emissions as discuss previously). Besides, for the sake of clarity, we neglect carriage distances, and we assume that distances between service centers are equal to distances between customers' origins and destinations. This is reasonable in practice as service centers are usually located in very closed proximity of customers' locations. The provisioning rate is a measure of the repositioning intensity in the network of service centers. It is defined from an origin service center to a destination service center. We refer to $Pr_{A,B}$ as the provisioning rate from service center A to service center B.

Let C be the set of all service centers in the network. For all $i \in C$, let Out_i be the number of packaging leaving i for delivery (outbound flow). Besides, let In_i be the number of packaging repositioned to i. We assume that the impact of repositioning the In_i packaging to i are evenly distributed among the Out_i packaging leaving I for delivery. Let $d_{i,j}$ be the distance from i to j and let d_i be the average repositioning distance for the In_i packaging repositioned to i. Then, if the provisioning rate from i to j is defined as follows:

$$Pr_{i,j} = \frac{In_i}{Out_i}\frac{d_i}{d_{i,j}}. \tag{3}$$

Figure 2 provides four cases used as illustrative examples. We focus on a shipment from customer's origin A to customer's destination B and we are therefore interested to measure $Pr_{A,B}$. In case A, $In_A = 0$, therefore $Pr_{A,B} = 0\%$. In case B, $In_A = 1$, $Out_A = 4$, and $d_A = d_{A,B}$. It implies that $Pr_{A,B} = 1/4 * 1/1 = 25\%$. In case C, we assume that the distance from service center C to service center A is half of the distance from service center A to service center B. Therefore, $In_A = 3$, $Out_A = 4$, and $d_A = (d_{A,B} + 2 * 1/2\ d_{A,B})/3 = 2/3 d_{A,B}$. It implies that $Pr_{A,B} = 3/4 * 2/3 = 50\%$. In case D, $In_A = 0$, therefore $Pr_{A,B} = 0\%$. Note also that in a special case for which $In_i > 0$ and $Out_i = 0$, then it implies that i is an intermediary repositioning hub with only inbound and outbound repositioning flow. In this case, i is not a service center and we can remove It from the analysis and recalculate the distances. This ensures allocating all carbon emissions from repositioning to the packaging used for delivery.

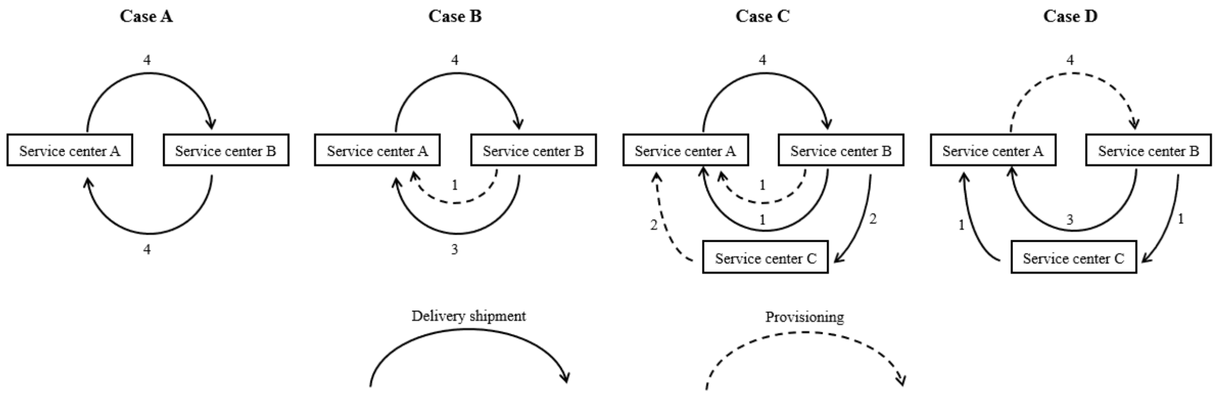

Figure 2: Illustration of packaging movements through a network of service centers

We can make 2 additional observations from Figure 2. First, the provisioning rate can exceed 100%. This applies to case D if we assume that the distance from service center A to service center B is twice the distance from service center B to C. Then, we obtain that $Pr_{B,C}$ = 4/4*2/1=200%. Second, the same service center can be associated to several repositioning rates in case it is used to ship packaging to different destinations. We can indeed observe that $Pr_{B,A}$ = 100% in case D, which is different from $P_{B,C}$.

Provisioning emissions are then obtained by multiplying $Pr_{A,B}$ by the distance $d_{A,B}$, by the packaging weight (or by a proxy: it can be volumetric weight in case of air transport or by the inverse of the number of packaging that can be loaded into a twenty-foot container in case of maritime repositioning), and by the mode specific emission factor as discussed in subsection 3.2.

4 Insights from 2 cases

We measure and compare the carbon footprint of several packaging options for international delivery of temperature and time sensitive pharmaceutical products. These options can be classified into four categories, that is, passive non-reusable packaging, active reusable packaging, hybrid reusable and passive reusable packaging. Note that we are not aware of any non-reusable active or hybrid packaging as these technologies are expensive and require multiple uses. We study two cases. At first, we assess the carbon footprint of the delivery of one euro pallet from Germany to China. Second, we evaluate emissions for the delivery of four US pallets from the USA to China. In the base case, we assume that pallets are loaded with 1 cubic meter for euro pallets and with 1.2 cubic meter for US pallets (this corresponds to pallets of approx. 1 meter high) and that the cargo density is 250kg/m^3. We further make a sensitivity analysis for these assumptions. We start by focusing on the scenario in which reusable packaging does not require repositioning, that is, when the network is balanced. We complement this analysis by varying the provisioning rate and the provisioning mode. Moreover, we assume that the return distance from the customer's destination to the service center is the same as the distance to the waste facility where the packaging is sent in case it is not returned by the customer.

We focus on standard weight in our analysis, but we subsequently analyze the impact of using volumetric weight for air transport emissions. Besides, all results when using volumetric weight can be found in appendix A.

4.1 Case 1: 1 euro pallet from Germany to China

4.1.1 Base case

We focus here on the shipment of 1 euro pallet from Germany to China. We compare the carbon footprint of five different packaging systems. We study two passive non-reusable options proposed by Taracell (TC432) and Softbox Systems (Silverpod MAX). We compare these two non-reusable options to three reusable options. Among them, one packaging corresponds to active technology (Envirotainer RKNe1), one corresponds to hybrid technology (Skycell 1500X), and one is passive (EMBALL'ISO PREMIUM Quarter PMC (PCM)). All key data about the five packaging options considered can be found in Table 1. Data related to packaging weight, exterior and interior volume were retrieved from the companies' websites and technical description of the packaging. Fixed emissions for 1500X, RKNe1 and TC432 were retrieved from Lehmann et al. (2023). Fixed emissions for the Quarter PMC were provided by the company based on internal carbon footprinting performed in accordance with the ADEME guidelines (Bilan Carbone®). Finally, we were not able to access information about fixed emissions for Silverpod MAX. We assume that they are proportional to TC432 as the packaging solutions are made from the same material. We multiplied fixed emissions of TC432 by the ratio of weight of Silverpod MAX and TC432 to obtain 331 $kgCO_{2e}$. We assumed a return rate (ω) of 100% for active and hybrid reusable packaging, no return for non-reusable packaging and a return rate of 90% for Quarter PMC. This corresponds to the actual return rate observed at EMBALL'ISO. The maximum number of uses (n) for active packaging is set to 100 in accordance with Lehmann et al. (2023). Non-reusable packaging can be used only once. Finally, the maximum number of uses for a reusable passive packaging was set by multiplying the maximum eligible use time of the components (7 years) by the average number of uses per year. We took the very conservative assumption of 2 uses per year leading to $n=14$ for Quarter PMC. We set the damage probability to 0% and success rate to 100% for all reusable packaging options. We also calculated the folding ratio for Quarter PMC. Indeed, Quarter PMC can be folded when repositioned and this impacts carbon emissions for maritime transport (as emissions are accounted per maritime container according to the GLEC framework) and carbon emissions from air transport in case of volumetric weight calculations. 45 folded Quarter PMC can be placed into a 40ft container vs. 14 unfolded ones, leading to a folding ratio of 3.214.

	Quarter PMC	1500X	RKN e1	TC432	Silverpod MAX
fixed emissions ($kgCO_2e$)	309	3248	7470	330	331
packaging weight (t)	0.148	0.379	0.635	0.249	0.250
exterior volume (m^3)	2.718	2.726	4.973	1.680	2.027
useable volume (m^3)	1.448	1.662	2.324	0.477	1.195
ω	0.9	1	1	0	0
U	14	100	100	1	1
folding ratio	3.214	1	1	N/A	N/A

Table 1: Packaging characteristics for case 1

We provide in Table 2 all information related to emission factors, cargo characteristics and distances for case 1. Note that we assume that the distance for the customer's destination to service center B is equivalent to the distance to the waste facility.

road transport emissions	95	gCO_2e/tkm
maritime transport emissions	55.6	gCO_2e/TEUkm
air transport emissions	817	gCO_2e/tkm
cargo weight	0.25	t
cargo density	0.25	t/m^3
volume	1	m^3
positioning distance	32	km
return or EoL distance	25	km
carriage distance (first leg)	20	km
long haul distance	9053	km
carriage distance (last leg)	41	km
default density (volumetric)	0.167	t/m^3

Table 2: emissions factors, cargo characteristics and distances for case 1

We present the total carbon footprint and the proportion of emissions for each process in Table 3. As we can observe, total emissions vary from 3.02 tCO_{2e} to 8.38 tCO_{2e} for the case under study. This significant variation shows that the choice of the packaging option can have a huge impact on the carbon footprint of a temperature and time sensitive pharmaceutical shipment. Transportation emissions related to the loaded packaging represent most of emissions for all packaging. They vary from one packaging option to another due to variation in packaging weight. Note that 3 TC432 are required to deliver the shipment vs. 1 packaging for the other options. For non-reusable packaging solutions, the total carbon footprint depends heavily on the fixed emissions as the packaging is used only once. They represent 11.82% and 8.21% of total emissions for TC432 and for Silverpod MAX respectively. We can clearly observe from Table 3 that fixed emissions play a marginal role in the carbon footprint of reusable packaging solutions. They represent only 1.33%, 0.69% and 1.13% of total emissions for Quarter PMC, 1500X and RKNe1 respectively. Note also that refurbishing accounts for 1.02% of total emissions for Quarter PMC. This is based on a very conservative assumption, that is, refurbishing emissions were set up to 10% of the fixed emissions for Quarter PMC and to zero for other reusable packaging solutions. Other sources of emissions have a marginal impact as they all represent at most 0.15% of the total in the base case.

	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
TOTAL emissions (tCO_2e)	***3.02***	***4.69***	***6.64***	***8.38***	***4.04***
fixed/U ($kgCO_2e$)	**1.33%**	**0.69%**	**1.13%**	**11.82%**	**8.21%**
positioning emissions ($kgCO_2e$)	**0.03%**	**0.04%**	**0.05%**	**0.05%**	**0.03%**
provisioning emissions ($kgCO_2e$)	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
conditioning emissions ($kgCO_2e$)	**0.05%**	**0.07%**	**0.15%**	**0.05%**	**0.04%**
transportation emissions ($kgCO_2e$)	**97.57%**	**99.19%**	**98.67%**	**88.08%**	**91.72%**
incl. cargo emissions	*61.29%*	*39.42%*	*27.87%*	*22.09%*	*45.86%*
incl. packaging emissions	*36.28%*	*59.77%*	*70.80%*	*66.00%*	*45.86%*
refurbishing emissions (kgCO2e)	**1.02%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

Table 3: Results for the base case 1 with no repositioning

In this assessment, we can conclude that Quarter PMC is the solution with the lowest carbon emissions. It allows for a 25% reduction of carbon emissions compared with Silverpod MAX, a 36% reduction compared with 1500X, a 55% reduction compared with RKNe1 and a 64% reduction compared with TC432. These results show that packaging weight and the ability to spread fixed emissions over multiple use are the key driving factors for carbon-efficient transportation of time and temperature sensitive pharmaceuticals products.

4.1.2 Sensitivity analysis

We further study the sensitivity of the results to cargo volume, cargo density, provisioning rate and provisioning mode. We study 45 settings by combining different volumes (0.75 m^3, 1 m^3, 1.25 m^3) and densities (0.1 t/m^3, 0.25 t/m^3 and 0.4 t/m^3). This corresponds to classical features for pharmaceutical products. Besides, we study different provisioning rates (100%, 50%, 0%) and provisioning modes (air, maritime). We compute the carbon footprint of the 5 packaging options for these 45 settings. Detailed results can be found in Table 4. Note that we were not able to collect real data about provisioning for the different packaging options considered. Therefore, we cannot use the methodology proposed in Subsection 3.3. Consequently, we consider theoretical provisioning rates, and we multiply them by return rates to obtain the percentage of packaging that requires repositioning.

We can make the following observations. At first, Quarter PMC appears to be the best option in terms of carbon emissions due to its light weight. Indeed, air transport is a major source of emissions, and the emissions factor is multiplied by weight and distance according to the GLEC framework (see Subsection 3.2). Therefore, shippers should select lightweighted packaging options if they aim at reducing their carbon footprint. Note that we propose computing the *standardized weight factor* to assess the weight performance of different packaging options. This new indicator can be easily computed via available data. We provide more details in Subsection 4.4. A second observation from Table 4 is that Silverpod MAX has a maximal usable volume of 1.195 m^3 and therefore, 2 packaging are required for shipping 1.25m^3. This heavily impacts the carbon footprint of the solution. Note that the same issue occurs for TC432 due to its limited usable volume. We can conclude that TC432 does not seem appropriate for reducing carbon emissions for the shipment of 1 euro pallet of temperature and time sensitive pharmaceutical product due to its limited interior volume. The same conclusion applies to RKNe1 that is heavy with large interior volume and cannot compete in terms of carbon footprint for the settings we consider here. Overall, the results highlight that Quarter PMC is the best option in terms of carbon footprint.

				emissions (tCO_2e)				
Density (t/m^3)	Volume (m^3)	Provisioning rate	Provisioning mode	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
0.25	1	100%	air	4.00	7.50	11.34	8.38	4.04
0.25	1	50%	air	3.51	6.10	8.99	8.38	4.04
0.25	1	0%	maritime	3.02	4.69	6.64	8.38	4.04
0.25	1	100%	maritime	3.04	4.77	6.78	8.38	4.04
0.25	1	50%	maritime	3.03	4.73	6.71	8.38	4.04
0.25	0.75	100%	air	3.54	7.03	10.87	5.74	3.57
0.25	0.75	50%	air	3.05	5.63	8.52	5.74	3.57
0.25	0.75	0%	maritime	2.56	4.23	6.18	5.74	3.57
0.25	0.75	100%	maritime	2.58	4.30	6.32	5.74	3.57
0.25	0.75	50%	maritime	2.57	4.27	6.25	5.74	3.57
0.25	1.25	100%	air	4.47	7.96	11.80	8.84	6.68
0.25	1.25	50%	air	3.97	6.56	9.45	8.84	6.68
0.25	1.25	0%	maritime	3.48	5.16	7.10	8.84	6.68
0.25	1.25	100%	maritime	3.50	5.23	7.25	8.84	6.68
0.25	1.25	50%	maritime	3.49	5.19	7.17	8.84	6.68
0.1	1	100%	air	2.89	6.39	10.23	7.27	2.92
0.1	1	50%	air	2.40	4.99	7.88	7.27	2.92
0.1	1	0%	maritime	1.91	3.58	5.53	7.27	2.92
0.1	1	100%	maritime	1.93	3.66	5.67	7.27	2.92
0.1	1	50%	maritime	1.92	3.62	5.60	7.27	2.92
0.1	0.75	100%	air	2.71	6.20	10.04	4.91	2.74
0.1	0.75	50%	air	2.22	4.80	7.69	4.91	2.74
0.1	0.75	0%	maritime	1.72	3.40	5.34	4.91	2.74
0.1	0.75	100%	maritime	1.74	3.47	5.49	4.91	2.74
0.1	0.75	50%	maritime	1.73	3.43	5.42	4.91	2.74
0.1	1.25	100%	air	3.08	6.57	10.41	7.45	5.29
0.1	1.25	50%	air	2.59	5.17	8.06	7.45	5.29
0.1	1.25	0%	maritime	2.09	3.77	5.71	7.45	5.29
0.1	1.25	100%	maritime	2.11	3.84	5.86	7.45	5.29
0.1	1.25	50%	maritime	2.10	3.80	5.79	7.45	5.29
0.4	1	100%	air	5.11	8.61	12.45	9.49	5.15
0.4	1	50%	air	4.62	7.21	10.10	9.49	5.15
0.4	1	0%	maritime	4.13	5.80	7.75	9.49	5.15
0.4	1	100%	maritime	4.15	5.88	7.89	9.49	5.15
0.4	1	50%	maritime	4.14	5.84	7.82	9.49	5.15
0.4	0.75	100%	air	4.37	7.87	11.71	6.57	4.41
0.4	0.75	50%	air	3.88	6.47	9.36	6.57	4.41
0.4	0.75	0%	maritime	3.39	5.06	7.01	6.57	4.41
0.4	0.75	100%	maritime	3.41	5.14	7.15	6.57	4.41
0.4	0.75	50%	maritime	3.40	5.10	7.08	6.57	4.41
0.4	1.25	100%	air	5.86	9.35	13.19	10.23	8.07
0.4	1.25	50%	air	5.36	7.95	10.84	10.23	8.07
0.4	1.25	0%	maritime	4.87	6.54	8.49	10.23	8.07
0.4	1.25	100%	maritime	4.89	6.62	8.63	10.23	8.07
0.4	1.25	50%	maritime	4.88	6.58	8.56	10.23	8.07

Table 4: Sensitivity analysis for the base case 1

We additionally provide the average values for all cases as well as for some subsets of instances in Table 5. We distinguish all cases from instances with only maritime repositioning (for reusable packaging), as well as instances for which one Silverpod MAX can accommodate all the shipment. Quarter PMC is always repositioned via maritime transport as this corresponds to the business model of EMBALL'ISO. The results show that in case of maritime repositioning, Quarter PMC can achieve an average decrease in emissions of at least 36% as compared to all investigated competitors for the shipment of 1 euro pallet from Germany to China.

	emissions (tCO_2e) in case of standard weight				
	Quarter PMC	**1500X**	**RKNe1**	**TC432**	**Silverpod MAX**
all cases	3.32	5.56	8.09	7.65	4.76
only maritime repositioning	3.03	4.73	6.71	7.65	4.76
only useable volume of Silverpod MAX	3.09	5.33	7.86	7.06	3.80
only useable volume of Silverpod and maritime	2.80	4.50	6.48	7.06	3.80

Table 5: Average emissions from the sensitivity analysis for the base case 1

We provide the ranking of the different packaging in terms of their carbon footprint for all instances in Table 6. We can observe that Quarter PMC achieves the best results in terms of carbon emissions for all instances studied due to its reusable nature and lightweight. Silverpod MAX and 1500X are the second-best options. 1500X outperforms Silverpod MAX only in case of maritime repositioning when the shipment does not meet the useable volume of one Silverpod MAX packaging.

				ranking in emissions				
Density (t/m^3)	**Volume (m^3)**	**Provisioning rate**	**Provisioning mode**	**Quarter PMC**	**1500X**	**RKNe1**	**TC432**	**Silverpod MAX**
0.25	1	100%	air	1	3	5	4	2
0.25	1	50%	air	1	3	5	4	2
0.25	1	0%	maritime	1	3	4	5	2
0.25	1	100%	maritime	1	3	4	5	2
0.25	1	50%	maritime	1	3	4	5	2
0.25	0.75	100%	air	1	4	5	3	2
0.25	0.75	50%	air	1	3	5	4	2
0.25	0.75	0%	maritime	1	3	5	4	2
0.25	0.75	100%	maritime	1	3	5	4	2
0.25	0.75	50%	maritime	1	3	5	4	2
0.25	1.25	100%	air	1	3	5	4	2
0.25	1.25	50%	air	1	2	5	4	3
0.25	1.25	0%	maritime	1	2	4	5	3
0.25	1.25	100%	maritime	1	2	4	5	3
0.25	1.25	50%	maritime	1	2	4	5	3
0.1	1	100%	air	1	3	5	4	2
0.1	1	50%	air	1	3	5	4	2
0.1	1	0%	maritime	1	3	4	5	2
0.1	1	100%	maritime	1	3	4	5	2
0.1	1	50%	maritime	1	3	4	5	2
0.1	0.75	100%	air	1	4	5	3	2
0.1	0.75	50%	air	1	3	5	4	2
0.1	0.75	0%	maritime	1	3	5	4	2
0.1	0.75	100%	maritime	1	3	5	4	2
0.1	0.75	50%	maritime	1	3	5	4	2
0.1	1.25	100%	air	1	3	5	4	2
0.1	1.25	50%	air	1	2	5	4	3
0.1	1.25	0%	maritime	1	2	4	5	3
0.1	1.25	100%	maritime	1	2	4	5	3
0.1	1.25	50%	maritime	1	2	4	5	3
0.4	1	100%	air	1	3	5	4	2
0.4	1	50%	air	1	3	5	4	2
0.4	1	0%	maritime	1	3	4	5	2
0.4	1	100%	maritime	1	3	4	5	2
0.4	1	50%	maritime	1	3	4	5	2
0.4	0.75	100%	air	1	4	5	3	2
0.4	0.75	50%	air	1	3	5	4	2
0.4	0.75	0%	maritime	1	3	5	4	2
0.4	0.75	100%	maritime	1	3	5	4	2
0.4	0.75	50%	maritime	1	3	5	4	2
0.4	1.25	100%	air	1	3	5	4	2
0.4	1.25	50%	air	1	2	5	4	3
0.4	1.25	0%	maritime	1	2	4	5	3
0.4	1.25	100%	maritime	1	2	4	5	3
0.4	1.25	50%	maritime	1	2	4	5	3

Table 6: Ranking of instances by ascending order of carbon footprint for case 1

4.2 Case 2: 4 US pallets from the USA to China

4.2.1 Base case

We focus here on the shipment of 4 US pallets that represent 4.8m^3 from the USA to China. We compare the carbon footprint of five different packaging options. Similar to the case presented in subsection 4.1, we study TC432, Silverpod MAX, and 1500X. Besides, we study larger reusable packaging solutions. We focus on Envirotainer RAPe2 and on EMBALL'ISO PREMIUM Half PMC (PCM). All key data about the five packaging options considered can be found in Table 7. Data related to packaging weight, exterior and interior volume were retrieved from the companies' websites and technical description of the packaging. Fixed emissions from Half PMC were provided by the company based on internal carbon footprinting performed in accordance with the ADEME guidelines (Bilan Carbone®). Fixed emissions for RAPe2 were obtained by taking fixed emissions of RKNe1 and by multiplying by the weight ratio.

	Half PMC	1500 X	RAP e2	TC432	silverpod MAX
fixed emissions (kgCO_2e)	499	3248	12940	330	331
packaging weight (t)	0.247	0.379	1.1	0.249	0.250
exterior volume (m^3)	5.840	2.726	11.538	1.680	2.027
useable volume (m^3)	3.410	1.662	6.359	0.477	1.195
ω	0.9	1	1	0	0
U	14	100	100	1	1
folding ratio	3.214	1	1	N/A	N/A

Table 7: Packaging characteristics for case 2

For case 2, the shipment of 4 US pallets implies that several units of packaging are required in many cases. The only exception is for RAPe2 that is designed to accommodate 4 US pallets. The number of packaging required for case 2 can be found in Table 8.

	Half PMC	1500 X	RAP e2	TC432	silverpod MAX
required packaging	2	3	1	11	5

Table 8: number of packaging required for case 2

We provide in Table 9 all information related to emission factors, cargo characteristics and distances for case 2.

road transport emissions	100	gCO_2e/tkm
maritime transport emissions	81.4	gCO_2e/TEUkm
air transport emissions	817	gCO_2e/tkm
cargo weight	1.20	t
cargo density	0.25	t/m^3
volume	4.8	m^3
positioning distance	50	km
return or EoL distance	50	km
carriage distance (first leg)	333	km
long haul distance	11430	km
carriage distance (last leg)	41	km
default density (volumetric)	0.167	t/m^3

Table 9: emissions factors, cargo characteristics and distances for case 2

We present the total carbon footprint and the proportion of emissions for each process in Table 10. As we can observe, total emissions vary from 16.12 tCO_{2e} to 40.60 tCO_{2e} for the case under study. The variation is in the same magnitude as for case 1, and that confirms that the choice of the packaging option is of primary importance for reducing emissions of temperature and time sensitive pharmaceutical shipments. We note the same observations as for case 1 in terms of the share emissions for each process. Emissions are mainly driven by transportation of the loaded packaging as well as by fixed emissions for non-reusable packaging options. We can also observe that Half PMC is the solution with the lowest carbon emissions. It allows for a 26% reduction in carbon emissions compared with RAPe2, a 27% reduction compared with 1500X, a 35% reduction compared with Silverpod MAX and a 60% reduction compared with TC432.

	Half PMC	1500 X	RAP e2	TC432	silverpod MAX
TOTAL emissions (tCO_2e)	***16.12***	***22.03***	***21.71***	***40.60***	***24.65***
fixed/U ($kgCO_2e$)	**0.80%**	**0.44%**	**0.60%**	**8.94%**	**6.72%**
positioning emissions ($kgCO_2e$)	**0.03%**	**0.05%**	**0.05%**	**0.07%**	**0.05%**
provisioning emissions ($kgCO_2e$)	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
conditioning emissions ($kgCO_2e$)	**0.02%**	**0.05%**	**0.05%**	**0.04%**	**0.03%**
transportation emissions ($kgCO_2e$)	**98.53%**	**99.46%**	**99.31%**	**90.95%**	**93.20%**
incl. cargo emissions	*69.80%*	*51.07%*	*51.81%*	*27.71%*	*45.65%*
incl. packaging emissions	*28.73%*	*48.39%*	*47.49%*	*63.24%*	*47.55%*
refurbishing emissions (kgCO2e)	**0.62%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

Table 10: Results for the base case 2 with no repositioning

4.2.2 Sensitivity analysis

We further study the sensitivity of the results to cargo volume, cargo density, provisioning rate and provisioning mode. We study 45 settings by combining different volumes (3.6 m^3, 4.8 m^3 and 6 m^3), densities (0.1 t/m^3, 0.25 t/m^3 and 0.4 t/m^3), provisioning rates (100%, 50%, 0%) and provisioning modes (air, maritime). Detailed results about the carbon footprint for the 5 packaging under study can be found in Table 11.

We can observe from Table 11 that Half PMC leads to the lowest carbon footprint for the 45 instances. Besides, TC432 does not seem appropriate for case 2 in terms of carbon emissions as it shows the worst results for the 45 instances. Overall, our results show that Half PMC seems very suitable for shipping 4 pallets of temperature and time sensitive pharmaceutical products for the US to China when considering carbon emissions.

				emissions (tCO_2e)				
Density (t/m^3)	Volume (m^3)	Provisioning rate	Provisioning mode	Half PMC	1500 X	RAP e2	TC432	Silverpod MAX
0.25	4.8	100%	air	18.20	25.57	31.99	40.60	24.65
0.25	4.8	50%	air	17.16	23.80	26.85	40.60	24.65
0.25	4.8	0%	maritime	16.12	22.03	21.71	40.60	24.65
0.25	4.8	100%	maritime	16.16	22.16	21.98	40.60	24.65
0.25	4.8	50%	maritime	16.14	22.10	21.85	40.60	24.65
0.25	3.6	100%	air	15.38	22.76	29.17	29.79	19.16
0.25	3.6	50%	air	14.34	20.99	24.04	29.79	19.16
0.25	3.6	0%	maritime	13.31	19.22	18.90	29.79	19.16
0.25	3.6	100%	maritime	13.34	19.35	19.17	29.79	19.16
0.25	3.6	50%	maritime	13.33	19.28	19.03	29.79	19.16
0.25	6	100%	air	21.01	31.98	34.80	48.75	30.14
0.25	6	50%	air	19.97	30.21	29.66	48.75	30.14
0.25	6	0%	maritime	18.93	28.44	24.53	48.75	30.14
0.25	6	100%	maritime	18.97	28.57	24.79	48.75	30.14
0.25	6	50%	maritime	18.95	28.50	24.66	48.75	30.14
0.1	4.8	100%	air	11.44	18.82	25.24	33.85	17.90
0.1	4.8	50%	air	10.41	17.05	20.10	33.85	17.90
0.1	4.8	0%	maritime	9.37	15.28	14.96	33.85	17.90
0.1	4.8	100%	maritime	9.41	15.41	15.23	33.85	17.90
0.1	4.8	50%	maritime	9.39	15.35	15.10	33.85	17.90
0.1	3.6	100%	air	10.32	17.69	24.11	24.72	14.09
0.1	3.6	50%	air	9.28	15.92	18.97	24.72	14.09
0.1	3.6	0%	maritime	8.24	14.15	13.84	24.72	14.09
0.1	3.6	100%	maritime	8.28	14.29	14.10	24.72	14.09
0.1	3.6	50%	maritime	8.26	14.22	13.97	24.72	14.09
0.1	6	100%	air	12.57	23.54	26.36	40.32	21.70
0.1	6	50%	air	11.53	21.77	21.23	40.32	21.70
0.1	6	0%	maritime	10.49	20.00	16.09	40.32	21.70
0.1	6	100%	maritime	10.53	20.13	16.35	40.32	21.70
0.1	6	50%	maritime	10.51	20.06	16.22	40.32	21.70
0.4	4.8	100%	air	24.95	32.32	38.74	47.36	31.40
0.4	4.8	50%	air	23.91	30.55	33.60	47.36	31.40
0.4	4.8	0%	maritime	22.87	28.78	28.47	47.36	31.40
0.4	4.8	100%	maritime	22.91	28.91	28.73	47.36	31.40
0.4	4.8	50%	maritime	22.89	28.85	28.60	47.36	31.40
0.4	3.6	100%	air	20.45	27.82	34.24	34.85	24.22
0.4	3.6	50%	air	19.41	26.05	29.10	34.85	24.22
0.4	3.6	0%	maritime	18.37	24.28	23.96	34.85	24.22
0.4	3.6	100%	maritime	18.41	24.41	24.23	34.85	24.22
0.4	3.6	50%	maritime	18.39	24.35	24.10	34.85	24.22
0.4	6	100%	air	29.45	40.41	43.24	57.19	38.58
0.4	6	50%	air	28.41	38.64	38.10	57.19	38.58
0.4	6	0%	maritime	27.37	36.87	32.97	57.19	38.58
0.4	6	100%	maritime	27.41	37.01	33.23	57.19	38.58
0.4	6	50%	maritime	27.39	36.94	33.10	57.19	38.58

Table 11: Sensitivity analysis for the base case 2

4.3 Impact of provisioning mode

The two cases studied above highlight that the carbon emissions from reusable packaging are heavily influenced by the provisioning rate and provisioning mode. We discuss this feature further by comparing emissions in case of air and maritime provisioning. In the sensitivity analysis of case 1, we can identify 9 scenarii with 100% air provisioning as well as 9 scenarii with 100% maritime provisioning. We compute average emissions for these two settings for the 3 reusable packaging options (Quarter PMC, 1500X and RKNe1). The results appear in Table 12.

	emissions (tCO_2e)		
100% maritime vs. 100% air	**Quarter PMC**	**1500X**	**RKNe1**
100% air	4.00	7.50	11.34
100% maritime	3.04	4.77	6.78
difference	24%	36%	40%

Table 12: Comparison of air and maritime provisioning for case 1

We perform the same analysis for case 2, the results appear in Table 13.

	emissions (tCO_2e)		
100% maritime vs. 100% air	**Half PMC**	**1500 X**	**RAP e2**
100% air	18.20	26.77	31.99
100% maritime	16.16	23.36	21.98
difference	11%	13%	31%

Table 13: Comparison of air and maritime provisioning for case 2

The results in Tables 12 and 13 clearly demonstrate the influence of air repositioning in the carbon footprint of time and temperature sensitive pharmaceutical products in case of shipment with reusable packaging. Note that this practice is quite developed for active and hybrid packaging options due to their high price. This ensures fast rotation that is necessary for efficient asset utilization. Using air transport for repositioning reusable packaging increases emissions by 11% to 40% for the different options considered. We conclude that this is not advisable to reposition reusable packaging via air transport as this negatively impacts carbon emissions. Reusable packaging option providers have to carefully manage their assets to ensure that repositioning is performed solely via maritime transportation to reduce the carbon emissions of their solution.

4.4 Impact of weight factor

The results above demonstrate that packaging weight is a key driver of carbon emissions for the shipment of time and temperature pharmaceuticals. We define here the ratio of packaging weight versus cargo weight, and we refer to this as the *weight factor*. Let q be the number of packaging required for a shipment, let P_w be the packaging weight and let C_w be the cargo weight. Then, we define the weight factor F as:

$$F = \frac{qP_w}{C_w}\,. \tag{4}$$

The weight factor is a measure of weight efficiency for packaging. The lower the weight factor is, the better in terms of carbon emissions. Note also that a weight factor greater than 1 implies that the weight of the packaging exceeds the weight of the cargo transported. We present the weight factors and an analysis of their ranking for case 1 and case 2 in Tables 14 and 15 respectively. For case 1, Quarter PMC is the option with the smallest (best) weight factor, and this is also the one with the lowest carbon footprint. The ranking in terms of weight factors is similar to the ranking in terms of emissions for the 5 packaging options considered. For case 2, half PMC is the option with the lowest (best) weight factor and the lowest carbon footprint. The ranking in weight factors is similar to the ranking in emissions as well.

	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
weight factor (F)	0.59	1.52	2.54	2.99	1.00
TOTAL emissions (tCO_2e)	3.02	4.69	6.64	8.38	4.04
ranking in weight factor	1	3	4	5	2
ranking in emissions	1	3	4	5	2

Table 14: Weight factor analysis for case 1

	Half PMC	1500 X	RAP e2	TC432	silverpod MAX
weight factor (F)	0.41	0.95	0.92	2.28	1.04
TOTAL emissions (tCO_2e)	16.12	22.03	21.71	40.60	24.65
ranking in weight factor	1	3	2	5	4
ranking in emissions	1	3	2	5	4

Table 15: Weight factor analysis for case 2

Note that the analysis above is made for a given known shipment. While making their decisions for selecting a packaging option, pharmaceutical companies do not necessarily have very specific requirements about shipment weights. In this setting, this can be challenging to compare packaging options that have different usable volumes. Therefore, we propose to define the *standardized weight factor* as the packaging weight per unit of usable volume. Let P_w be the packaging weight and P_{uv} be the usable volume. Then, we define the standardized weight factor F^S as:

$$F^S = \frac{P_v}{P_{uw}} \,. \quad (5)$$

The lower F^S is, the better it is in terms of carbon emissions. Indeed, a low value for F^S implies that the packaging is lightweight with a large usable volume. Table 16 provides standardized weight factors for the 7 packaging options studied. The results clearly demonstrate that EMBALL'ISO solutions are very efficient from a standardized weight factor perspective, and this explains their efficiency in terms of carbon footprint.

	Half PMC	Quarter PMC	RAP e2	Silverpod MAX	1500 X	RKNe1	TC432
standardized weight factor (t/m3)	0.07	0.10	0.17	0.21	0.23	0.27	0.52

Table 16: Standardized weight factors

4.5 Impact of volumetric weight

We study the impact of using volumetric weight instead of standard weight for measuring air transport emissions based on the two cases presented above. Note that air transport is used for the long-haul leg of the cargo shipment. Besides, air transport might be used for repositioning some reusable packaging if the asset price is high even if we highlight in subsection 4.3 that this practice is not advisable from a carbon emissions perspective. We compute average emissions for the 45 instances tested for case 1 in case of standard weight and in case of volumetric weight and we measure the difference. The results appear in Table 17.

	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
standard weight	3.32	5.56	8.09	7.65	4.76
volumetric weight	3.98	5.73	8.77	7.65	4.82
diff.	16%	3%	8%	0%	1%

Table 17: Impact of standard weight and volumetric weight on emissions for case 1

We perform the same analysis for case 2, the results appear in Table 18.

	Half PMC	1500 X	RAP e2	TC432	Silverpod MAX
standard weight	16.75	24.33	24.88	39.72	24.65
volumetric weight	21.56	27.52	28.27	39.72	24.65
difference	29%	13%	14%	0%	0%

Table 18: Impact of standard weight and volumetric weight on emissions for case 2

Note that the detailed results, besides the averages provided here, can be found in the appendix. We can make the following observations. Using volumetric weight instead of standard weight impacts all packaging solutions except TC432 for the instances tested. There are two types of possible impact. First, light packaging options with large exterior volumes are likely to be impacted for cargo shipment via air in case emissions are measured with volumetric weight. Indeed, they would require high cargo weight for the laden density to exceed the default density of 0.167 t/m^3. As an example, we measure the minimum weight to load in one packaging for the density to be greater or equal to the default density for the 5 packaging options studied in case 1. The results appear in Table 19. While it requires only 76 kg of cargo in one unit of 1500X to reach the default density, Quarter PMC needs to be loaded with 306 kg of cargo. Note that Table 19 also explains why TC432 is not affected by volumetric weight. Indeed, it requires only 32 kg of cargo per packaging to reach the default density and this applies to all instances tested. Besides, TC432 is non-reusable and therefore, it is never transported empty via air. This analysis also highlights that packaging options that are less efficient in terms of *standardized weight factors* are also less likely to be affected by volumetric weights.

	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
minimum cargo weight to exceed default density (t)	0.306	0.076	0.196	0.032	0.089

Table 19: Minimum cargo weight per packaging to reach default density for case 1

Second, reusable packaging options can be impacted by volumetric weight if they are transported empty via air. This could happen for active and hybrid solutions to fasten their reutilization. As these solutions are non-foldable, the minimum cargo weight to exceed the default density is not achieved when empty. Therefore, emissions from air repositioning can be impacted if calculated by using volumetric weight instead of standard weight.

While these results emphasize that accounting for volumetric weight instead of standard weight can have an impact when measuring the carbon emissions of time and temperature sensitive pharmaceutical product shipment, we want to highlight that the main conclusions of this study are not impacted by the choice of the weight measurement methodology. Our study shows that the debate about standard vs. volumetric weight is of marginal importance for carbon emissions measurements of time and temperature sensitive pharmaceutical shipments.

5 Conclusion

We provided a methodology for measuring emissions from time and temperature sensitive pharmaceutical shipments. These emissions strongly depend on the type of packaging used as well as the way the packaging solution is managed. Our methodology complements existing methods by including three key features related to some reusable packaging solutions. We allow for a return rate of less than 100% and for packaging solutions that can be folded in case of repositioning. Finally, we extend existing methods for allocating emissions from repositioning.

We applied our methodology for two cases to compare the performance of five packaging options. First, we focus on the delivery of one euro pallet from Germany to China. Our results show that Quarter PMC is the solution with the lowest carbon emissions for this first case. It reduces emissions by 25% compared with Silverpod MAX, by 36% compared with 1500X, by 55% compared with RKNe1 and by 64% compared with TC432. Second, we evaluate emissions for the delivery of four US pallets from the USA to China. Our results show that Half PMC is the solution with the lowest carbon emissions for this second case. It reduces emissions by 26% compared with RAPe2, by 27% compared with 1500X, by 35% compared with Silverpod MAX and by 60% compared with TC432.

We conducted some sensitivity analyses on cargo volume, cargo density, repositioning mode and repositioning rate. We further study the impacts of repositioning mode and packaging weight. Besides, we evaluate the implications of using volumetric weight instead of standard weight for air transport. The results clearly show that the most efficient packaging solutions in terms of carbon emissions are lightweight, reusable, and repositioned via maritime transport. Besides, a good foldability ratio allows for a better use of maritime transport in case of repositioning. These results can help pharmaceutical companies in selecting the most appropriate packaging solution. In order to ease the process, we propose an easy-to-compute indicator of packaging weight performance, and we compute this standardized weight factor for the seven solutions studied. Our results also help packaging solution providers to make better design and operation decisions with the objective of reducing carbon emissions for their customers.

As a future direction, the methodology could be extended to help pharmaceutical companies to select the most appropriate mode and route for each temperature and time sensitive shipment. This could help reduce further carbon emissions, especially by reducing the reliance on air transport that is responsible for a large share of total emissions.

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Appendix A: volumetric weight calculations

We present the results for the two case studies of Section 4 in case air transport emissions are measured by using volumetric weight instead of standard weight.

	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
TOTAL emissions (tCO_2e)	***3.43***	***4.69***	***6.64***	***8.38***	***4.04***
fixed/U ($kgCO_2e$)	**1.2%**	**0.7%**	**1.1%**	**11.8%**	**8.2%**
positioning emissions ($kgCO_2e$)	**0.0%**	**0.0%**	**0.1%**	**0.0%**	**0.0%**
provisioning emissions ($kgCO_2e$)	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
conditioning emissions ($kgCO_2e$)	**0.0%**	**0.1%**	**0.2%**	**0.1%**	**0.0%**
transportation emissions ($kgCO_2e$)	**97.9%**	**99.2%**	**98.7%**	**88.1%**	**91.7%**
incl. cargo emissions	*53.9%*	*39.4%*	*27.9%*	*22.1%*	*45.9%*
incl. packaging emissions	*44.0%*	*59.8%*	*70.8%*	*66.0%*	*45.9%*
refurbishing emissions (kgCO2e)	**0.9%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

Table A.1: Results for the base case 1 with no repositioning (volumetric weight)

				emissions (tCO_2e) in case of volumetric weight				
Density (t/m^3)	**Volume (m^3)**	**Provisioning rate**	**Provisioning mode**	**Quarter PMC**	**1500X**	**RKNe1**	**TC432**	**Silverpod MAX**
0.25	1	100%	air	4.42	8.06	12.78	8.38	4.04
0.25	1	50%	air	3.93	6.38	9.71	8.38	4.04
0.25	1	0%	maritime	3.43	4.69	6.64	8.38	4.04
0.25	1	100%	maritime	3.45	4.77	6.78	8.38	4.04
0.25	1	50%	maritime	3.44	4.73	6.71	8.38	4.04
0.25	0.75	100%	air	4.42	7.60	12.38	5.74	3.57
0.25	0.75	50%	air	3.93	5.91	9.31	5.74	3.57
0.25	0.75	0%	maritime	3.43	4.23	6.24	5.74	3.57
0.25	0.75	100%	maritime	3.45	4.30	6.38	5.74	3.57
0.25	0.75	50%	maritime	3.44	4.27	6.31	5.74	3.57
0.25	1.25	100%	air	4.47	8.52	13.24	8.84	6.68
0.25	1.25	50%	air	3.97	6.84	10.17	8.84	6.68
0.25	1.25	0%	maritime	3.48	5.16	7.10	8.84	6.68
0.25	1.25	100%	maritime	3.50	5.23	7.25	8.84	6.68
0.25	1.25	50%	maritime	3.49	5.19	7.17	8.84	6.68
0.1	1	100%	air	4.42	6.95	12.38	7.27	2.92
0.1	1	50%	air	3.92	5.27	9.31	7.27	2.92
0.1	1	0%	maritime	3.43	3.58	6.24	7.27	2.92
0.1	1	100%	maritime	3.45	3.66	6.38	7.27	2.92
0.1	1	50%	maritime	3.44	3.62	6.31	7.27	2.92
0.1	0.75	100%	air	4.42	6.77	12.38	4.91	2.84
0.1	0.75	50%	air	3.92	5.09	9.31	4.91	2.84
0.1	0.75	0%	maritime	3.43	3.41	6.24	4.91	2.84
0.1	0.75	100%	maritime	3.45	3.48	6.38	4.91	2.84
0.1	0.75	50%	maritime	3.44	3.44	6.31	4.91	2.84
0.1	1.25	100%	air	4.42	7.14	12.38	7.45	5.68
0.1	1.25	50%	air	3.92	5.45	9.31	7.45	5.68
0.1	1.25	0%	maritime	3.43	3.77	6.24	7.45	5.68
0.1	1.25	100%	maritime	3.45	3.84	6.38	7.45	5.68
0.1	1.25	50%	maritime	3.44	3.80	6.31	7.45	5.68
0.4	1	100%	air	5.11	9.17	13.89	9.49	5.15
0.4	1	50%	air	4.62	7.49	10.82	9.49	5.15
0.4	1	0%	maritime	4.13	5.80	7.75	9.49	5.15
0.4	1	100%	maritime	4.15	5.88	7.89	9.49	5.15
0.4	1	50%	maritime	4.14	5.84	7.82	9.49	5.15
0.4	0.75	100%	air	4.42	8.43	13.15	6.57	4.41
0.4	0.75	50%	air	3.93	6.75	10.08	6.57	4.41
0.4	0.75	0%	maritime	3.43	5.06	7.01	6.57	4.41
0.4	0.75	100%	maritime	3.45	5.14	7.15	6.57	4.41
0.4	0.75	50%	maritime	3.44	5.10	7.08	6.57	4.41
0.4	1.25	100%	air	5.86	9.91	14.63	10.23	8.07
0.4	1.25	50%	air	5.36	8.23	11.56	10.23	8.07
0.4	1.25	0%	maritime	4.87	6.54	8.49	10.23	8.07
0.4	1.25	100%	maritime	4.89	6.62	8.63	10.23	8.07
0.4	1.25	50%	maritime	4.88	6.58	8.56	10.23	8.07

Table A.2: Sensitivity analysis for the base case 1 (volumetric weight)

	emissions (tCO_2e) in case of volumetic weight				
	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
all cases	3.98	5.73	8.77	7.65	4.82
only maritime repositioning	3.69	4.73	6.95	7.65	4.82
only useable volume of Silverpod PRO	3.85	5.50	8.57	7.06	3.82
only useable volume of Silverpod and maritime	3.56	4.50	6.76	7.06	3.82

Table A.3: Average emissions from the sensitivity analysis for the base case 1 (volumetric weight)

				ranking in emissions in case of volumetic weight				
Density (t/m^3)	Volume (m^3)	Provisioning rate	Provisioning mode	Quarter PMC	1500X	RKNe1	TC432	Silverpod MAX
0.25	1	100%	air	2	3	5	4	1
0.25	1	50%	air	1	3	5	4	2
0.25	1	0%	maritime	1	3	4	5	2
0.25	1	100%	maritime	1	3	4	5	2
0.25	1	50%	maritime	1	3	4	5	2
0.25	0.75	100%	air	2	4	5	3	1
0.25	0.75	50%	air	2	4	5	3	1
0.25	0.75	0%	maritime	1	3	5	4	2
0.25	0.75	100%	maritime	1	3	5	4	2
0.25	0.75	50%	maritime	1	3	5	4	2
0.25	1.25	100%	air	1	3	5	4	2
0.25	1.25	50%	air	1	3	5	4	2
0.25	1.25	0%	maritime	1	2	4	5	3
0.25	1.25	100%	maritime	1	2	4	5	3
0.25	1.25	50%	maritime	1	2	4	5	3
0.1	1	100%	air	2	3	5	4	1
0.1	1	50%	air	2	3	5	4	1
0.1	1	0%	maritime	2	3	4	5	1
0.1	1	100%	maritime	2	3	4	5	1
0.1	1	50%	maritime	2	3	4	5	1
0.1	0.75	100%	air	2	4	5	3	1
0.1	0.75	50%	air	2	4	5	3	1
0.1	0.75	0%	maritime	3	2	5	4	1
0.1	0.75	100%	maritime	2	3	5	4	1
0.1	0.75	50%	maritime	2	3	5	4	1
0.1	1.25	100%	air	1	3	5	4	2
0.1	1.25	50%	air	1	2	5	4	3
0.1	1.25	0%	maritime	1	2	4	5	3
0.1	1.25	100%	maritime	1	2	4	5	3
0.1	1.25	50%	maritime	1	2	4	5	3
0.4	1	100%	air	1	3	5	4	2
0.4	1	50%	air	1	3	5	4	2
0.4	1	0%	maritime	1	3	4	5	2
0.4	1	100%	maritime	1	3	4	5	2
0.4	1	50%	maritime	1	3	4	5	2
0.4	0.75	100%	air	2	4	5	3	1
0.4	0.75	50%	air	1	4	5	3	2
0.4	0.75	0%	maritime	1	3	5	4	2
0.4	0.75	100%	maritime	1	3	5	4	2
0.4	0.75	50%	maritime	1	3	5	4	2
0.4	1.25	100%	air	1	3	5	4	2
0.4	1.25	50%	air	1	3	5	4	2
0.4	1.25	0%	maritime	1	2	4	5	3
0.4	1.25	100%	maritime	1	2	4	5	3
0.4	1.25	50%	maritime	1	2	4	5	3

Table A.4: Ranking of instances by ascending order of carbon footprint for case 1 (volumetric weight)

	Half PMC	1500 X	RAP e2	TC432	silverpod MAX
TOTAL emissions (tCO_2e)	***18.52***	***22.03***	***21.71***	***40.60***	***24.65***
fixed/U ($kgCO_2e$)	**0.7%**	**0.4%**	**0.6%**	**8.9%**	**6.7%**
positioning emissions ($kgCO_2e$)	**0.0%**	**0.1%**	**0.1%**	**0.1%**	**0.1%**
provisioning emissions ($kgCO_2e$)	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
conditioning emissions ($kgCO_2e$)	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
transportation emissions ($kgCO_2e$)	**98.7%**	**99.5%**	**99.3%**	**91.0%**	**93.2%**
incl. cargo emissions	*60.8%*	*51.1%*	*51.8%*	*27.7%*	*45.6%*
incl. packaging emissions	*38.0%*	*48.4%*	*47.5%*	*63.2%*	*47.5%*
refurbishing emissions (kgCO2e)	**0.5%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**

Table A.5: Results for the base case 2 with no repositioning (volumetric weight)

				emissions (tCO_2e) in case of volumetic weight				
Density (t/m^3)	Volume (m^3)	Provisioning rate	Provisioning mode	Half PMC	1500 X	RAP e2	TC432	Silverpod MAX
0.25	4.8	100%	air	23.62	34.78	39.71	40.60	24.65
0.25	4.8	50%	air	21.07	28.41	30.71	40.60	24.65
0.25	4.8	0%	maritime	18.52	22.03	21.71	40.60	24.65
0.25	4.8	100%	maritime	18.55	22.16	21.98	40.60	24.65
0.25	4.8	50%	maritime	18.53	22.10	21.85	40.60	24.65
0.25	3.6	100%	air	23.60	31.97	36.90	29.79	19.16
0.25	3.6	50%	air	21.05	25.59	27.90	29.79	19.16
0.25	3.6	0%	maritime	18.50	19.22	18.90	29.79	19.16
0.25	3.6	100%	maritime	18.54	19.35	19.17	29.79	19.16
0.25	3.6	50%	maritime	18.52	19.28	19.03	29.79	19.16
0.25	6	100%	air	24.03	45.44	42.52	48.75	30.14
0.25	6	50%	air	21.48	36.94	33.52	48.75	30.14
0.25	6	0%	maritime	18.93	28.44	24.53	48.75	30.14
0.25	6	100%	maritime	18.97	28.57	24.79	48.75	30.14
0.25	6	50%	maritime	18.95	28.50	24.66	48.75	30.14
0.1	4.8	100%	air	23.59	28.03	36.20	33.85	17.90
0.1	4.8	50%	air	21.04	21.66	27.20	33.85	17.90
0.1	4.8	0%	maritime	18.49	15.28	18.20	33.85	17.90
0.1	4.8	100%	maritime	18.53	15.41	18.47	33.85	17.90
0.1	4.8	50%	maritime	18.51	15.35	18.34	33.85	17.90
0.1	3.6	100%	air	23.58	26.91	36.19	24.72	14.09
0.1	3.6	50%	air	21.03	20.53	27.20	24.72	14.09
0.1	3.6	0%	maritime	18.48	14.15	18.20	24.72	14.09
0.1	3.6	100%	maritime	18.52	14.29	18.46	24.72	14.09
0.1	3.6	50%	maritime	18.50	14.22	18.33	24.72	14.09
0.1	6	100%	air	23.59	37.00	36.20	40.32	21.70
0.1	6	50%	air	21.04	28.50	27.20	40.32	21.70
0.1	6	0%	maritime	18.49	20.00	18.21	40.32	21.70
0.1	6	100%	maritime	18.53	20.13	18.47	40.32	21.70
0.1	6	50%	maritime	18.51	20.06	18.34	40.32	21.70
0.4	4.8	100%	air	27.97	41.53	46.46	47.36	31.40
0.4	4.8	50%	air	25.42	35.16	37.46	47.36	31.40
0.4	4.8	0%	maritime	22.87	28.78	28.47	47.36	31.40
0.4	4.8	100%	maritime	22.91	28.91	28.73	47.36	31.40
0.4	4.8	50%	maritime	22.89	28.85	28.60	47.36	31.40
0.4	3.6	100%	air	23.62	37.03	41.96	34.85	24.22
0.4	3.6	50%	air	21.07	30.66	32.96	34.85	24.22
0.4	3.6	0%	maritime	18.52	24.28	23.96	34.85	24.22
0.4	3.6	100%	maritime	18.56	24.41	24.23	34.85	24.22
0.4	3.6	50%	maritime	18.54	24.35	24.10	34.85	24.22
0.4	6	100%	air	32.47	53.88	50.96	57.19	38.58
0.4	6	50%	air	29.92	45.38	41.96	57.19	38.58
0.4	6	0%	maritime	27.37	36.87	32.97	57.19	38.58
0.4	6	100%	maritime	27.41	37.01	33.23	57.19	38.58
0.4	6	50%	maritime	27.39	36.94	33.10	57.19	38.58

Table A.6: Sensitivity analysis for the base case 2 (volumetric weight)