An environmental impact comparison of packaging methods in the cold-chain industry

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TABLE OF CONTENTS

Abstract	1
Background, aims, and scope	2
Methodology	3
System Description	8
Material extraction	8
Component manufacture	8
Component assembly	8
Transportation prior to use	9
Use scenarios	10
End-of-life	11
Recycling activities	11
Results	13
Sensitivity analysis	15
Single-use component weight requirements	15
Use-phase transportation distance	16
Recycling Rates	17
Cradle-to-gate supplier to supplier transportation assumption	19
Discussion	23
Conclusion	24
Acknowledgments	24
References	25
Appendix 1 – Summary of potential multipliers	28
Appendix 2 – Single-use packaging detailed system boundary	30
Appendix 3 – Reusable packaging detailed system boundary	31
Appendix 4 – Summary of material potentials	32
Appendix 5 – Emissions per vehicle type	33
Appendix 6 – Use transportation calculation method	36

ABSTRACT

Purpose

Pharmaceutical and biological materials require thermally controlled environments when transporting between manufacturers, clinics, and hospitals. It is the purpose of this report to compare the life cycle impacts of two distinct logistical approaches to packaging commonly used in facilitating a clinical drug trial and identify the method of least environmental burden. Considered herein is analysis of a single-use approach utilising containers insulated with either polyurethane or polystyrene and a reusable approach utilising containers with vacuum insulated panels.

Methods

This study has taken a cradle-to-grave approach which covers material extraction, manufacture, assembly, usage, transportation, and end-of-life realities. The functional unit of comparison is "a two-year clinical trial consisting of 30,000 individual package shipments able to maintain roughly 12L of payload at a controlled 2-8°C temperature range for approximately 96 hours." Published life cycle inventory data were used for process and material emissions. A population-centered averaging method was used to estimate transportation distances to and from clinical sites during container use. Environmental impacts of the study include global warming potential, eutrophication potential, acidification potential, photochemical oxidation potential, human toxicity potential, and post-consumer waste.

Results and discussion

The average single-use approach emits 1,122 tonnes of CO2e compared with 241 tonnes with the reusable approach. This is a 78% difference in global warming potential between the two approaches. Similar differences exist in other impact categories with the reusable approach showing 66% less acidification potential, 67% less eutrophication potential, 86% less photochemical ozone potential, 56% less human toxicity potential, and 95% less post-consumer waste. The cradle-to-gate emissions of the single-use container were the overwhelming cause of its high environmental burden as 30,000 units were required to satisfy the functional unit rather than 772 for the reusable approach. The reusable container was about half the weight of the average single-use container which lowered its transportation below the single-use approach emissions despite an extra leg of travel.

Conclusion

The reusable logistical approach has shown to impose a significantly smaller environmental burden in all impact categories of interest. A sensitivity analysis has shown a moderate uncertainty in the degree of environmental advantage, but it confirms the conclusion that the reusable approach is environmentally superior to the single-use approach in this analysis.

Remote deliveries into logistically undeveloped areas can present a significant challenge to retrieving a reusable shipper. When the reusable shipper is unable to be re-used, the single-use shipper produces less environmental impact than reusable shippers due to lower cradle-to-gate product emissions.

BACKGROUND, AIMS, AND SCOPE

The demand for thermally controlled logistics is growing in response to emerging pharmaceutical and biological markets serving an aging population. These critical activities invariably require transport between many geographically separated locations. A thermally controlled environment is required during transport in order to maintain efficacy of the payload. This situation necessitates innovative packaging and transportation means, which contribute significantly to the environmental footprint of these segments of the healthcare market.

It is the goal of this research to identify current packaging options that limit this environmental impact.

There are two commonly accepted logistical approaches for the conveyance of biological and pharmaceutical payloads, each defined by its longevity of use, insulation type, and thermal management means. The most common conveyance packaging is single-use containers, implemented by the utilisation of either extruded polystyrene (EPS) or polyurethane (PUR) insulation and gel pack heat sinks. The second method of interest here is a growing utilisation of durable reusable containers, using vacuum-insulated-panel (VIP) insulation and phase-change-media-based (PCM) heat sinks. The reusable container of interest in this analysis is the Credo Cube® 4-1296 produced by Peli BioThermal. There has been a variety of packaging life cycle analysis (LCA) comparison studies that focus on payload sizes and encasing materials such as the assessment of coffee packaging in Italy (De Monte, Padoano, & Pozzetto, 2005) and soda packaging in the UK (Amienyo, Gujba, Stichnothe, & Azapagic, 2012). Other studies have focused exclusively on encasing materials such as the comparison between packaging options for mail-order soft goods (Franklin Associates, 2004). There has been no LCA study to this date concerning thermal performance packaging used in cold-chain logistics.

The scope of this analysis focuses on a two-year time span, a period which covers at least half of a typical Phase III clinical trial in the pharmaceutical industry (Abrantes-Metz, Adams, & Metz, 2004). During such a period, thousands of shipments to various clinical sites around the country are expected to occur. A cradle-to-grave LCA approach has been aligned with the methodology standardised in ISO 14044:2006 and PAS2050 (ISO, 2006). Although the present research is focused specifically on the pharmaceutical market, it is expected that the methodology and results will apply to similar high-volume markets in the cold-chain industry.

Global warming potential (GWP, commonly known as the carbon footprint), eutrophication potential (EP), acidification potential (AP), photochemical oxidation potential (PCOP), human toxicity potential (HTP), and post-consumer solid waste are the environmental impacts to be addressed and quantified here. Comparisons of these environmental impacts will be made between the aforementioned packaging approaches in order to identify the logistical method(s) with the lower environmental burden. A table of potential multipliers used in this study and definitions of the aforementioned potentials are conveyed in Appendix 1. These potential values have been collected from three sources: PAS2050, IPCC's Climate Change 2007: The physical science basis (Solomon et al.), and an online compendium by Summerscales (2006) based on the work by Azapagic (2004).

METHODOLOGY

A cradle-to-grave approach was utilised for the environmental impact analysis to be performed here. The functional unit of the study that is used to logically compare the two logistical approaches is a two-year clinical trial requiring 15,000 cold-chain shipments per year, using containers qualified to transport 12L of product maintained at temperatures of 2-8°C for a duration of approximately 96 hours. Although these conditions cover a small portion of the totality of cold-chain scenarios, they are typical of the individual payloads conveyed in clinical trials.

The breakdown of component weights and materials for each logistical approach is set forth in Tables 1 and 2.

NOTE: This comparison uses water-based single-use products versus PCM-based single-use products.

Table 1 - Component materials and weights per single-use container

Component	Weight (kg)	Material(s)
Insulation*	4.84/6.06	PUR/EPS
Gel packs	8.92	Water, CMC, LDPE
Gel bricks	2.95	Water, phenolic foam, LDPE
Corrugate	1.14	Cardboard
Total	17.85/19.07	PUR model/EPS model

* - Equivalent performance insulation, two materials analysed independently

Table 2 - Component materials and weights per reusable container

Component	Weight (kg)	Material(s)
Vacuum insulated panels	2.90	Carbon silica, carbon black, metalized PET film, LLDPE film, PVC film, PU adhesive
Thermal isolation chamber	1.70	HDPE
Phase change media	3.87	Paraffin wax blend
Outer corrugate	0.93	Polypropylene (PP)
Tape	0.09	Polypropylene (PP)
Total	9.49	

The analysis of each of the selected logistical approaches was subdivided into the five stages described schematically in Figure 1. A detailed system boundary showing each component included in impact modelling of the single-use and reusable approaches is available in Appendices 2 and 3 respectively.

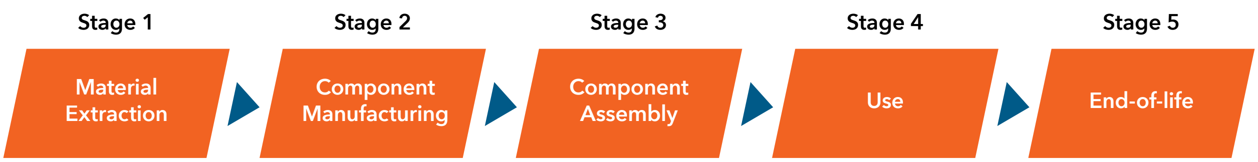


Figure 1 - Stages of environmental impact occurrence

The functional unit displays some of the critical assumptions:

- A two-year clinical trial
- 30,000 total pharmaceutical deliveries
- A container qualified to maintain its payload between 2-8°C for a duration of approximately 96 hours

Further assumptions include:

- All clinical trial sites reside in the contiguous US
- Pharmaceutical production originates in Indianapolis, Indiana
- The reusable container ships two times per month
- Reusable container inventory sustains losses of 10% per year; combined with the foregoing assumption, this results in 772 containers needed over the two-year clinical trial
- The polypropylene corrugate component of the reusable container is replaced every quarter
- The lifespan of the reusable packages is designated to be two years, although they typically last longer
- Shipping distances between stages 1, 2, and 3 are assumed to be 1000km when no primary data are available, assuming a regional and national supply chain
- When no primary data are available, 3% product loss during manufacturing is assumed

Material and process emissions data

Materials, manufacturing, and assembly data for the reusable packaging approach were obtained mainly from primary sources of a single producer. Data from several single-use packaging options on the market were averaged in order to estimate material requirements for a typical single-use container. For the latter, some emission sources may not have been captured in the same detail as for the reusable approach due to limited access.

Data on the variety of plastics involved in the two types of packaging approaches were collected from the work published by Franklin & Associates on nine plastic resins and PUR precursors (2011) as well as Plastic Europe's eco-profiles (2008, 2010) and eco-profile reports written by Boustead (2005, 2006). Although Plastic Europe's eco-profiles focus was mainly on European polymer production, comparisons between their data and that of Franklin & Associates for the same materials resulted in similar emissions data (5-15% difference), validating their use for this U.S. domestic case. Data on LLDPE and PET films were not directly available. Their impact after film processing was estimated by adding the film processing emissions of LDPE film to that of LLDPE and PET resin. The processing energy required to manufacture multilayered film was estimated by use of the work of Dimenna (2005).

Emissions data for paraffin were estimated from the work performed by Tufvesson and Börjesson (2008), as no other source was available. Their data incorporates averaged information from a variety of primary and secondary sources.

Silica and carbon black make up the bulk of the VIP insulating material. Their production energy requirements and emissions data were estimated from an industrial process best-practice report collected by the European Commission (2007). Impact due to the extraction of silica sand was estimated from LCI data published by IMA-Europe (2007).

Cardboard corrugate production and emissions data are based on U.S. industry-average corrugate emissions published by PE Americas (2009). Recycling rates of 78% were included in their study, and thus were assumed here.

The emissions resulting from the processing and treatment of tap water, the primary component of cooling gels and bricks, were estimated from a Franklin Associates report on drinking water in the state of Oregon (2009). Only the processing and treatment emissions data for tap water were used. The impact uncertainty of water sourcing is insignificant in comparison to transporting it by truck, so that any geographically based uncertainty is considered to be of negligible impact.

Electricity production emissions from component production and refrigeration required during product use phases were determined from the U.S. EPA eGRID database (2012). The eGRID database details emissions by state based on the mix of energy production means in that state. Regionally averaged electricity transmission losses were taken into account.

SYSTEM DESCRIPTION

Material extraction

Emissions involving raw material extraction were included in a majority of the published LCA studies from which data were collected. In cases where it was not included, as for crude oil extraction and refining for transportation emissions, the emissions were determined separately and added into the respective life cycle inventory (LCI). Crude oil extraction data are based on the report on Crude Oil by Boustead (2005). Co-product breakdowns and refining data were obtained from the NREL U.S. Life-Cycle Inventory Database.

Extraction of materials required to manufacture ethyl acetate was not accounted for and is considered negligible as it comprises only 0.06% of the total reusable package weight.

Component manufacture

There were a few manufacturing processes and materials not included in the analysis due to minimal contribution to product weight and to difficulty finding a reliable data source. These include aluminum contribution to the metalised PET in the VIP lamination (0.01% of total reusable package weight), manufacturing emissions from adhesive manufacturing of ethyl acetate and PU resin (0.16% reusable package weight), and the process of manufacturing phenolic foam from phenolic resin (≈1.44% of single-use package weight).

Ethyl acetate manufacturing emissions were not accounted for; rather, the direct impact of the chemical itself was used. Only the CO_2e emissions from the manufacturing of CMC were accounted for due to the inaccessibility of more detailed data (Eco-costs for Carboxymethyl Cellulose, 2012).

Component assembly

Assembly of the single-use and reusable containers is fairly straightforward due to minimal components and the lack of moving parts. Issues with supplier quality are normally discovered and damage to the components can occur during the assembly stage. VIP assembly losses due to puncture for example are typically not noticed until after the package has been assembled, which results in other product losses such as the PVC film encapsulation of the VIP and any tape that was used in the assembly process. These losses were accounted for.

The assembly energy required to fill and seal the gel packs and bricks utilised in the single-use container was omitted due to lack of data.

SYSTEM DESCRIPTION

Transportation prior to use

In many cases, intermediate transportation steps, such as the transport of crude oil to a refinery, that occur during the manufacture of specific components were included in published LCI data. The contribution of this transportation to the overall environmental impact of these materials was generally in the range of 1-3%. Due to this small impact, it was determined unnecessary to modify the data when more specific transportation data were available. In cases where transportation steps were not accounted for in the literature, subsequent transportation emissions were included.

Four types of trucking vehicles were used in transportation emissions modelling: (a) long-haul single unit truck, (b) short-haul single unit truck, (c) light commercial vehicle, and (d) long-haul combination truck. Vehicle types are as defined in the EPA MOVE documentation (2012) as seen in Table 3 and were selected depending on distance traveled and cargo tonnage. All vehicles were assumed to run on diesel fuel. Adaptations to the emissions from light commercial vehicles were made to account for higher efficiency UPS and FedEx fleets; CO_2 and NO_X emissions were adjusted using carrier performance rankings as compiled by the EPA (2012). Average US emissions data from these vehicles as well as freight train emissions were obtained from aggregated MOVES data on the U.S. Life-Cycle Inventory Database (NREL). Emissions due to air transport were estimated using both the U.S. Life-Cycle Inventory Database and recent fleet data from UPS (2012) and FedEx (2012). Emissions summaries for each vehicle type are conveyed in Appendix 5.

Table 3 - Vehicle type characteristics

Vehicle Type	Shipping Distance	Description
Long-haul single unit truck	> 200 mi/322 km	Single unit trucks with more than four tyres
Short-haul single unit truck	< 200 mi/322 km	Single unit trucks with more than four tyres
Light commercial vehicle (FedEx, UPS adjusted)		Four wheel, two axle trucks used primarily for cargo transport
Long-haul combination truck	> 200 mi/322 km	Combination tractor/trailer trucks with more than four tyres

SYSTEM DESCRIPTION

Use scenarios

Refrigeration

Both the gel packs and PCM must be frozen prior to use in clinical shipments to ensure a functional heat sink. The energy required to freeze the PCM required for single containers is 960 Btu. Correspondingly, in metric units, 8.44MWh of refrigeration are required for the two-year clinical trial. With a typical COP (metric of efficiency) of commercial refrigerators of 3.8 (International Institute of Refrigeration, 2002), it is estimated that 2.22 MWh of grid energy are required to thermally protect 30,000 shipments.

Energy required to freeze the gel packs and bricks utilised in single-use containers was estimated using the thermodynamic properties of water. The mass of water to be frozen was taken as the mass of all the gel materials. Assuming a temperature drop of 22°C prior to freezing, a heat capacity of 4.186 kJ/kg-°C, and a heat of fusion of 334 kJ/kg, the resulting energy requirement to freeze the gel packs and bricks is 436 kJ/kg. This requires an estimated 11.04 MWh of grid energy over the two-year period, given a COP of 3.8.

The large difference in energy required to create heat sinks for each method is due to differences in heat storage and heat transfer efficiencies. Greater heat losses of the single-use container require more thermal energy input to protect the payload.

Reusable component replacement

Outer polypropylene corrugate boxes are expected to be replaced every quarter due to general wear and tear during shipping. Over the two-year clinical trial period, 5,000 of these boxes are used. Individual reusable components generally have a lifespan greater than the box as a whole, so replacing other parts is uncommon.

Transportation

Transportation during the use phase is a differentiating factor in this comparison due to the return trip required for each reusable box shipment. Transportation emissions are based on vehicle emissions only. Facility utility requirements and other overhead emissions associated with logistical processes are beyond the scope of these calculations.

Transportation was assumed to provide next-day delivery with logistical steps determined by regional location and distance from the payload origin. Distances were weighted by regional location and population distribution (US Census Bureau, 2010). Transportation distances were allocated to the total 30,000 shipments based on the distribution of pharmaceutical clinical trials around the United States (National Institute of Health, 2012). Return shipments of the reusable package are not time critical and are assumed to be ground transported primarily in combination long-haul trucks from the clinical site back to the pharmaceutical manufacturer in Indianapolis, IN. A graphic depicting average transportation distances and calculations involved can be seen in Appendix 6.

SYSTEM DESCRIPTION

End-of-life

Transport

Transport of materials to landfills and recycling centres was taken into account. Emissions data for a refuse truck obtained through the U.S. Life-Cycle Inventory Database was used in calculating emissions due to transport to landfill and recycling facilities. Transportation distances in each case were assumed to be 50km.

Landfill activities

The majority of components utilised in each packaging method are polymer based and will not break down in any reasonable length of time. Their environmental impact has been conglomerated into a "post-consumer solid waste" metric. Based on discussions with pharmaceutical providers about current practices in clinical trials, all components of the single-use container, except for the majority of the cardboard corrugate, are assumed to be landfilled. Non-polymer components that end up in landfills include a portion of cardboard corrugate that is not recycled and gel pack and brick contents in single-use containers.

The reusable container components that are typically landfilled include PVC film and the multilayered VIP film.

Recycling activities

Analysis of component recycling differs based on whether the recycled material is used to remake the same product, or a different product. The recycling system is considered to be closed-loop or open-loop respectively.

Closed-loop impact allocations are calculated utilising Eq. (1) as given by the PAS:2050 literature (British Standards Institution, 2011),

$$Impact = (1 - r)\,E_V + rE_R + (1 - r)\,E_D \qquad \textbf{(1)}$$

where r is the rate of recycling, E_V is the emissions total using all virgin raw material, E_R is the emissions total using all recycled raw material, and E_D is the emissions total arising from disposal of non-recycled material.

For the baseline case, it is assumed that 50% of recyclable products are in fact recycled.

SYSTEM DESCRIPTION

VIP

VIPs are shipped back to the manufacturer by the client for recycling. There is no quality loss of the insulating material during its first lifespan and no material processing is required for reuse in this closed-loop system. The silica and carbon black comprising the silica are the only recyclable materials in the VIP component, with Eq. (1) being used accordingly.

PCM

The PCM is reclaimed and reused in future TICs; therefore, its recycling contributions can be analysed in the closed-loop framework of Eq. (1). No material processing is required due to no loss in material quality.

Corrugate outer (PP)

The outer component of the reusable package is comprised of fully recyclable polypropylene. Actual end-of-life recycling rates are unknown; however, all process scrap is recycled. The component is extruded using 100% virgin PP resin so that recycling is accounted for using an open-loop methodology. The 50/50 open-loop method for a two-product system was applied in a fashion similar to that described by Ekvall and Tillman (1997). This method is based on the assumption that a demand for recycled material is required to facilitate recycling. Half of the virgin resin production impact, eventual disposal impact, and recycling impact is allocated to the original product virgin material. The allocation procedure is shown in Eq. (2).

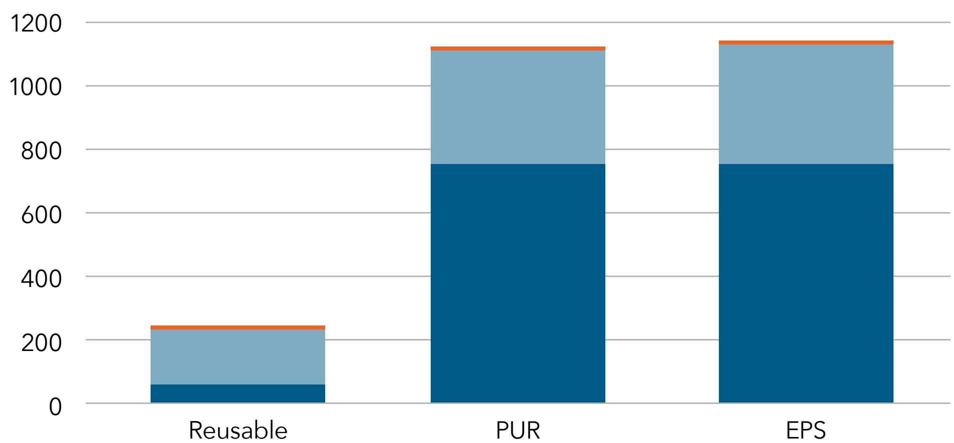
$$Impact = r\left(\frac{V - W}{2} + \frac{R}{2}\right) + (1 - r)(V + W) \quad \textbf{(2)}$$

Where r is the rate of recycling, V is the impact from sourcing all virgin material, W is the impact from disposal, and R is the impact from recycling.

Air emissions from the re-extrusion of PP during the recycling process were estimated from the work by Adams et al. (1999).

RESULTS

The results for the three analysed containment methods are shown in Figures 2, 3, and 4. The single-use approach has a far greater environmental burden across all impact categories analysed. The difference in cradle-to-gate emissions between the single- and reusable approaches is the primary cause of the increased environmental impact of the former. There are 91.4% more CO_2e emissions for the PUR case during this cradle-to-gate interval compared to 78.5% from cradle-to-grave. The distinction between these lifecycle intervals is that cradle-to-gate includes activities beginning with material extraction until the finished product leaves the assembly floor ready for consumption (the gate in this case), whereas cradle-to-grave encompasses the cradle-to-gate activities as well as those associated with product usage and end-of-life realities (from gate-to-grave). The average single-use approach has 4.7 times higher cradle-to-grave global warming emissions than the reusable approach over the functional unit. End-of-life contributions to the overall environmental impact comprise less than 1% of the overall impact, encompassing only the transportation to landfills and recyclers since recycled material benefits were discounted during the cradle-to-gate stage. Between the two single-use approaches, the PUR insulated option has a slight overall edge over the EPS option in all impact categories.



	Reusable	PUR	EPS
End-of-life	12	4	4
Product Use	174	354	377
Cradle-to-gate	65	754	752

Figure 2 – Comparison of cradle-to-grave global warming potential (GWP) per functional unit among the reusable, PUR single-use, and EPS single-use approaches

RESULTS

Figure 3 sets forth categories that display environmental impacts to the greater ecosystem. As previously mentioned, the average single-use approach has a much greater environmental burden then does the reusable approach with 66% more AP emissions, 68% more EP emissions, 87% more PCOP emissions, and 57% more HTP emissions. Cradle-to-gate production emissions contribute the bulk of the AP and PCOP impacts for the single-use approach. Use-phase emissions contribute the bulk of EP and HTP emissions for the single-use approach and contribute the majority of all impact categories for the reusable packaging approach. The use-phase emissions are made up almost entirely of transportation emissions. Use-phase transportation accounts for 63% of AP emissions, 90% of EP emissions, 81% of PCOP emissions, and 56% of human toxicity emissions for the reusable approach. Emissions for use-phase transportation for the single-use approaches in these categories lower to about 44%, 66%, 24%, and 53% of their total footprints, respectively. Overall, the single-use logistical approach is expected to cause an increased environmental burden of 3070kg more SO_2e, 880kg more $PO4^{3-}e$, 2030kg more C_2H_4e, and 2150kg more toxic substances than the reusable logistical approach over the functional unit of 30,000 shipments.

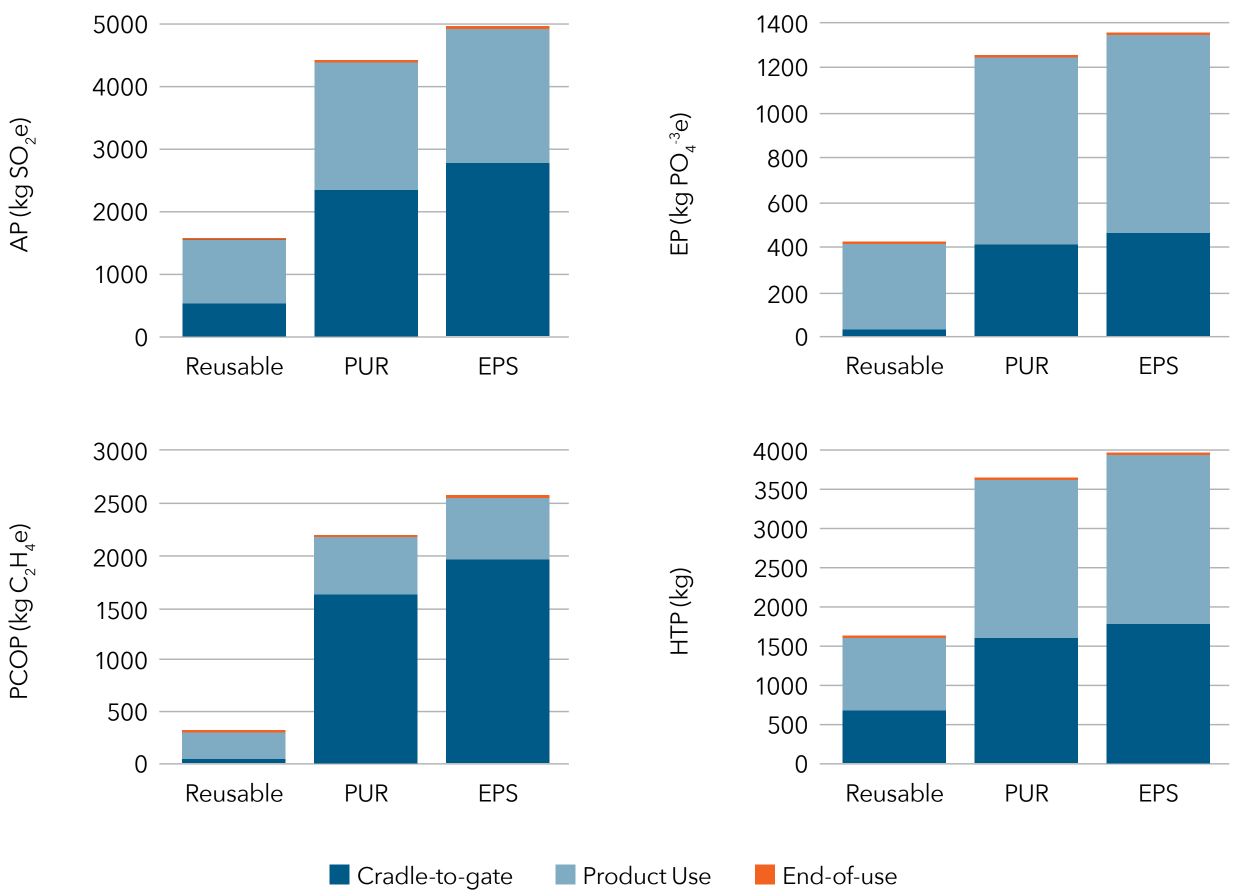
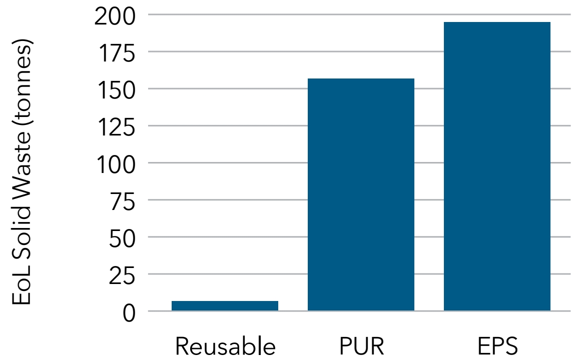


Figure 3 – Comparisons of acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and human toxicity potential (HTP) per functional unit among the reusable, PUR single-use, and EPS single-use approaches

RESULTS

A comparison of post-consumer solid-waste is shown in Figure 4. There is a substantial difference between the two options. Only seven tonnes of landfilled material is generated by the reusable approach over the functional unit versus 157 tonnes for the PUR option, and 194 tonnes for the EPS option.

Figure 4 - Comparison of end-of-life (EoL) consumer solid waste per functional unit among the reusable, PUR single-use, and EPS single-use approaches



Sensitivity analysis

There are several assumptions made in this analysis that lead to uncertainty in the accuracy of the comparisons. A sensitivity analysis with respect to these assumptions is critical in providing an unbiased view of the data prior to making conclusions.

Single-use component weight requirements

The foremost assumption to be evaluated concerns the quantity of components that comprise of an "average" single-use package. All emissions are a function of mass: material production, refrigeration energy, and transportation emissions. The sensitivity of emissions based on component mass is shown in Table 4 (differences may not add due to rounding). A comparison of GWP sensitivity can be seen in Figure 5. The best-case scenario for the single-use approach lowers the increased CO_2e emissions relative to the reusable approach from 78.5% to 74.5%. This 4% reduction is relatively small and may result in a container whose material makeup is unable to meet the thermal qualifications necessary to fulfill the functional unit. The worst-case scenario for the single-use approach, which may be typical of a low-end product, increases the CO_2e emissions difference to 81.5%.

Table 4 - Sensitivity of material weight requirement for single-use approach

		GWP (tonnes CO_2e)	AP (kg SO_2e)	EP (kg PO_4^{3-}-e)	PCOP (kg C^2H^4e)	HTP (kg)
PUR	Baseline	1,112	4,381	1,253	2,161	3,623
	-15%	945	3,724	1,065	1,838	3,079
	15%	1,278	5,038	1,441	2,486	4,166
	diff. (+/-)	167	657	188	324	543
EPS	Baseline	1,133	4,926	1,355	2,537	3,946
	-15%	963	4,187	1,151	2,157	3,354
	15%	1,303	5,665	1,558	2,918	4,538
	diff. (+/-)	170	739	203	381	592

RESULTS

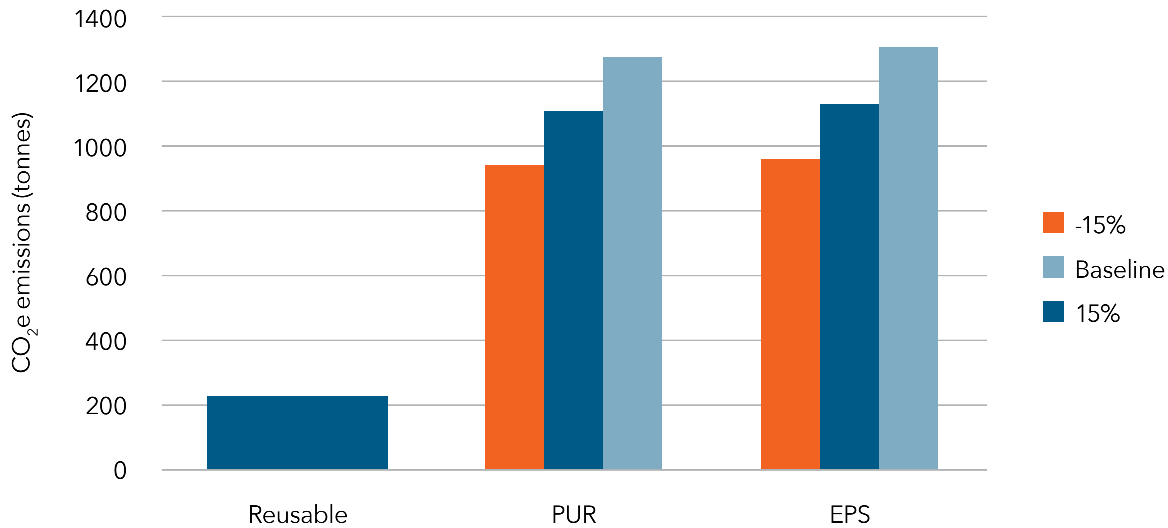


Figure 5 - Single-use material weight requirement sensitivity analysis effect on carbon footprint

Use-phase transportation distance

The use-phase transportation analysis assumes average distances that may over or underestimate actual shipping distances. The sensitivity of results to the averaging can be seen in Table 5 (differences may not add due to rounding). It is clear that single-use container emissions are more sensitive to the average transportation distance than the reusable container due to its heavier shipping weight. Sensitivity to the average transportation distance however is notably smaller than to material weight requirements.

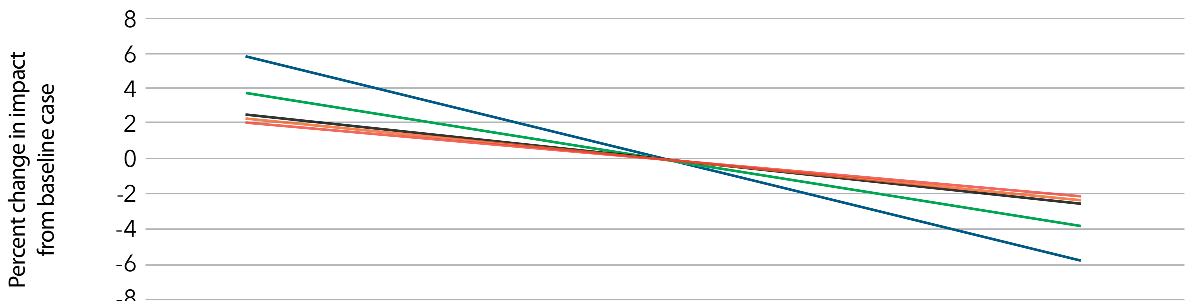
Table 5 - Sensitivity of use-phase transportation distance on environmental impact

		GWP (tonnes CO_2e)	AP (kg SO_2e)	EP (kg PO_4^{3}-e)	PCOP (kg C^2H^4e)	HTP (kg)
Reusable	Baseline	171	996	374	254	913
	-15%	145	847	318	216	776
	+15%	197	1,146	430	293	1,050
	diff. (+/-)	26	149	56	38	137
PUR	Baseline	277	1,642	518	367	1,325
	-15%	235	1,396	440	312	1,127
	+15%	318	1,889	596	423	1,524
	diff. (+/-)	41	246	78	55	199
EPS	Baseline	295	1,752	553	392	1,414
	-15%	251	1,489	470	333	1,202
	+15%	339	2,015	635	451	1,626
	diff. (+/-)	44	263	83	59	212

RESULTS

Recycling Rates

The lifespan of VIPs and PCM components of the reusable approach is quite long in comparison with their manufacturing frequency, causing some difficulty in determining actual recycling rates. Recycling rates of plastic corrugate are also unknown and may be above or below the 50% rate assumed in the baseline calculation. Sensitivity of environmental impacts to recycling rates of these components can be seen in Figures 6 and 7, which show the change in environmental indicators and post-consumer solid waste respectively. It is clear from Figure 6 that PCOP and EP emissions are the most sensitive to recycling rates. Considering the difference between 0% recycling and 100% recycling, there is a 12.2% difference in PCOP and a 7.9% difference in EP.

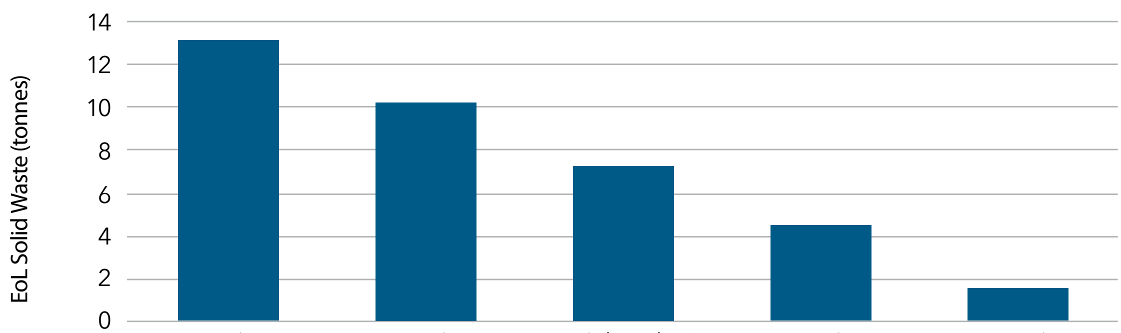


	0%	25%	50%	75%	100%
GWP	2.5	1.3	0	-1.3	-2.5
AP	2.1	1.0	0	-1.0	-2.1
EP	3.8	1.9	0	-1.9	-3.8
PCOP	3.5	2.9	0	-2.9	-5.8
HTP	2.3	1.2	0	-1.2	-2.3

Consumer recycling rate and subsequent changes in indicator potential (%)

Figure 6 - Sensitivity of reusable approach impacts to assumption of recycling rates

The largest impact that recycling has on the reusable logistical approach is on the amount of post-consumer solid waste that ends up in the landfill. The 50% baseline recycling rate reduces landfill waste by 5.7 tonnes, or by 44% compared with a situation of zero post-consumer recycling as seen in Figure 7. It is estimated that every percent increase in recycling rate results in a reduction of roughly 115kg of post-consumer waste.



	0%	25%	50% (baseline)	75%	100%
EoL Solid Waste	13.0	10.2	7.3	4.4	1.6

Consumer recycling rate and subsequent post-consumer solid waste generated (tonnes)

Figure 7 - Sensitivity of reusable approach post-consumer waste to recycling rates

RESULTS

Cradle-to-gate supplier to supplier transportation assumption

Transportation distances from suppliers to targeted destinations, when unknown, were estimated at 1000km. This assumption corresponds with regional and national product sourcing, where local transport distances are balanced by out-of-state distances. This may be an underestimate if the product mix involves many international interactions or an overestimate if local interactions dominate. The sensitivity of the baseline results to this assumption can be seen in Figures 8, 9, and 10 for the reusable, PUR insulated, and EPS insulated approaches respectively.

It is clear from Figure 8 that the aforementioned assumption has little bearing on the reusable approach due to supplier distances being known from primary sources.

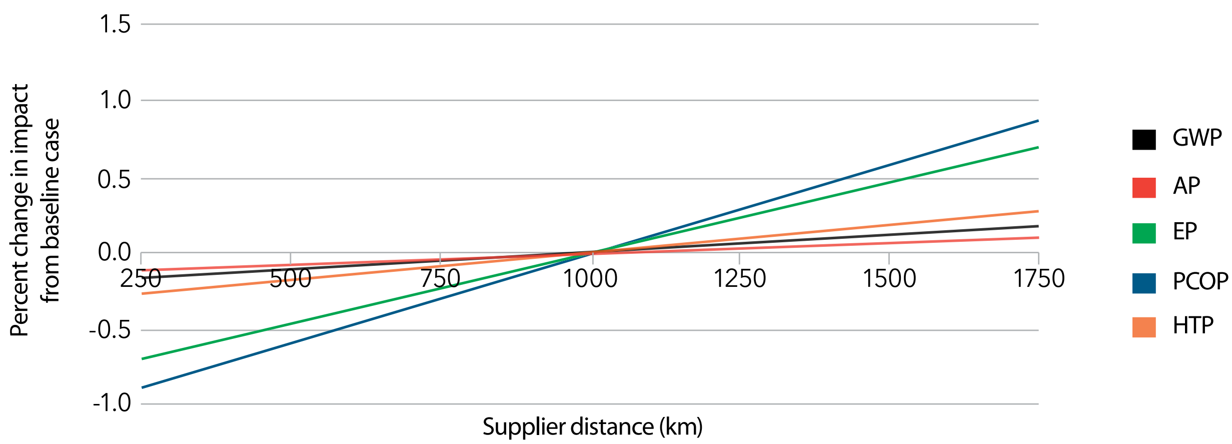


Figure 8 - Sensitivity of reusable approach to supplier distance assumption

Figures 9 and 10, both of which relate to single-use logistics tell a different story about the sensitivity to the assumption. The greatest sensitivity is seen in the EP and HTP of the single-use approaches.

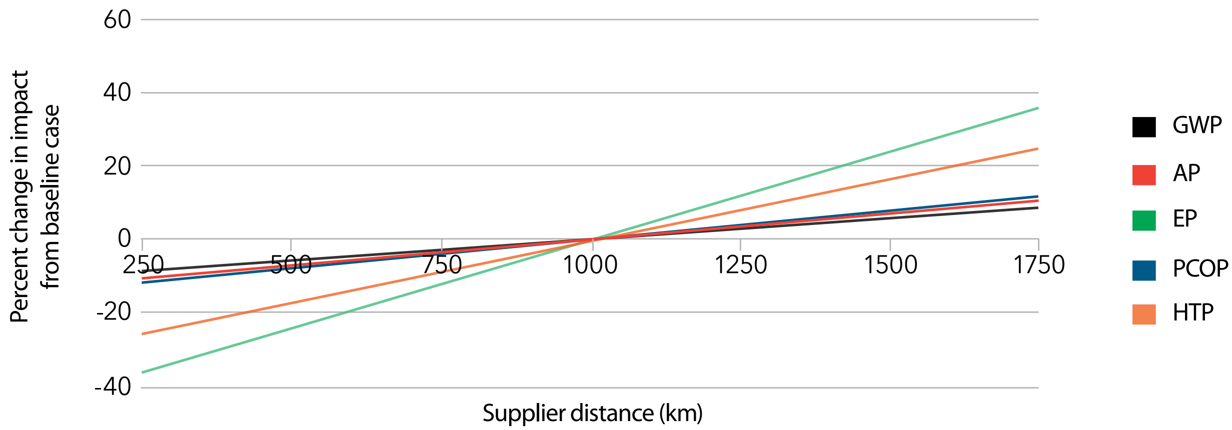


Figure 9 - Sensitivity of PUR option to supplier distance assumption

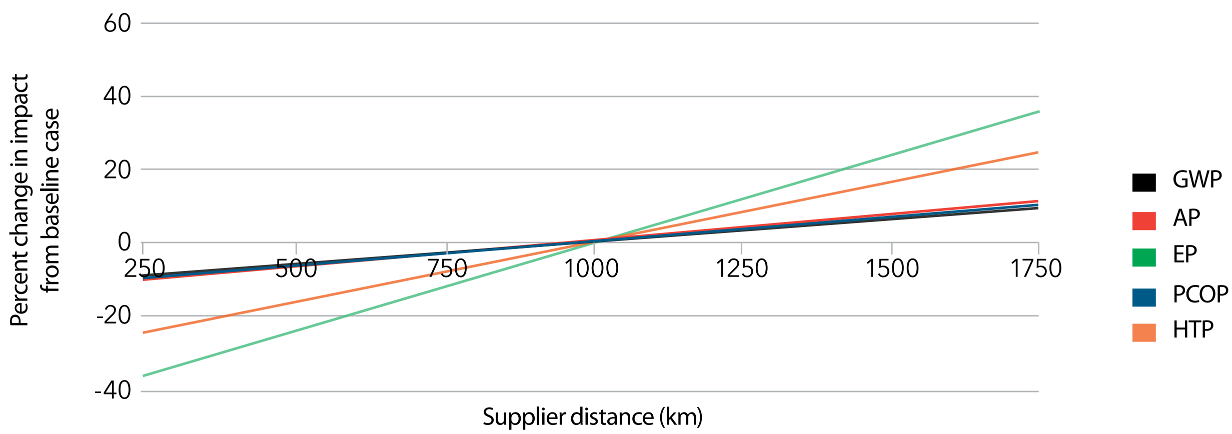


Figure 10 - Sensitivity of EPS option to supplier distance assumption

RESULTS

Figure 11 shows the side-by-side comparison of EP and HTP for all logistical approaches given the best-case (250km) supplier shipping distance. This assumes all material is sourced and produced locally and that the containers are produced close to Indianapolis, IN.

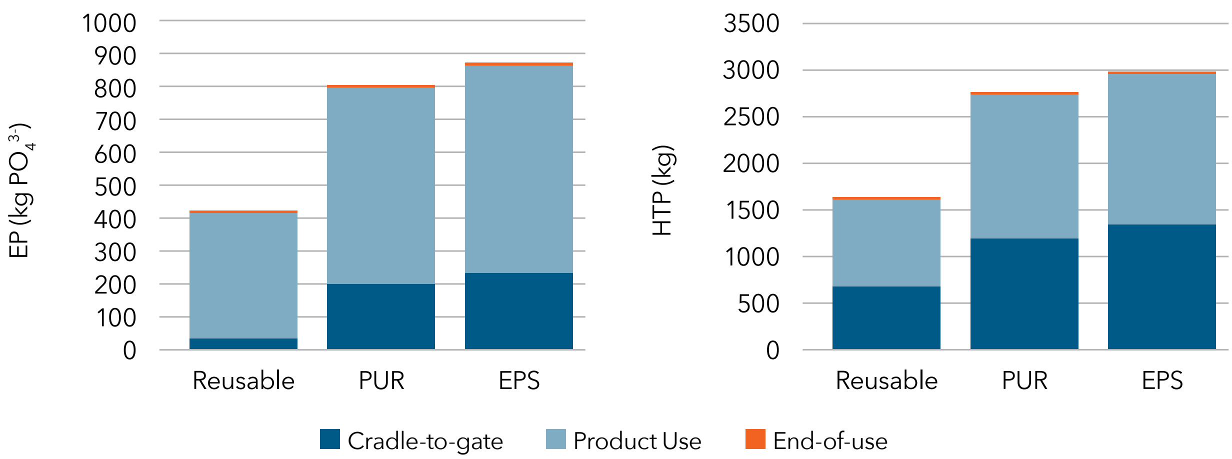


Figure 11 - Best case scenario for single-use approaches (250km supplier distance assumption)

DISCUSSION

The life cycle analysis performed in this study has identified which alternative logistic approach to container use and reuse will incur the least potential impact to the environment. Containment will always be needed to protect payloads during transportation. While it is important to the protection of the value of the payload, it has no environmental benefit.

> It is important for organisations to carefully consider the impact of their containment, packaging, and shipping decisions, especially when high volumes of transactions are involved.

It has been shown in this study that a reusable logistical approach can considerably reduce the environmental impacts of transporting thermally protected payloads. The foremost disadvantages of the single-use logistical approach lie in the emissions generated in the cradle-to-gate phase, where 12 times the GWP is generated relative to the reusable approach. This considerable difference is intrinsic to the single-use approach as 30,000 new boxes must be manufactured in order to fulfill the functional unit compared to 772 for the reusable.

DISCUSSION

The weight of the container has been shown to be critical to transportation impacts. The reusable logistical approach requires return transportation during its use-phase, a key difference between the two approaches. It was found, however, that the reusable case had less use-phase transportation emissions. This is due to the difference in container weight between logistical approaches. This difference is further compounded by expanding the use-phase transportation emissions to include those resulting from delivery of the containers to Indianapolis from the manufacturer.

The weight was shown just as critical when considering the differences between the two single-use insulation options. Although PUR insulation inflicts a greater environmental burden than does EPS insulation per kg of product during production, the increased weight of EPS required for equivalent thermal performance results in increased production and transportation emissions, making it a less desirable single-use insulation option from an environmental perspective.

The single-use logistical approach will be able to lessen its impact and may be able to compete with the reusable approach by means of a robust PUR and EPS insulation recycling infrastructure. The major barrier to realistic recycling of single-use containers is the scattering of clinical sites that do not have the local capability to recycle these materials. This is accompanied by a psychological barrier that may prevail at these sites where the quantity of containers is so small as to create the perception that there is not much waste. These barriers do not exist in the case of recycling the reusable components because they are already in a logistical framework that utilises multiple instances of return shipping. Routing the last return shipment of the containers lifespan to a recycling facility is a simple change in procedure and removes any local recyclability issues.

The sensitivity analysis has exposed the plasticity of the environmental impact assessment to key assumptions regarding single-use container material requirements, use-phase transportation distances, recycling rates of the reusable approach, and supplier transportation distances. A reduction in the weight of material necessary for the single-use container has been shown to be the greatest source of reduction in the GWP of that approach. This 15% weight reduction would save about 170 tonnes of GWP emissions. It is important to note, however, that this amount of weight reduction may not be feasible without reducing the thermal performance of the box. Reduction in the supplier distance was shown to reduce the GWP for the single-use approach up to 10%. The single-use approach is more sensitive to changes in transportation distances because its container is nearly twice the weight of the reusable approach.

CONCLUSION

This LCA study has evaluated critical environmental impact differences between reusable and single-use logistical approaches to thermally controlled transport. The reusable logistical approach utilising VIP insulation and PCM heat sinks has exceeded the environmental performance of the single-use approach in all metrics studied in this report. It is estimated that choosing a reusable logistical approach relative to the single-use approach over a course of 30,000 shipments would reduce environmental impacts by the following percentages:

- Global warming emissions (GWP) – 78%
- Acidification emissions (AP) – 66%
- Eutrophication emissions (EP) – 67%
- Photochemical ozone emissions (PCOP) – 86%
- Human toxicity emissions (HTP) – 56%
- Post-consumer waste – 95%

A sensitivity analysis has shown a moderate uncertainty in the above percentages, but it also confirmed the conclusion that the reusable approach is environmentally superior to the single-use approach.

The environmental break-even point between the two logistical approaches occurs after as few as six shipments PCOP and as many as 17 shipments for HTP. This outcome strongly suggests that a reusable approach is environmentally preferable for any organization that utilises large shipping volumes that require thermal control.

Remote deliveries into logistically undeveloped areas can present a significant challenge to retrieving a reusable shipper. When the reusable shipper is unable to be re-used, the single-use shipper produces less environmental impact than reusable shippers due to lower cradle-to-gate product emissions.

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APPENDIX 1 – SUMMARY OF POTENTIAL MULTIPLIERS

Burden	GWP	AP	EP	PCOP	HTP
Acetaldehyde	1.3				
Acetone	0.5				
Aldehydes				0.443	
Ammonia (NH3), air		1.88	0.33		0.01
Ammonia, water and soil			0.33		0.01
Arsenic vapour (As)					4700
As (arsenic solid)					1.4
Butane	4			0.416	1.7
Carbon dioxide (CO2)	1				
Carbon Monoxide (CO)	1.9			0.03	0.012
Chemical oxygen demand (COD)			0.022		
Chlorinated Hydrocarbons					0.98
Chlorinated solvents and compounds					0.29
Chlorofluorocarbons					0.022
Chromium (Cr)					0.57
Copper (Cu)					0.02
Cyanides					0.057
Ethane	5.5			0.416	1.7
Ethene (Ethylene)	3.7			1	1.7
Ethyl acetate	2			0.32	2.8
Flouorides					0.041
Flourine (F2)					0.48
hydrogen chloride (HCL)		0.88			
Hydrogen flouride (HF), air		1.6			0.48
Hydrogen flouride, water and soil					0.48
Iron (Fe)					0.0036
Isoprene	2.7			0.416	1.7
Lead (Pb)					0.79
Mercury liquid (Hg)					4.7
Mercury vapor (Hg)					120
methane (CH4)	25			0.007	
Methanol	2.8				
Nickel (Ni)					0.057
Nitrates (NO(-)3)			0.42		0.00078
Nitrous oxide/Dinitrogen monoxide (N2O)	298				
non-methane VOC's				0.416	
other VOCs	11			0.007	
Oxides of nitrogen (NOx)		0.7	0.13		0.78
Pesticides					0.14
Phenols					0.048
Phosphates (PO(3-)4)			1		0.00004

APPENDIX 1 – SUMMARY OF POTENTIAL MULTIPLIERS

Burden	GWP	AP	EP	PCOP	HTP
Propane	3.3			0.416	1.7
Propylene	1.8			0.416	1.7
Styrene				0.142	
Sulphur dioxide (SO2)		1			1.2
Toluene, air	2.7			0.416	1.7
Toluene, water and soil					1.7
Zinc (Zn)					0.0029

Global warming potential – Defined in units of equivalent carbon dioxide emissions (CO_2e), GWP represents how gases trap heat in the atmosphere compared to CO_2 over a 100 year timespan, which is the primary indicator of global warming

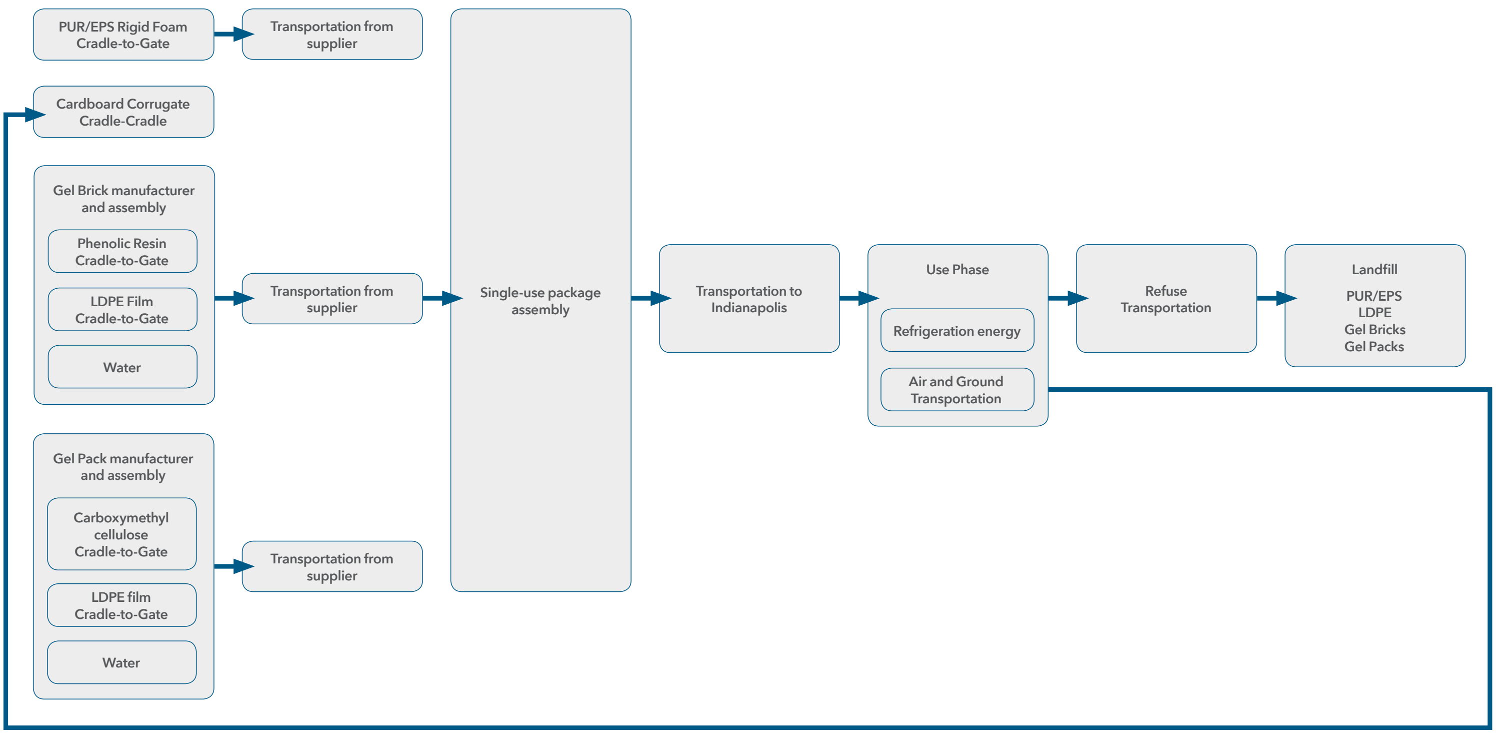
Acidification potential – Defined in units of equivalent sulphur dioxide (SO_2e), AP represents air emissions that contribute to acid rain, which is damaging to trees, aquatic life, and accelerates corrosion on man-made structures (Summerscales, 2006).

Eutrophication potential – Defined in units of equivalent phosphates ($PO_4^{3-}e$), EP represents the "over-fertilisation of water and soil" (Summerscales, 2006), causing aquatic 'dead-zones' due to increased bio-mass which saps oxygen from the immediate area.

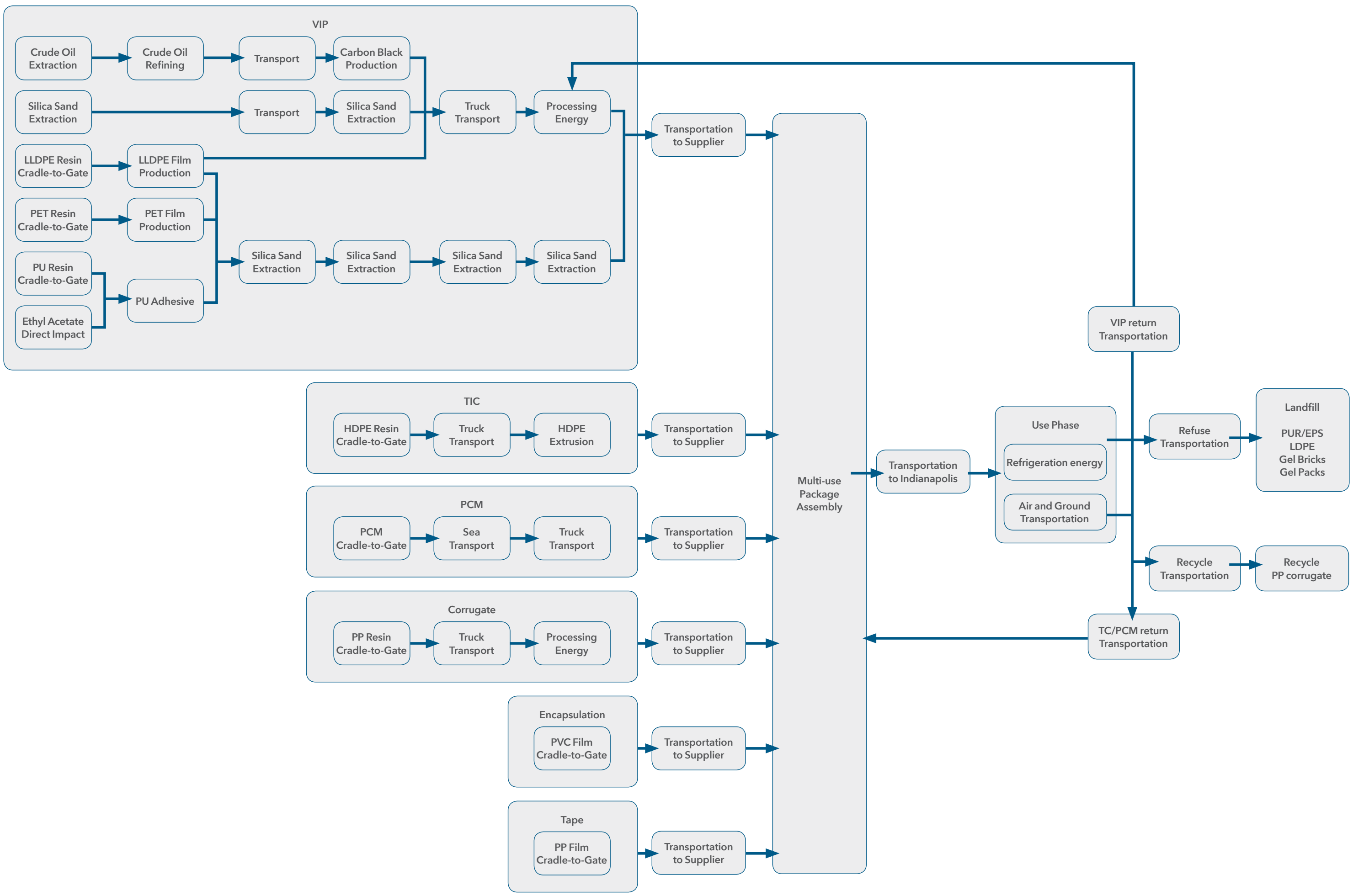
Photochemical oxidation potential – Defined in units of equivalent ethylene (C_2H_4e), POCP represents the oxidising force of air emissions which result in ground level ozone (O_3) and particles, causing summer smog and damage to plants and animals (Summerscales, 2006).

Human toxicity potential – Defined by individual toxicological effects on the human body, HTP is indicative of the negative health effects of gaseous, liquid, and solid emissions. The weight of toxic substances measured is in reference to the tolerable daily intake of each substance. Still in the development field, this measure is primarily an indicator rather than an absolute measure.

APPENDIX 2 – SINGLE-USE PACKAGING DETAILED SYSTEM BOUNDARY



APPENDIX 3 – REUSABLE PACKAGING DETAILED SYSTEM BOUNDARY



APPENDIX 4 – SUMMARY OF MATERIAL POTENTIALS

Material	CO2e	SO2e	PO(3-)4e	C2H4e	HTP
LLDPE film	2.22	0.0087	0.00045	0.0087	0.0031
LDPE film	2.40	0.0112	0.00065	0.0097	0.0052
OPP film	3.20	0.0146	0.00085	0.0124	0.0052
PET film	3.13	0.0136	0.00099	0.0138	0.0065
PVC film	3.10	0.0140	0.00110	0.0003	0.0166
HDPE resin	1.89	0.0055	0.00032	0.0057	0.0023
PP resin	1.86	0.0055	0.00038	0.0054	0.0027
PUR foam	4.16	0.0174	0.00111	0.0139	0.0065
EPS foam	3.29	0.0104	0.00063	0.0087	0.0039
Phenolic resin	2.19	0.0101	0.00060	0.0085	0.0036
CMC	4.21	---	---	---	---
Corrugate	1.01	0.0100	0.00082	0.0008	0.0121
Paraffin wax	0.70	0.0037	0.00017	0.0011	---
Silica sand	2.93	0.0097	0.00106	0.0012	0.0133
Carbon black	0.60	0.0545	0.00238	0.1852	0.0658
PU adhesive	3.30	0.0104	0.00066	0.1363	1.1239
Water (extraction & transport)	0.0003	0.000007	0.000006	0.0001	---

Potential units are in $kg_{equivelant}/kg_{material}$

APPENDIX 5 – EMISSIONS PER VEHICLE TYPE

Vehicle type	GWP	AP	EP	PCOP	HTP
Long-haul single unit truck	0.37	0.00143	0.00072	0.00034	0.00204
Short-haul single unit truck	0.31	0.00122	0.00069	0.00033	0.00181
Light commercial vehicle (FedEx, UPS adjusted)	0.14	0.00069	0.00110	0.00041	0.00121
Long-haul combination truck	0.12	0.00063	0.00058	0.00032	0.00115
Refuse truck	0.14	0.00074	0.00060	0.00032	0.00128
Freight aircraft	0.63	0.00385	0.00091	0.00070	0.00254
Freight train	0.06	0.00023	0.00050	0.00052	0.00071

Potential units are kg/t*km

APPENDIX 6 – USE TRANSPORTATION CALCULATION METHOD

Transportation distances between the origin and clinical trial sites during the use phase are finite in practice. A complex averaging method was used to estimate shipping distances in order to remove any bias that would be occur from selecting discreet points.

There are a variety of transport modes and vehicles accounted for including air, combination trucks, and package cars. The mode(s) of transport required to get a package from origin to clinical trial site depends on the discrete location of the clinical site. A three stage geographic breakdown of the United States was used to estimate distances for each transport mode:

A regional breakdown was used for the allocation of air transport. The locations of UPS and FedEx air hubs around the country were located in each region. For regions where multiple air hubs were located, an 'equivalent' airport location was determined through the averaging of latitude and longitudes of airports in that region, providing an 'average' air distance for all states in that region.

A state-by-state breakdown was used for the allocation of trucking distances from the regional air hub to clinical sites in that state.

The average delivery distance to each state was weighted by the population distribution of counties in that state as seen in Eq. (3)

$$\bar{d}_s = \sum_{c=1}^{n} \left(d_c \frac{p_c}{p_s}\right) \qquad (3)$$

given d-distance, p-population, s-state, c-county, n-last County in state

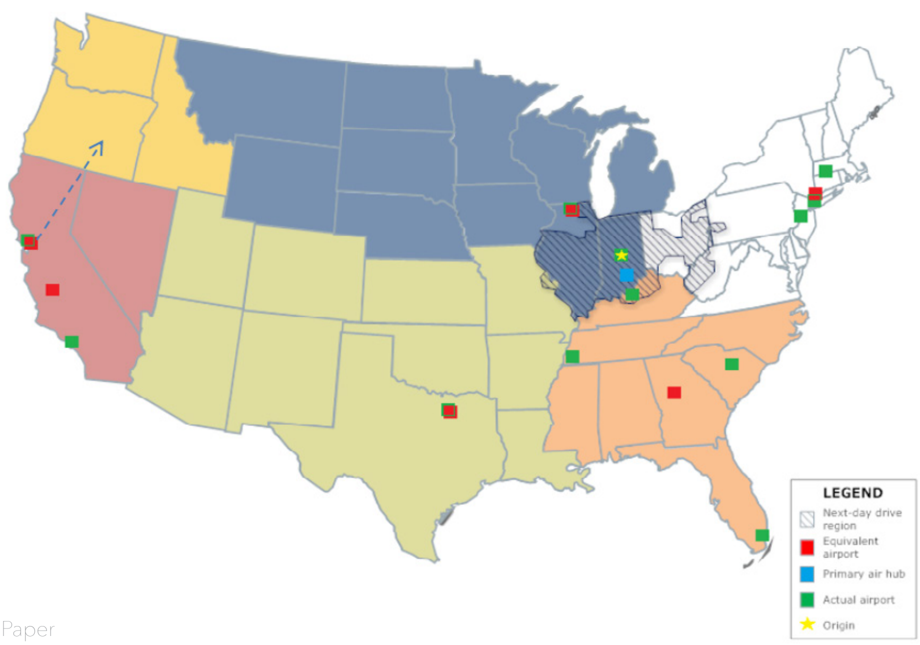
The result of this analysis is an 'average' transportation distance per state, broken into an air freight and trucking components. The National Institute of Health's clinical trial portal shows a breakdown of thousands of pharmaceutical clinical trials on a state-by-state basis (2012). The ratio of clinical trials occurring in each state compared to those occurring in all the contiguous US was used as a multiplier to the 30,000 total shipments, indicating the number of shipments to each state. With transportation distances now applied to each delivery, the summation across all 30,000 provides an estimate of the distance covered by each transportation mode over the two year clinical trial period.

There is a zone around the origin (Indianapolis, IN) which no air freight is required due to being a single day drive distance. Counties within UPS's one-day delivery zone from the origin were withheld from the airport measurements, having their own individual trucking distances to Indianapolis. The numbers of deliveries that are directly trucked vs. through an air freight leg were allocated based on the percentage of the state population in the one-day delivery zone.

The distances from air hub to clinical site is often >100mi/160km. The last leg of delivery to the clinical site is always made with a package car. Allocation of vehicle type during road transport was determined using the following metric:

Distance from regional hub	**Combination Truck**	**Package Truck**
<100mi/160km	N/A	Full journey
>100mi/160km	Full journey less 25mi/40km	25mi/40km

An added payload of 1lb/0.45kg was added to the shipping weight per box for the calculations. This weight was removed for the reusable package empty return trip which is made almost entirely by combination truck. A map depicting the geographic breakdown of calculations can be seen below.



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Kai Goellner has B.A. in Industrial Engineering and an M.S. in Mechanical Engineering with a focus in fluid and thermal sciences from the University of Minnesota. Kai has been involved with many technical areas of the company in his five years with Peli Biothermal. His first contribution was a first in the industry peer-reviewed publication International Journal of Life Cycle Assessment entitled "An environmental impact comparison of single-use and reusable thermally controlled shipping containers". Kai has implemented efficiency improvements to manufacturing and developed internal component recycling practices. His extensive research into Phase Change Materials and Vacuum Insulation Panels have contributed toward material and quality control improvements. As lead design engineer, he has worked comprehensively with Canadian Blood Services to redesign their cold-chain practices through improved shipper design and performance, standardized PCM conditioning practices, and multi-level redundancy plans to ensure compliance with enhanced blood product regulations and an uninterrupted supply of products to hospitals.