PACKAGING SYSTEMS INCLUDING RECYCLING

An environmental impact comparison of single-use and reusable thermally controlled shipping containers

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Abstract

Purpose Pharmaceutical and biological materials require thermally controlled environments when being transported 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 cold chain logistics and to identify the method of least environmental burden. The approaches of interest are single-use packaging utilizing containers insulated with either polyurethane or polystyrene and reusable packaging utilizing containers with vacuum-insulated panels.

Methods This study has taken a cradle-to-grave perspective, which covers material extraction, manufacture, assembly, usage, transportation, and end-of-life realities. The functional unit of comparison is a 2-year clinical trial consisting of 30,000 individual package shipments able to maintain roughly 12 L of payload at a controlled 2–8 °C temperature range for approximately 96 h. 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 postconsumer waste.

Results and discussion The average single-use approach emits 1,122 tonnes of CO_2e compared with 241 tonnes with the reusable approach over the functional unit. This is roughly a 75 % difference in global warming potential between the two approaches. Similar differences exist in other impact categories with the reusable approach showing 60 % less acidification potential, 65 % less eutrophication potential, 85 % less photochemical ozone potential, 85 % less human toxicity potential, and 95 % less postconsumer 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 mass of the average single-use container, which lowered its transportation emissions below the single-use approach despite an extra leg of travel.

Conclusions The reusable logistical approach has shown to impose a significantly smaller environmental burden in all impact categories of interest. A sensitivity analysis has shown some leeway in the degree of the environmental advantage of the reusable approach, but it confirms the conclusion as no case proved otherwise.

1 Introduction

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 the physical and chemical viability of the payload. This situation necessitates innovative packaging and transportation means, which contribute

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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 utilization of either extruded polystyrene (EPS) or polyurethane (PUR) insulation and gel pack heat sinks. The second method of interest here is a growing utilization of durable reusable containers, based on 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 Minnesota Thermal Science. There have 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 et al. 2005) and carbonated beverage packaging in the UK (Amienyo et al. 2013). Others 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 publically available LCA study to this date concerning thermal performance packaging used in cold-chain logistics.

2 Scope

This analysis focuses on a 2-year time span, a period that covers half of a typical phase III pharmaceutical clinical trial (Abrantes-Metz et al. 2004). During such a period, thousands of shipments to various clinical sites around the country are expected to occur. Although the present research is focused specifically on the pharmaceutical market, it is expected that the comparative assessment will apply to similar high-volume markets in the cold-chain industry. Understanding the environmental implications of packaging decisions will help organizations meet their sustainability goals.

The functional unit used to compare the two logistical approaches of this study is a 2-year clinical trial requiring 30,000 cold-chain shipments, using containers qualified to transport 12 L of product maintained at temperatures of 2–8 °C for a duration of approximately 96 h. 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 stand-alone performance of containers for transporting pharmaceutical and biological payloads are qualified through laboratory testing to International Safe Transit Association procedure 7D and ASTM D3103 standards. The materials comprising the payload as well as any logistical overhead (e.g., warehouse lighting) were

excluded from the system boundary. The system boundary for each logistical approach can be seen in the Electronic Supplementary Material.

Global warming potential (GWP), 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. Life-cycle inventory (LCI) data were converted into the aforementioned environmental indicators utilizing potential values collected from three sources: PAS2050 (British Standards Institution 2011), IPCC's *Climate Change 2007: the physical science basis* (Solomon et al. 2007), and an online compendium by Summerscales (2006) based on the work by Azapagic (2004).

3 Methods

A cradle-to-grave LCA approach has been aligned with the methodology standardized in ISO 14044 (2006) and PAS2050. The breakdown of component materials and respective mass for each logistical approach is set forth in Tables 1 and 2.

The analysis of each of the selected logistical approaches was subdivided by stages of impact occurrence as seen in Fig. 1.

The functional unit displays some of the critical assumptions of analysis. 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 2-year clinical trial
- The polypropylene corrugate component of the reusable container is replaced every quarter
- Shipping distances between suppliers are assumed to be 1,000 km when no primary data are available, assuming a regional and national supply chain

Table 1 Component makeup per single-use container

Component	Mass (kg)	Material(s)
Insulation[a]	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

[a] Equivalent performance insulation, two materials analyzed independently

Table 2 Component makeup per reusable container

Component	Mass (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	

- When no primary data are available, 3 % product loss during manufacturing is assumed.

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.

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, emissions were determined separately and added into the respective LCI. Coproduct breakdowns and refining data of crude oil were obtained from the NREL US Life-Cycle Inventory Database (2012). A complete list of LCI data sources can be seen in Table 3. The impacts of high volume polymers (EPS and PUR) were calculated using European data. The European data were taken as a valid estimate of US emissions based on the cross-referencing of other polymer impacts [high density polyethylene (HDPE), linear low density polyethylene, polyethylene terephthalate, polyvinyl chloride, and polypropylene (PP)], which showed differences limited to 5–15 %. Considerable effort was placed in obtaining the most applicable publicly available data. The resulting impacts per kilogram of each material can be seen in Table 4.

A 2% cutoff rule by mass was used to determine which components could safely be disregarded in the analysis. Under this rule, the omitted manufacturing emissions include ethyl acetate (0.06 %), PU resin (0.16 %), aluminum (0.01 %), and manufacturing phenolic foam from phenolic resin (1.44 %). Only the CO_2e emissions from the manufacturing of carboxymethyl cellulose (CMC) were accounted for due to the inaccessibility of more detailed data.

Averaged losses occurring during the assembly process were accounted for. The assembly energy required to fill and

Fig. 1 Life-cycle breakdown of differing logistical approaches
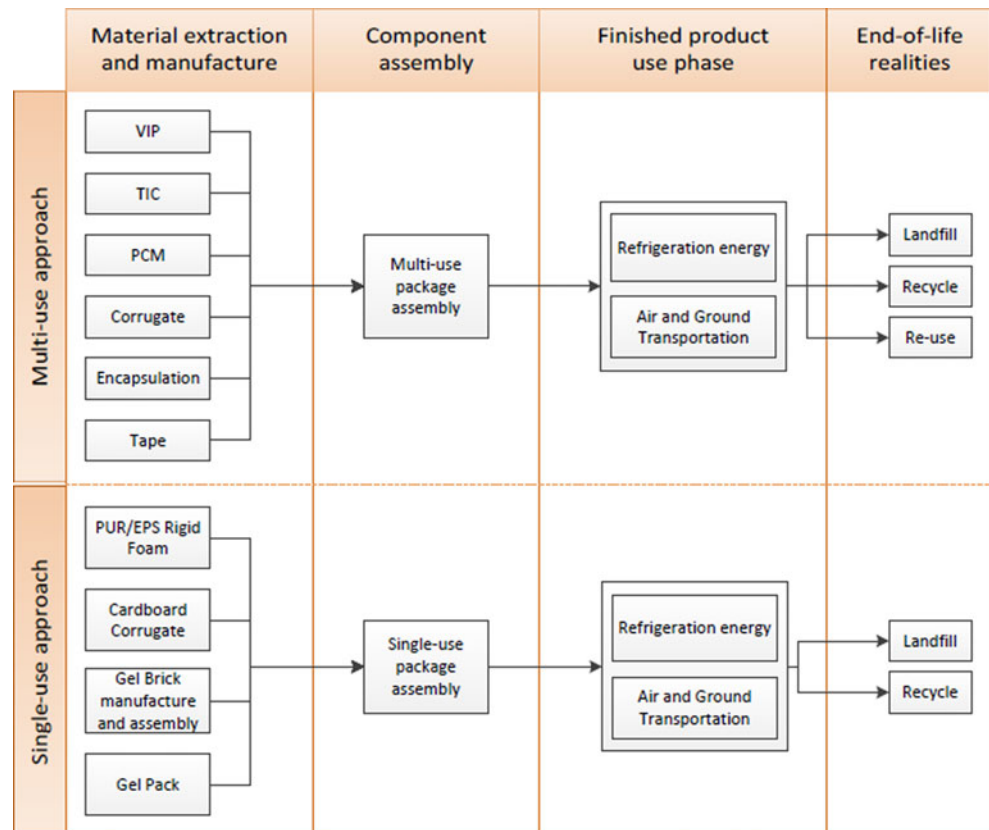
Table 3 LCI data sources

Component	Data source
Polymer components (LLDPE, PET, PUR, HDPE, PP, PVC, EPS, phenol)	Franklin Associates (Franklin 2011);Boustead (2005b, 2006) Plastic Europe's Eco-profiles (2008, 2010)
Multilayered polymer processing energy	Dimenna (2008)
Paraffin	Tufvesson and Börjesson (2008)
Silica and carbon black	European Commission (2007)
Silica extraction	IMA-Europe (2007)
Cardboard corrugate	PE Americas (2009)
Tap water processing and treatment	Franklin Associates (2009)
Electricity production	US EPA eGRID database (2012b); IMEP (2008)
Crude oil extraction	Boustead (2005a)
Carboxymethyl cellulose (CMC)	Eco-costs for carboxymethyl cellulose (2012)
Transportation emissions	NREL (2012), UPS (2012), FedEx (2012)
Polypropylene recycling	Adams et al. (1999)

seal the gel packs and bricks utilized in the single-use container was omitted due to lack of data.

In many cases, transportation steps 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 %. In cases where transportation steps were not accounted for in the literature, subsequent transportation emissions were included.

3.1 Use phase

Both the gel packs and PCM must be frozen prior to use in clinical shipments to ensure a functional heat sink. A COP of commercial refrigerators of 3.8 was used for energy conversion calculations (International Institute of Refrigeration 2002). Experimental data of the energy required to freeze the PCM was utilized. Energy required to freeze the gel packs and bricks utilized in single-use containers was estimated using the thermodynamic properties of water (freezing from a 22 °C liquid to a 0 °C solid). The mass of water to be frozen was taken as the mass of all the gel materials. It has thus been assumed that 0.12 kWh/kg is required to freeze the bricks and gel packs and 0.08 kWh/kg is required to freeze the PCM.

Four types of trucking vehicles were used in transportation emissions modeling: (a) long-haul single unit truck, (b) short-haul single unit truck, (c) light commercial vehicle, and (d) long-haul combination truck. Vehicle types were selected depending on distance travelled and cargo tonnage based upon definitions provided by EPA MOVE documentation (2012c). CO_2 and NO_x emissions were adjusted for the light commercial vehicle to account for higher efficiency UPS and FedEx fleets using carrier performance rankings as compiled by the EPA (2012a).

Table 4 LCI results per material (potential units are in kg$_{equivelant}$/kg$_{material}$)

Material	CO_2e	SO_2e	PO_4^{3-}e	C_2H_4e	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 and transport)	0.0003	0.000007	0.000006	0.0001	–

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 US (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, USA.

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.

3.2 End-of-life

Nonrecycled components utilized in each packaging method are conglomerated into a "postconsumer 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. The reusable container components that are typically landfilled include PVC film and the multilayered VIP film. The cut-off recycling method has been applied in consideration of the HDPE TIC's coating process, which requires it to use all-virgin resins and makes it not readily accepted by local recyclers. Thus, any TIC recycling reduces its "postconsumer solid waste" impact category only. Transport of materials to landfills and recycling centers are assumed to be 50 km. Refuse truck emissions data were obtained through the US Life-Cycle Inventory Database.

Both closed- and open-loop allocation techniques were used in calculating the positive effect of recycling on emissions and were employed based on the whether the recycled material is used to remake the same product, or a different product, respectively. Closed-loop impact allocations are calculated utilizing Eq. (1) as given by the PAS:2050 literature (British Standards Institution 2011),

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

It is assumed that 50 % of recyclable products are in fact recycled for baseline calculations, where r is the fraction recycled, 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 nonrecycled material.

PCM and VIPs are shipped back to the manufacturer by the client for recycling. There is no quality loss of the PCM or the insulating core and no material processing is required for reuse

in this closed-loop system. The silica and carbon black are the only recyclable materials in the VIP component, with Eq. (1) being used accordingly.

The outer component of the reusable package is comprised of fully recyclable polypropylene. Actual end-of-life recycling fractions 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) under 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) where r is the fraction recycled, V is the impact from sourcing all virgin material, D is the impact from disposal, and R is the impact from recycling.

$$\text{Impact} = r\left(\frac{V-D}{2} + \frac{R}{2}\right) + (1-r)(V+D) \qquad (2)$$

4 Results

The single-use approach, as seen in Figs. 2, 3, and 4, has a far greater environmental burden across all impact categories analyzed. The difference in cradle-to-gate emissions between the single-use and reusable approaches is the primary cause of the increased environmental impact of the former. The gate in this case refers to the end of the component assembly phase.

In Fig. 2, it is seen that 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 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 <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.

Figure 3 sets forth categories that display environmental impacts to the greater ecosystem. As with GWP, the average single-use approach has a much greater environmental burden under this broader scope of measure then does the reusable approach with 66 % more AP emissions, 68 % more EP emissions, 87 % more PCOP emissions, and 57 % more HTP emissions. Use-phase emissions make up almost entirely of transportation emissions and contribute the majority of all impact categories for the reusable packaging approach and contribute the bulk of EP and HTP emissions for the single-use approach. The foregoing percentages correspond to an
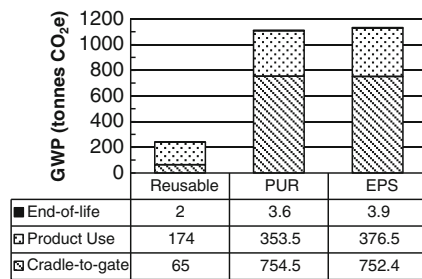
Fig. 2 Comparison of cradle-to-grave global warming potential per functional unit among the reusable, PUR single-use, and EPS single-use approaches

Fig. 3 Comparisons of acidification potential, eutrophication potential, photochemical ozone creation potential, and human toxicity potential per functional unit among the reusable, PUR single-use, and EPS single-use approaches

increased environmental burden of 3,070 kg more SO_2e, 880 kg more $PO_4^{3-}e$, 2,030 kg more C_2H_4e, and 2,150 kg more toxic substances for the single-use approach compared with the reusable logistical approach over the functional unit of 30,000 shipments. The reusable approach transportation accounts for 63 % of AP emissions, 90 % of EP emissions, 81 % of PCOP emissions, and 56 % of human toxicity emissions. Emissions for the single-use approaches in these categories lower to about 44, 66, 24, and 53 % of their total footprints, respectively.

A comparison of postconsumer solid waste is shown in Fig. 4. There is a substantial difference between the two options. Only 7 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.

4.1 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 model prior to making conclusions. Among the factors investigated in the sensitivity analysis are mass requirements for the single-use approach, transportation distance during the use-phase, fraction recycled, and supplier-to-supplier transportation distance assumption.

4.1.1 Single-use component mass requirements

All emissions arising from material production, refrigeration energy, and transportation are a linear function of mass. Table 5 shows the calculated sensitivity of each environmental indicator given ±15 % change in mass requirements.

From Fig. 5, it is seen that the reduction of mass by 15 % gives rise to a corresponding reduction in the CO_2e tonnage emission. For instance, the ratio of the baseline emissions for the single-use and reusable use situations is 4.6. In contrast, for a 15 % mass reduction for the single-use case, the ratio
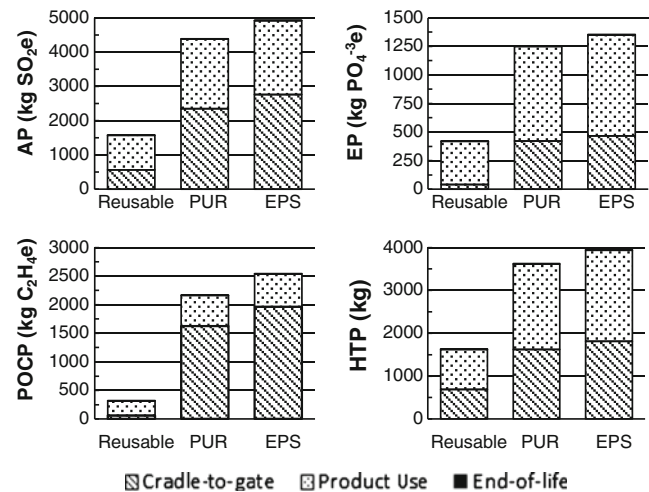
diminishes to 3.9. This reduction may result in a container whose material makeup is unable to meet the thermal qualifications necessary to fulfill the functional unit.

4.1.2 Use-phase transportation distance

The use-phase transportation analysis assumes average distances that may exceed or underestimate actual shipping distances. Because emissions calculations use an equally weighted function of mass and distance, a 15 % change in mass results in a 15 % change in the emission. It is clear that single-use container emissions are more sensitive to the average transportation distance than are those of the reusable container due to its heavier shipping weight, which results in greater use-phase transportation emissions given the baseline case. Sensitivity to the average transportation distance is notably smaller than to material mass requirements.
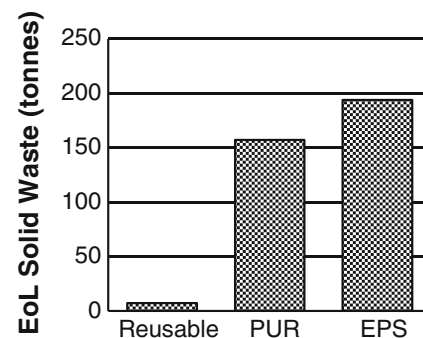
Fig. 4 Comparison of end-of-life consumer solid waste per functional unit among the reusable, PUR single-use, and EPS single-use approaches

Table 5 Sensitivity of material mass 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 option	±15 % mass	±167	±657	±188	±324	±543
EPS option	±15 % mass	±170	±739	±203	±381	±592

4.1.3 Fraction recycled

Current component recycling fractions are unknown and may be above or below the 50 % value assumed in the baseline calculation. Sensitivity of environmental impacts to recycling fraction can be seen in Fig. 6 for the extreme values of 0 and 100 %. It is clear that recycling has the greatest impact on the amount of postconsumer solid waste that ends up in the landfill. It is estimated that every percent increase in fraction recycled results in a reduction of 115 kg of postconsumer waste.

4.1.4 Supplier–supplier transportation distance

Transportation distances between suppliers were estimated at 1,000 km when unknown. This assumption generalizes regional product sourcing. This may be an underestimate if the product mix involves many international interactions or an overestimate if local interactions dominate.

Analysis has shown that the supplier–supplier assumption has little bearing on the reusable approach due to the majority supplier distances being known from primary sources. The analysis of the single-use logistical approaches, however, shows greater sensitivity to this assumption since *all* supplier–supplier distances are assumed at 1,000 km. Figure 7 shows the sensitivity of the PUR container to supplier–supplier distance. The greatest sensitivity is seen in the EP and HTP of the single-use approaches with average increases of 23.8 and 16.5 % of the respective indicator emissions per 500 km increase in distance between suppliers. The best-case scenario of complete local sourcing reduces the GWP by 8.6 % from the baseline.
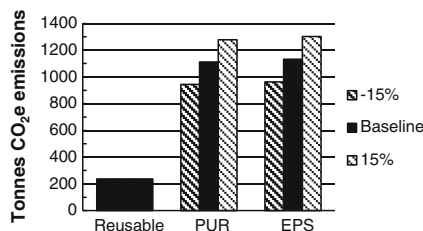
Fig. 5 Single-use material mass requirement sensitivity analysis effect on carbon footprint

5 Discussion

The life-cycle analysis performed in this study has identified which logistic approach to cold-chain shipments will incur the least potential impact to the environment. It has been shown that a reusable logistical approach can considerably reduce the environmental impacts of transporting thermally controlled 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 approach. Containment will always be needed to protect payloads during transportation. It is important for organizations to carefully consider the impact of their containment, packaging, and shipping decisions, especially when high volumes of transactions are involved.

Container mass has 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. Despite this increased travel per use, the reusable case had reduced use-phase transportation emissions due to the considerable differences in container mass between these logistical approaches. This difference is further compounded by the initial delivery of the containers to the distribution point from the manufacturer.

The mass was also shown to be 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 kilogram of product during production, the increased mass of EPS required for equivalent thermal performance results in increased production and transportation emissions, making it a less desirable single-use insulation option over the product lifespan.

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 recycling of single-use containers is the scattering of clinical sites that do not have the local capability to recycle these materials. This may be accompanied by a perception barrier at these sites where the quantity of containers is so small as to create the view that

Fig. 6 Sensitivity of reusable approach impacts to assumption of fraction recycled
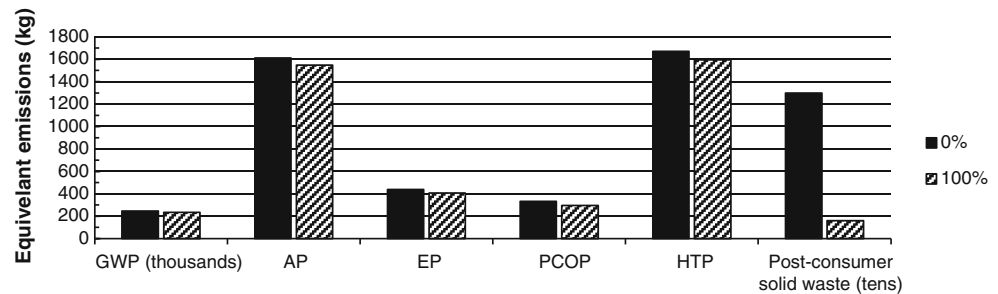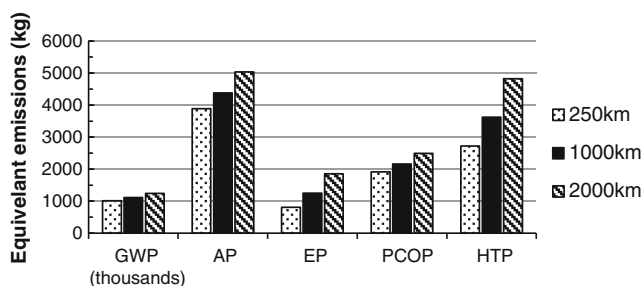
there is not much waste. These barriers do not exist in the case of recycling the reusable components because they already reside in a logistical framework that utilizes multiple instances of return shipping.

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 fractions of the reusable approach, and supplier transportation distances. A reduction in the mass of material necessary for the single-use container has been shown to be the greatest source of reduction in the GWP of that approach. An assumed 15 % mass reduction would save about 170 tonnes of GWP emissions over the functional unit. It is important to note, however, that this amount of mass reduction may not be feasible without reducing the thermal performance of the container. The magnitude of the recycling fraction for the reusable approach components had a substantial effect on the amount of postconsumer waste generated, with other impact categories moderately affected. The single-use approach is more sensitive to changes in use-phase transportation distances because its container has nearly twice the mass of the reusable approach. Maximum reduction in supplier–supplier distance was shown to reduce the GWP for the single-use approach up to 8.6 %.

6 Conclusions

This LCA study has evaluated critical environmental impact differences between reusable and single-use logistical

approaches to thermally controlled containments. The reusable logistical approach utilizing VIP insulation and PCM heat sinks has substantially exceeded the environmental performance of the single-use approach in all metrics studied in this paper. 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 %

The use of nondomestic European data adds some uncertainty to the baseline percentages; however, the expected emissions error affecting the cradle-to-gate phase is a small fraction of the differences seen in the comparison between the two logistical approaches. A sensitivity analysis has also shown a moderate uncertainty in the above percentages, but has 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 for PCOP and as many as 17 shipments for HTP emissions. This outcome strongly suggests that a reusable approach is environmentally preferable for any organization that utilizes large shipping volumes that require thermal control.

Fig. 7 Sensitivity of PUR single-use approach to supplier–supplier average distance

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