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Life Cycle Assessment (LCA) of Package Deliveries: Sustainable Decision-Making for the Academic Institutions

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Abstract: Due to globalization, digitalization, and competition, the number and frequency of customer requests have grown quickly over the past few years in the fast-growing commercial trade. With this steady growth, express deliveries have become one of the most important things to study and research in order to lower costs and meet more customer orders. This study uses life cycle assessment (LCA) to analyze the environmental footprints of current delivery packaging materials, mainly comprising corrugated cardboard boxes and polystyrene (PS) foam that arrives at the University of Regina Central Receiving and also suggests viable alternatives to reduce the life cycle environmental impact. The study's objective is to identify the stages that contribute the most to environmental emissions and suggest viable alternatives to reduce the life cycle environmental impact. We sourced packaging material data from GaBi Education Database 2020 and obtained other product-specific data from published LCAs for consistency. The current study on packaging materials analysis in the base scenario revealed that the cradle-to-grave PS packaging material has the highest environmental impact. These results have significant implications for decision-makers in identifying sustainable packaging materials for long-term use and for stakeholders in comprehending environmental impacts.

Keywords: life cycle assessment, environmental impacts, packaging box, carbon emission, corrugated cardboard box

1. Introduction

The express industry has seen astonishing progress in the past decade due to the rapid development of digitalization and increased globalization. Any research that is conducted to study the industrial consumption of material and energy will help to develop enduring progress for the industry and educate stakeholders about environmental protection. In this research paper, a case study of academic institution is taken to study the implications of packaging materials on the environment. The University of Regina has seen a steady growth in their student enrollments with over 16,000 full-time and part-time students in 2021 (University of Regina, 2022). It goes without saying that as the number of student enrollment increases, there is a sheer increase in facilities and assets consumption and maintenance due to the increased frequency of usage. Additionally, a vast establishment such as the University of Regina requires replenishment of supplies, spare parts, furniture, electronics, cables, and other essential materials that contribute to a high level of service by the stakeholders. These replenishment cycles involve high volume of packaging materials which can adversely affect the environment if not treated properly. This study will shed some light on the economic and environmental aspects of different packaging materials consumed by the University of Regina on a regular basis by utilizing life cycle assessment (LCA) and also evaluate feasible alternatives that can improve the environmental footprints.

ISO 14040 and ISO 14044 standards define LCA as the grouping and evaluation of a product or service's inputs and outputs and their environmental impacts throughout its life cycle from the initial raw materials phase, usage phase, and end-of-life scenarios (ISO, 2006). Specifically, ISO 14040 standard outlines the LCA principles and ISO 14044 standard sets the guidelines for directing an LCA. An LCA can be defined as a standardized framework which governs how one can measure the impacts of various stages in the development and consumption of a product or service provided and determine the processes that contribute most to the environmental footprint (Tampubolon et al., 2022). The information from the LCA of a product or service can help us improve the environmental impact at different stages of its life cycle. An LCA can be conducted for various reasons and the most common reason is generally to comply with regulations which mandates organizations to have transparency in their environmental footprint in order to sell products or provide services. Some of the other common reasons to conduct an LCA includes following customer demand or marketing purposes and streamlining the goal to lead the industry by introducing strategic vision (ISO, 2006). This paper will attempt to assess the significance of life cycle stages of packing materials used in the supply chain of express deliveries where the life cycle typically consists of four phases: goal and scope definition, inventory analysis, impact assessment, and finally the interpretation phase as depicted in Figure 1 (ISO, 2006). The assessment will aid in

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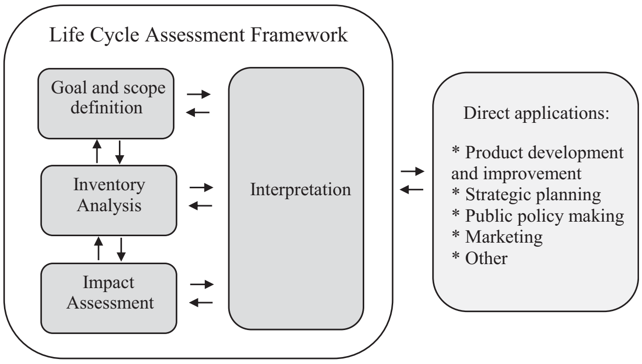
Figure 1
Different stages of a life cycle assessment as defined by ISO 14040:2006



identifying the stages in the life cycle stages that are major contributors to the environmental emissions impact categories which are acutely discussed in this paper.

The typical life cycle of these materials involves four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 1 (ISO, 2006). Through this assessment, we aim to identify which life cycle stages have the greatest impact on environmental emissions, which is the focus of this paper. The information obtained from this assessment can be applied in various areas, such as product development, strategy planning, public policy making, marketing, and other fields where LCA information can be useful. Additional direct applications or uses of the information provided by the LCA beyond those explicitly listed could include environmental or sustainability reporting, regulatory compliance, supplier selection, and education and research.

This research mainly focuses to answer the following research questions:

RQ1: What type of packaging materials are the least significant environment impactors?
RQ2: How to utilize LCA technique for developing an environmental supply chain framework and set the analysis system boundaries?
RQ3: How to measure the functional unit impression on the impact categories? What does this measurement tell us?

The objectives of this study are:

To compare LCAs between current delivery packaging materials and multiple feasible alternatives to analyze and identify the stages that are major contributors to the environmental emissions.
To determine the sustainable choice of packaging materials for the long run and educate the stakeholders of its environmental impacts.

2. Literature Review

Package deliveries are made easier and safer by containing goods into packaging materials. These packaging materials may consist of corrugated cardboard boxes, air bubble sheets, plastic wrapper, expanded polystyrene (EPS) foam, wooden box/crate, and packaging papers. Frequent deliveries of packages produce greenhouse gases such as CO2 emissions (CO2e) throughout their life cycle stages starting from raw materials, production, warehousing, transportation, consumption, and end-of-life treatment. Verma et al. (2019) and Verma et al. (2021) showed in their research on production of corrugated boxes that the major source of environmental impact during the production cycle of corrugated boxes was from electricity consumption and unrecycled material in landfills. Corrugated cardboard boxes are being used very widely in the express delivery industry and hence there are multiple LCAs available for this common packaging material. Package deliveries have become increasingly prevalent in today's world, and the use of packaging materials is essential to ensure the safety and convenience of goods during transportation. The packaging materials commonly used for express deliveries include corrugated cardboard boxes, air bubble sheets, plastic wrappers, EPS foam, wooden boxes/crates, and packaging papers (Bosona, 2020). However, the production and disposal of these materials can contribute to the emission of greenhouse gases such as CO2 (CO2e) throughout their life cycle stages, including raw material extraction, manufacturing, transportation, use, and disposal.

Several studies have investigated the environmental impact of different types of packaging materials, with a particular focus on corrugated cardboard boxes due to their widespread use in the express delivery industry. For example, Verma et al. (2019) and Verma et al. (2021) found that electricity consumption and the disposal of unrecycled materials in landfills were the major sources of environmental impact during the production cycle of corrugated boxes. In addition, Su et al. (2020) conducted a comparative LCA of corrugated cardboard boxes and EPS foam and found that EPS foam had a lower environmental impact in terms of greenhouse gas emissions, although it had a higher overall impact on resource depletion.

Recent research has also focused on developing more sustainable packaging materials to reduce the environmental impact of package deliveries. For instance, researchers have explored the use of biodegradable materials such as plant-based polymers as an alternative to traditional plastic packaging (Wu et al., 2021). Furthermore, the adoption of circular economy principles, such as material reuse and recycling, has been proposed as a potential solution to reduce waste and mitigate environmental impact in the packaging industry (Bocken et al., 2016).

In summary, while packaging materials play a critical role in ensuring the safety and convenience of package deliveries, they also have significant environmental impacts throughout their life cycle. As such, research into sustainable packaging alternatives and the adoption of circular economy principles could help mitigate these impacts and promote a more sustainable express delivery industry.

A study on comparison between nanomaterial-based active agents for packaging application found that one of the compositions which consisted of silver nanoparticles and titanium dioxide nanoparticles had the lowest carbon footprint (Zhang et al., 2017). LCA of packaging materials such as glass for carbonated drinks and polyethylene terephthalate was conducted by Boutros et al., (2021) which showed that waste scenarios have a major impact on the outcome of the LCA. Koskela et al. (2014) introduced a very interesting comparison of LCA between reusable high-density polyethylene (HDPE) plastic crates and corrugated cardboard boxes in the express delivery industry and their analysis shows that although one may consider multiple reuses of HDPE plastic crates, it is in fact more environmentally friendly to use single use corrugated boxes. However, on the

Table 1
Literature review summary

References	Objective	Material	Database	Focus	Software
Boutros et al. (2021)	LCA of carbonated beverage packaging	Polyethylene terephthalate vs. glass	Ecoinvent	Cradle-to-grave	SimaPro
Verma et al. (2019) and Verma et al. (2021)	LCA of corrugated box	Corrugated boxes	ILCD[1]	Gate to Gate	GaBi
Zhang et al. (2017)	LCA of packaging material	Nanomaterial-based active agents, silver nanoparticles, titanium dioxide nanoparticles	Ecoinvent	Cradle-to-gate	SimaPro
Koskela et al. (2014)	LCA of express delivery materials	Plastic crates, corrugated box	Ecoinvent and Finnish Lipasto	Cradle-to-grave	GaBi
Tan and Khoo (2005)	To explore the environmental impacts of inserts	Expanded polystyrene, corrugated paperboard	EDCPLC[2]	Cradle-to-gate'	SimaPro
Lee and Xu (2004)	LCA of re-usable and single-use bulk transit packaging	Shrink wrap, wooden pallets, cardboard boxes	Pallet Enterprise	Gate-to-gate'	–

Note: [1]ILCD: International reference Life Cycle Database. [2]EDCPLC: European Database for Corrugated Paperboard Life Cycle Studies

contrary to the aforementioned research, a LCA conducted by Lee and Xu (2004) showed that package deliveries in corrugated boxes which are shrink wrapped on wooden pallets actually impacted the environment more than plastic packaging systems (an alternate for wooden pallets and corrugated boxes) due to its multiple reuses and light weight.

Packaging materials generally include some cushioning materials such as expandable polystyrene (EPS) foam, crinkle paper, and other such materials. Tan and Khoo (2005) studied the impact of EPS and corrugated paperboard inside delivery packages to evaluate the environmental effects and found that the most damage is caused by the percentage of material in landfills. End-of-life scenarios play a significant role in sustainable product life cycle and different disposal/recycle options exist depending on the choice of packaging material. A summary of the literature review findings is presented in Table 1. These studies illustrate the diverse environmental impacts associated with various packaging materials and provide insight into ways to minimize their impact.

The gap in the literature was the less popular discussions and assessments of wooden box/crate combinations and their implications on environment. To summarize, this study concentrates on assessing the environmental effects of the current delivery packaging received by the University of Regina from their stages such as transport, storage, usage, and end-of-life stage using LCA method. Additionally, potential alternative packaging combinations are assessed and compared side-by-side to minimize the carbon footprint and promote sustainable operations.

3. Methodology

To draw a better picture of the system, we will follow the systematic phases of a life cycle analysis as defined by ISO 14040 and ISO 14044 standards (ISO, 2006). This will allow us to link the significance of different stages of a product to the environmental impacts.

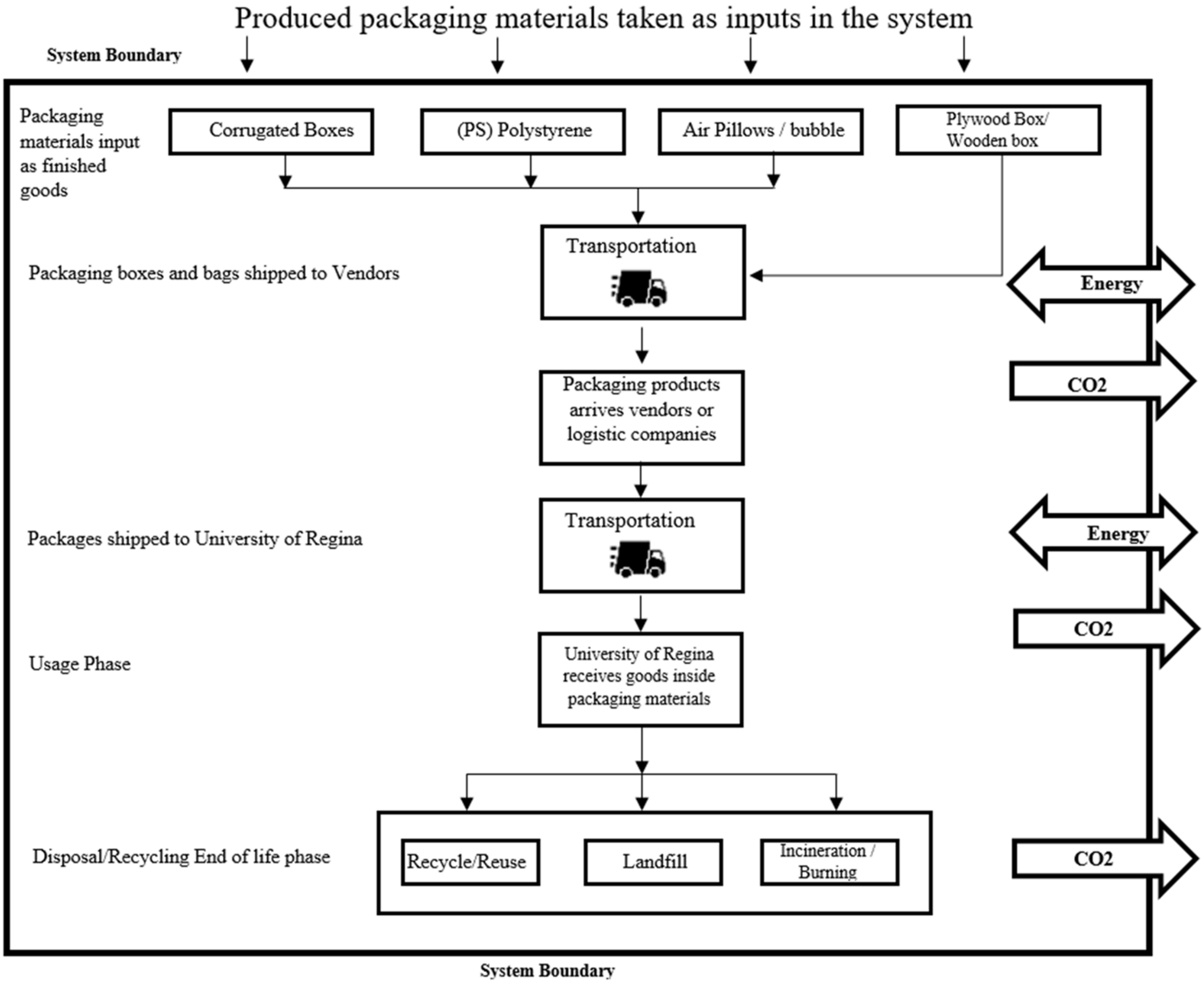
3.1. Goal and scope

It is important that we define what we are trying to measure in our LCA with respect to products, services provided, or an organization in general. The functional unit is the base reference that tells us how much we need to analyze in terms of CO2 emissions and equivalents. Next, we have to define the system and its boundaries, as well as which stages of the product cycle we are assessing for the LCA. An LCA is, in other words, a simulation of processes as close as possible to reality; hence, the results might vary to some extent from assessment to assessment. In this research, assumptions and limitations are made carefully in order to minimize variation in results and comparisons (ISO, 2006).

The main objective of this study is the comparison between current delivery packaging (simplified) and multiple feasible alternatives to analyze and identify the stages that are major contributors to the environmental emissions. For data consistency purposes, packaging material data are retrieved from GaBi Education Database 2020 as available, and other required product specific data are retrieved from published LCAs. Since there is a comparison between multiple packaging model LCAs in this research, it is important to highlight that the goal and scope has to be same in order to be compatible to one another. Currently, the base scenario LCA is conducted on corrugated cardboard boxes with polystyrene (PS) foam inside the boxes for cushioning and safety purposes. Other alternative packaging models include corrugated cardboard boxes with plastic air pillows or plastic bubble wraps, wooden box with PS foam, and wooden box with air bubble sheet/plastic sheets. Each packaging model has their pros and cons with respect to environmental impacts. The end-of-life phase is modeled based on Regina City waste management and disposal practices in Canada. An overview of the LCA framework is shown in Figure 2.

The study explains the importance of defining the functional unit, system boundaries, and stages of the product cycle when conducting the LCA. It also highlights the need for making careful assumptions and limitations to minimize variation in results and comparisons. The main objective of the study is to compare the environmental impact of current delivery packaging with multiple feasible alternatives and identify the stages that contribute the most to environmental emissions. The scope of the study is limited to the comparison of delivery packaging options and identifying the major contributors to environmental emissions.

Figure 2
LCA framework (state the sytem boundary with the clarification of "cradle to grave")



The study provides the methodology and framework for conducting the LCA, which is directly related to the objectives of the study. Therefore, the content and scope of the study are interrelated as the content defines the approach for achieving the study objectives within the scope of the research.

The impact of different substances on the environment is characterized by different factors, such as methane having a higher factor than CO2. These factors are included in different LCA methodologies, such as CML, TRACI, and ReCiPe. The ReCiPe 2016 (H) life cycle impact assessment (LCIA) Methodology is chosen for environmental characterization due to its ability to convert emissions to environmental impacts at both midpoint and endpoint levels and it is explained in detail in the Section 3.3.

The production cycle phase of these packaging materials and operations related to packing of valuable goods inside these packaging materials is excluded from the scope of this LCA; however, production-related outputs such as product itself and emissions for a unit of that product are included due to their significance in this study. The limitations of this study are that it excludes the production cycle phase of the packaging materials and packing operations, which may affect the overall environmental impact. Additionally, the exclusion of certain stages in the LCA may limit the accuracy of the results; however, we have tried to capture and factor all significant aspects. The LCA model is simplified as much as possible due to limitation in time and availability of accurate data. Some other things that are excluded from the scope of this study comprise of plastic packaging tape, product manuals/packing lists, second tier vendor operations energy consumptions and emissions, storage facility internal operations, and other forms of wastes between any stages such as liquids, non-usable gases, and waste solids. This is due to the limitation of available data and ratio of significance.

To summarize, the functional unit is defined as "delivery of one packaging," the goal of this assessment is to make delivery packaging to the University of Regina Central Receiving more sustainable by reducing its environmental impacts during its life cycle, and the scope of this study is to evaluate multiple packaging alternatives and analyze CO2e (carbon dioxide emissions) from cradle-to-grave. As mentioned in the scope, the end-of-life phase is modeled based on Regina City waste management and disposal practices in Canada

3.2. Life cycle inventory

In an LCA, we have the life cycle inventory (LCI) phase where we consider the environmental inputs and outputs of the concerned product or service provided with the primary objective to quantify them (Matustik & Koci, 2020; Tampubolon et al., 2021). When we utilize LCA tools and software, we can often use LCI databases that already have tested and verified data of standard materials and products as discussed in Section 3.1. Although these databases provide valuable data, it is important to highlight that these databases give an estimate of the environmental impact as close as possible to the real system boundary. The objective of the LCI analysis is to obtain a flow model that depicts all the environmental inputs and outputs in a systematic manner.

The primary system data were acquired from sources such as GaBi ts Education Database 2020, and material specific data when not found were acquired from literature with respect to the functional unit. The frequency and order rate data were acquired from the University of Regina Central Receiving via survey, and an average was estimated due to inconsistent delivery frequency and replenishment rate. The type of packages delivered varied from small to large dimensions after inspecting the mail room; hence, for simplification, one package dimension is only considered for the whole assessment as the idea is to average out the delivery packaging material consumption and its respective environmental impact (Table 2). The transportation distance from packaging material production to the vendor warehouse is assumed to be 50 km and from vendor warehouse to the University of Regina Central Receiving area it is assumed to be 20 km. The transportation distances have been kept constant to eliminate any bias in the comparison of alternative packaging material scenarios. For simplification purposes, the energy consumption, water consumption, and gas consumption at the vendor warehouse for operations related to the handling and storage of packages are not included in the scope of this assessment due to the lack of sufficient supporting data. Table 2 includes the packaging materials, respective dimensions used in the LCAs, weight, and reference material images.

The number of parcels arriving at the University of Regina Central Receiving department is averaged at 50 boxes per order cycle according to a survey from the University of Regina Supply Department. It is possible that the number of boxes is lesser or more than 50 units per order cycle; however, for simplicity of the LCA, a constant scale is determined based on average quantities. It is also assumed that the packaging materials are disposed using end-of-life scenarios immediately. The waste management model in the end-of-life scenarios is modeled based on current waste management plan of City of Regina and overall practice in Canada. Corrugated cardboard boxes are determined to be recycled at a rate of 70%, 20% sent to landfill, and the remaining 10% for incineration.

It is important to note that actual rate of recycling and disposal may vary from the aforementioned rates due to updates in policies and involvement from the City Council. The Waste Management Hierarchy 2021 as Figure 3 (reproduced after City of Regina, 2022) shows, which was published by the City of Regina is utilized internationally to shape the strategic waste management plan and emphasizes on source reduction, reuse, recycling options, and recovering energy from waste treatment and landfilling (City of Regina, 2022). The City of Regina does not recycle styrofoam PS foam packaging material) according to Saskatchewan Waste Reduction Council as they do not have the facilities required to recycle it (City of Regina, n.d.; Crown Shred & Recycling, 2018; Saskatchewan Waste Reduction Council, n.d.); they treat styrofoam as

Table 2
Packaging material and their respective attributes

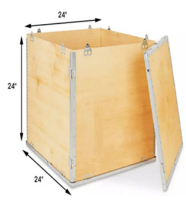
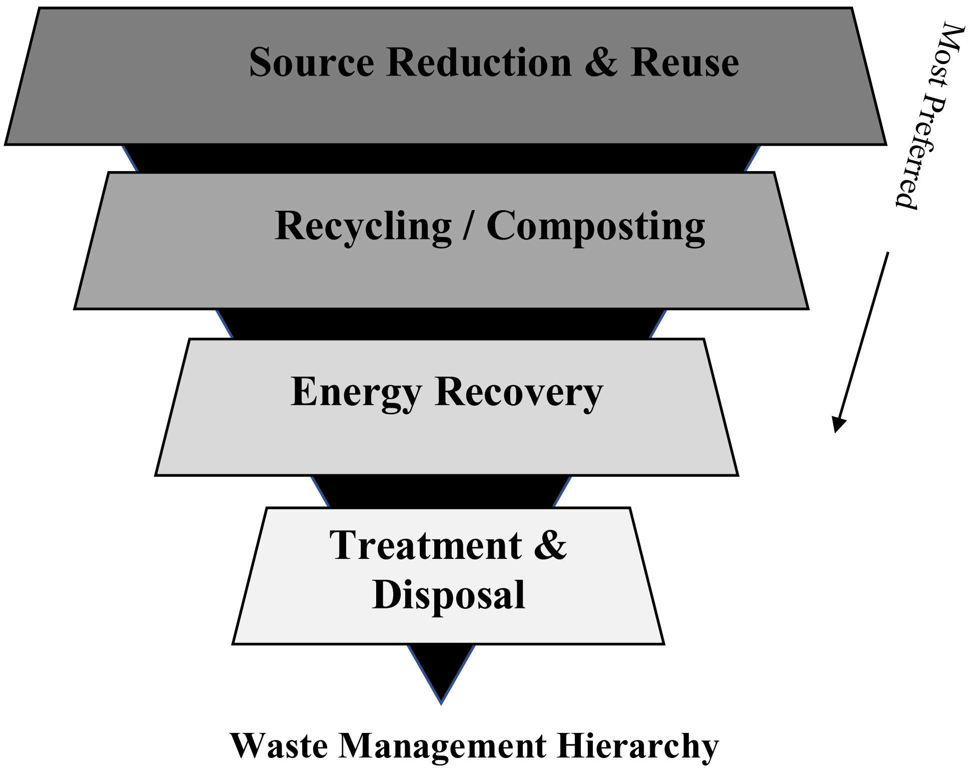
Material	Dimension (In)	Weight	Reference image
Corrugated cardboard box	24 x 24 x 24	1.907 kg	
Expanded polystyrene (EPS)	–	0.45 kg	
Air bubble/plastic sheet	1 m	40 GSM	
Wooden crate (plywood)	24 × 24 × 24	10.8862 kg	

Figure 3
Waste management hierarchy by City of Regina 2022 Plan



a non-recyclable material and sends the retrieved waste to landfill. Although it is known for a fact that EPS packaging materials are 100% recyclable, it is not currently being recycled in the City of Regina.

3.3. Impact assessment

In Section 3.2, we discussed the quantifiable environmental inputs (such as materials, energy, and composition) and outputs (such as materials, emissions, and waste) of different stages in the LCA system processes. This collection of data is important for impact assessment phase to quantify the significance of inventories in terms of effect on the environment. For example, one element might have lesser quantities of inventory as compared to another element; however, impact assessment will determine which element has higher significance than the other in terms of environmental effect. Impact assessment determines what is more important to focus for reduction and provides a reference for improvement areas (ISO, 2006). Here, we can take our indicators and convert them to the impact category of our choice such as CO2 since our unit of measurement is CO2 and our impact category is climate change.

GaBi ts LCA software was used to calculate the impact assessment and within the software there are available data of processes and materials that eliminate the need to repeat some

Table 3
Different scenarios that compares LCA

Base model	Alternate model 2	Alternate model 3	Alternate model 4
Corrugated cardboard Styrofoam Not weather/damage proof Single use then recycles/dispose	Corrugated cardboard Air pillows/bubble wraps Not weather/damage proof Single use then recycles/dispose	Wooden box Styrofoam Weather/damage resistant Multiple use then recycles	Wooden box Air pillows/bubble wraps Weather/damage resistant Multiple use then recycles
			

data collection steps. Table 3 shows the base model and alternate models that are subject to LCA comparisons in the scope of this study. The main purpose of this study is to compare these distinct packaging systems to determine the lowest environmental impact. It is also important to note that some packaging materials have only single uses such as corrugated cardboard boxes, styrofoam, plastic bubble sheets, and packaging material such as wooden crate/box can be reused multiple times.

Depending on the type of wood, we can reuse a wooden crate without any modifications or servicing done to it. For simplicity and ease of life cycle calculations, 20 reuses per wooden box are assumed although it can be reused for a greater number of times over the years of service according to a wood crate manufacturing company (Coloradowood, 2019). Characterization is done wherein all the elements are multiplied by a factor which shows their relative environmental contribution (Sphera Solutions, 2023).

For instance, the impact category climate change can have characterization factor equal to 1 while for methane it could be a higher factor such as 21 which means that 1 kg of methane released in the air is equivalent to 21 kg of CO2 (Sphera Solutions, 2023) (Table 4 shows a tabulated data for reference). CML, TRACI, and ReCiPe methodologies include the characterization factors in their results. We will use ReCiPe 2016 (H) LCIA Methodology for the environmental characterization of the emission flows. The reason for selecting ReCiPe 2016 (H) LCIA Methodology is due to its ability to convert emissions to environmental impacts in both midpoint and endpoint levels (Matustik & Koci, 2020). The ReCiPe 2016 (H) method is a commonly used LCIA methodology that covers a wide range of environmental impact categories and has been updated to reflect the latest scientific understanding of environmental impacts. Its broad scope and updated characterization factors make it a suitable choice for many types of LCA studies.

3.3.1. Base scenario

The base model LCA model is depicted in Figure 4, and its LCIA results are in Figure 5. The base model consists of corrugated cardboard box of dimensions 24 × 24 × 24 inches, weight 1.907 kg, and PS foam material for cushioning purposes. The material details can also be referred from Table 2. The impact category climate change ranges to a total of 220 kg CO2 eq. where the highest contributors to it are PS packaging material production output (cradle-to-gate) and end-of-life PS packaging (75.9 kg CO2 eq.). The end-of-life wood material in landfills contributes to approximately 34 kg CO2 eq. It is also apparent that although PS packaging material quantity ratio is very small as compared to corrugated boxes, the impact on the environment is significantly more due to no recycle option for it (Figure 5). When biogenic carbon is included, Figures A1 and A2 in

Figure 4
Base scenario LCA model in GaBi ts

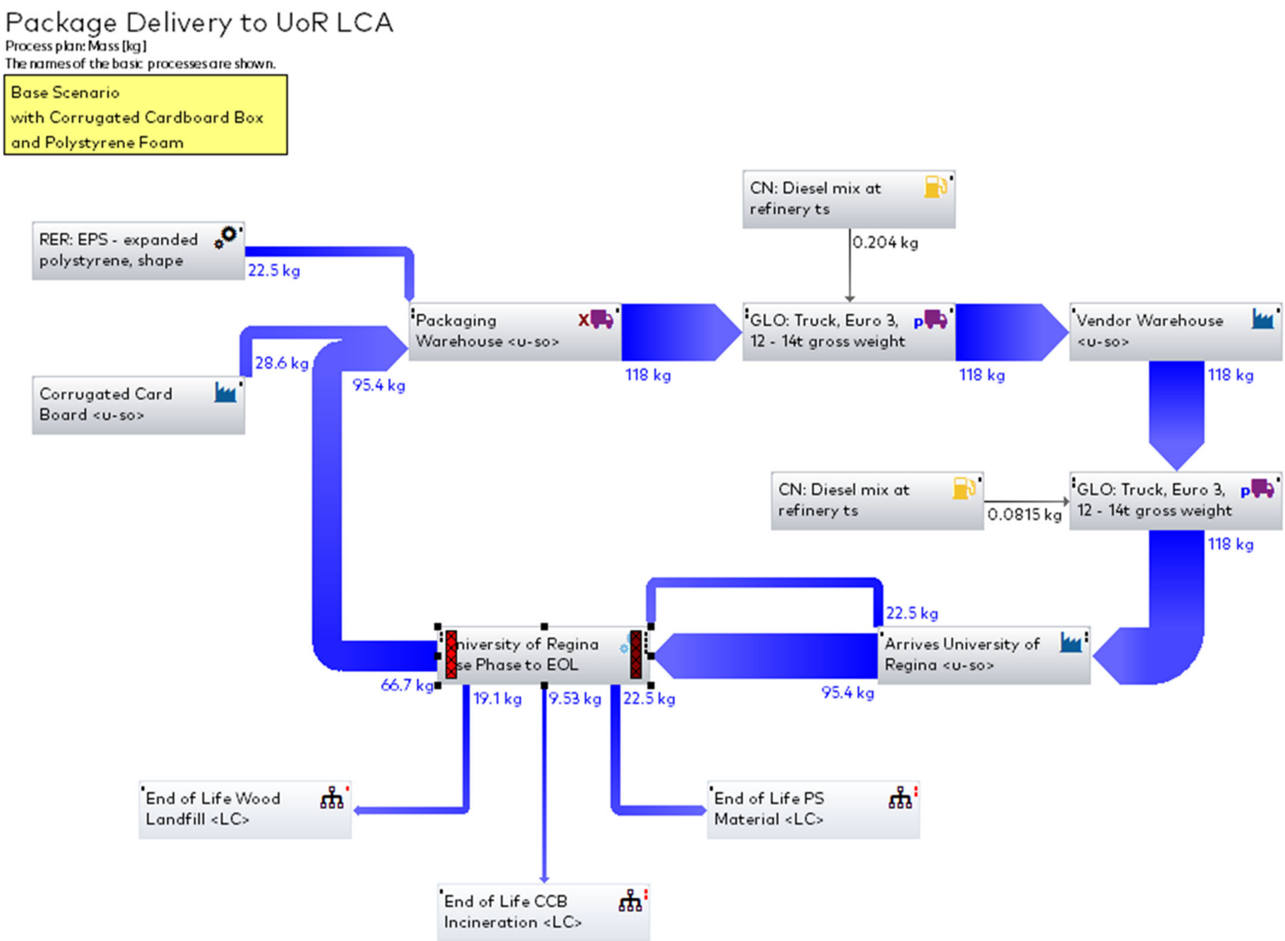
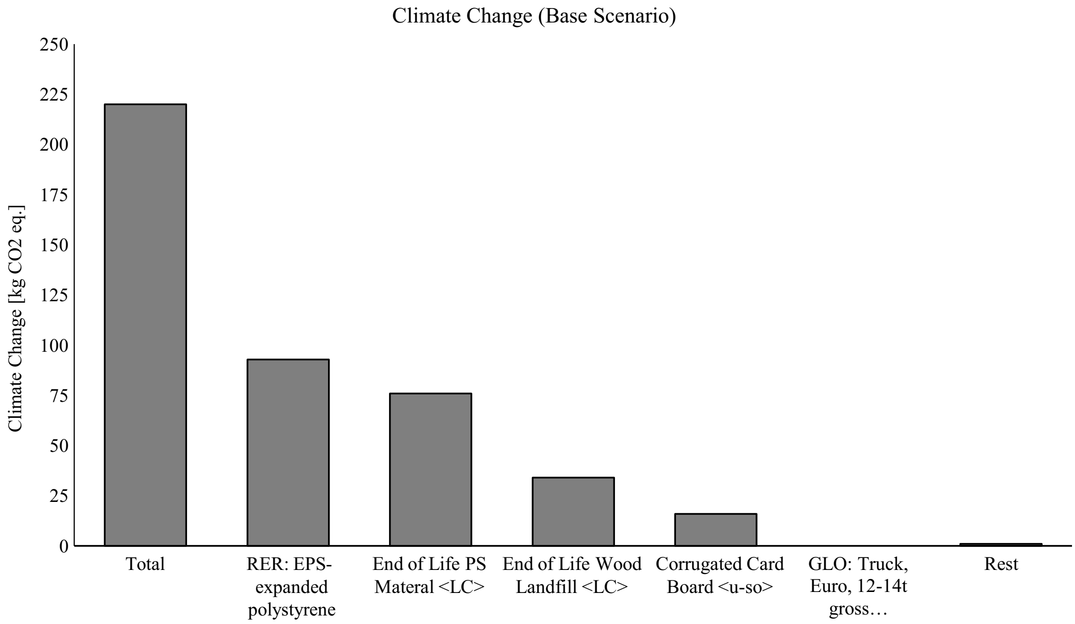


Figure 5
Climate change (kg CO2 eq.) base scenario



Appendix shows that the significance of end-of-life corrugated cardboard box incineration phase increases (13.5 kg CO2 eq.).

3.3.2. Alternative model 2

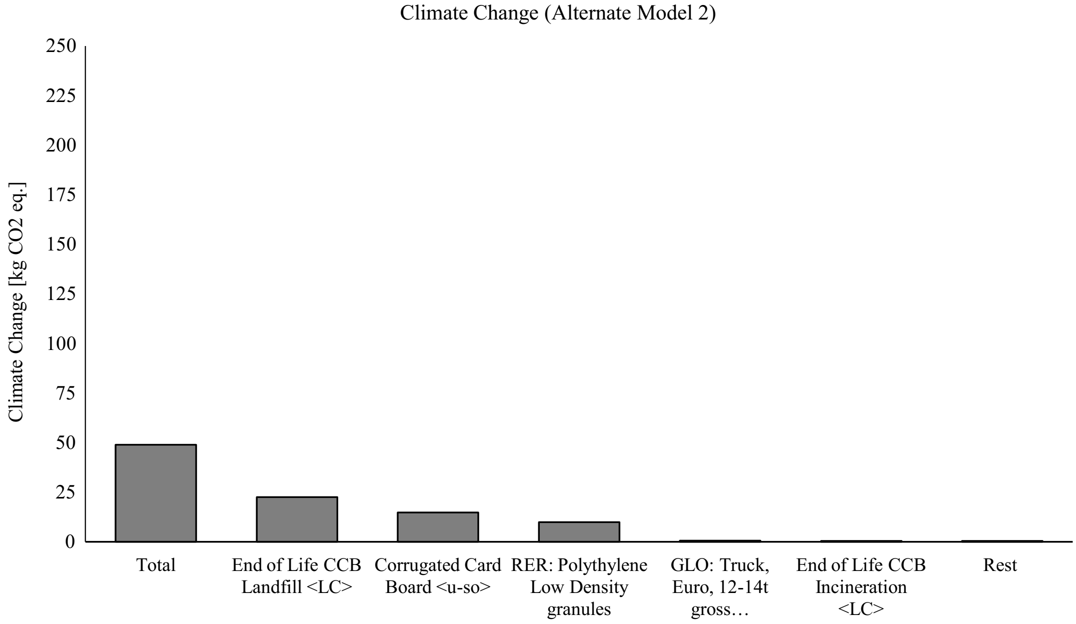
An LCA was conducted for an alternative packaging system containing corrugated cardboard box along with plastic air bubble wraps instead of PS foam material. The LCA was modeled in GaBi similar to the base model and the results obtained reflected on the assumptions and specifications of corrugated cardboard box from base model and low-density polyethylene (LDPE) plastic air bubble wrap with 40 GSM. The total air bubble wrapping material used inside a packaging box is assumed to be directly proportional to the inner area inside the 24 × 24 × 24” box and the production phase of the bubble wrap is out of scope in this study. The LCA model in GaBi is shown in Figures A1, A2 and A3 in Appendix. According to the City of Regina and its associated recycling units, polyethylene plastics such as bubble wrap are recyclable and processed such that the collected bubble wraps are first separated, shredded into flakes, then cleaned against any debris and dirt to finally dry, and melted to turn into pellets (City of Regina, n.d.; Crown Shred & Recycling, 2018; Saskatchewan Waste Reduction Council, n.d.). Hence, the end-of-life scenario for LDPE bubble wraps is assumed to be recycled and reused as inputs in the production phase of bubble wraps. The impact category climate change ranges to a total of 48.9 kg CO2 eq. where the highest contributor to it is end-of-life corrugated cardboard material in landfills (22.5 kg CO2 eq.). It is also seen that although LDPE bubble wrap packaging material quantity ratio is very insignificant as compared to corrugated boxes, the impact on the environment is significant as a whole life cycle from cradle-to-grave (Figure 6). When biogenic carbon is included, Figure A4 in Appendix shows that the significance of end-of-life corrugated cardboard box incineration phase increases (13.5 kg CO2 eq.) as seen on base model.

3.3.3. Alternative model 3

The third alternate model analyzed in this study under LCA consists of a wooden crate/box with dimensions 24 × 24 × 24”, approximate weight 10.8862 kg (ULINE Canada, n.d.) and enclosed inside the wooden box is PS foam material for cushioning and padding purposes. Since the dimensions of the wooden box are assumed to be same as the base model corrugated cardboard box dimensions, the assumption of similar quantity of PS foam material required in the base model is made. Although wooden crate can be reused multiple times, some fraction of the crate can be assumed to be scrapped due to usage or logistic damages. In practice, the reusability of wooden crates is often effective for multiple order cycles since these boxes do not get damaged easily. In this study, an average of 30 reuses of wooden boxes are assumed which reflects to roughly 5% wooden material to be scrapped pertaining to a small contribution toward landfill. This means the wooden box will go to complete disposal after every roughly 30–40 order cycles in a progressive manner (Coloradowood, 2019).

Figure A5 in Appendix shows the LCA model in GaBi of alternate model 3. The impact category climate change ranges to a total of 223 kg CO2 eq. where the highest contributor to it is PS foam production output (93.9 kg CO2 eq.) and the end-of-life phase of PS foam material (75.9 kg CO2 eq.). This shows that the cradle-to-grave alone for PS foam is a huge contributor to negative environmental impacts (Figure 7). It is also seen that end-of-life phase for small quantities of wood in the landfills generates 49.9 kg CO2 eq. due to composting over long time. When biogenic carbon is included, Figure A6 in Appendix shows that the significance of end-of-life wooden box landfill phase increases (61 kg CO2 eq.). The order cycles consisting wooden boxes generally will contribute less wooden material for end-of-life scenarios due to their reusability as compared to single use packaging materials.

Figure 6
Climate change (kg CO2 eq.) alternate model 2



3.3.4. Alternative model 4

The fourth alternate model analyzed in this study under LCA consists of a wooden crate/box with dimensions 24 × 24 × 24”, approximate weight 10.8862 kg (ULINE Canada, n.d.) as seen from alternate model 3 and enclosed inside the wooden box is LDPE plastic air bubble sheet material for cushioning and padding purposes. Since the dimensions of the wooden box are assumed to be same as the base model corrugated cardboard box dimensions, the assumption of similar quantity of plastic air bubble sheet material required in the base model is made. Figure A7 in Appendix shows the LCA model in GaBi of alternate model 4. The impact category climate change ranges to a total of 63.4 kg CO2 eq. where the highest contributor to it is end-of-life phase for small quantities of wood in the landfills which generate 48.6 kg CO2 eq. due to composting over long time. This shows that the cradle-to-grave alone for PS foam is a huge contributor to negative environmental impacts (Figures 7 and 8). When biogenic carbon is included, Figure A8 in Appendix shows that the

Figure 7
Climate change (kg CO2 eq.) alternate model 3

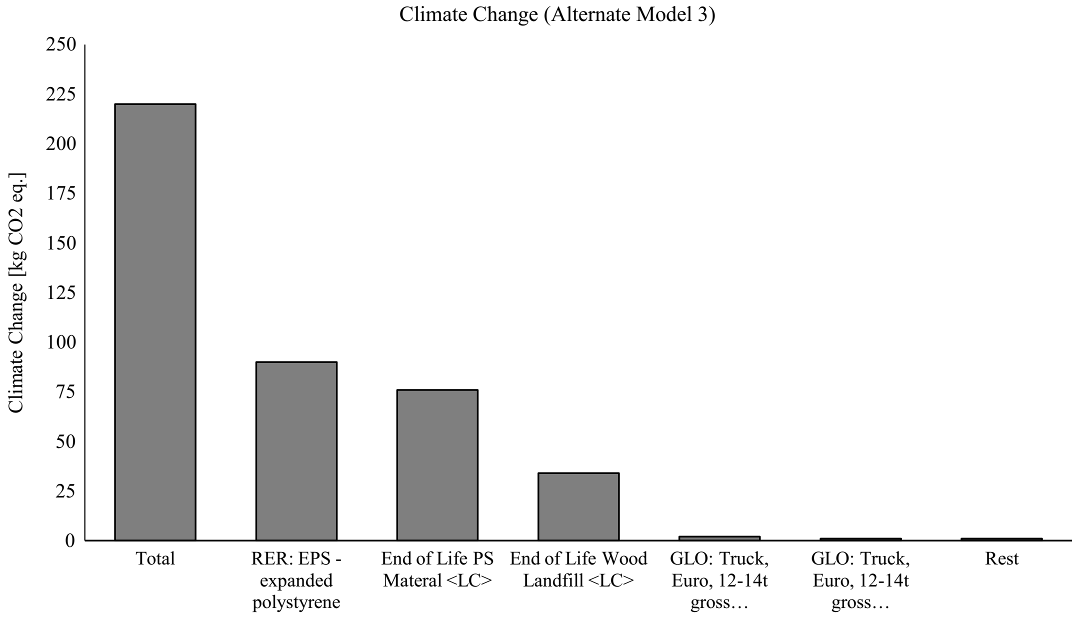
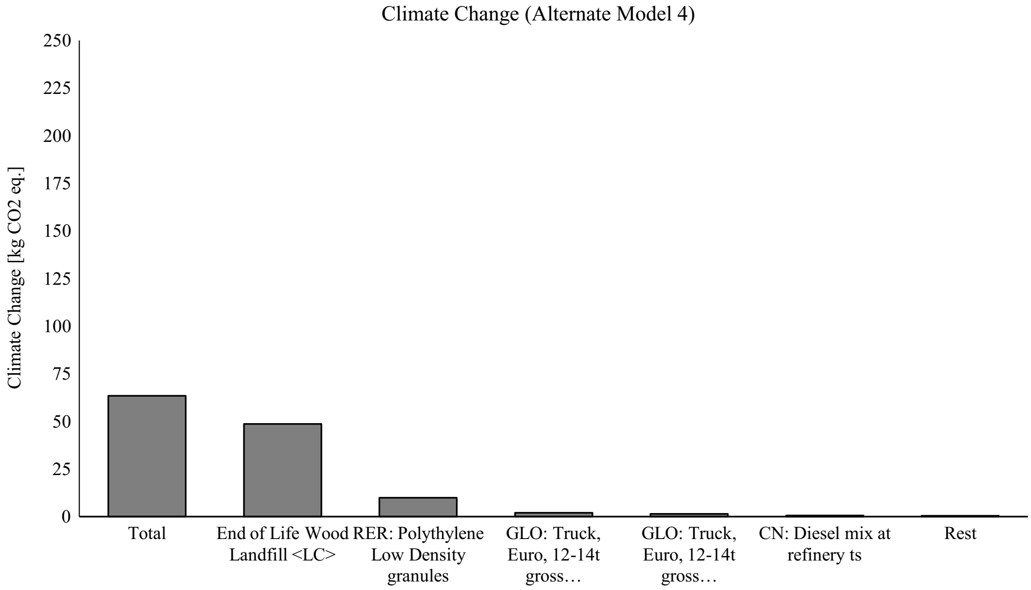


Figure 8
Climate change (kg CO2 eq.) alternate model 4



significance of end-of-life wooden box landfill phase increases (61 kg CO2 eq.) as we have seen previously from alternate model 2 LCIA.

3.4. Interpretation

In this study, there are four packaging models that are compared with their respective life cycle analyses keeping multiple factors constant such as travel distances and out of scope factors in all four models. The summary of the LCIA for the four respective packaging models is presented in Table 4, which are calculated using ReCiPe 2016 (H) midpoint methodology.

The ReCiPe 2016 (H) midpoint methodology evaluates various impact categories as seen in Table 4; however, the significant impacts are only visible on four impact categories, namely climate change excluding biogenic carbon (kg CO2 eq.), climate change including biogenic carbon (kg CO2 eq.), fossil depletion (kg oil eq.), and terrestrial ecotoxicity (kg 1,4-DB eq.).

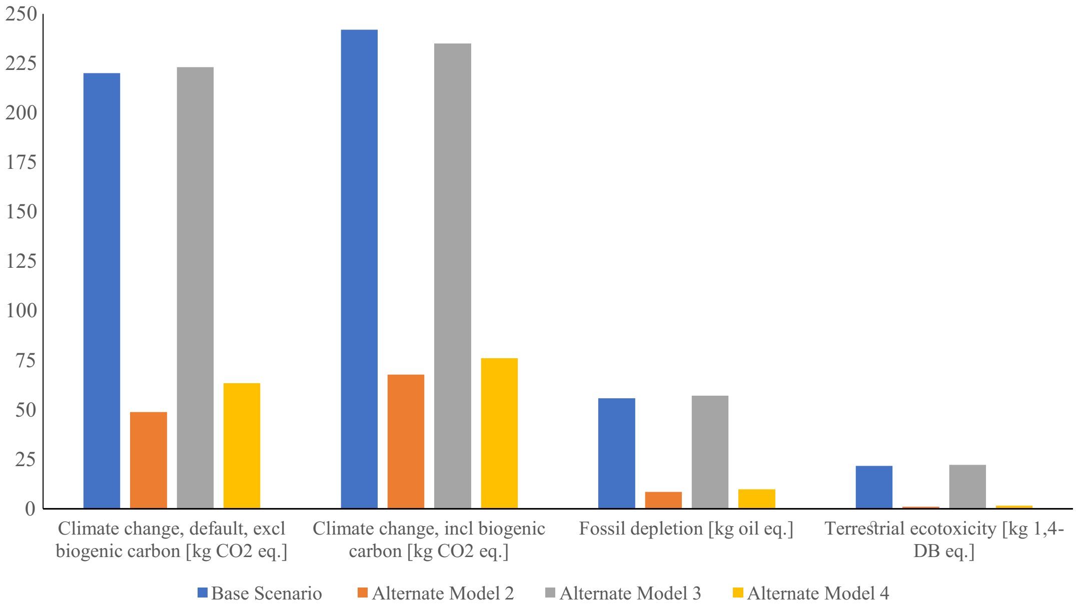
When evaluating the overall results of these packaging models, it is clear that alternative model 2 yields the lowest climate change

Table 4
Life cycle impact assessment results of the four alternatives calculated using ReCiPe 2016 (H) midpoint methodology

Package delivery to UoR LCA <LC>	Base scenario	Alternate model 2	Alternate model 3	Alternate model 4
Climate change, excl biogenic carbon (kg CO2 eq.)	220	48.9	223	63.4
Climate change, incl biogenic carbon (kg CO2 eq.)	242	67.8	235	76
Fine particulate matter formation (kg PM2.5 eq.)	0.0559	0.0116	0.0615	0.0175
Fossil depletion (kg oil eq.)	55.8	8.47	57.2	9.84
Freshwater consumption (m3)	0.469	0.192	0.446	0.171
Freshwater ecotoxicity (kg 1,4 DB eq.)	0.00725	0.00104	0.00844	0.0022
Freshwater eutrophication (kg P eq.)	8.56E-05	0.000129	0.000106	7.09E-05
Human toxicity, cancer (kg 1,4-DB eq.)	0.0297	0.00111	0.0317	0.0033
Human toxicity, non-cancer (kg 1,4-DB eq.)	1.62	0.182	2.1	0.665
Ionizing radiation (kBq Co-60 eq. to air)	0.218	0.0104	0.215	0.00765
Land use (annual crop eq.·y)	0.0313	0.0215	0.0308	0.0209
Marine ecotoxicity (kg 1,4-DB eq.)	0.0911	0.00194	0.0936	0.00442
Marine eutrophication (kg N eq.)	0.00339	0.000557	0.0046	0.00408
Metal depletion (kg Cu eq.)	0.135	0.0976	0.171	0.133
Photochemical ozone formation, ecosystems (kg NOx eq.)	0.378	0.0361	0.418	0.0786
Photochemical ozone formation, human health (kg NOx eq.)	0.289	0.0357	0.329	0.078
Stratospheric ozone depletion (kg CFC-11 eq.)	2.07E-05	9.15E-07	2.13E-05	1.81E-06
Terrestrial acidification (kg SO2 eq.)	0.182	0.0384	0.199	0.0553
Terrestrial ecotoxicity (kg 1,4-DB eq.)	21.7	1.11	22.2	1.61

Note: Characterization for each impact category is also mentioned for reference. The visual depiction of the significance of each packaging material on the impact categories is shown in Figure 9.

Figure 9
Environmental impacts of the four packaging models



CO_2 eq. which is followed closely by alternate model 4. The commonality in both of these alternatives is that they do not consist of EPS foam material. In the base model as well as alternate model 3, we can see that the cradle-to-grave environmental impact of the EPS is the major contributor to the impact categories mainly climate change (Figures 9 and A9).

Figure A9 shows the percentage of contribution of the most impactful environmental impactors, which can be assumed to include the cradle-to-grave environmental impact of EPS. Therefore, Figure A9 provides a visual representation of the percentage of contribution of various environmental impact categories, including climate change, to the overall environmental impact of the packaging models under consideration.

Although it is observed that the alternate model 2 with the composition of corrugated cardboard box along with LDPE plastic air bubble sheets is environment friendly packaging option for one order cycle, alternate model 4 must be chosen with preference based on benefits of using wooden boxes such as multiple reusability, in-transit damage protection, and 100% recyclability of wooden materials. On the contrary, the added weight for wooden boxes is almost 9 times higher as compared to corrugated boxes that might negatively impact the transportation fuel consumption.

4. Results and Discussions

This study is conducted to analyze the life cycle environmental impacts of package deliveries to academic institutions on a frequent basis, and the case of University of Regina is examined. It was found that the current packaging design that is mostly received at the Central Receiving is not the best packaging design since the EPS foam material in it mainly disrupts the efficiency of corrugated cardboard boxes. It has been shown with results in this study that if we replace the EPS foam packaging material with LDPE plastic air bubble sheets (bubble wraps) we can cut the environmental impact by 127% less carbon emission. Using LCA methodology, four packaging models were compared based on realistic data acquired from verified databases and material suppliers.

Although alternate model 4 compares very closely to alternate model 2 in the LCIA, we should still opt for alternate model 4 with a wooden box and LDPE plastic air bubble sheet based on the priority of needs by the strategic decision-makers. For example, if the long-term goal is to minimize in-transit package damages and minimize single-use packaging material while also minimizing the environmental impact, alternate model 4 stands out to be the best choice. The civic opinion of plastic, in general, might be negative; however, due to LDPE's low-density property, recycling is a possibility with less waste as compared to no recycling or reusability option for EPS foam packaging material. The results of the packaging models that consist of corrugated cardboard boxes are similar to literature studies and hence confirm its correctness. The waste management scenarios simulated in the LCA were considered with as much practicality as possible and the contributions of end-of-life treatment alone were shown to be major contributors to the environmental impact (impact category: climate change). This points out that before considering a packaging material type for long-term usage, it is crucial to consider their respective waste management scenarios specific to the region.

This paper concludes the research questions with the following points:

- it was shown by conducting LCA that both corrugated boxes and wooden boxes combined with LDPE air bubble sheets are the most efficient packaging materials.
- the LCA tools are useful to measure and comprehend the economic and environmental impacts by following the four standard phases of LCA.
- in an LCA, characterization helps to compare two different impact categories and measure its significance with respect to their environmental emissions.

Further research can be conducted in the future with a focus on the comprehensive cradle-to-grave life cycle of packaging materials which should also emphasize the production stage of these packaging materials as the production operations and related activity energy consumptions were out of scope in this research paper. A combination of various waste treatment techniques which are not currently utilized as well as effective reusability applications can also be further studied as part of future research. This paper also confirms that the LCA tools can be used for making decisions in the industry as seen in the impact analysis section to minimize environmental emissions at different stages of a product life cycle.

5. Implications of This Study

The findings of this study offer theoretical and practical implications for its stakeholders.

5.1 Theoretical implications

To begin with, this study offers a wide-ranging understanding of the type of packaging materials currently being used for academic institution procurement cycles on a frequent basis and compares it with other alternative packaging models in terms of their environmental consumption and emissions. The life cycle analysis tool provides an informative basis that decision-makers can utilize in assessing the long-term feasibility of material selection and place their judgment for developing strategic solutions (Verma et al., 2019; Verma et al., 2021). Moreover, this study breaks the common understanding on wooden boxes are expensive and clarifies that in the long term the investment justifies its reusability and environmental impact.

5.2. Practical implications

This study used LCA tools to determine the impact of various packaging materials on the environment and the results show that in a single order cycle with current packaging materials, the choice of corrugated cardboard boxes with PS foam material (alternate model 3) is the worst performing material selection among the other packaging models analyzed in scope of this research. This is mainly due to the significant contributions of PS foam material environment footprint. On the contrary, when the packaging model is a reusable wooden box with PS foam padding which is also reused along with the wooden box, its impact on the environment significantly drops. The high impact of PS foam material on the environment should be a consideration for the government to introduce sustainable recycling options to address the alarming disposal process of these materials.

6. Conclusions

In this study, we analyzed the environmental impacts of package deliveries to academic institutions and identified the sustainable choice of packaging materials for the long run. Through conducting a LCA using the ReCiPe 2016 (H) midpoint methodology, we compared four packaging models and found that alternate model 2, composed of a corrugated cardboard box and LDPE plastic air bubble sheets, yields the lowest climate change CO_2 equivalent emissions. However, alternate model 4, composed of a wooden box and LDPE plastic air bubble sheets, is the best choice for minimizing in-transit package damages, minimizing single-use packaging material, and minimizing the environmental impact in the long run. The study concludes that LCAs are useful for measuring and comprehending the economic and environmental impacts of packaging materials, and that waste management scenarios specific to the region should be considered when selecting packaging materials for long-term usage.

The findings of this study can be used to educate stakeholders on the environmental impacts of packaging materials and to make informed decisions in the industry to minimize environmental emissions at different stages of a product life cycle. Future research can focus on the comprehensive cradle-to-grave life cycle of packaging materials and the production stage of these materials, as well as on a combination of various waste treatment techniques and effective reusability applications. Overall, this study has successfully addressed the defined research questions and provided valuable insights for sustainable packaging choices in the delivery industry.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data is available on request from the authors.

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Appendix

Figure A1
Base scenario acidification: Climate change including biogenic carbon (kg CO2 eq.)

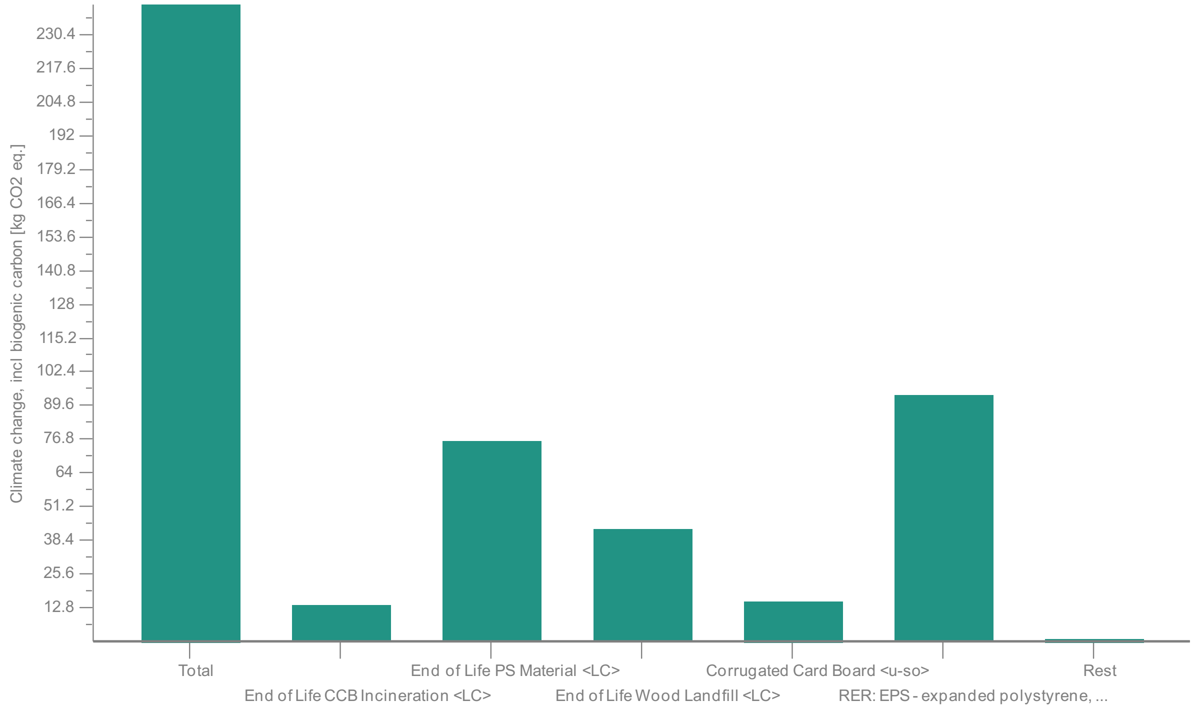

Figure A2
Base scenario inputs/outputs mass composition diagram

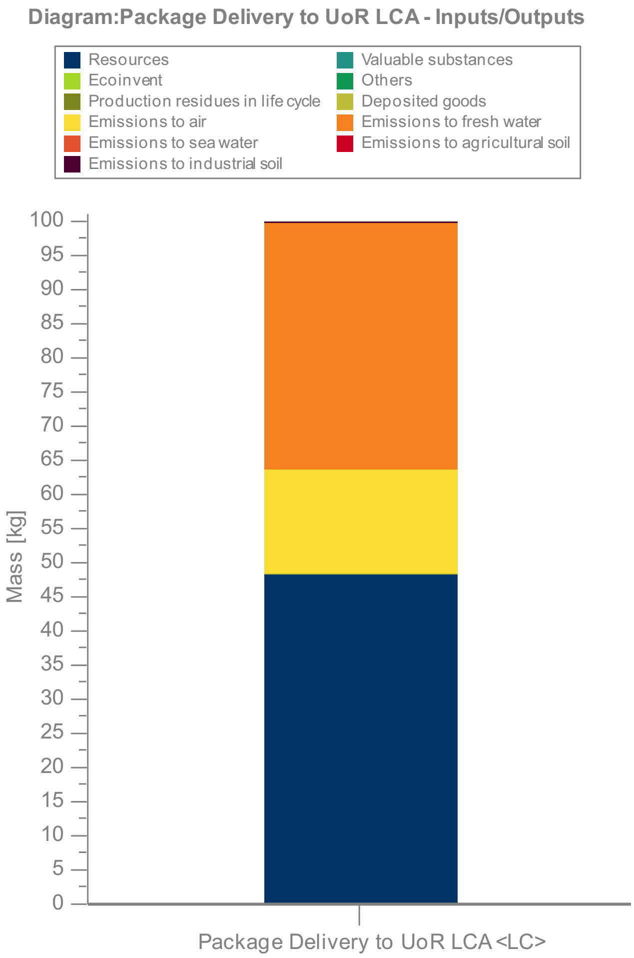

Figure A3
Alternate model 2 LCA model in GaBi ts

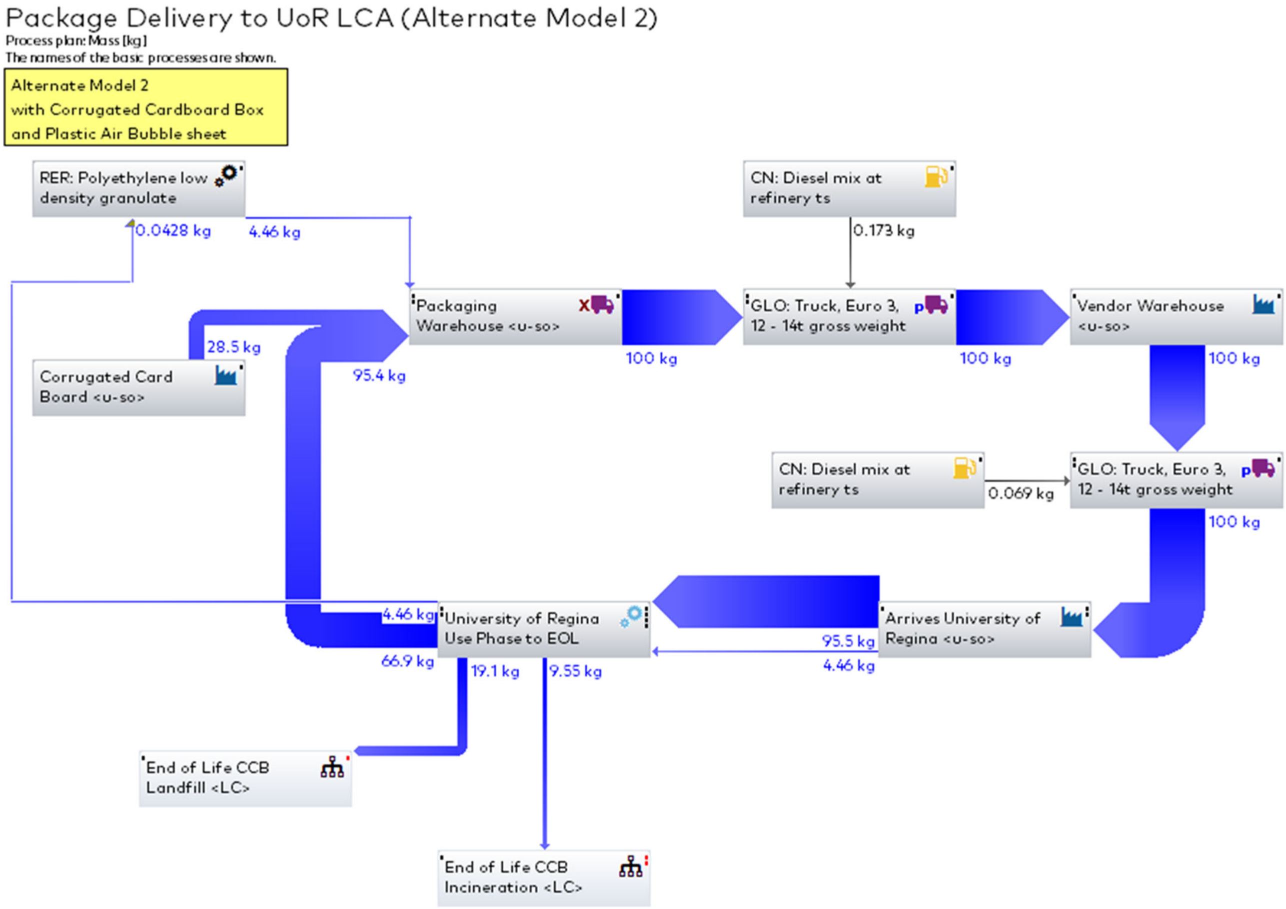

Figure A4
Alternate model 2 acidification: Climate change including biogenic carbon (kg CO2 eq.)

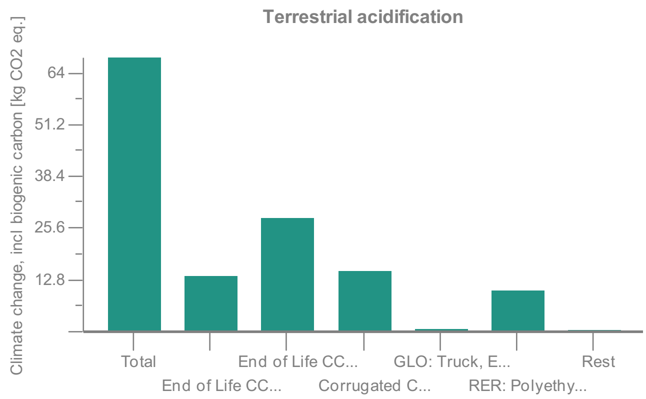

Figure A5
Alternate model 3 LCA model in GaBi ts

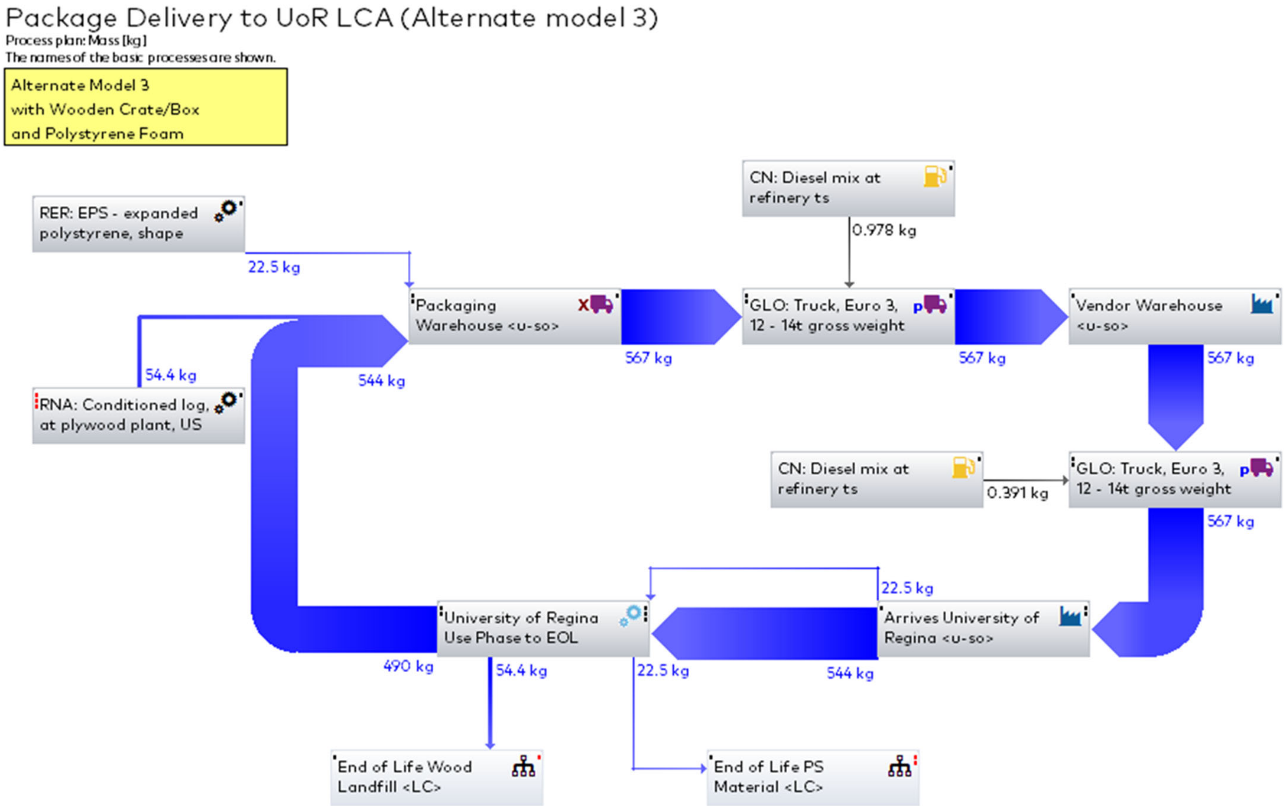

Figure A6
Alternate model 3 acidification: Climate change including biogenic carbon (kg CO2 eq.)

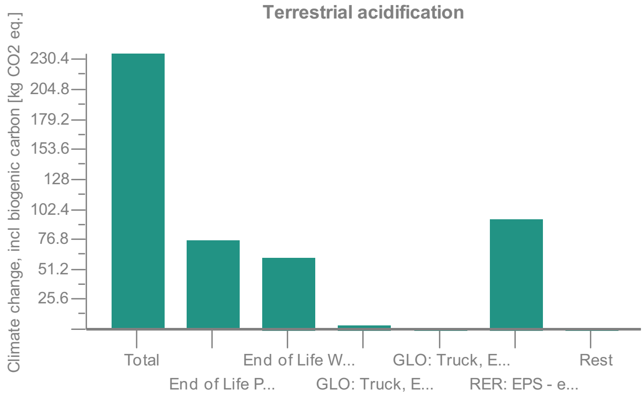

Figure A7
Alternate model 4 LCA model in GaBi ts

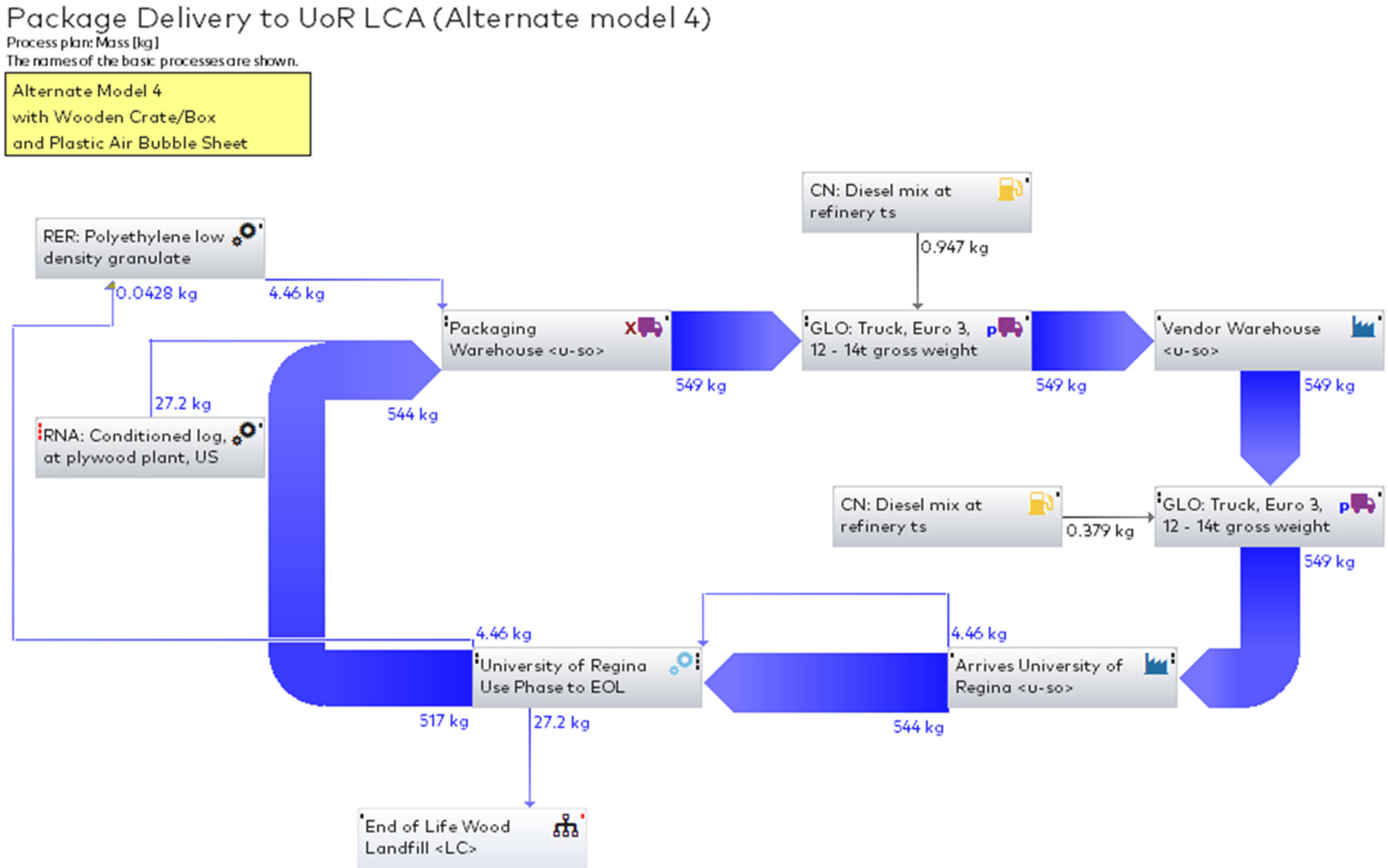

Figure A8
Alternate model 4 acidification: Climate change including biogenic carbon (kg CO2 eq.)

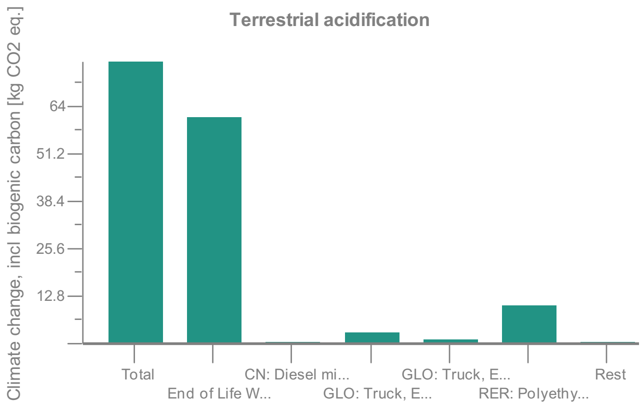

Figure A9
Percentage contribution of environmental impacts by four different packaging systems