A Life Cycle Analysis and Eco-Efficiency Portfolio of Single-Use Containers

(Polystyrene, Plastic, Biodegradable Plastic, Paper, and Aluminum)

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Course: ENVR 400, Community Project in Environmental Science
April 26, 2018
EXECUTIVE SUMMARY

Introduction

Waste management is a rising global issue; waste disposal in landfills is not only expensive, but also environmentally damaging. A significant contributor to the waste stream is single-use containers, which are commonly distributed at restaurants and fast food chains. Disposable cups and take-out containers constitute 50% of residential waste by volume in Vancouver (City, 2017). One of the most commonly-used containers, expanded polystyrene (EPS), more commonly known as Styrofoam, is un-recyclable unless clean and free of food-residue. Due to the large volume of EPS entering the landfill, the City of Vancouver plans on implementing a Styrofoam ban within the next five years as part of their single-use item reduction strategy (City, 2017). While using reusable containers would be ideal for waste reduction (SPEC, 2013), reusable containers have high start-up costs and pose various food safety related issues for businesses. Thus, alternative disposable container options will be needed that can be composted or recycled.

Objective

Recyclable and compostable alternative containers have varying environmental impacts so in order to minimize the damage from single-use containers, these impacts should be compared. With the oversight of the Society Promoting Environmental Conservation (SPEC), a non-profit charitable and volunteer-driven organization addressing environmental issues in British Columbia, the objective of this project is to determine the associated environmental impacts of recyclable and compostable single-use takeout container compositions throughout their entire life cycle. Ultimately, this project aims to help businesses in Vancouver reduce their environmental footprint by presenting them with alternative environmentally friendly disposable container options in order to decrease the volume of solid waste delivered to the local landfill.

Life Cycle Analysis Methodology

A myriad of single-use takeout containers exists, each with a unique environmental impact. A Life Cycle Analysis (LCA) was performed on five single-use takeout containers: Polyethylene Terephthalate (PETE), Polypropylene (PP), corn-based Polylactic Acid (PLA), Paper, and Aluminum. The LCA helped quantify the associated environmental impacts (Global Warming Potential, Human Toxicity Potential, Water Usage, and Natural Resource Usage) of each respective container (Figure 1).
Figure 1. The Life Cycle methodology of various single-use containers, from their beginning to end of life. Parameters include: raw material acquisition, manufacturing, waste, and reuse. Energy emissions and substance/product flows are also included.

Free access GaBi education software with data from both the GaBi database and primary literature was used to determine the environmental impacts of each of the containers. Parameters in the LCA include raw material, energy, water, and land requirement inputs along with solid waste, air emissions, freshwater emissions, and heavy metals to air and water outputs. The methods were standardized through ISO 14044 requirements in the LCA software. A sensitivity analysis for various composting/recycling rates was performed on PP, PETE, Aluminum, PLA, and Paper: Styrofoam was excluded from the analysis due to its generally unrecyclable nature.

These scenarios relate to the container’s end of life and include:

1) 0% composting/recycling and 100% landfilling
2) 67% composting/recycling and 34% landfilling
3) 100% landfilling

Impact Category Analysis

The LCA results under scenario 2) with 67% composting/recycling are summarized in the graph below, with the environmental impacts Global Warming Potential, Human Toxicity Potential, Water Use and Natural Resources weighted equally (Figure 2). Styrofoam (EPS) exhibits the container with the overall lowest environmental impact due to a low Global Warming Potential (GWP) and Human Toxicity Potential (HTP), with paper a close second lowest.
Figure 2. The environmental impact of expanded polystyrene (ESP), Aluminum, Polyethylene Terephthalate (PETE), Paper, Corn-Based Polylactic Acid (PLA), and Polypropylene (PP) for four impact categories: Natural Resources, Water Use, Human Toxicity Potential, and Global Warming Potential. The impact of each container was normalized for the different impact categories from 0 to 1, and each impact category was weighted equally for comparison.

Eco-efficiency Analysis

To better understand business manager’s motivation for container choice and what would encourage them to change to a more environmentally friendly option, an eco-efficiency graph was formulated (Figure 3). This standardized LCA graph compares the cost of each respective container to its associated CO2 emissions during its life cycle.

Survey

In order to determine business manager’s motivation behind their choice of single use container and to determine how much more they’d be willing to pay for more environmentally friendly options, a survey was completed for five businesses at the University of British Columbia’s basement food court. All five of the business manager’s stated that they’d be willing to pay approximately 5% more for environmentally conscious containers, as environmental issues are of concern to most of them.
Figure 3. The relative purchasing cost of various take-out containers in relation to the relative Global Warming Potential in kg CO$_2$ equivalent. The containers in the green area represent the highest eco-efficient containers (low cost, low CO$_2$ emissions), while those in the yellow area represent the lowest eco-efficient containers (high cost, high CO$_2$ emissions).

Conclusion

Excluding Styrofoam, plastic clamshell (PP and PETE) represent the most eco-efficient containers. Thus, these containers should be promoted to businesses by government and nonprofits. While paper represented the material with the second-lowest environmental impacts (Figure 2), due to its high cost, it scores low on the eco-efficiency graph due to its high purchasing cost. When the purchasing cost of Paper containers decreases in the future, such as through the aid of the Styrofoam ban, it is suggested that this type of container be promoted to businesses.
THE TEAM

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Annette, a fourth-year environmental science major specializing in conservation ecology. Annette has assisted at the Solid Waste Department of her local county government in Washington State; she has toured landfills, transfer stations, and material recycling facilities. Furthermore, she has interned at an environmental engineering consulting firm where she helped write reports in relation to chemical cleanups and solid waste plans for clients.

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## I. ACRONYMS

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<tbody>
<tr>
<td>C&amp;D</td>
<td>Construction &amp; Demolition</td>
</tr>
<tr>
<td>CAD</td>
<td>Canadian Currency ($)</td>
</tr>
<tr>
<td>EPS</td>
<td>Expanded Polystyrene (Styrofoam)</td>
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<tr>
<td>FU</td>
<td>Functional Unit</td>
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<tr>
<td>GaBi</td>
<td>Ganzheitlichen Bilanzierung (German for holistic balancing)</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HTP</td>
<td>Human Toxicity Potential</td>
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<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>LCA</td>
<td>Life Cycle Analysis</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>USLCI</td>
<td>Life Cycle Inventory dataset from the United States</td>
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<tr>
<td>PETE</td>
<td>Polyethylene terephthalate</td>
</tr>
<tr>
<td>PLA</td>
<td>Polylactic Acid</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>SPEC</td>
<td>Society Promoting Environmental Conservation</td>
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<td>UBC</td>
<td>University of British Columbia</td>
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1. INTRODUCTION

1.1 Context

The topic of waste management is a rising global issue. Waste disposal in landfills is not only expensive, but also environmentally damaging. A significant contributor to the waste stream is single-use containers. Disposable cups and take-out containers constitute 50% of residential waste by volume in Vancouver (City, 2017) and are commonly distributed at restaurants. One of the most commonly-used containers, expanded polystyrene (EPS), more commonly known as Styrofoam, is un-recyclable unless clean and free of food residue. Although EPS only accounts for 1-2% of the total generated waste in Vancouver by weight, since 95% of the material contains air, it is one of the largest contributors to the waste stream by volume (Evanelz, 2017). The City of Vancouver plans on implementing a Styrofoam ban within the next five years as part of their single-use item reduction strategy (City, 2017).

While reusable containers are the most environmentally conscious due to their multi-use function (SPEC, 2013), city-wide reusable container programs have high start-up costs and pose various food safety related issues for businesses. Alternatives in the form of recyclable and compostable containers need to be explored to replace Styrofoam. Recyclable and compostable alternative containers have environmental impacts including greenhouse gas emissions associated with their production. Thus, it is important to compare recyclable and compostable containers based on the environmental and health associated impacts during their complete life cycle.

In order to conduct a life cycle analysis (LCA) of these containers, it is imperative to determine their recyclability. Expanded polystyrene (EPS) and paper products lined with plastic cannot be recycled or composted in Vancouver unless clean and free of residue. Clean aluminum, plastic (including propylene (PP) and polyethylene terephthalate (PETE)), and paper coated with polyethylene film containers are recyclable. Polylactic acid (PLA) and paper coated with wax containers are also compostable.

Plastic containers (PP, PETE) are composed of petroleum-based synthetic polymers; these containers are slow degrading and sometimes take half a decade to decompose in the natural environment (Webb, 2012). Within artificial environments, such as an anaerobic landfill, polymer degradation rates are unknown but estimated to be slow due to the anaerobic conditions. Accelerated degradation experiments estimate that plastic containers require a minimum of 50 years to degrade in the natural environment, and these rates are expected to be much lower in anaerobic conditions of landfills (Müller, 2001). In comparison, Aluminum containers are slow to degrade and thus contribute to the volume of landfilled solid waste. Not only this, but aluminum recycling requires 95% less energy than primary aluminum manufacturing (Rombach, 2013). Therefore, through the recycling process, the volume of landfilled aluminum and of energy requirements associated with this container’s life cycle can be reduced.

Compostables polylactic acid (PLA) containers are biodegradable and require processing at industrial-grade compost facilities. Although no industrial compost facility currently exists in Vancouver, there is a proposed facility planned for construction on Mount Seymour, BC.
PLA containers are slow to degrade in a landfill, but due to their vegetable base, they efficiently degrade under compost conditions (Shah, 2008). Comparatively, food-soiled paper containers efficiently degrade under compost conditions due to their cellulose composition (Imperial, 2018), and clean paper containers can be recycled. Hence, it is important to consider recycling and composting as a mechanism to avoid non-degradative mummification in a landfill.

The City of Vancouver owns and operates a landfill in Delta, BC that manages commercial and residential waste. At the landfill, waste disposal of byproducts such as leachate cost on the magnitude of 3 million dollars in 2015 (City 2016). Plastics consist of 20-30% of the total volume of solid waste in landfills (Leja, 2010). In order to decrease the volume of landfilled solid waste and to decrease the cost of managing these materials at their end of life, there should be a push towards enforcing the use of recyclable and compostable containers in the commercial sector.

1.2 Research Questions

How do compostable and recyclable single-use takeout containers (PETE, PP, PLA, Aluminum, and Paper) compare in their environmental impacts, as measured by a Life Cycle Analysis (LCA), from their production to final disposal?

What are business manager’s reasoning behind their choice of single-use container and how can an eco-efficiency analysis on various recyclable and compostable containers better inform their purchasing choices?

1.3 Implications

Upon completion of the above tasks, SPEC will communicate the environmental impacts of the analyzed takeout containers to the public and businesses. While EPS containers are the most common among businesses, in reality only about 0.2% of all EPS containers are recycled and diverted from the waste stream (SPEC, 2013). Upon the completion of this LCA and the formulation of an informational brochure including an eco-efficiency analysis, SPEC will disseminate to businesses this brochure illustrating the environmental costs of each analyzed container in relation to energy usage, human health, and ecosystem impacts in metro Vancouver.

2. METHODS

2.1 Life Cycle Analysis (LCA)

Various Life Cycle Analysis (LCA) software exist; yet, many are expensive. The most commonly used system, Simapro, costs 4,000 euros for a yearly subscription, or 1,000 euros for a basic model (SimaPro, 2017). The free GaBi Education software was used for this project. With the application of GaBi Education, extensive databases were provided through GaBi thinkstep datasets and through free USLCI datasets. Datasets gained from primary literature and reports were standardized according to the container’s weight to volume ratio and input into the GaBi
software. GaBi abides by the International Organization for Standardization (ISO) standards. In order to standardize the LCA container comparison, these globally accepted regulations were included.

2.2 Project Overview

The project encompasses the following single-use takeout containers: Styrofoam (EPS), plastic clamshell (PETE/PP), Compostable (corn-based PLA), Paper and Aluminum. The containers were compared via connected functions between the various life cycle stages of the containers (OpenLCA, 2014).

The chosen functional unit (FU), which is the basis of comparison across the various containers, is 1,000 containers with the dimensions of $21.4 \times 19.4 \times 6.05$ cm (Appendix A, Table A1). This unit was used as a baseline to compare the various containers in the GaBi Education software. An eco-efficiency analysis that combined the Global Warming Potential (GWP) of each material container along with its cost (per 1,000 containers) was performed to help business manager’s identify the most environmentally conscious and cost-efficient container.

2.3 Product systems

The project consists of six product systems, one for each container: EPS, PETE, PP, corn-based PLA, Paper and Aluminum (OpenLCA, 2015). Expanded polystyrene foam (EPS) was only analyzed under the 100% landfilling scenario, due to its generally unrecyclable nature (EPEAT, 2014). Corn-based PLA containers were included instead of the popular bagasse-based PLA containers since China is currently the only place where bagasse is being produced for commercial use resulting high in transport costs and would violate the assumption that transportation parameters are negligible for the analysis (PrimeLink Solutions, 2009). The life cycle flow begins with the raw material acquisition, followed by the container manufacturing for all materials. The container’s end of life management consisted of landfilling, or recycling/composting (Figure 1).
2.4 Flows

Three flows are included in the project:
(For detailed information of the sources and descriptions of the collected data, see Appendix B, Table C1~C3 and Appendix C, Figure C1~C6.)

2.4.1 Elementary flows

Elementary flows include emissions, energy and material costs in the raw material acquisition (Figure 1 Step 1) and manufacturing process of each container (Figure 1 Step 2).

2.4.2 Product flows

Product flows include energy, materials and emissions associated with each container. Upon consultation with Milind Kandlikar, director of the Institute for Resources Environment and Sustainability at the University of British Columbia (UBC), transportation costs were excluded from this analysis, due to its relatively minimal role when compared to other processes, such as manufacturing.

2.4.3 Waste flows

Waste flows include disposal at a general landfill (Figure 1 Step 3). As most landfills are anaerobic, as is the case for the City of Vancouver’s municipal landfill; it is assumed that the generation of greenhouse gases in the landfill is zero. The study considers different end-of-life
scenarios in terms of landfill and recycling/composting. Under the recycling scenarios, either 0%, 67%, or 100% of the containers are diverted from the landfill and re-enter the manufacturing phase of the material. Under the composting scenarios, either 0%, 67%, or 100% of containers are diverted from the landfill and composted. More specifically, the three scenarios pertain to:

1) 100% landfilling;
2) 67% recycling/composting and 33% landfilling:
   a) The 67% recycling/composting waste diversion scenario is representative of UBC’s waste stream, according to a waste audit conducted by Ivana Zelenika in 2015/16, a PhD candidate for management of biodiversity and urban sustainability at UBC. This rate includes construction and demolition (C&D) waste (83%) and campus operation waste (43%), (Figure 1 Step 4) (UBC, 2016);
3) 100% recycling/composting:
   a) The 100% landfill and 100% recycling/composting scenarios are hypothetical scenarios, which are used for sensitivity tests for various disposal options.

2.5 Assumptions

Life Cycle Analysis (LCA) assumptions:

- The containers are manufactured globally;
- The transportation costs in relation to the analyzed parameters are negligible (Figure 1);
- No container is being retained by the consumers and that all 1,000 containers for the six materials undergo the waste treatment;
- While metro Vancouver also operates an incineration plant, for the purposes of this project, it is assumed that all containers will be disposed of at a municipal landfill or compost facility. While the compost facility includes associated environmental degradation emissions, the municipal landfill does not include associated degradation emissions, due to the anaerobic environment;
- For recycled containers (PETE, PP, Aluminum & Paper), due to data limitations, only CO₂ related emissions are considered. EPS was excluded from the sensitivity analysis due to its general unrecyclable nature (EPEAT, 2014);
- All recycled containers are remanufactured into the raw materials to reformulate the same container see Sankey diagrams (Appendix C, Figure C1~C6)
- For composted container (PLA), CO₂ emissions and inorganic fertilizers are considered, as indicated by Leejarkpai (2016);
- The chosen recycling diversion rate (67%) was retrieved from Ivana Zelenika’s analysis of UBC’s waste stream in 2015/16 (UBC, 2016). It is assumed that UBC’s recycling rate is indicative of metro Vancouver’s recycling rate. Also, it is assumed that the proportion of biodegradable PLA containers composted (67%) in Vancouver is equivalent to the recycling diversion rate taken from Ivana Zelenika’s report;
- UBC’s 67% diversion rate is indicative of metro Vancouver’s recycling and composting rate
All recycled paper containers are non-food-soiled;
The assumptions made in collection of the data from the various sources were consistent and the differences in data collection methods are negligible.

2.6 Impact Assessment
The energy and emission information collected were analyzed in relation to Global Warming Potential, Human Toxicity, Water, and Natural Resources usage. The parameters analyzed were chosen in accordance with previous LCA analysis (PRé Sustainability, 2000).

Table 1. Descriptions of the various impact parameters included in the Life Cycle Analysis

<table>
<thead>
<tr>
<th>Impact Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Global Warming Potential (GWP)</strong></td>
<td>GWP includes CO₂ emissions and other processes that contribute to the greenhouse gas effect. GWP is often a reference unit defined as ‘CO₂ equivalency’ where potential emissions are converted to CO₂ emissions (GaBi, 2010).</td>
</tr>
<tr>
<td><strong>Human Toxicity Potential (HTP)</strong></td>
<td>HTP calculates the potential toxicity (in relation to harmful chemicals released into the environment) of a substance based on its concentration (Hertwich, 2001). HTP includes damage inflicted on an ecosystem based on its composition, physical properties, contingent on its point of emission release into the atmosphere (GaBi, 2010).</td>
</tr>
<tr>
<td><strong>Water Use</strong></td>
<td>Water Use includes anthropogenic impacts to watersheds, defined as extractive and degradative use of water (GaBi, 2016).</td>
</tr>
<tr>
<td><strong>Natural Resource Use</strong></td>
<td>Natural Resource Use includes the depletion of natural resources along with fossil material usage associated with energy generation (e.g. metal ores, crude oil, etc.) (GaBi, 2010).</td>
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</table>

2.7 Eco-efficiency Calculation

2.7.1 Cost Estimate
In order to calculate the eco-efficiency of each material, the cost per volume and associated CO₂ emissions of 1,000 containers was compared. The cost of each container was retrieved from SupplyBox.ca, a common distributor of single-use containers for Canadian restaurants. The cost retrieved from SupplyBox.ca was assumed to consistent with other supplier’s pricing. Carbon dioxide (CO₂) emissions were extracted from the Global Warming Potential (GWP) associated with each container from the LCA.
2.7.2 Eco-Efficiency Analysis

The following equations were used to determine the eco-efficiency of each container, by finding the cost indicator (Xn) and the GWP impact indicator (Yn) in relation to the five single-use containers (Leejakpai, 2016):

**Equation 1.**

\[ X_n = X_H - \left( X_H - X_L \right) \times \left( \frac{C_H - C_n}{C_H - C_L} \right) \]

Where \( C_H \) is the highest container purchasing cost, \( C_L \) is the lowest container purchasing cost, \( C_n \) is the purchasing cost of the nth container, \( X_H \) is 0.9, which is the highest purchasing cost indicator, and \( X_L \) is 0.1, which is the lowest purchasing cost indicator.

**Equation 2.**

\[ Y_n = Y_H - \left( Y_H - Y_L \right) \times \left( \frac{GWP_H - GWP_n}{GWP_H - GWP_L} \right) \]

Where \( GWP_H \) is the highest container Global Warming Potential, \( GWP_L \) is the lowest container Global Warming Potential, \( GWP_n \) is the Global Warming Potential of the nth container, \( Y_H \) is 0.9, which is the highest GWP impact indicator, and \( Y_L \) is 0.1, which is the lowest GWP impact indicator.

2.8 UBC Village Case Study

The project also included a survey distributed to five restaurants in the UBC Village basement. These businesses were chosen since they are not governed by UBC, which mandates all on-campus businesses to use recyclable or compostable containers. Thus, the UBC Village businesses are free to make their own container-use decisions.

In order to conduct the survey, ethics approval was retrieved from UBC’s Office of Research Ethics upon the completion of a Behavioral Ethics Review Application (BREB). The survey was distributed to determine the types of containers used by each business, the number of containers used in a day by a business, and the business manager’s motivation behind their choice of container (Appendix D). The survey was distributed to five consenting business managers during non-peak business hours, in person.

2.9 Public and Business Communication Materials

A brochure was formulated for businesses to illustrate the varying degree of environmental impacts of the analyzed containers in relation to human health, ecosystem quality, and resource consumption. The brochure includes information on costs of each container type and its associated CO2 emissions (Appendix F). This brochure can be used by SPEC to communicate with the local business managers and the general public to encourage use of sustainable containers. It is hoped that such information will also help to reduce the number of containers reaching the Vancouver Landfill.
3. RESULTS

3.1 Global Warming Potential (GWP)

Considering a 67% recycling rate as shown in Figure 2, EPS, Paper, PP, PETE, Aluminum, and PLA have the lowest to highest respective Global Warming Potentials (GWPs). EPS exhibits the lowest at 6.76 kg CO\textsubscript{2} equiv. while PLA exhibits the highest GWP at 413 kg CO\textsubscript{2} equiv. Increased recycling rates (zero to 67% recycling) makes an appreciable difference in GWP for Aluminum and PETE containers by decreasing emissions by more than half (Figure 2). Recycling appeared to have less of an effect on PP, Paper and PLA.

![Figure 2: The Global Warming Potential (kg CO\textsubscript{2} equiv) of 1,000 EPS, Aluminum, PETE, Paper, PLA, and PP takeout containers. The various shaded bars show the sensitivity analysis for various waste diversion rates. For Aluminum, PETE, Paper, and PP containers the diversion rate relates to the recycling rate; for PLA containers the diversion rate relates to the composting rate; EPS was excluded from this sensitivity analysis due to its generally low recycling rate in metro Vancouver. Data derived from the life cycle analysis (Appendix E, Table E1 a–c).](image)

3.2 Human Toxicity Potential (HTP)

Paper, EPS, Aluminum, PP, PETE, and PLA have the lowest to highest respective HTP (Figure 3). Paper exhibits the lowest at 0.959e-09 CTUh while PETE exhibits the highest Human Toxicity at 1.226e-6 (Appendix E, Table E1). Recycling appears to notably affect HTP for PETE containers (HTP is higher under zero recycling and decreases from 67 to 100% recycling).
Changes in recycling appear to have little to no effect on Aluminum, PP, Paper and PLA.

*Figure 3. The Human Toxicity (CTUh) of 1,000 EPS, Aluminum, PETE, Paper, PLA, and PP takeout containers. The various shaded bars show the sensitivity analysis for various recycling rates. For Aluminum, PETE, Paper, and PP containers the diversion rate relates to the recycling rate; for PLA containers the diversion rate relates to the composting rate; EPS was excluded from this sensitivity analysis due to its generally low recycling rate in metro Vancouver. Data derived from the life cycle analysis (Appendix E, Table E1 a-c).*

### 3.3 Water Use

Paper, EPS, PLA, PP, Aluminum, and PETE show the lowest to highest respective Water Usage (Figure 4). Paper requires the least at near zero m$^3$ while PETE requires the highest input of water at 67.9 m$^3$ (Appendix E, Table E1). Recycling appears to make notable differences in Water Use for PETE containers (decreased Water Use under 67% and 100% recycling and higher Water Use under zero recycling) (Figure 4). Recycling appeared to have little to no effect on Aluminum, PP, Paper and PLA.
Figure 4. The Water Use (m$^3$) of 1,000 EPS, Aluminum, PETE, Paper, PLA, and PP takeout containers. The various shaded bars show the sensitivity analysis for various recycling rates. For Aluminum, PETE, Paper, and PP containers the diversion rate relates to the recycling rate; for PLA containers the diversion rate relates to the composting rate; EPS was excluded from this sensitivity analysis due to its generally low recycling rate in metro Vancouver. Data derived from the life cycle analysis (Appendix E, Table E1 a–c).

3.4 Natural Resource Use

Paper, PP, EPS, PLA, PETE, and Aluminum show the lowest to highest respective natural resource consumption (Figure 5). Paper required the least resources at 9.27e-6 while Aluminum required the most resources at 1.9e-3 (Appendix E, Table E1). Recycling appears to make notable differences in natural resource consumption for Aluminum containers, where zero recycling more than doubles natural resource requirements when compared to the 67% scenario (Figure 5). Recycling appeared to have little to no effect on PETE, PP, Paper and PLA.
Figure 5. The Natural resource consumption (kg Sb-Equiv) of 1,000 EPS, Aluminum, PETE, Paper, PLA, and PP takeout containers. For Aluminum, PETE, Paper, and PP containers the diversion rate relates to the recycling rate; for PLA containers the diversion rate relates to the composting rate; EPS was excluded from this sensitivity analysis due to its generally low recycling rate in metro Vancouver. The various shaded bars show the sensitivity analysis for various recycling rates. Data derived from the life cycle analysis (Appendix E, Table E1 a–c).

3.5 Cost estimate

For 1,000 containers, upon standardization of these containers with an equivalent volume and varying mass-to-volume ratios (Appendix A, Table A1), Aluminum, PLA, PP, PETE, and Paper show the lowest to highest respective price. Paper has the highest cost at $780.25/1,000 containers while Aluminum has the lowest cost at $316.97/1,000 containers.

3.6 Eco-Efficiency

EPS, PP, PETE have the highest eco-efficiency of all the recyclable or compostable containers analyzed while paper, PLA and Aluminum containers exhibit lower eco-efficiency (Figure 6). In the anticipation of the future Styrofoam ban, the advantageous recyclable/compostable containers are the other plastics: PP and PETE. These containers not only are cost and environmentally efficient, but they also exhibit a high market share in the recycling market, on the magnitude of $274.00 in 2014 with a compound annual growth rate of 6% (Research and Market, 2015). They are also commonly identified by the public as recyclable, thus decreasing the quantity of contamination in the compost and landfill.
Figure 6. The relative purchasing cost of various take-out containers (expanded polystyrene (ESP), polyethylene terephthalate (PETE), polypropylene (PP), corn-based polylactic acid (PLA), paper, and aluminum) in relation to the relative Global Warming Potential in kg CO₂ equivalent for the 67% diversion rate scenario. The containers in the top right corner represent the highest eco-efficient containers (low cost, low CO₂ emissions), while those in the bottom left represent the lowest eco-efficient containers (high cost, high CO₂ emissions). The total GWP (Global Warming Potential) impact indicator, Yₙ, is the normalized Global Warming Potential of each container with 0.1 representing the lowest GWP and 0.9 representing the highest GWP of the containers analyzed (Appendix E, Table E3). The total cost indicator, Xₙ, is the normalized purchasing cost of each container with 0.1 representing the lowest purchasing cost and 0.9 representing the highest purchasing cost of the containers analyzed (Appendix E, Table E3).
3.7 UBC Village Basement Businesses: Case Study

See Appendix D for the complete set of survey questions

3.7.1 Number of containers used

Four of five businesses responded to the question relating to the number of single-use containers used per day; utilization rates ranged from approximately 70 containers/day to about 300 containers/day depending on the business. All five of these businesses use polystyrene containers. Yet, one business also uses paper soup bowls with a plastic lid, along with reusable trays. Another business also uses plastic bowls.

3.7.2 Criteria for container choice

Of the five UBC village basement food court businesses surveyed, two business’ managers indicated that price is important criteria for their choice in container type, two business’ managers had no response, and one was primarily concerned about the functionality (e.g. having the salad separated from the main dish). One of the business managers who expressed price as their primary criteria also noted that functionality (containers that are easy to clean, such as in relation to reusable containers) was also important to them. This manager also indicated that the environmental impact of their containers were secondary considerations they made when choosing a container type.

3.7.3 Understanding of environmental issues

Three out of five business’ managers responded to the questions about comprehension of environmental issues; they had some understanding of and concern for environmental issues including climate change, air pollution and waste management.

3.7.4 Willingness to pay for a more environmentally friendly container

Four out of five business’ managers said they would be willing to pay at most 5% more for a more environmentally friendly container. The fifth business’s manager said they would pay at most 5 cents more.

3.8 Cost Comparison

All of the containers analyzed were more expensive than polystyrene. The alternative containers were all greater than 150% the cost of polystyrene, which is much greater than the amount business managers at the UBC village basement food court indicated they would be willing to pay (Figure 7).
Figure 7. The cost of alternative container types to polystyrene as a percentage of the cost of polystyrene. The line indicates the amount businesses would be willing to pay for a more environmentally friendly container, which is 5% more than the cost of polystyrene. The cost of polystyrene is indicated by 100% at the bottom of the y-axis.

4. DISCUSSION

4.1 Life Cycle Analysis (LCA)

4.1.1 Global Warming Potential (GWP) Analysis (Figure 2)

Under the 0% waste diversion scenario, Paper shows the lowest total GWP per functional unit (FU) for all scenarios, indicating that among all container options Paper containers have the lowest greenhouse effects. This could be due to the low CO$_2$ emissions in the manufacturing stage. This value could also be due to the pine log involved in the raw material acquisition phase of Paper’s LCA which may sequester CO$_2$ from the atmosphere, decreasing this material’s carbon footprint.

Expanded polystyrene (EPS) exhibits the lowest total GWP under the 67% and 100% waste diversion scenarios. When examining the standardized volume to mass ratios, EPS exhibits the lowest at 25 kg $m^3$. EPS is 95% air (Evanetz, 2017), thus the concentration of polymers in EPS is much less than that in other plastic containers. These factors might result in that EPS having a low observed GWP. For the petroleum-based containers (PETE & PP) in the zero waste-diversion scenario, PETE reveals a 1.93 times higher total GWP than PP. This result might be due to the higher resin use required for PETE container production compared to PP container production because PETE has higher mass to volume ratio. Aluminum has the highest total GWP
impact in zero recycling scenario compared to all the other materials, as the carbon footprint of aluminum production is over eight times than that of plastics and paper (SPEC, 2013).

For the 67% waste diversion scenario, the results demonstrate that PLA is the least favorable option with the highest GWP impact at 413 kg CO\textsubscript{2} equivalent per FU. Increasing the composting rate of PLA augments the Global Warming Potential (Figure 2), likely because when composted, these containers completely degrade and generate CO\textsubscript{2} emissions (Leejarkai et al., 2016).

In relation to waste management, when the recycling rate increases from zero to 67%, the total GWP impact of Aluminum, PETE, and PP decrease by 45.2%, 71.0%, and 48.4% respectively. On the contrary, PLA and Paper do not exhibit a decrease in total GWP impact with increased waste diverted rates. Instead, the total GWP impact of PLA and Paper under the zero-waste diversion scenario are lower by 8.5% and 80.7% when compared to the 67% waste diversion scenario. The CO\textsubscript{2} emissions were included in recycling/composting phase of the materials and omitted from landfill for all containers, which helps explain this trend.

However, unlike other materials, CO\textsubscript{2} emitted from the paper production stage is relatively small; hence, the CO\textsubscript{2} emissions included in the recycling stage likely affect the total GWP to a large extent. Also, since PLA undergoes composting instead of recycling, the change in GWP is only a consequence of CO\textsubscript{2} emissions in the composting stage. While recycling reduces raw material requirements due to the feedback stage back from recycling to manufacturing, composting does not include this feedback stage, since the compost facility acts as the container’s final end of life (Appendix C, Figure C4). As a result, increasing the proportion of compostable containers diverted from the landfill could result in increased CO\textsubscript{2} emissions. Therefore, the total beneficial effect of decreasing the total GWP values can be obtained by increasing the recycling rates for PETE, PP and Aluminum, but decreasing the recycling/composting rates for PLA and Paper.

4.1.2 Human Toxicity Potential (HTP) Analysis (Figure 3)

In the 67% recycling scenario, PETE represents the container with the highest HTP. When the recycling rate increases from zero to 67%, the HTP for PETE decreases by 69.3%, indicating that feedback of raw materials from the recycling phase back into the manufacturing phase significantly decreases the HTP of PETE (Appendix C, Figure C3). Under the assumption that all the studied polymers have the same resin manufacturing process (Appendix B, Table B1), it is concluded that the PETE resin production step contributes the largest percentage to the calculated HTP during PETE’s life cycle. As a result, increasing the PETE recycling rate will lower the release of harmful chemicals to the environment.

Contrastingly, Paper represents the container with the lowest HTP under all recycling scenarios. While toxicity might arise during the manufacturing phase at the paper and pulp mill, these impacts are mitigated due to the pine log input in the raw material acquisition phase of paper’s life cycle (Appendix C, Figure C6), that likely reduces and sequesters chemicals released into the environment. By analyzing all Sankey diagrams (Appendix C) and associated HTP
values (Appendix E), it is summarized that changing the recycling/composting rates of Aluminum, Paper, PLA and PP will not make distinct differences in terms of chemical release into the environment that could negatively impact human health.

4.1.3 Water Consumption Analysis (Figure 4)

PETE exhibits the highest water consumption under the zero and 67% waste diversion scenarios, likely due to the water input needed to cool the plastic resin during the molding process (Mechanical, 2018). Similar to the analysis made in the HTP section, the PETE resin production step contributes the largest percentage to the Water Use during PETE’s life cycle. In fact, increasing the recycling rate from zero to 100% decreases the Water Use by 99.9%; thus, it is recommended that nonprofits and government encourage PETE recycling in order to promote sustainable water use and to reduce chemical pollution (as illustrated in section 4.1.2).

Aluminum requires the second highest input of water under all recycling scenarios. This is likely due to Aluminum’s Bayer process which converts bauxite to alumina and requires water inputs for cooling (Conklin, 1956). Paper requires the least water under all recycling scenarios due to transpirative processes from the pine log that was included in the raw material phase of paper’s life cycle (Appendix C, Figure C6). In relation to materials other than PETE, changing the recycling/composting rate does not significantly change Water Usage.

4.1.4 Natural Resource Use Analysis (Figure 5)

Aluminum requires the highest input of Natural Resources. This high natural resource requirement could be attributed to the mining of bauxite ore, a nonrenewable resource in aluminum’s raw material acquisition phase (Conklin, 1956). When compared to a 0% diversion recycling rate, a 67% and 100% rate decreases natural resource use by 65.5 and 97.6% respectively; hence, increasing the recycling of Aluminum is beneficial due to decreased natural resource requirements. PETE, PP, and EPS contain plastic components; these plastic’s monomers (ethylene, propylene, and styrene respectively) are often formulated from fossil hydrocarbons such as oil, which must be mined, resulting in a depletion of these natural resources (Jambeck, 2017). PLA is manufactured primarily from harvested corn, a natural resource that completely degrades into organic material in nature, which could explain its low natural resource requirement. Paper requires the least Natural Resources, as its composition primary consists of cellulose, a renewable resource found in the cells of trees. Excluding Aluminum, the remaining materials (PP, PETE, PLA, and Paper) exhibit a minor change in natural resource use with changes to the diversion (recycling/composting) rates.

4.1.5 Diversion Rate

The diversion rate is meant to provide an approximation of the recycling and composting rate. However, this rate varies annually. For instance, in 2015/16 UBC had a 67% (UBC, 2016) recycling rate but in 2016/17 UBC’s recycling rate decreased to 57% (Tansey, 2017). Furthermore, the provided diversion rate consists of: 83% construction and demolition (C&D)
waste and 43% campus operations waste (UBC, 2016). Thus, this diversion rate might not solely reflect the residential side of takeout container waste from consumers.

Furthermore, on the UBC campus, food vendors are required to use compostable or recyclable containers. Hence, UBC’s diversion rate is likely higher than metro Vancouver’s. In 2015, metro Vancouver had a 62% diversion rate (Evanetz, 2017), a value 5% lower than UBC’s rate this year. The sensitivity analysis provides insight into the impacts of drastic decreases in the diversion rate (at 0%) and of the impacts of drastic increases in the diversion rate (at 100%). For certain containers (such as PETE, PP), changes in the diversion rate significantly affects the environmental impact parameters. As most of these diversion rates are calculated from waste audits, there is also variability in the manner that these investigations are conducted. Accurately quantifying these rates will help determine the environmental impacts associated with various container compositions.

4.2 Eco-efficiency (Figure 6)

EPS, PP and PETE containers have the highest eco-efficiency compared to other types of containers due their relatively low cost and low CO₂ emissions, which is consistent with the results of the study of Leejarkpai (2016). According to the previous studies (Leejarkpai et al., 2016; Mardival et al., 2009), the GWP impacts of petro-based containers (EPS, PETE and PP) are relatively low due to slow degradation rate in anaerobic landfills. However, corn-based PLA containers demonstrates low eco-efficiency. The complete degradation of PLA containers during the composting processes leads to the highest total GWP impacts, due to the generation of greenhouse gases (i.e. CO₂) during the degradation process (as illustrated in section 4.1.1). Thus, the increase in GWP for PLA containers is consistent with the increase in the composting rate from 0% to 100%.

While PLA containers might exhibit high GWP impacts, it is important to note that this material is environmentally beneficial in the sense that it is compostable, has overall low total environmental impacts and diverts the volume of solid waste delivered to the landfill (Appendix C, Figure C4). Since PLA containers look similar to general plastics, such as PETE, the general public is often misled to recycle them in the plastic bin. Once contaminated, the entire recycling bin must then be landfilled. As a result, PLA often acts as a source of contamination that reduces recycling rates. What’s more, this material may only be composted at an industrial-grade compost facility. Currently, no such facility exists in metro-Vancouver. If the proposed industrial compost facility at Mount Seymour’s permit passes, it is suggested that the City of Vancouver and nonprofits promote the use of this container to businesses. In the interim, it is suggested that recyclable PP and PETE containers be suggested to businesses due to their high eco-efficiency and high market price in the recycling market (Research and Market, 2015).

In relation to Paper, this material also shows a relatively low eco-efficiency due to its high market cost. While Paper has a low Global Warming Potential (GWP), its high cost per 1,000 containers renders it low in relation to eco-efficiency. From this analysis, it can be concluded that corn-based bioplastics (PLA) and Paper under the 67% waste diverted scenario
will not be the best option for businesses. However, it is suggested that government pursue options to reduce the cost of Paper containers. One such route is the proposed Styrofoam ban: once there is no longer a market for Styrofoam containers, businesses will fuel the recyclable/compostable container market, helping to drive down purchasing costs over time.

4.3 Business motivation

Most of the business managers in the UBC Village basement who responded to the survey have both some understanding and concern for environmental issues, indicating that increasing manager’s knowledge of environmental issues would likely not be the most advantageous method, on its own, to convince business managers to switch to a more environmentally friendly container. Managers of businesses in the UBC Village food court chose containers based on their cost, functionality, and/or environmental impact.

Based on the results, it would likely be difficult to convince business managers in the UBC village basement to switch to more environmentally friendly single-use containers if the cost exceeds 5% per 100 containers. Yet, the alternative containers cost 150% more than the cost of polystyrene containers (Figure 7). Since polystyrene alternative options are more expensive, it is suggested that government-regulations be enforced relating to takeout container use (e.g. a ban on styrofoam) or in relation to formulating more economically viable containers, so that small businesses could purchase and use more environmentally friendly containers.

Paper exhibits relatively low environmental impacts when compared to the other containers (Figure 2-5). Yet, Paper exhibits a low eco-efficiency due to its high cost per 1,000 containers (Figure 6). Once the cost of environmentally beneficial containers such as Paper decrease, their eco-efficiency status will improve and appeal to business managers. There may also be some variability in the purchasing cost offered to businesses by suppliers, which was not considered in this study as only one Canadian supplier’s pricing was used. Another supplier may offer lower costs for paper containers, which would make paper a more viable option for businesses.

4.4 Future Considerations and Tradeoffs

Styrofoam exhibits a low recycling rate since it must be completely clean and free of food residue in order to be recycled; thus, it is often landfilled and causes a waste issue. The City of Vancouver plans on implementing a Styrofoam ban in landfills within the next five years. In fact, cities such as Portland, Seattle, and San Francisco have already banned the use of this material (City, 2017). Since December 2017, China has been enforcing a foreign import ban against waste plastic and paper due to environmental and health concerns (Miles, 2017). Hence, business managers need to consider alternatives to this material in relation to their choice of single-use container. As this LCA demonstrates, plastic clamshell (PP and PETE) containers represent the most eco-efficient container out of all the recyclable and compostable containers included in the study. Businesses will benefit from the use of PP and PETE containers not only due to their low Global Warming Potential, but also due to their low cost. Since PP exhibits lower environmental
impacts than PETE, it is suggested that business managers first consider PP before PETE when choosing a takeout container.

While polystyrene recycling presents a waste diversion route from the landfill, the feasibility of this method remains to be seen. Indeed, polystyrene may be recycled via mechanical, chemical, or thermal compaction (Maharana 2007) and be reformulated into materials such as furniture, countertops, and tiles (EPS, 2018). However, chemical and thermal melting have potential volatile organic compounds (VOCs) associated with processing, which could negatively affect EPS’ Global Warming Potential score. Not only this, but polystyrene isn’t technically considered recyclable. In 2015, polystyrene only had a 5.7% recycling rate, in order to be considered recyclable, according to the US Environmental Protection Agency, polystyrene must pass the 15% recyclability threshold (EPEAT, 2015).

Additionally, polyactic acid (PLA) containers should be promoted once an industrial-grade compost facility is constructed in Vancouver, so that this stream of waste can be properly disposed (as illustrated in Section 4.2).

4.5 LCA Considerations

A Life Cycle Analysis (LCA) is often used as a baseline to quantify the environmental impacts of a product for policy formulation (Mohia, 2016). LCAs may be useful for government entities and business managers when choosing the most environmentally beneficial container from an array of options. In particular, by choosing a more environmentally conscious material that has reduced environmental impacts according to data from an LCA, businesses can brand themselves as environmentally conscious. Thus, businesses can improve their public image and cater to an environmentally-aware consumer market.

Yet, LCA’s also have several limitations. In particular, LCA’s often have a long list of assumptions, and these assumptions may not hold true in reality. For instance, in this analysis, transportation impacts were excluded; however, according to Madival (2009), transportation-associated environmental emissions are a major contributor to a material’s life cycle. In the future, the transportation associated emissions could be added to this analysis.

Furthermore, robust LCA databases are expensive; when free databases are utilized, the programs must be supplemented with primary literature whose emission data might not proxy emissions in the LCA database. In this study, the recycling emissions for each container were collected from various primary literature sources (Appendix B, Table B1-B3); in the future, another LCA could be conducted with recycling emission information from one source, in order to further standardize the analysis.

Within the databases themselves, methodologies also differ between different LCA sources and introduce variability with data comparison (Wolf, 2012). While the results from the LCA might be helpful for policy and environmentally aware businesses, the variability within the results decreases their robustness.
5. CONCLUSION

To determine the impact of recycling and composting from the waste stream on the containers analyzed, various suboptimal, current, and ideal recycling rate scenarios are included. The City of Vancouver plans on improving the recycling and composting rate within the next five years (City, 2017); hence, various recycling rate scenarios are considered in the analysis (no recycling, the current recycling rate, and 100% recycling). GWP impacts are mitigated by increasing the recycling rates for PETE, PP and Aluminum containers; hence, these containers will have an increasing eco-efficiency with increasing recycling rates; GWP impacts are heightened by increasing the recycling/composting rates for Paper and PLA. While recycling/composting might mitigate greenhouse gas emissions for some materials, they amplify emissions for others. Therefore, the emissions associated with the recycling phase of materials should be considered by government and nonprofits when choosing environmentally friendly containers.

In order to anticipate the future ban on Polystyrene (City, 2017), the feasibility of recyclable and compostable single-use containers was determined through a life cycle analysis coupled with a cost analysis of each container. While EPS was included in the analysis and generally exhibits low environmental impacts, due to its low recyclability, it is important to consider alternatives that are recyclable and compostable. In all analyzed parameters (Global Warming Potential, Human Toxicity Potential, Water Use, Natural Resource consumption), Paper exhibits the lowest impact in each category of all alternative compostable and recyclable containers analyzed. Aluminum and PETE generally exhibit the highest impact in each category. When the cost of each container and the CO₂ emissions released during the life cycles are considered, biodegradable (PLA) and plastic clamshell (PP) exhibit the lowest and highest eco-efficiency, respectively. If business managers want to move beyond polystyrene to a compostable or recyclable container, we suggest they choose a container with a high eco-efficiency or low environmental impact, such as PP and PETE, or Paper.

6. ACKNOWLEDGEMENTS

We would like to thank Tara Ivanochko and Michael Lipsen, our ENVR 400 professors and Theodore Eyster, our ENVR 400 TA. We would also like to thank our SPEC community partners: Angie Nicolas and Oliver Lane. Furthermore, we would like to thank Milind Kandlikar from the Institute for Resources, Environment and Sustainability of UBC along with Ivana Zelenika and her provision of UBC’s recycling rate from her 2015/16 waste audit.
REFERENCES


APPENDIX A.

Functional Unit Standardization

Table A1. Mass ($kg$) and mass-to-volume ratio ($kg/m^3$) (or mass-to-area ratio ($kg/m^2$) for paper) of the respective single-use containers (one unit of container with the same dimension $21.4\times19.4\times6.05 \text{ cm}$). Assume the thickness of all the materials to be $0.00045672 \text{ m}$ (except paper).

<table>
<thead>
<tr>
<th>Container Type</th>
<th>Mass ($kg$)</th>
<th>Mass- to-Volume Ratio ($kg/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>0.0015</td>
<td>25</td>
</tr>
<tr>
<td>PETE</td>
<td>0.083</td>
<td>1370</td>
</tr>
<tr>
<td>PP</td>
<td>0.057</td>
<td>946</td>
</tr>
<tr>
<td>PLA</td>
<td>0.079</td>
<td>1310</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.11</td>
<td>1900</td>
</tr>
<tr>
<td>Container Type</td>
<td>Mass ($kg$)</td>
<td>Mass- to-Area Ratio ($kg/m^2$)</td>
</tr>
<tr>
<td>Paper</td>
<td>0.021</td>
<td>0.16</td>
</tr>
</tbody>
</table>
APPENDIX B.

LCA Methodology

Table B1. Since EPS, PETE, PP & PLA are polymers, same processes were considered when building their LCAs (Madival et al., 2009). This table includes the exact steps made in the GaBi software (i.e. the system boundaries for polymers) with detailed descriptions of the sources.

<table>
<thead>
<tr>
<th>EPS, PETE, PP &amp; PLA</th>
<th>Sources</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resin production</strong></td>
<td>1. The LCI data for production of ESP, PETE &amp; PP resins were collected from the GaBi database that is available with GaBi software (Education version); 2. The LCI data for production of PLA resin (“The Eco-profile for the Near-future PLA Production System”) was collected from the literature (Vink et al., 2007).</td>
<td><strong>1(a).</strong> Data included all the processes from cradle to gate including extraction and production of crude oil to resin manufacturing; <strong>1(b).</strong> GaBi database uses data representing manufacturing at European production sites; <strong>1(c).</strong> Assumption: The transportation stage of crude oil to the European factories is similar to other factories worldwide.</td>
</tr>
<tr>
<td><strong>Resin manufacturing (Container production)</strong></td>
<td>Data for the extrusion and thermoforming of ESP, PETE, PP &amp; PLA resins were taken from the literature (Madival et al., 2009).</td>
<td><strong>(a).</strong> Data for both operations included energy use and emissions for the extrusion and thermoforming of a general plastic film. On the other hand, the electricity consumption during the thermoforming process was calculated separately by the literature for materials polystyrene (PS), PETE &amp; PLA; Assumptions:  - PS and EPS resins have similar amounts of electricity usage;  - PETE resin thermoforming electricity consumption is the same as PP resin thermoforming. <strong>(b).</strong> Data was representative of different European companies.</td>
</tr>
</tbody>
</table>
| Recycling & Landfill | 1. For EPS, assume the material is not recyclable (SPEC, 2013);  
2. For PETE & PP, the recycling data including the waste specific emissions were taken from the literature (Turner et al., 2015);  
3. For PLA, the recycling data (i.e. composting data) comprising the emissions was taken from the literature (Leejarkpai et al., 2016). | 1. 100% EPS goes into landfill.  
2. Data included CO2 emissions.  
3. Data included CO2 emissions and the formation of inorganic fertilizers. |

**Table B2.** LCI methodology associated with the production and disposal of paper containers (M’hamdi et al., 2017).

<table>
<thead>
<tr>
<th>Paper</th>
<th>Sources</th>
<th>Descriptions</th>
</tr>
</thead>
</table>
| Pine logging | The LCI data for pine logging was collected from GaBi database that is available with GaBi software (Education version); | (a). Data included all the processes from cradle to gate including air usage, land usage, water usage, natural resource usage, and energy usage;  
(b). GaBi database uses data representing pine logging at German production sites. |
| Pulp manufacturing | The LCI data for pulp manufacturing was collected from the literature (M’hamdi et al., 2017). | (a). Data included crushing, sieving, hydrolysis and delignification processes with associated electricity utilization, air emissions, water usage, and chemical waste;  
(b). Pulp manufacturing occured at European production sites. |
| Paper manufacturing | The LCI data for paper manufacturing was collected from the literature (M’hamdi et al., 2017). | (a). Data included energy and water utilization and accounted for the generation of various forms of solid waste (chemical and wood).  
(b). Paper manufacturing occured at European production sites. |
| Plastic-coated paper manufacturing | 1. The LCI data for PETE film was collected from the GaBi database that is available with GaBi software (Education version);  
2. The amounts of PETE coating on the Paper were collected from literature (Yan, 2011). | 1(a). Data included all the processes from cradle to gate including extraction and production of crude oil to PETE film production;  
1(b). GaBi database uses data representing manufacturing at European production sites.  
2. The grammage of PETE is 17 g/m², and hence, the mass of 2.155g PETE/container was used during coating. |
The recycling data including the waste specific emissions were taken from the literature (Turner et al., 2015).

Data included CO2 emissions.

**Table B3.** LCI methodology associated with the manufacturing and disposal of aluminum containers (Liu et al., 2012).

<table>
<thead>
<tr>
<th>Aluminum</th>
<th>Sources</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bauxite mining</strong></td>
<td>The LCI data for mining of Bauxite was collected from the GaBi database that is available with GaBi software (Education version);</td>
<td>(a). Data included air usage, land usage, water usage, natural resource usage and energy usage;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b). GaBi database uses data representing manufacturing at European production sites.</td>
</tr>
<tr>
<td><strong>Alumina extraction</strong></td>
<td>The LCI data for extraction of Alumina was collected from the GaBi database;</td>
<td>(a). Data included electricity and energy usage;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b). GaBi database uses data representing manufacturing at US production sites.</td>
</tr>
<tr>
<td><strong>Aluminum formation</strong></td>
<td>The LCI data for formation of Aluminum was collected from the GaBi database;</td>
<td>(a). Data included all the processes from gate to gate including the smelting of alumina to ingot production;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b). GaBi database uses data representing manufacturing at North American production sites.</td>
</tr>
<tr>
<td><strong>Aluminum ingot production</strong></td>
<td>The LCI data for production of Aluminum ingot was collected from the GaBi database;</td>
<td>(a). Data included all the processes from gate to gate including alloying, cleaning and casting for alloy ingot to ingot manufacture;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b). GaBi database uses data representing manufacturing at North American production sites.</td>
</tr>
<tr>
<td><strong>Aluminum ingot manufacturing</strong> (Container production)</td>
<td>The LCI data for manufacturing of Aluminum ingot was collected from the GaBi database;</td>
<td>(a). Data included all the processes from gate to gate including rolling, extrusion and casting for Aluminium foil.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b). GaBi database uses data representing manufacturing at European production sites.</td>
</tr>
<tr>
<td><strong>Recycling &amp; Landfill</strong></td>
<td>The recycling data including the waste specific emissions were taken from the literature (Turner et al., 2015).</td>
<td>Data included CO2 emissions.</td>
</tr>
</tbody>
</table>
APPENDIX C

Sankey Diagrams

**Figure C1.** Sankey diagram for EPS container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.

**Figure C2.** Sankey diagram for aluminum container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.
Figure C3. Sankey diagram for PETE container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.

Figure C4. Sankey diagram for PLA container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.
Figure C5. Sankey diagram for PP container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.

Figure C6. Sankey diagram for Paper container production illustrating the flows between various processes based on the quantities present in the flows. Diagram formulated in the GaBi Education software.
APPENDIX D

UBC Village Basement Survey

Case Study of Take-out Containers at the UBC Village: Survey 1

1. Please fill out the following table. Place a checkmark next to the containers your business uses. Then fill out how many of that container you go through in a time increment of your choice (per day, per month, or alternative metric). Then write the cost of each container you use in Canadian $ (either per container, per 1000 containers or alternative metric). Provide a range if necessary.

<table>
<thead>
<tr>
<th>Circle if you use this container</th>
<th>Number Used</th>
<th>Cost of Containers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1250/day or 25000/month or</td>
<td>5 cents/container or 50 dollars / box of 100 containers or</td>
</tr>
<tr>
<td>Styrofoam Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrofoam Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrofoam Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compostable Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compostable Medium</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circle if you use this container</th>
<th>Number Used</th>
<th>Cost of Containers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1250/day or 25000/month or</td>
<td>5 cents/container or 50 dollars / box of 100 containers or</td>
</tr>
<tr>
<td>Compostable Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. What are your main criteria for choosing the containers your business uses (e.g. holding liquid, cost, lid retention)?
3. **Question** | **How would you rate the statements below?**
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I understand what pollution is.</td>
<td>Strongly Disagree</td>
<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
</tr>
<tr>
<td>I understand the issues with plastic in the ocean.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I understand what climate change is.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I have little interest in environmental issues.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am concerned about climate change.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am concerned about air pollution.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I am concerned about waste management.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. Would your business be willing to switch to a more environmentally friendly container if it was no extra cost to your business? If not, why?

7. How much more would your business be willing to spend on containers if you knew the alternative container was more environmentally friendly and why? (1% more? 5%? 10%? 50%?)
APPENDIX E

LCA Results

Table E1. Global Warming Potential, Human Toxicity, Water, and Natural Resource utilization for the various single-use containers in different scenarios (i.e. 0% recycling, 67% recycling, and 100% recycling)

(a). Scenario 1: 0% Waste Diverted

<table>
<thead>
<tr>
<th>Container (per 1000 containers with volume 0.0025 m³)</th>
<th>Global Warming Potential (CO2 equivalent) kg</th>
<th>Human Toxicity (CTUh)</th>
<th>Water (m³)</th>
<th>Natural Resources (kg Sb-Equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>6.76</td>
<td>0.667e-9</td>
<td>-19.4e-4</td>
<td>2.15e-5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>546</td>
<td>8.73e-8</td>
<td>-36</td>
<td>5.5e-3</td>
</tr>
<tr>
<td>PETE</td>
<td>359</td>
<td>3.99e-6</td>
<td>-206</td>
<td>2.02e-4</td>
</tr>
<tr>
<td>Paper</td>
<td>-23.4 (5.66 excludes biogenic)</td>
<td>3.78e-9</td>
<td>2.25</td>
<td>9.52e-6</td>
</tr>
<tr>
<td>PLA</td>
<td>378</td>
<td>2.13e-7</td>
<td>-765e-4</td>
<td>4.47e-5</td>
</tr>
<tr>
<td>PP</td>
<td>186</td>
<td>1.94e-7</td>
<td>-0.052</td>
<td>1.06e-4</td>
</tr>
</tbody>
</table>

(b). Scenario 2: 67% Waste Diverted

<table>
<thead>
<tr>
<th>Container (per 1000 containers with volume 0.0025 m³)</th>
<th>Global Warming Potential (CO2 equivalent) kg</th>
<th>Human Toxicity (CTUh)</th>
<th>Water (m³)</th>
<th>Natural Resources (kg Sb-Equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>6.76</td>
<td>1.16e-8</td>
<td>-19.4e-4</td>
<td>2.17e-5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>299</td>
<td>5.83e-8</td>
<td>-34</td>
<td>1.9e-3</td>
</tr>
<tr>
<td>PETE</td>
<td>104</td>
<td>1.226e-6</td>
<td>-67.9</td>
<td>6.37E-5</td>
</tr>
<tr>
<td>Paper</td>
<td>29.4 (excludes biogenic)</td>
<td>0.959e-09</td>
<td>0.615</td>
<td>9.27e-6</td>
</tr>
<tr>
<td>PLA</td>
<td>413</td>
<td>1.97e-7</td>
<td>-769e-4</td>
<td>1.84e-5</td>
</tr>
<tr>
<td>PP</td>
<td>95.9</td>
<td>1.93e-7</td>
<td>-8.21E004e-6</td>
<td>5.78e-6</td>
</tr>
</tbody>
</table>
### (c). Scenario 3: 100% Waste Diverted

<table>
<thead>
<tr>
<th>Container (per 1000 containers with volume 0.0025 m³)</th>
<th>Global Warming Potential (CO2 equivalent) kg</th>
<th>Human Toxicity (CTUh)</th>
<th>Water (m³)</th>
<th>Natural Resources (kg Sb-Equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>6.76</td>
<td>0.667e-9</td>
<td>-19.4e-4</td>
<td>2.15e-5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>177</td>
<td>4.4e-8</td>
<td>-33</td>
<td>1.33e-4</td>
</tr>
<tr>
<td>PETE</td>
<td>121</td>
<td>2.82e-7</td>
<td>-0.12</td>
<td>8.41e-6</td>
</tr>
<tr>
<td>Paper</td>
<td>41.6 (excludes biogenic)</td>
<td>-0.996e-10</td>
<td>-228e-3</td>
<td>9.14e-6</td>
</tr>
<tr>
<td>PLA</td>
<td>540</td>
<td>2.13e-7</td>
<td>-765e-4</td>
<td>4.47e-5</td>
</tr>
<tr>
<td>PP</td>
<td>71.3</td>
<td>1.94e-7</td>
<td>-0.0821</td>
<td>3.4e-5</td>
</tr>
</tbody>
</table>

**Table E2.** Comparison of the CO2 Emissions (per 1000 containers) for each container type and their associated cost (per 1000 containers in Canadian currency)

<table>
<thead>
<tr>
<th>Container Type</th>
<th>CO2 Emissions (kg) per 1000 containers</th>
<th>Cost (CAD $) per 1000 containers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Styrofoam</strong> (ESP, Polystyrene)</td>
<td>6.76</td>
<td>124.85</td>
</tr>
<tr>
<td><strong>Plastic Clamshell</strong> (PETE, Polyethylene Terephthalate)</td>
<td>104</td>
<td>526.65</td>
</tr>
<tr>
<td><strong>Plastic Clamshell</strong> (PP, Polypropylene)</td>
<td>95.9</td>
<td>437.40</td>
</tr>
<tr>
<td><strong>Biodegradable</strong> (PLA, Polylactide/corn-based biodegradable)</td>
<td>413</td>
<td>319.27</td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td>29.4</td>
<td>780.26</td>
</tr>
<tr>
<td><strong>Aluminum</strong></td>
<td>299</td>
<td>316.97</td>
</tr>
</tbody>
</table>
Table E3. Eco-efficiency indicators for each container type.

<table>
<thead>
<tr>
<th>Container Type</th>
<th>Cost Indicator (Xn)</th>
<th>GWP Impact Indicator (Yn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Styrofoam (ESP, Polystyrene)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Plastic Clamshell (PETE, Polyethylene Terephthalate)</td>
<td>0.5904</td>
<td>0.2915</td>
</tr>
<tr>
<td>Plastic Clamshell (PP, Polypropylene)</td>
<td>0.4815</td>
<td>0.2755</td>
</tr>
<tr>
<td>Biodegradable (PLA, Polylactide/corn-based biodegradable)</td>
<td>0.3373</td>
<td>0.9</td>
</tr>
<tr>
<td>Paper</td>
<td>0.9</td>
<td>0.1446</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.3345</td>
<td>0.6755</td>
</tr>
</tbody>
</table>
**APPENDIX F**

**Public Informational Brochure**

**Front**

Disposable cups and take-out containers make up 50% of Vancouver’s residential waste by volume (City, 2017).

Help Vancouver reduce its waste by switching to a recyclable or compostable container.

**Back**

The relative purchasing cost of various alternative containers to EPS in relation to the relative global warming potential (kg CO$_2$-eq) is shown in the graph to the right.

The containers in the green area represent the highest eco-efficient containers.

While those in the yellow area represent the lowest eco-efficient containers.