Evaluating the Benefits of Flax Bio-Composites in Automotive Applications using Life Cycle Assessment

by

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Abstract

Recent developments in increasingly sophisticated and high preforming biomaterials has provided automobile manufacturers the opportunity to implement the use of more environmentally friendly and sustainable products. Although the prevalence of greenwashing in the automotive industry has made it hard to determine the environmental merits of many vehicles, using life cycle assessment provides empirical evidence that can be used to justify the adoption of products made using natural materials. Based on ISO standards, these assessments look at the entire life cycle of a product from cradle-to-grave. Given Manitoba's abundance of agricultural materials, it stands to reason the province can position itself as a leader in the emerging biomaterials industry.

Manufactured by Westward Industries Ltd., the GO-4 urban utility vehicle's aluminum and steel passenger tub is attempting to be replaced by a flax fibre bio-composite produced by the Composites Innovation Centre. To evaluate the advantages of the bio-composite my study applied the use of LCA and compared the environmental impacts of each option using the TRACI 2.1 methodology. Replacing the metal passenger tub resulted in a 12 kg weight savings, producing on average 10% less global warming, 28.8% less fossil fuel depletion and 52.7% less ozone depletion. When the vehicles use was extended, these impacts were further amplified reducing global warming by as much as 22.1%. Three different disposal scenarios were also examined, of which the impacts of the metal passenger tub were shown to be highly dependant on recycling. The impact categories in which the bio-composite preformed worse are largely related to nitrate use. Although the use-phase was not as dominate for both tubs as compared to other automobile LCA's, the typical driving environments of the GO-4 indicate that emissions reductions due to light-weighting may be larger than this study suggests.

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Chapter 1: Purpose of Research

1.1 Introduction

Increasing concerns towards climate change and rising gasoline prices have forced many automotive companies to rethink the way they will do business in the 21st century. Attempting to rebrand themselves by introducing smaller, more fuel efficient and better designed products, automobile manufacturers have provided consumers with more options than they've ever had before. One result of these changes has been the systemic use of personal relations and marketing campaigns created to deceive consumers, otherwise known as greenwashing. In 2014, after a two-year investigation, Kia Motors Corporation agreed to a $360 million settlement with the U.S. Environmental Protection Agency (EPA), after their automobiles were found to overestimate fuel economy, in some cases by as much as 6 mpg [Woodyard 2014]. Recent developments in functional materials and environmentally friendly manufacturing technology, has however, provided automobile manufacturers the opportunity to improve. To utilize these opportunities, comprehensive environmental assessments must be made to establish how these new products impact the environment.

Westward Industries Ltd. (WI Ltd.), the manufacturer of the GO-4, a small street legal three-wheel utility vehicle used for issuing parking tickets, police patrol and delivery services, working in partnership with the Composite Innovation Centre (CIC) are attempting to develop a bio-composite material that can be used to replace the vehicles metal passenger tub. These passenger tubs, or underbellies, are traditionally produced using steel, aluminum and other materials that are environmentally unsustainable and sourced from considerable distances. Developing vehicles that incorporate materials made from agricultural fibre-residue, which being rapidly renewable and less environmentally impactful, has the potential to reduce the environmental loads associated with automobile use and establish new more sustainable business practices.

Having been traditionally used in many European countries, flax, hemp, sisal and jute fibres are being adopted by North American companies to replace glass fibres (i.e. fibreglass) in many plastic composites, particularly for those used in the automotive sector [MAN-Flax 2016]. At present, Manitoba has a total of 10.7 million acres of usable cropland and accounts for 12.3% of Canada's total area [Government of Manitoba 2012]. In 2006, the province had 2,212 farms growing 383,509 acres of flax [Statistics Canada 2012]. By incorporating natural fibres into composite materials, Manitoba offers a unique opportunity to provide farmers and manufacturers the means to produce more sustainable and less environmentally impactful products. To determine the differences between Westward Industries Ltd. GO-4 aluminum and steel passenger tub to that of one produced using natural fibres, an environmental assessment tool called Life Cycle Assessment (LCA) can be applied.

By conducting a cradle-to-grave comparative attributional life cycle assessment, I examined the environmental impacts associated with the production, use and disposal of both, the metal and bio-composite passenger tubs for the GO-4 vehicle. By developing reference models mapping the flows of relevant energy and material inputs I was able to compare the two passenger tubs and draw conclusions towards the environmental merit of each option. Additionally, I identified weaknesses within the current production process and offered suggestions with regards to how Westward Industries Ltd. can further improve their operations going forward. Results from this research provides evidence of the environmental impacts associated with each tub and demonstrates which option causes the least amount of environmental harm.

1.2 Problem Statement

Although many efforts have been made within the automotive industry to decrease the impacts that vehicles have on the environment, the persistence of greenwashing has made it hard to determine whether these efforts are legitimate. Composite materials created using locally sourced agricultural fibres have the potential to replace automotive parts traditionally made using unsustainable materials. In order for companies like Westward Industries Ltd. to implement the use of these composites, the environmental impacts of each option must be examined through empirical research. By applying the use of life cycle assessment, two different products can be compared to determine which choice is optimal. My research will help provide Westward Industries Ltd. and the Composites Innovation Centre an informed perspective on current and proposed manufacturing activities, offer consumers a transparent statement towards the advantages of bio-composite adaptation and encourage the growth of natural fibre use within the automotive industry.

1.3 Objectives

The purpose of this research is to understand and compare the environmental impacts associated with the production, use and disposal of the metal and bio-composite passenger tubs for the GO-4 vehicle. Specific objectives include:

- Model the inputs and outputs of the GO-4 metal and bio-composite passenger tubs to identify impact categories and quantify environmental stress.
- Compare both GO-4 passenger tubs using LCA to determine which option is more ideal.
- Identify weaknesses within the current product chain and offer suggestions for improvement.

1.4 Research Rationale

Gaining a greater understanding of how products impact the environment is essential for companies to implement more sustainable business practices and appease the demands of consumers wanting more environmentally friendly choices. For the biomaterials industry to establish itself in the automotive sector, the benefits of bio-composite materials must be proven through transparent and empirical research. Due to public skepticism created by greenwashing within the automotive industry, objective studies following international guidelines, such as the ISO 14000 environmental management standards, must be conducted to reassure consumers the environmental merits of emerging green technologies and materials. By using LCA the full range of effects caused by the production, use and disposal of a bio-composite part can be compared to existing materials to determine which product is superior. Although research has been conducted using LCA for automobile bio-composites in the past, no such work has been done within Manitoba.

Quantifying the manner and degree to which the metal and bio-composite passenger tubs impact the environment allows for not only product comparison, but also weaknesses within current manufacturing to be identified. Understanding the impacts that are caused over the course of a products lifetime allows the manufacturer to address these weaknesses by implementing the use of materials and production techniques proven to be more environmentally friendly. If the results of LCA studies are communicated to the public in an intelligible and transparent manner, the adverse effects caused by greenwashing can be combated. As such, life cycle assessments will continue to play an integral role in the adoption of biomaterials for industrial applications.

Chapter 2: Literature Review

2.1 Life Cycle Assessment

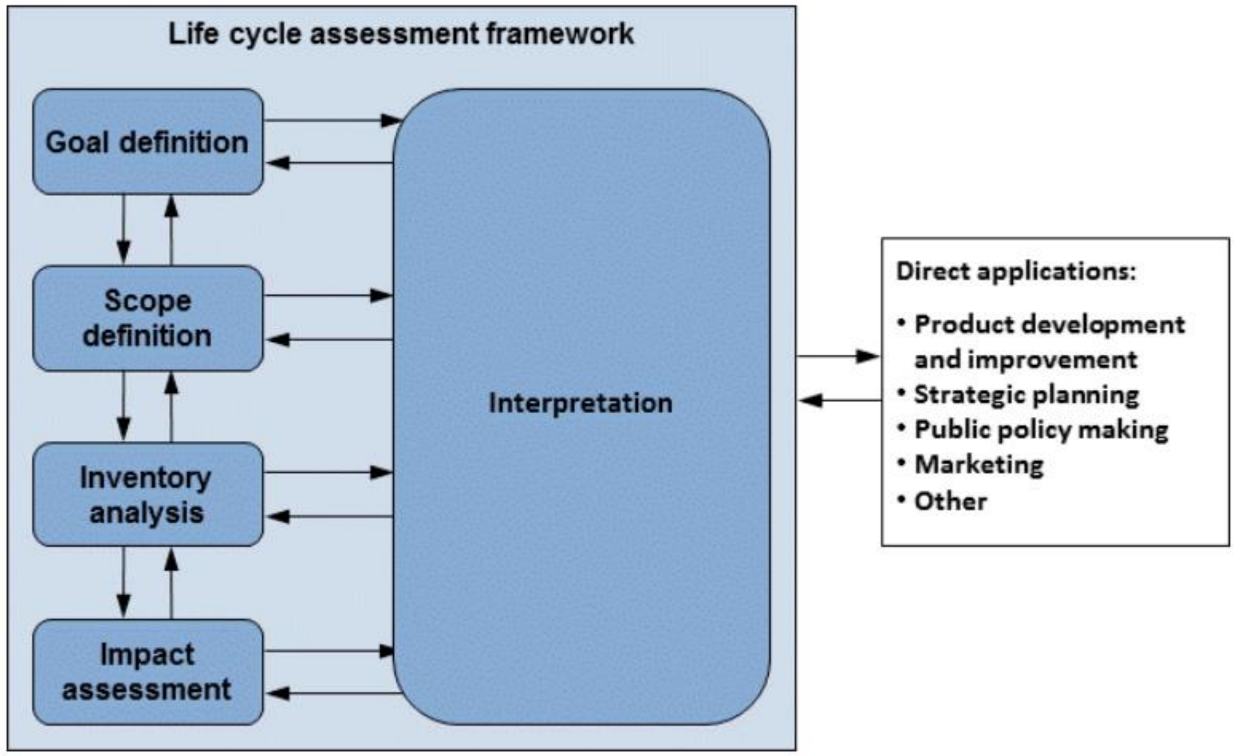
Life cycle assessment is a technique used to assess environmental impacts associated with all the stages of a product's life from cradle to grave. Included in the analysis is everything from raw material extraction, manufacture, distribution, use, disposal and recycling. LCA's are divided into attributional and consequential types. The former seeks to establish the burden associated with the production and use of a product at a given point in time, most typically in the recent past or present, meanwhile the latter seeks to identify the environmental consequences of a decision or a proposed change in a system oriented towards the future, often taking market and economic implications into account. Although many variants exist, the primary goal of an LCA is to assess the environmental impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system.
- Evaluating the potential environmental impacts associated with those input and outputs.
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. [Baumann and Tillman 2004]

Beginning in 1997, ISO 14040-14044 were created as part of the ISO 14000 environmental management series [Baumann and Tillman 2004]. According to these standards, a life cycle assessment is carried out in four distinct phases. The phases are as follows:

1. Goal and Scope
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

Figure 1. Framework for life cycle assessment (from ISO 14040)



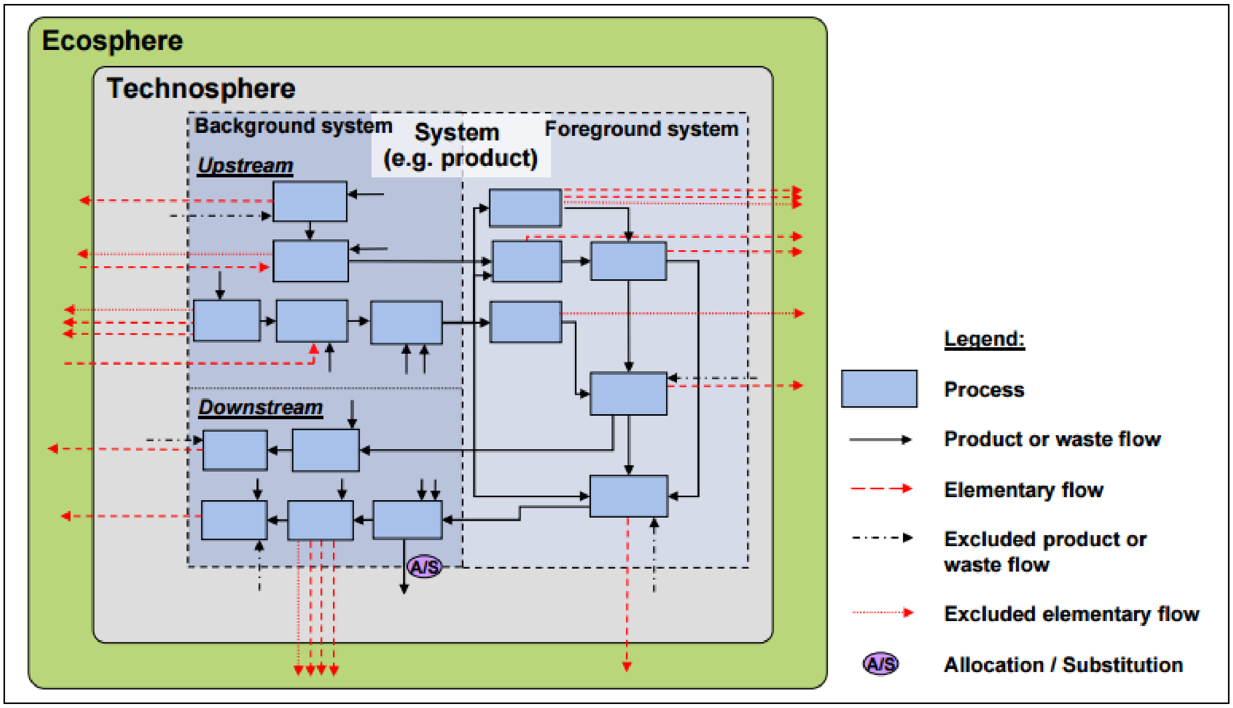
1. *Goal and Scope*

All LCA's begin with an explicit statement of the goal and scope of the study. This statement sets out the context of the study and explains how and to whom the results are to be communicated. Key to the ISO requirements, the goal and scope of the LCA should be clearly defined and consistent with the intended application. During this phase, several technical details are addressed that help guide the rest of the LCA. These include the establishment of a functional unit, definition of system boundaries, descriptions of any assumptions and limitations within the study, solving any issues related to allocation and finally the selection of impact categories that occur during the LCIA.

For an LCA to accurately compare different systems and products a common unit is required, called a functional unit. The functional unit defines precisely what is being studied and sets the unit that all material and energy flows are quantified with respect to [Argerich 2016]. Determining a functional unit is an important basis that allows a LCA to compare and analyze alternative goods and services. An example of a functional unit for instance could be a 22-cubic foot refrigerator that is used over the course of 10 years. Important to note, the functional unit should as far as possible relate to the functions of the product rather than the physical product [Weidema et al., 2004]. For example, seating support for one person working at a computer for one year rather than one computer workstation chair.

After the goal, purpose and functions are set, the system boundaries are then defined. System boundaries are indicated in a flow chart to illustrate the processes or inputs that should be included in the study. Divided into foreground and background systems, these boundaries separate the analyzed system from both, the rest of the technosphere and the ecosphere (i.e. boundary where the exchange of elementary flows with nature and outside businesses occur) [ILCD 2010]. These boundaries also help to determine process identification during LCI. Included below is an illustration describing the relationship between system boundaries within a LCA.

Figure 2. Foreground system and background system in the specificity perspective.



LCA does provide allocation procedures used to partition the environmental loads of a process when several products or functions share the same process. For example, how should the emissions from an incineration plant be allocated between packaging materials and a local heating system. Allocation is commonly dealt with by system expansion, substitution or partitioning. For the application of this study the problem of allocation will be avoided as all inputs and outputs relating to the manufacture, use and disposal of the passenger tubs serve the same purpose (i.e. functional unit).

2. *Life Cycle Inventory*

During the LCI phase an inventory is made up of the various flows between the system boundaries as they relate to the functional unit. These flows can include things like energy, raw materials and other releases to air, land and water. A flow model is constructed to provide a clear picture of the technical system boundaries and assess relevant activities that occur throughout the products life cycle. All data must be related to the functional unit that was previously defined in the goal and scope phase. The results from the LCI provides information about all inputs and outputs in the form of elementary flows to and from the environment for all the unit processes involved in the study.

3. *Life Cycle Impact Assessment*

At this stage data collected from the LCI is interpreted to analyze its potential environmental impact. LCIA is used to present and describe what kind of environmental impacts are analyzed in the study and also introduces the models and calculations that are used to obtain the desired results. Data gathered from the LCI flow charts is then sorted into different classes, each representing a particular type of environmental impact (e.g. global warming potential). Once the data has been characterized, the researcher can apply additional LCIA elements, such as normalization, grouping and weighting, although these steps are considered optional. According to ISO 14044, LCIA must consist of the following mandatory elements:

- Selection of impact categories, category indicators and characterization models.
- Classification stage, where the inventory parameters are sorted and assigned to specific impact categories.
- Impact measurement, where the LCI flows are characterized using one of many possible LCIA methodologies (e.g. RECIPE, Cumulative Energy Demand, Eco Indicator, etc.) into common equivalence units that are summed to provide an overall impact total. [Menoufi 2011]

4. *Interpretation*

In the interpretation phase the analyses made in the LCI and LCIA are evaluated, which leads to conclusions and recommendations. Any questions raised in the goal should be answered and suggestions with regards to changes in the system process or product(s) comparison be finalized. The credibility of the LCA study is also evaluated by conducting a variety of checks. These checks can include such things as dominance, contribution, break-even, decision-maker, uncertainty, sensitivity and variation analysis etc. According to ISO 14040, interpretation should include:

- Identification of significant issues based on the results of the LCI and LCIA phases.
- Evaluation of the study considering completeness, sensitivity and consistency checks.
- Conclusions, limitations and recommendations. [ISO 1997]

2.2 Greenwashing

2.2.1 Introduction to Greenwashing

Beginning in the late 1960's, private companies like Coca-Cola began using research firms to conduct in-house LCA's [Baumann and Tillman 2004]. These studies provided insight towards the adoption of emerging manufacturing processes and related product decision making. Although many of the early LCA's were never published due to the confidential nature of the work, during the 1970's many private companies and public authorities began utilizing the practice [Baumann and Tillman 2004]. Via marketing mechanisms, the idea continued to spread allowing manufacturers to make more informed decisions, while at the same time providing them an edge over competitors by addressing consumer awareness.

Coined by environmentalist Jay Westervelt in a 1986 essay, greenwashing became increasingly prevalent amongst many organizations as a way to take advantage of environmental movements [Black 2008]. In some cases, public utilities spent eight times more money on green advertising then they had on pollution reduction research [Black 2008]. The prevalence of greenwashing continued as companies like Chevron developed entire ad campaigns designed to take advantage of the publics perception. When asked if the environmental reputation of a company affected their decision to buy a product, a study conducted by the American Marketing Association found that 77% of people said that it did [Lynn 2014]. Although organizations like the U.S. Federal Trade Commission (FTC) would eventually create guidelines used to define environmental marketing, often little could be done to enforce them as the claims were outside their jurisdiction.

Throughout the world, most notably in more developed countries, efforts to curb greenwashing have persisted. Although well intentioned, these efforts continue to lack the enforceable standards required to prevent companies from using the practice. In Canada for example, the Competition Bureau and Canadian Standards Association are only able to discourage companies from making environmentally vague claims, while in the U.S., similarly, the FTC has created voluntary guidelines [Naish 2008]. Countries like Australia have however taken more progressive steps to curb greenwashing by developing policies like the Trade Practices Act, which forces companies found guilty of making misleading environmental claims to be held legally responsible and open to fines [Naish 2008].

2.2.2 Prevention of Greenwashing in Life Cycle Assessments

One of the primary goals of any LCA is to provide companies and their intended custumers with objective and fully transparent product assessments. These assessments not only help to validate claims made towards a products environmental impact, but can also help companies identify previously unknown opportunities for improvement throughout the manufacturing process. While the principles inherent in LCA are meant to promote an objective examination of a products lifecycle, many skeptics argue that due to the lack of enforceable industry standards and governmental oversight, claims are often made by manufacturers who purposely intend to deceive the public by introducing bias into their LCA's. As such, there remains a need to prevent these outcomes by developing international standards and other regulatory mechanisms aimed to provide more scientifically sound and transparent LCA's.

Although created to provide a uniform set of guidelines for LCA applications, standards such as ISO 14040 and ISO 14044, have yet to completely address the many problems associated with data manipulation. Because these standards do not provide requirements for data completeness or specify which processes should be used in order to evaluate results, much of the responsibility ends up being left to the LCA practitioner. Many critiques of the current ISO standards point to things like unrepresentative sampling, differing system boundaries, varying assumed product uses, etc. Continued efforts to develop a more formalized LCA methodology is further witnessed with the advent of documents like the Publicly Available Specification (PAS) 2050 and GHG Protocol Life Cycle Accounting and Reporting Standard. On the grounds that many LCA's are comparative and are used to determine a better process or product, it is essential that the credibility of these projects remains through strict adherence to current guidelines and that in the future more progressive standards continue to be implemented.

2.2.3 Greenwashing in the Automotive Industry

A more accurate understanding of the effects and causes of global warming throughout the 21st century has raised many environmental concerns within the automotive industry. Currently one-fifth of all U.S. emissions are caused by automobiles, while two-thirds of this comes from personal vehicle use [Biological Diversity 2016]. Globally, the transportation industry is responsible for over 13% of the worlds anthropogenic greenhouse gas emissions [IPCC 2014]. Unsurprisingly, many of the world's largest automotive companies have attempted to quell these concerns by developing new products that are less impactful, utilizing ad campaigns aimed to promote potential advantages. Although many positive examples exist, like for instance the state of California's decision to set emissions standards that are stricter than the EPA's, or the rise in the popularity of electric vehicles, such as the Tesla Model 3, the automotive industry remains plagued by the continued presence of greenwashing.

In 2014 Hyundai and KIA were forced to pay $360 million to settle a dispute with the U.S. EPA after 1.2 million of their vehicles were found to overestimate fuel consumption by as much as 6 miles per gallon [Woodyard 2014]. More recently, Volkswagen was found to have installed illegal software in their vehicles to bypass U.S. emissions tests, allowing them to advertise a 34 mpg driving average when in fact the vehicles were averaging over 37 mpg [Edmunds 2015]. Other companies like Mitsubishi, Fiat Chrysler and Chevrolet/GMC/Buick have also found themselves wrapped in scandal as emissions and fuel economy irregularities continue to be uncovered [Sorokanich 2016]. Examples such as these illustrate well the steps companies are willing to take to convince consumers that their vehicles are far more environmentally friendly than they actually are.

2.3 Manitoba Biomaterials Industry

As stated by the provinces Growing Green Bioproducts Strategy, Manitoba is well situated to take advantage of biomass production and supply from the agriculture sector. Using renewable natural fibres in composite materials has the potential to establish a sustainable and competitive bioproducts industry that will diversify and strengthen Manitoba's economy. Growing concerns over climate change and price fluctuations in the oil and gas industry has driven many companies to address these problems by developing new products through research and innovation, as witnessed by the work being done between the Composites Innovation Centre and Westward Industries Ltd. on the GO-4 vehicle. Supporting the development of this industry through the use of LCA has the potential to provide additional product value and demand, resulting in an agricultural sector that produces better quality residues for high performance applications. The objectives for developing Manitoba’s biomaterials industry include:

- To advance the research and innovation capacities for production, processing and industrial applications of biofibres and biomaterials.
- To increase the use of biofibres and biomaterials in the provinces manufacturing sector.
- To establish Manitoba’s position as the capital of biofibres and biomaterials in terms of research, development and commercialization in Canada. [Government of Manitoba 2016]

Currently Manitoba has 36.2 million acres of land with agricultural potential, of which approximately 19 million acres are devoted to farming [Government of Manitoba 2016]. In the mid 1980’s, Manitoba grew roughly 1 million acres of flax a year [Statistics Canada 2006]. Unfortunately, since that time flax production within the province has been steady declining, as in 2006, 383,509 acres were grown and in 2011 only 167,367 acres [Statistics Canada 2012]. As of 2015 Manitoba is growing less than 100,000 acres of flax per year and is now trailing behind Saskatchewan and Alberta [Insightrix 2015]. A large reason for this decline has been the increasing demand for crops like soybeans and canola which now make up much of the prairie landscape. Included in **Appendix A** is a map detailing the average flax yields within the province between 1991-2011, illustrating where the highest concentrations are grown.

A study conducted in 2015 of 72 different flax producer's highlights some of the reasons why farmers are planting less flax and what it would take to encourage them to begin growing it again. As of 2013, 66% of the respondents mentioned crop rotation/diversity as being the single largest advantage to growing flax, while 36% and 30% stated that straw management and weed control were the biggest disadvantages respectively [Insightrix 2015]. The main crops replacing flax were barley, soybeans, canola, corn and hemp [Insightrix 2015]. When asked what flax agronomics needed the most improvement, 58% mentioned yield and yield stability [Insightrix 2015]. Included below are two tables providing a summary of the study.

Table 1. Manitoba grower survey, advantages of growing flax. (2015)

Biggest Advantages to Growing Flax	2011 (n=4)	2012 (n=15)	2013 (n=53)
Crop rotation/diversity	50%	60%	66%
Good return on investment/low inputs	25%	27%	47%
Longer harvest time	0%	20%	9%
Low maintenance/easy to harvest	0%	13%	8%
Suitable 'cover' crop	0%	7%	6%
Other	0%	7%	9%
Don't know/no comment	25%	0%	2%
None	0%	0%	2%

Table 2. Manitoba grower survey, disadvantages of growing flax. (2015)

Biggest Disadvantages to Growing Flax	2011 (n=4)	2012 (n=15)	2013 (n=53)
Straw management	75%	20%	36%
Weed control	0%	27%	30%
Inconsistent/low yield	0%	33%	19%
Hard on combine	25%	0%	15%
Not economical/no profit	0%	27%	15%
Weather conditions	25%	13%	11%
Late harvest	25%	0%	8%
Other	0%	13%	9%
Don't know/no comment	0%	0%	2%
None	0%	7%	4%

Although many Manitoba farmers were keen to plant flax in the past, looking at the trend developing in more recent years, coupled with concerns over things like yield stability and straw management, it becomes clear that going forward flax yields within the province should be expected to decrease, or at the very least remain somewhere around 100,000 acres. Although this decrease will likely affect applications requiring larger quantities of flax straw, such as for biomass, it will unlikely have a meaningful impact on high performance biomaterials, such as the GO-4 passenger tub. As the introduction of biomaterials into Manitoba's manufacturing sector is still a relatively new phenomenon, the need for higher quality flax fibres that can be used for more experimental purposes trumps the need for larger and less controlled yields. Work being done by organizations like FibreCITY and Prairie Genome illustrate well the efforts being made to establish a reliable production network within the province. By experimenting with different flax varieties, decortication and processing techniques, as well as quality controls, these efforts have begun to encourage value creation as companies like Westward Industries Ltd. are now being offered increasingly sophisticated and high preforming biomaterial product options. As Manitoba's biomaterials industry continues to grow it should be expected initial concerns related to product quality and availability will begin to shrink as the growers, manufacturers and consumers of these biomaterials further develop stronger working relationships and become more accustomed to each others needs.

2.4 Bio-Composite Manufacturing

Created using natural fibres, along with a matrix or resin, bio-composites can serve a variety of purposes in many different applications. By using natural fibres and in some cases natural polymers, bio-composites are often used as a more environmentally friendly alternative to tradition non-renewable materials. Applications vary widely from automobile components to sports equipment and construction materials. Bio-composites are classified into either non-wood or wood categories depending on the source of the fibre. Non-wood bio-composite fibres are divided into straw fibres, bast, leaf, seed or fruit and grass fibres, with the most common sources coming from crops such as flax, hemp, kenaf, jute, sisal and coir [Dzalto 2013]. Wood fibres can be sourced from either hard and soft woods or recycled materials such as newspapers. The composites are produced using many different manufacturing techniques which include machine pressing, filament winding, pultrusion, extrusion, injection molding, compression molding, resin transfer molding and sheet moulding compound [Joshi 2003]. Roughly 95% of all natural fibre composites are produced using compression moulding [Dzalto 2013].

As environmental and sustainability concerns become increasingly common, advocates for biomaterials often point to the many advantages of them such as their renewable, cheap, biodegradable and recyclable nature. Natural fibre composite densities are also low compared to other composite materials with the same mechanical properties allowing these composite components to reduce weight without compromising functional performance, as is the case with the GO-4 passenger tub. Additionally, many have argued towards the aesthetic appeal of bio-composites as they can often take on a wood-like appearance. Although wood fibres can be used in a range of applications, often it is non-wood fibres that are the most sought after due to the more attractive physical and mechanical properties.

To produce the bio-composite GO-4 passenger tub, the CIC utilizes a vacuum molding technique. First wax is applied to the A and B side moulds, which typically will last for the production of five to ten parts. Once this has been done, the flax fibre plies are cut and kit per the layout requirements of the vehicle, which are then laid onto the A-side mould. Carefully positioning the B-side counter-mould overtop of the A-side mould, both parts are then lowered into position. Vacuums are pulled fully into the mould's vacuum chamber and at half vacuum into the part cavity, after which time they are left to consolidate. The resin is then mixed with a hardener and injected into the part cavity at half vacuum. Once fully infused, the resin injection port is closed off and the assembly is left to cure typically overnight at room temperature, until finally the passenger tub is demoulded. The production process itself does not demand a great deal of heat or electricity as most of the work at the CIC is done by hand and the only electrical requirement comes in the form of the vacuum pump which runs for roughly 20-30 minutes.

Chapter 3: Methods

3.1 Goal

The goal of this study is to evaluate and compare the environmental impacts caused by the production, use and disposal of a metal and bio-composite passenger tub for Westward Industries Ltd. GO-4 vehicle to determine which option is better for the environment. The environmental impact of the aluminum and steel passenger tub currently being used will be compared to a prototype being designed by the Composites Innovation Centre that utilizes flax fibres and a PHA resin. Results from my study will be used to help inform the CIC and Westward Industries Ltd. towards which option causes the least amount of environmental impact, as well as to offer recommendations for improvement in current and proposed manufacturing processes. Additionally, the results will contribute to the academic understanding of biomaterials, more specifically as they apply to Manitoba. The study is being carried out in large part due to the need for more empirically credible environmental product data for bio-composite alternatives and to provide insight towards the challenges and opportunities facing an emerging biomaterials industry in Manitoba. Conducting a cradle-to-grave comparative attributional life cycle assessment, ten unique impact categories will be examined using the TRACI 2.1 LCIA methodology. To make this comparison my study will contain two individual life cycle assessments for each passenger tub. Once LCA's have been conducted for both, the traditional non-renewable and proposed renewable passenger tub, the environmental impacts of each option will be compared and the results explicitly stated. The study includes comparative assertions intended to be disclosed to the public.

3.2 Functional Unit

The functional unit for this study is the passenger tub used in the production of Westward Industries Ltd. GO-4 urban utility vehicle. Set within the vehicles frame, the passenger tub provides structural support and safety for the vehicles occupants. Since this LCA is a cradle-to-grave assessment, the entire life cycle of the component will be taken into consideration including the extraction, processing, manufacture, transportation, use and disposal of the product. Data collected from Westward Industries Ltd. through customer feedback and product testing has placed a maximum road life of 120,000 miles for the vehicle. Although this value represents the longest the current GO-4 can be driven, typical usage for the vehicle is between 60 to 70 thousand miles. As such, a 65,000-mile driving distance will be included in this study to represent the average expectancy for the vehicle. Using this distance will provide the opportunity to examine the relationship between the manufacture, use and disposal stages for each passenger tub under normal driving conditions. The passenger tub currently being used is made from ten different aluminum and steel components, weighing 31.8 kg lbs in total. The bio-composite passenger tub is made up from flax fibre and a PHA resin, which weighs 19.64 kg. Because the aim of my study is to examine the impacts associated with each individual tub and not the entire vehicle, miscellaneous impacts such as vehicle maintenance and parts replacement will not be included in this LCA.

Often the impacts associated with the extraction and manufacture of one product will be much different than those attributed to a different product serving the same function. While one of the products may initially produce a large impact during production, the subsequent characteristics of the product may offset any drawbacks by offering certain advantages such as light weighting or being recyclable. For most vehicle LCA's the use phase often represents the largest environmental impact. As the bio-composite passenger tub weighs less than the one currently being used, it is expected that over time the advantages associated with this reduction will become increasingly apparent. The aim of this study will be to provide evidence of the relationship between the manufacture and intended use of each component, allowing Westward Industries. Ltd. to make more informed decisions with regards to their business practices. For example, how each individual tub impacts the environment during the production and use phases and whether the degree of any inherent benefits warrants making a change. Finally, as the production processes for each passenger tub do not have more than one product as output and each unit shares equivalency, multifunctionality will not be addressed in this study.

3.3 System Boundaries

The system boundaries for the flax bio-composite and metal passenger tub extend from the extraction of feedstock materials to the end of life for each component. For the bio-composite passenger tub, the system can be sorted into seven main phases: raw material extraction, fibre production, resin production, assembly, transportation, use and end of life. The extraction phases for both the fibre and PHA resin include the cultivation practices and harvesting techniques required to produce the natural feedstocks. Material processing encapsulates the substances and energy inputs required to transform the raw agricultural materials into the finished products used to create the bio-composite tub. Assembly represents the injection moulding process conducted at the CIC. Use phase represents the average driving expectancy for the GO-4, which will be discussed later. Due to the bio-composite tub being made from natural materials, the end of life phase is represented by a compost scenario which inherently makes the composite materials carbon neutral.

The metal passenger tub is divided into eight main phases: raw material extraction, aluminium production, steel production, stainless steel production, transportation, use and two end of life scenarios, which for this study is represented by landfilling and recycling. Much like the bio-composite, material extraction represents the impacts associated with the acquisition of the raw materials needed to produce the various metals. Material processing once again represents the substances and energy inputs required to transform the raw materials into the final components used in the current passenger tub. Unlike the bio-composite component, recycling and landfill waste treatments have been included for the metal passenger tubs end of life scenario.

3.4 LCIA Methodology

The Tool for the Reduction and Assessment of Chemical and other environmental impacts (TRACI), is a mid-point impact assessment method developed by the U.S. Environmental Protection Agency to help conduct LCA's within North America. Although originally designed for the use in LCA, the tool has begun to find broader applications for anyone interested in evaluating environmental impacts [EPA 2016]. TRACI adopts a mid-point oriented approach which is consistent with the EPA's decision not to aggregate between environmental impact categories, caused in part by higher levels of societal consensus concerning the certainties at this point in the cause-effect chain [Pre-Sustainability 2016]. The method includes classification, characterization and normalization. Although the methodology includes a wide range of impact categories, it does not include such things as odor, noise, radiation, waste heat, etc. Included below is a brief description of the TRACI 2.1 impact categories:

***Acidification* –** A natural process that is made worse by human activities, acidification occurs when nutrients like magnesium, potassium and calcium are replaced with acidic elements such as aluminum and hydrogen by leaching. Sulfur dioxide and nitrogen oxides from fossil fuel combustion are the largest contributors to acidification and when emitted into the air may travel for hundreds of miles prior to deposition. Increasing acidity levels has the potential to kill animals and organisms in soil and can leach into water bodies causing harm to ecosystems. [APIS 2004]

***Eutrophication* –** Much like acidification, eutrophication does occur naturally. Problems begin to arise however, when phosphates and nitrates are released into local ecosystems due to human activities, namely those related to agriculture. This chemical runoff accelerates biological productivity in surrounding aquatic ecosystems and causes an undesirable accumulation of algal biomass. Algae blooms remove nutrients from the upper water column and prevent sunlight from producing photosynthesis creating oxygen-poor water. Consequences of eutrophication include reduced biodiversity, toxicity to humans and animals and impacted land use. [Science Encyclopedia 2016]

***Global Climate Change* –** Anthropogenic global warming occurs when Greenhouse Gases (GHG's) such as carbon dioxide, nitrous oxide, methane and ozone are released into the atmosphere by various human activities, most notably those activities associated with the use of fossil fuels. Once in the atmosphere, these GHG's affect the Earth's natural radiative forcing, which in turn causes rising temperatures due to the increased capture of the Sun's radiation. In order to measure these effects, Global Warming Potential (GWP) is used which develops CO2 equivalents. Global warming causes changes in temperature, precipitation and sea level, which in turn can negatively affect human health, agriculture, forests, water resources and species damage.

Human Health Cancer, Noncancer and Ecotoxicity – Based on the EPA Risk Assessment Guidelines and the Exposure Factors Handbook, Traci 2.1 includes this impact category to display the effects that primary and secondary particulates have on the environment. Each group of particulate matter is divided into "inhalable coarse particles" between 2.5-10um in diameter and "fine particles" which are smaller or equal to 2.5um [Rosenbaum 2008]. These impacts are further compartmentalized within the context of urban/rural air, agricultural/industrial soil, freshwater and coastal marine water and include many pathways including inhalation, ingestion of drinking water, produce, milk and meat [EPA 1997]. The most common sources of particulate emissions are caused by fossil fuel and wood combustion along with dust particles created by land-use changes.

***Photochemical Smog Formation* –** Low level tropospheric ozone, also known as smog, is created when sunlight causes a chemical reaction to occur between nitrogen oxides (NOx) and volatile organic compounds (VOC's). Ground level ozone is caused primarily using vehicles in city environments during summer months, although electric power utilities and industrial facilities also contribute. Photochemical smog creates a plethora of human health problems, namely respiratory issues such as bronchitis, asthma and emphysema, while it can also cause crop damage and ecosystem damage as well.

***Ozone Depletion* –** Ozone (O3) within the stratosphere provides protection from radiation, with subsequent decreases having been linked to increased rates of skin cancer, cataracts, crop damage, immune-system suppression and damage to materials and marine life.

Ozone depletion is caused primarily by Chlorofluorocarbons (CFC's), foam blowing agents, solvents and halons such as those used in fire extinguishers.

Resource Depletion **–** Resource depletion occurs when either renewable or non-renewable resources are used beyond their rate of replacement. It is most commonly used in reference to farming, fishing, mining, water usage and the consumption of fossil fuels. [Science Encyclopedia 2016] Resource depletion is an extremely important issue for the use and development of sustainability metrics and LCA methodologies. Unfortunately, it is one of the most difficult issues to quantify while attempting to minimize value choices and assumptions. Among the TRACI impact categories, the quantification of resource depletion is the most controversial [Venditti 2012].

For my LCA project, TRACI 2.1 was selected in large part because it was designed specifically for applications within North America, as opposed to several other methods available that cater to European products and processes. As mentioned, certain impact categories such as resource depletion are hard to quantify due to legislative and control measures that vary between countries. Using a LCIA method developed by the EPA for North American applications helps to alleviate some of these concerns. Additionally, the number of impact categories included in the assessment tool is numerous allowing a wide range of impacts to be identified. Finally, it is a mid-point assessment method which prevents data aggregation and helps to provide results that can be easily understood and implemented in future studies.

3.5 Fuel Consumption

To calculate the potential fuel savings of the bio-composite tub through light-weighting, work done by Koffler and Brandenburger, as well as a report released by the International Aluminum Institute (IAI) was used. Both resources provided the background and calculations necessary to determine the fuel reduction value (FRV), which is based on a standardized driving cycle known as the New European Driving Cycle (NEDC). The NEDC specifies speed and chosen gear as a function of time, as well as additional information related to ambient temperature, resistance factors, driving behaviour and energy supply [IAI 2003]. As the NEDC is used to measure all published fuel consumption figures in Europe, it often serves as a reference for automotive light-weight LCA's, also making it applicable for other driving cycles as well, including those in North America. In practice, a FRV between 0.15-0.35 l/(100km*100kg) for gasoline vehicles and 0.12-0.28 l/(100km*100kg) for diesel vehicles was determined [Koffler 2009]. Based on the calculations carried out by the IAI, power train adaptations through the extension of gear ratios or the reduction in engine displacement had the largest effect on the FRV. Because a weight savings of approximately 12 kg is achieved by replacing the metal passenger tub with the flax bio-composite, which is small compared to the vehicles curb weight, no adaptation was assumed to have taken place, thus for this study a FRV of 0.15 l/(100km*100kg) was selected. Included below are the calculations required to find the mass-induced fuel consumption, ascertained fuel reduction values and weight-induced decrease in fuel consumption of new design options.

Figure 3. Calculation of the weight-induced fuel consumption (NEDC) for naturally aspirated gasoline engines.

$$V_{100\text{ kg, NEDC}} = 1.95\text{ MJ}*1.02*0.07\overline{3}\text{ l/MJ} \approx 0.15\text{ l/(100 km*100 kg)}$$

Table 3. Ascertained fuel reduction values in (l/(100km*100kg)) (Rohde-Brandenburger and Obernolte 2008).

Engine type	No adaptation[a]	Adaptation[a]	Min	Max	Arithmetic mean
Gasoline	0.15	Gear ratio	0.29	0.39	0.32
		Displacement	0.36	0.45	0.39
Diesel	0.12	Gear ratio	0.27	0.30	0.29
		Displacement	0.24	0.29	0.26

[a] Power train adaptation to achieve equal driving performance, e. g., extension of gear ratio or reduction of engine displacement

Figure 4. Calculation for the decrease (or increase) in fuel consumption for a given design option i.

$$\Delta C_{comp,i} = \Delta m_i * V_{100\text{ kg, NEDC}} *0.01 = (m_{comp,i} - m_{comp,ref}) * V_{100\text{kg, NEDC}} *0.01$$

with

$\Delta C_{comp,i}$ weight-induced decrease (or increase) in fuel consumption of component design option *i* (l/100 km)

$m_{comp,i}$ component mass of design option *i* (kilogram), and

$m_{comp,ref}$ reference component mass (kilogram).

The current gasoline GO-4 has a curb weight of 1465 lbs. It is powered by a small automatic 69 horsepower 1.0 l engine, which averages 45 mpg or 5.23 l/100km. Equipped with a 9-gallon fuel tank, in ideal conditions the GO-4 has a maximum range of roughly 400 miles. Based on the calculations provided, around 19% of the GO-4's fuel consumption is weight induced. The metal passenger tub, which weighs a little more than 70 lbs is responsible for the consumption of roughly 47.7 ml/100km of gasoline, while the bio-composite passenger tub consumes a little more than 30 ml/100km. Replacing the current tub with the bio-composite, which weighs 43.3 lbs would result in a little over 18 ml/100km of fuel to be saved. Based on the 65,000-mile driving average included as part of this study's functional unit, the metal and bio-composite passenger tubs would be responsible for consuming roughly 50 litres and 30 litres of gasoline throughout the course of the GO-4's lifetime respectively. Vehicle emissions have been based on the estimates used by the EPA of 8,887 grams CO_2/gallon of gasoline. Included below are the specific fuel consumption values for each passenger tub.

Table 4. GO-4 passenger tub weight induced fuel consumption.

	Tub Weight (kg)	**Weight Induced Fuel Consumption (ml/100km)**	**Total Fuel Consumption (Litres)**
Metal Passenger Tub	31.8145152	47.7217728	49.9204866713
Bio-Composite Passenger Tub	19.64055	29.460825	30.8181912667

3.6 Transportation

For my study, all the metal was sourced from the American mid-west, and as such, a 2,000-km transportation distance was applied to the steel, aluminum and hardware components. A 500-km transportation distance was applied to the acquisition and processing of all materials needed to produce the bio-composite. The disposal of each tub is assumed to be conducted locally, hence a 100-km distance was applied to both, the recycling and landfilling waste treatment scenarios. LCI data for a 16-32 metric tonne lorry was used for all material transport in both LCA's.

3.7 Passenger Tub Weights and Materials

The metal passenger tub currently being used in the GO-4 is made up of 10 different steel and aluminum components, as well as some additional hardware. Weighing a little over 70 lbs the metal passenger tub represents 4.8% of the current vehicles total weight. LCI data for the manufacture of the metal components was acquired using SimaPro which was located in the Ecoinvent v3 library. For the 39.4 lbs of steel needed to produce the current passenger tub, an average global market allocation for the production and sheet rolling of unalloyed steel was used. The aluminum components, which weigh 27.6 lbs, as well as 3.139 lbs of the hardware, was similarly modelled on global market averages. These inputs provide cradle-to-gate LCI data and as such represent all the environmental impacts associated with the extraction and production of the metal components used in the current passenger tub. Important to note is that some of the inputs associated with the processing of these metal components has been excluded from this study. Data related to the cutting, bending or welding of sheet metal for each of the components was not readily available, making that incorporation into this study infeasible. Other automotive LCA's have run into the same problem as assembly data associated with a specific component often includes inputs that are extremely hard to quantify. Relative to the impacts associated with the production, use and disposal of the current passenger tub, activities such as the electricity required to operate the machinery that bends and cuts 40 lbs of sheet steel would be negligible. Examining the process flow chart for the metal passenger tub provides greater detail the materials and activities that have been modelled using SimaPro.

Table 5. GO-4 metal passenger tub material composition.

Component	Material	Weight (kg)
Brake Booster Box	Steel	3.81018

Heater Box	Steel	1.36078
Dash Panel Support	Steel	3.35658
Floor Support	Steel	5.715264
Floor Support Gussets	Steel	1.4515
Seat Support Gussets	Steel	0.635029
Seat Angle	Steel	1.54221
Seat Box Sides	Aluminum	2.17724
Seat Box	Aluminum	5.261671
Floor	Aluminum	5.080235
Hardware	Stainless	1.4238264
Total		31.8145152

The bio-composite passenger tub being designed by the CIC is made up from two different components produced using flax fibre and PHA resin. Once completed the composite tub will weigh roughly 43 lbs and represent 3% of the GO-4's curb weight. Based on the work done by Turunen and van der Werf, the LCI flax fibre data for my study was acquired from the *Life Cycle Assessment of Flax Fibres for the Reinforcement of Polymer Matrix Composites* [Dissanayake 2011, Turenen and Werf 2008]. The outcome of this LCA provided the inputs and energy used in the production of flax fibres using conventional tillage and bio-retting. All of the impacts associated with the production of one tonne of flax sliver have been provided, including things such as land use, fertilizers and pesticides, harvesting and fibre processing. The specific inputs for the flax fibre have been included in **Appendix D.**

LCI data for the PHA was acquired from work conducted by K.G. Harding, et al. Based on several LCA studies of biopolymers created using different carbon substrates, research members modelled the inputs associated with the cradle-to-factory gate production of one tonne of PHA [Harding et al. 2007]. This PHA uses agricultural residues to produce a resin that is renewable and largely biodegradable. Work currently being done by Genome Prairie and Dr. David Levin from the University of Manitoba, is attempting to create a biopolymer that will be used specifically for the application in the GO-4 vehicle. Although not yet complete, the aim of this research will be to produce an entirely biodegradable bio-composite passenger tub from locally sourced materials. For my thesis research done by K.G. Harding et al. was used as it provides the input data for PHA production that is based on several previously conducted LCA's and should be considered a reliable frame of reference. In keeping with the aim of this study, the impacts associated with the production of the passenger tub's biopolymer should be as site and material specific as possible, hence, it is recommended that the impacts of the biopolymer be re-examined once the work being done by Dr. Levin, and inclusion of the final resin into a working prototype is completed. The material weights of the bio-composite passenger tub have been included below and specific inputs for resin production included in **Appendix E**.

Table 6. GO-4 bio-composite passenger tub material composition.

	Flax Fibre (kg)	**PHA (kg)**	**Total (kg)**
Front Dash	0.84	5.11	5.95
Bottom Tub	4.87	8.82	13.69
Total (kg)	5.71	13.93	**19.64**

3.8 SimaPro 8

For my study SimaPro 8.2 was used to help map the process flow charts for the individual passenger tubs, as well as to calculate and compare the associated impacts of each tub. Used by many LCA practitioners, the SimaPro software suite was designed to help collect, analyse and monitor the sustainability performance data of a product or service. The software can be used for a variety of applications, such as sustainability reporting, carbon and water foot printing, product design, generating environmental product declarations and determining key performance indicators [Pre-Sustainability 2016]. Programs such as SimaPro are an essential tool for anyone interested in conducting LCA's as they allow complex life cycles to be easily modelled and analysed, can measure environmental impacts across all life cycle stages and identify hotspots in every link of the supply chain, from extraction of raw materials to manufacturing, distribution, use and disposal. Not only does SimaPro aid in the calculation of the various impacts associated with a product or processes life cycle, but it also offers access to a range of LCI databases which drastically reduces the burden associated with first hand data collection. Although other LCA programs are available, such as GaBi Life Cycle Assessment Software, having examined many peer-reviewed LCA studies, SimaPro seemed to be the preferred choice. Given the popularity of the program for LCA applications and the overall user-friendly nature of the software, SimaPro was deemed the ideal choice for my study.

Included in the software package is access to multiple LCI databases or libraries. These include Ecoinvent v3, Agri-footprint, US LCI, ELCD, EU and Danish Input Output, Industry data v2 and Swiss Input Output. Compliant with the ISO 14040 and 14044, these databases provide primary data from a range of materials, products and services that can be easily incorporated into a new LCA project. Ecoinvent itself provides access to over 12,800 LCI datasets in the areas of energy supply, agriculture, transport, biofuels and biomaterials, bulk and specialty chemicals, construction materials, packaging materials, basic and precious metals, metals processing, ICT and electronics, dairy, wood and waste treatment, making it one of the most extensive international LCI databases currently available [Wernet 2016]. Once the data for an LCA has been collected, SimaPro also allows many different LCIA methods to be applied to quantify the environmental impacts. Included in these methods are many European, North American, single and multi-issue options such as TRACI, BEES, ReCiPe and Cumulative Energy Demand. The methods themselves are further divided by characterization, damage assessment, normalization, weighting and addition. Once the results of an LCA have been calculated, SimaPro makes it easy to analyze them and present the findings in a transparent and accessible manner.

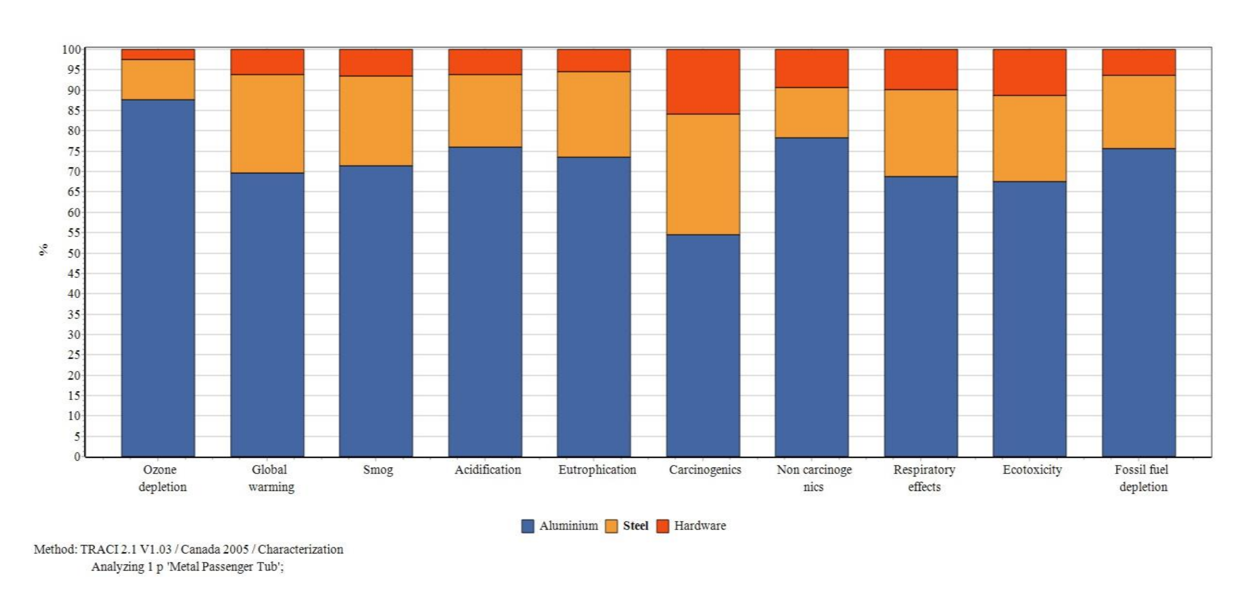
3.9 End of Life

For this LCA two different waste scenarios have been created for the metal passenger tub. In the United States, on average 90% of the aluminum and 80% of the steel components for a vehicle are recycled, with the remainder, known as automotive shredder residue (ASR) being put into landfill [EPA 2016]. Additionally, automotive components can be created using either primary or secondary metals. It is important to take these factors into account when applying an end of life scenario to a LCA as often the impacts associated with the production of primary metals can be significantly offset by various recycling processes. To avoid the issue of double counting and provide a representative sample, the tub has been modelled under the conditions that one half of the metal components have been created using primary manufacturing techniques while the other half is sourced using recycled metals. This assumption falls in line with the findings of the United States Geological Survey (USGS) that in 2002 found 45% of all vehicles produced in the U.S. were made using recycled metals [USGS 2002]. Input data related to the waste treatment of the metal passenger tub, including both disposal scenarios was acquired from the Ecoinvent v3 database.

Unlike the metal passenger tub, the bio-composite tub has only one disposal scenario. Because the flax fibre and PHA biopolymer are produced from agricultural residues, it was assumed that all product waste would be biodegradable. Using LCI data for the landfill operations of biodegradable waste, most of the emissions from this scenario are the result of any equipment or activities required to process the waste, albeit some of the energy is also recaptured. Although different waste scenarios exist for bio-composites, such as incineration, to limit the breadth of my study, landfilling was the only option explored.

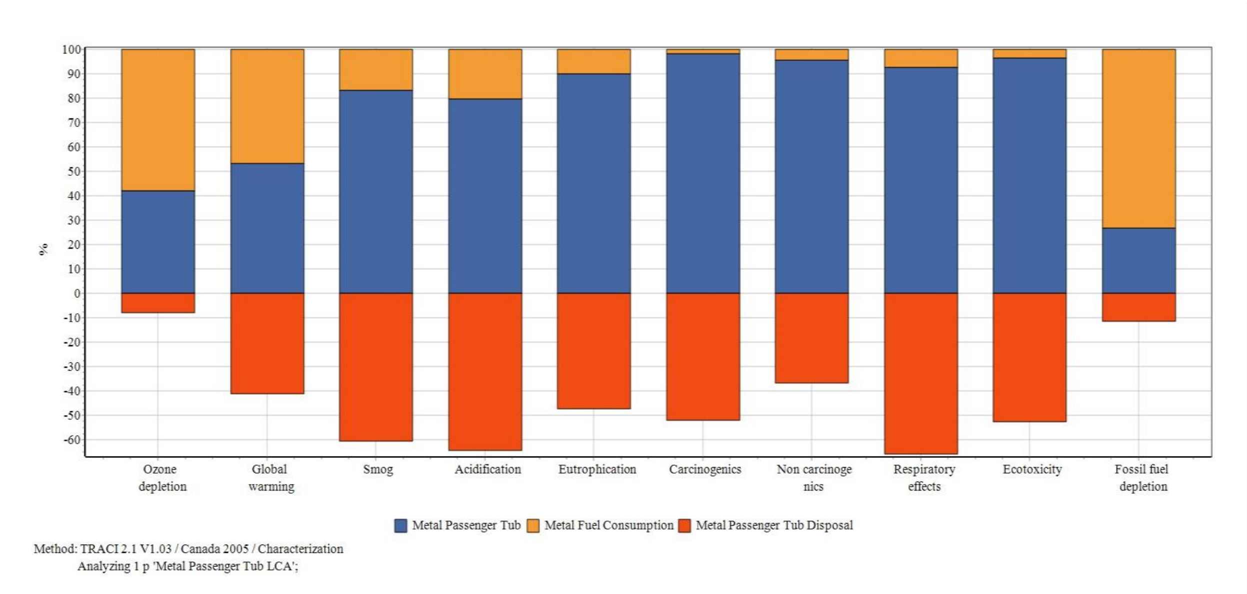
Chapter 4: Results

Figure 5. Metal passenger tub production impacts.



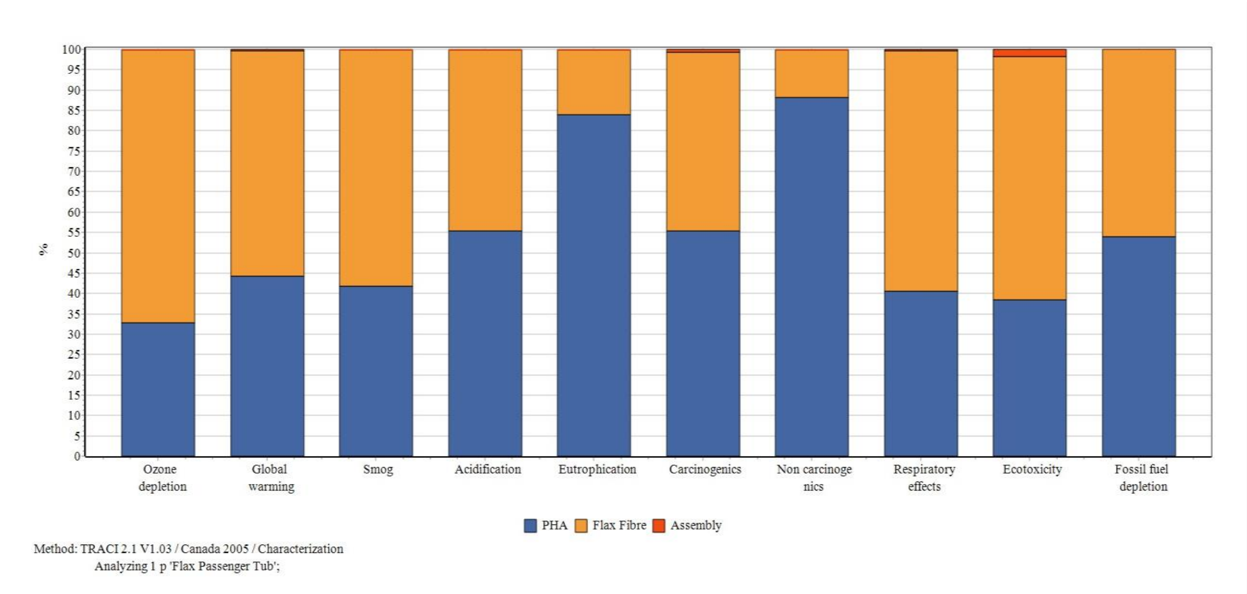
Although 39% of the metal passenger tub is made from aluminum, most of the environmental impact has been associated with aluminum production across all categories. The process of transforming raw bauxite into aluminum is incredibly energy intensive requiring large amounts of electricity, water and other resources. Of the 165 kg CO_2 eq caused during the manufacture of the metal tub, 115 kg CO_2 eq is due to the use of aluminum. Steel was responsible for creating 39.8 kg CO_2 eq, while the hardware produced 10.1 kg CO_2 eq. Other processing activities such as sheet rolling had negligible effects, causing 12.68 kg CO_2 eq. The steel and hardware components had the largest impact relative to aluminum in the carcinogenic category, representing 55.5% of the total. Roughly 85% of all the carcinogenic impacts are caused by chromium-6 releases into water. Across all categories aluminum production caused the largest environmental impact, albeit these impacts can be negated by recycling and vehicle light-weighting. Impacts associated with transportation represented less than 1% of the total.

Figure 6. Metal passenger tub life cycle impacts.



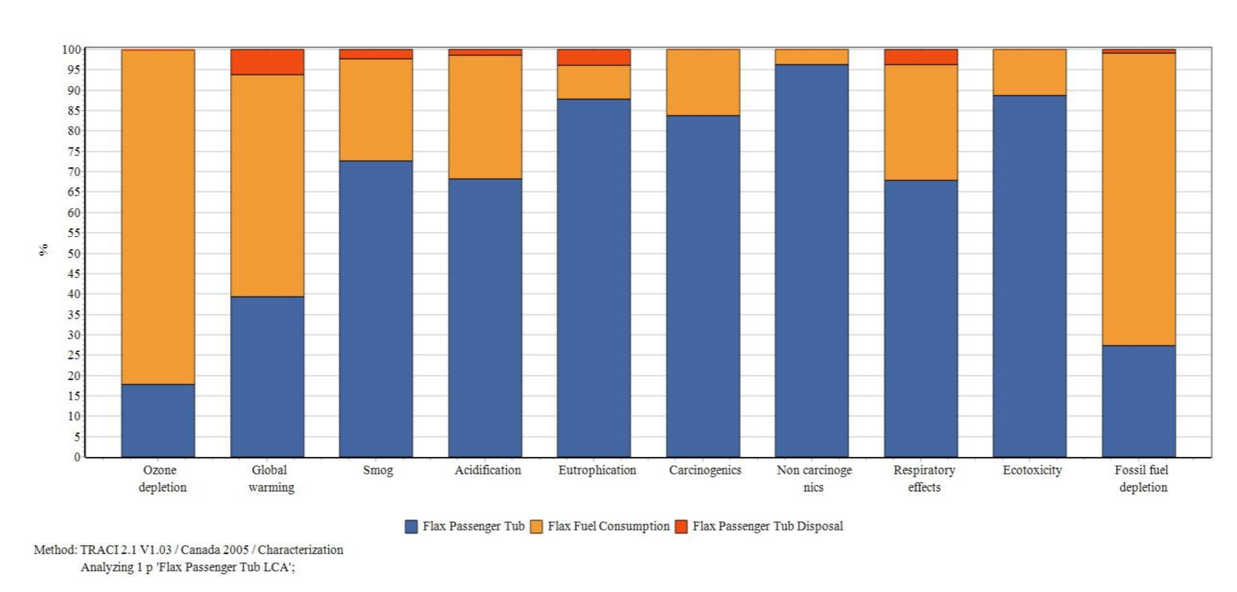
Looking at the entire life cycle of the metal passenger tub, steel and aluminum production dominate across most categories. Many of the cradle-to-gate impacts of the metal components can be prevented however, by introducing a recycling scenario. Recycling 90% of the aluminum and 80% of the steel resulted in 115 kg and 12.9 kg CO_2 eq to be saved respectively. Roughly 70% of the benefits associated with aluminum recycling were caused by the prevention of primary ingot production in background systems. Although the landfilling of the remaining shredder residue produced environmental harm, these impacts were outweighed by the advantages associated with recycling. Overall the metal tub produced 182 kg CO_2 eq over the course of its lifetime, with 145 kg CO_2 eq of the emissions coming from the use phase. 57.8% of the ozone depletion, 46.8% of the global warming and 73.3% of the fossil fuel depletion was caused by the combustion of gasoline. Although the use phase does not dominate many of the impact categories for the metal passenger tub under a 65,000-mile driving scenario, longer driving distances would likely encourage the use of more aluminum as the advantages associated with light-weighting would become increasingly apparent.

Figure 7. Flax bio-composite passenger tub production impacts.



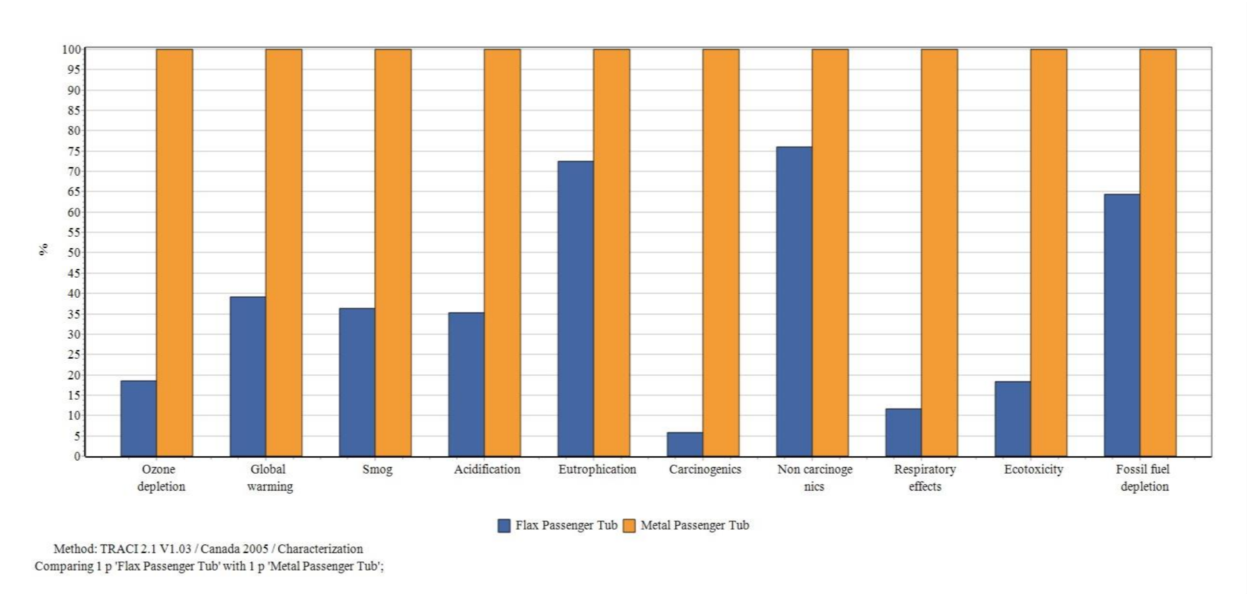
All the processes involved to manufacture the flax fibre bio-composite passenger tub resulted in 64.5 kg CO_2 eq. Of this, 35.7 kg and 28.6 kg CO_2 eq was caused by flax fibre and PHA production respectively. For the flax fibre, field operations such as harvesting contributed 2.97 kg CO_2 eq, meanwhile the decortication and processing of the flax caused 8.36 kg CO_2 eq in emissions. The largest contributor to the production of flax fibre was the use of fertilizers, namely ammonium nitrate, as it produced 19.8 kg CO_2 eq. The use of pesticides during farming operations also played a role in multiple impact categories for both the flax fibre and PHA. Much like flax fibre, the main global warming impacts of the PHA resin were caused by using ammonium nitrate, while the remaining emissions occurred during PHA production, namely generating steam or heat. Most of the eutrophication from the PHA was due to higher nitrate use for sucrose production, while non-carcinogenic impacts were caused by zinc releases into soil. Although it had very little impact, 1.76 kwh of electricity was also included to represent the impacts associated with operating the vacuum pump during the production of the bio-composite at the CIC.

Figure 8. Flax bio-composite passenger tub life cycle impacts.



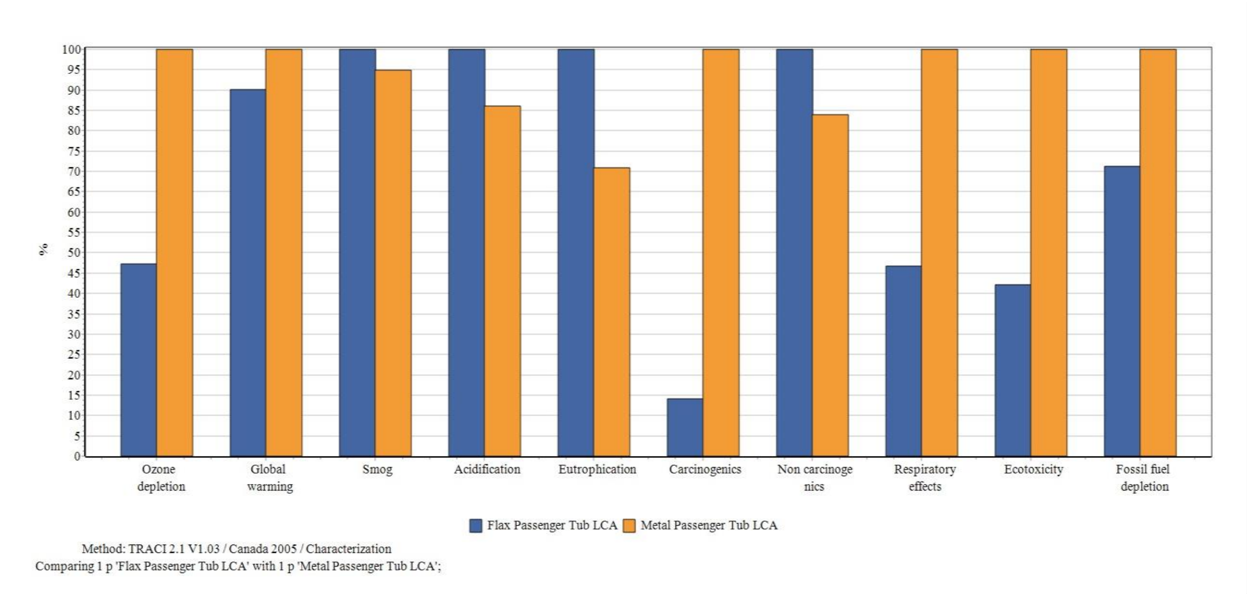
While examining the entire life cycle, the production of the bio-composite passenger tub created the largest impact in most categories apart from ozone depletion, global warming and fossil fuel depletion. In total 164 kg CO_2 eq is produced over the course of the bio-composite tubs lifetime, while 55% or 89.6 kg CO_2 eq is the result of the use-phase. 81.9% of the total ozone depletion and 71.7% of the fossil fuel depletion is also caused by vehicle use. Unsurprisingly, the use-phase for the bio-composite is much smaller than that of the metal passenger tub, due to roughly 20 less litres of gasoline being combusted. Environmental stress caused during disposal of the bio-composite is related to normal landfill operations and the data provided in the Ecoinvent v3 database. The impacts of material transportation unrelated to vehicle use represents less than 1% of the total in all categories.

Figure 9. Comparison of production impacts.



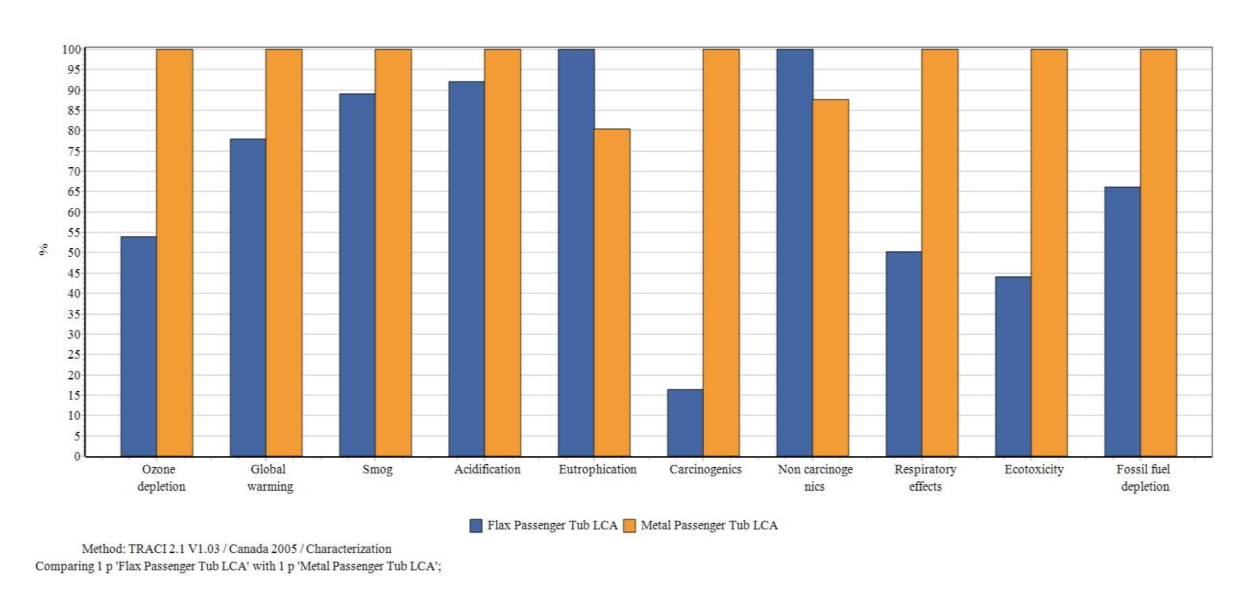
Comparing the cradle-to-gate impacts of both passenger tubs clearly indicates that the metal passenger tub causes the greatest amount of environmental harm during production across all categories. The flax passenger tub produces 81.5% less ozone depletion, 60.9% less global warming and 35.6% less fossil fuel depletion than the metal tub. Nearly double the amount of all CO_2 eq emissions for the bio-composite are caused by the aluminum production required for the metal passenger tub alone. Of the two impact categories in which the bio-composite is much closer to the metal tub, as mentioned, eutrophication and non-carcinogenic stress occurs primarily from agricultural activities required to produce sugar crops. The carcinogenic and respiratory impacts of metal production occur primarily from slag treatment, spoil from mining operations and electricity production. Looking strictly at the impacts of production and manufacturing it becomes clear that any benefits associated with the use of the metal passenger tub rely heavily on waste treatment as compared to the bio-composite.

Figure 10. Comparison of life cycle impacts.



Measuring the entire life cycle of each passenger tub, the bio-composite is ideal in all areas except for smog, acidification, eutrophication and non-carcinogenics. Removing use from the life cycle and looking strictly at production and disposal, interestingly the metal passenger tub is more ideal in some areas such as global warming as it produces 37 kg CO_2 eq as compared to the bio-composite which produces 74.4 kg CO_2 eq. One of the largest benefits associated with the bio-composite passenger tub occurs during the use-phase, in which light-weighting reduces CO_2 eq emissions by 92.4 kg. Overall, the bio-composite passenger tub produces 52.7% less ozone depletion, 10% less global warming and 28.8% less fossil fuel depletion. In certain categories, substantial differences exist, as the bio-composite produces 85% less carcinogenics, 53.2% less respiratory effects and 57.8% less ecotoxicity. Comparing the two products it becomes clear that the use and disposal phases play an essential role in determining which product is more environmentally ideal.

Figure 11. Comparison of life cycle impacts under a maximum driving scenario.



Applying a 120,000-mile driving distance to the use phase of both passenger tubs further illustrates the advantages associated with the bio-composite. 320 kg CO_2 eq would be produced by the metal tub in this scenario, with 283 kg or 88% of that coming from vehicle use. The bio-composite creates 249 kg CO_2 eq overall, again with the use phase contributing most the emissions at 175 kg CO_2 eq. Compared to the metal tub, extending the range of the vehicle from 65,000 to 120,000 miles improved the global warming impact of the bio-composite by 12%, as in the max driving scenario the flax component produced 22.1% less global warming. In other impact categories, such as smog and acidification, the continued use of the vehicle heavily disadvantaged the metal passenger tub. The only two areas in which the metal passenger tub produced less impact was eutrophication and non-carcinogenics.

Chapter 5: Discussion

5.1 Interpretation

Overall I was successful in developing reference flow models for both, the metal and bio-composite GO-4 passenger tubs. Working with Shawna DuCharme of the CIC and Stefano Franz from Westward Industries Ltd. I was provided a list of the metal components that are used to produce the current GO-4 passenger tub. Along with this data, I was provided the amounts of flax fibre and PHA that would be used to manufacture the bio-composite. Using these values, I began collecting LCI data relevant to the production of the materials needed for each tub.

All the inputs for the metal passenger tub were collected using SimaPro and included in the Ecoinvent v3 library. Based on data provided by the USGS, half of the metal components were assumed to be sourced from primary metal production, while the other half was made up from secondary or recycled metals [USGS 2002]. Transportation distances were selected to represent the use of metals manufactured in the United States. Using automobile statistics provided by the EPA, 90% of the aluminum and 80% of the steel was recycled, while the remaining ASR was put into landfill [EPA 2016]. A process flow chart for the entire life cycle of the metal passenger tub has been included in **Appendix B.**

The inputs associated with the production of flax fibre were based on research by N. Dissanayake, who conducted a life cycle assessment of flax fibres used for the reinforcement of polymer matrix composites. LCI data for the PHA was modelled after the work done by K.G. Harding et al. who compiled the results of several PHA LCA's to represent the typical impacts caused by PHA manufacturing. Because the bio-composite passenger tub is produced using agricultural residues and is considered biodegradable, the disposal scenario for the bio-composite was modelled using LCI data for the treatment of biodegradable waste. The life cycle of the flax bio-composite is included in **Appendix C.**

Based on information provided by Westward Industries Ltd. the typical vehicle usage was represented by a 65,000-mile driving scenario. Using NEDC driving cycles a FRV was selected and used to quantify the amount of gasoline each passenger tub was responsible for using, meanwhile the emissions of the use-phase were based on data provided by the EPA. Once the LCI data for both passenger tubs was collected and modelled, the TRACI 2.1 LCIA methodology was used to characterize the environmental impacts. Comparing the LCA's of each passenger tub revealed many differences.

One of the aims of my study was to determine which passenger tub produced the least amount of environmental harm. Comparing the results of each LCA it becomes clear that the bio-composite passenger tub is the ideal choice. Under normal driving conditions the flax passenger tub produced 10% less global warming, 28.8% less fossil fuel depletion and 52.7% less ozone depletion. The metal passenger tub also produced significantly more impact in the carcinogenic, respiratory and ecotoxicity categories. Interestingly, for the bio-composite the use-phase represented 55% of all global warming emissions, compared to nearly 80% for the metal tub. Extending the use of the vehicle widened the gap between the passenger tubs in most impact categories. Under a 120,000-mile driving scenario, the bio-composite excelled in most categories, apart from eutrophication and non-carcinogenics. Most importantly, extending the driving distance resulted in the bio-composite creating 71 kg less CO_2 eq or 22.1% less global warming compared to the metal passenger tub.

Most of the environmental stress associated with the current passenger tub is the result of aluminum production and vehicle use. Although many of the adverse effects of aluminum production can be offset by recycling, the use of metal in the GO-4 passenger tub means that these environmental impacts can be negated only if the vehicle is properly disposed. When most of the metal components are recycled, the use-phase dominates ozone depletion, global warming and fossil fuel depletion. The remaining impact categories are primarily controlled by aluminum production, namely in the form of slag treatment, mining operations and electricity generation. For both passenger tubs, the transportation of materials had negligible effects on the overall impact of the product, indicating that the material weight, composition and disposal technique, are by far the largest factors in determining the environmental benefits of a product.

5.2 Implications

5.2.1 GO-4 Use Cycle

Comparing the results of my study to other automotive LCA's provided very similar outcomes. Replacing a non-renewable component with a bio-composite in seven different vehicles, reduced GHG emissions by 19% on average in Claire Boland's study of the impacts of renewable material content and light-weighting [Boland 2014]. These results are similar to the GO-4, of which 10% and 22.1% CO_2 eq reduction was achieved using the bio-composite under normal and long distance driving. Like other automobile LCA's, the use-phase of the GO-4 caused most of the impacts for each passenger tub. Because the use phase is dominant, the mass induced fuel consumption strongly dictates the environmental impact of automobile parts. In comparison to other studies however, which look at the life cycle of vehicles that are expected to be driven much further, in some cases over 200,000-miles, the much smaller distance associated with normal driving of the GO-4 means that the use-phase is not as dominant with respect to production.

Because the FRV used in this study is based on the NEDC, which represents the average driving conditions and behaviours of a typical passenger vehicle, certain differences are likely to exist for the GO-4. Designed for urban activities including police patrol and parking enforcement, the expected use of the GO-4 is much different than the typical passenger car. Based on IAI estimates, in city environments rolling and acceleration resistance make up 88% of all resistance factors. As such, light-weighting plays a much larger role in reducing vehicle emissions when the vehicles speed is kept low. Any changes made to the gear ratio or engine displacement from light-weighting also produces significantly less environmental impact, as FRV's can range from 0.29-0.45 under these conditions, compared to the 0.15 used in this study. These factors indicate that there are substantial opportunities to change the FRV by replacing additional components of the GO-4 with biomaterials and that the benefits associated with replacing the current passenger tub would be even greater than the results of this study suggest if the vehicle was primarily used for city driving.

5.2.2 GO-4 Disposal

Impacts associated with the manufacture of the metal passenger tub are substantially larger than those of the bio-composite. Due mostly to the production of aluminum, the metal passenger tub relies heavily on recycling to offset these burdens. If more than 10% of the aluminum used to produce the current tub was not recycled, the bio-composite would quickly extend its advantage over the metal passenger tub in almost all the LCIA impact categories. Additionally, if more than 50% of the current tub was produced using primary rather than recycled metals, the advantages associated with the bio-composite would be considerably amplified.

Using natural materials that can be disposed of as biodegradable waste provides many advantages for the bio-composite passenger tub. Because the tub is made from agricultural residues means that they are renewable and carbon neutral. Any impacts that are caused throughout the life cycle of the bio-composite are related to the production of the materials themselves, and unlike the metal passenger tub, the advantages of this product do not hinge on adhering to a specific disposal scenario. This allows the flax component to be used in situations where the availability of metal recycling is limited without markedly changing the overall impact of the product. For instance, remote areas or even countries with poor recycling rates would be ideal candidates for biomaterial use. Using a passenger tub that can be disposed of as biodegradable waste would likely offset some additional impacts related to transportation, as the proximity of recycling facilities in many locations may be greater than that of a landfill.

5.2.3 Impact on Manitoba Bio-materials Industry

In keeping with Manitoba's Growing Green Bioproducts Strategy, the results of my study have provided strong evidence to support the use of renewable natural fibres in automotive applications. Not only does adopting the use of bio-composites reduce many environmental impacts, but also provides farmers and companies such as Westward Industries Ltd., the opportunity to position Manitoba as a leader in the emerging biomaterials sector. Although flax yields within the province have been historically declining, being replaced by crops such as soybean and canola, it stands to reason that developing a high value market for flax fibre could help combat some of these trends. Work being done by organizations like Prairie Genome and the CIC have made strong efforts to encourage the use of natural materials within the manufacturing sector by offering sophisticated and high preforming products, such as the bio-composite passenger tub included in this study. To protect the development of Manitoba's biomaterials industry, studies like my own must continue to be made to combat the effects of greenwashing and provide consumers practical evidence supporting the advantages of biomaterial use.

5.3 Recommendations

Based on the results of my study I strongly recommend that Westward Industries Ltd. replace the metal passenger tub they are currently using in favour of the flax bio-composite being designed by the CIC. Reducing the vehicles weight by roughly 30 lbs results in several advantages. Under normal driving conditions this would save the customer 20 litres of gasoline over the course of the vehicles lifetime and reduce GHG emissions by approximately 10%. Because the GO-4 is typically used in urban environments where the vehicles speed is reduced, requiring frequent starting and stopping, factors such as rolling and acceleration resistance create unusually large impacts. For example, estimates included in the NEDC state that aerodynamic resistance contributes only 12% to vehicles driving in city conditions, meanwhile this number jumps to 62% when travelling at 90km/h. Although the GO-4 weighs very little compared to other automobiles and has excellent fuel economy, the way the vehicle is often used means that any form of weight reduction will substantially help in reducing emissions. As such, the FRV of 0.15 l/100km*100kg used in this study should be considered a conservative estimate. In the future, if Westward Industries Ltd. decides to replace more of the GO-4 with bio-composites to the point a change to engine displacement or gear ratio occurred, the environmental benefits of using biomaterials would be much larger than those suggested by this study.

Replacing the metal passenger tub made from aluminum and steel with the bio-composite would also reduce the vehicles dependence on the disposal scenario. Current production of the metal tub causes large environmental impacts that can only be offset if almost all the materials are eventually recycled. Compared to the metal tub, the impacts associated with using parts made from renewable materials is much easier to quantify, as there is no real way to know how much of each GO-4 sold will be recycled. Choosing to incorporate natural materials into their product, Westward Industries Ltd. will hopefully encourage other companies to follow suit, strengthening Manitoba's role as a biomaterials leader. Addressing consumer demands for greener products, Westward Industries. Ltd. could also use the results of my study to market their vehicle in new ways.

Chapter 6: Conclusion

This study analyzes the replacement of a 31.8 kg vehicle passenger tub made using steel and aluminum with a 19.64 kg bio-composite produced using flax fibre and PHA. Using life cycle assessment, I developed reference flow models mapping the processes and materials involved throughout the course of each passenger tubs lifetime. LCI data was acquired from previously conducted LCA's and input into SimaPro where the TRACI 2.1 methodology was used to model environmental impacts. The NEDC was used to develop the mass induced fuel consumption for each component, which was then applied to two different driving conditions. Three different disposal scenarios were included in the study representing the treatment of biodegradable waste, metal recycling and landfilling of automotive shredder residue.

By proving how material choices affect the life cycle of the GO-4 utility vehicle, I provided the CIC and Westward Industries Ltd. evidence the environmental merit of using the bio-composite passenger tub. Intended applications of the GO-4 meant that driving distances were quite short, resulting in the use-phase not being as dominate as compared to other studies. Although these findings suggest that the emissions reductions from light-weighting may not be as significant for the GO-4 as they are for vehicles driving longer distances, because the GO-4 is often used in city environments means that rolling and acceleration resistance plays a much larger role, hence the FRV used in this study should be considered a conservative estimate. Additional weight reduction resulting in modifications to the vehicles engine displacement or gear ratios would change the FRV, resulting in significantly different use-phase impacts.

Comparing the life cycles of each passenger tub showed that the bio-composite was ideal in most impact categories. Under normal driving conditions the bio-composite reduced global warming emissions by 92.4 kg CO_2 eq or 10%. Extending the GO-4 driving range to 120,000-

miles resulted in the weight savings of the bio-composite being amplified reducing GHG emissions by 22.1%. Production impacts were much larger for the metal passenger tub than for the bio-composite, indicating that most of the metal components need to be recycled to avoid environmental harm. Eutrophication, acidification and non-carcinogenic impacts of the flax bio-composite were largely the result of nitrate use in the agriculture industry.

Examining the results of my study clearly indicates the potential for biomaterials to be an effective replacement for non-renewables by lowering material weight and reducing environmental impacts. Because the composition and manufacturing techniques of biomaterials can greatly vary, it is important that while the implementation of biomaterials is being considered, tools such as life cycle assessment are used to find out the potential benefits beforehand. As such, life cycle assessments will continue to provide an essential role for allowing companies to make more informed decisions, prevent greenwashing and encourage the growth of the biomaterial industry as a whole.

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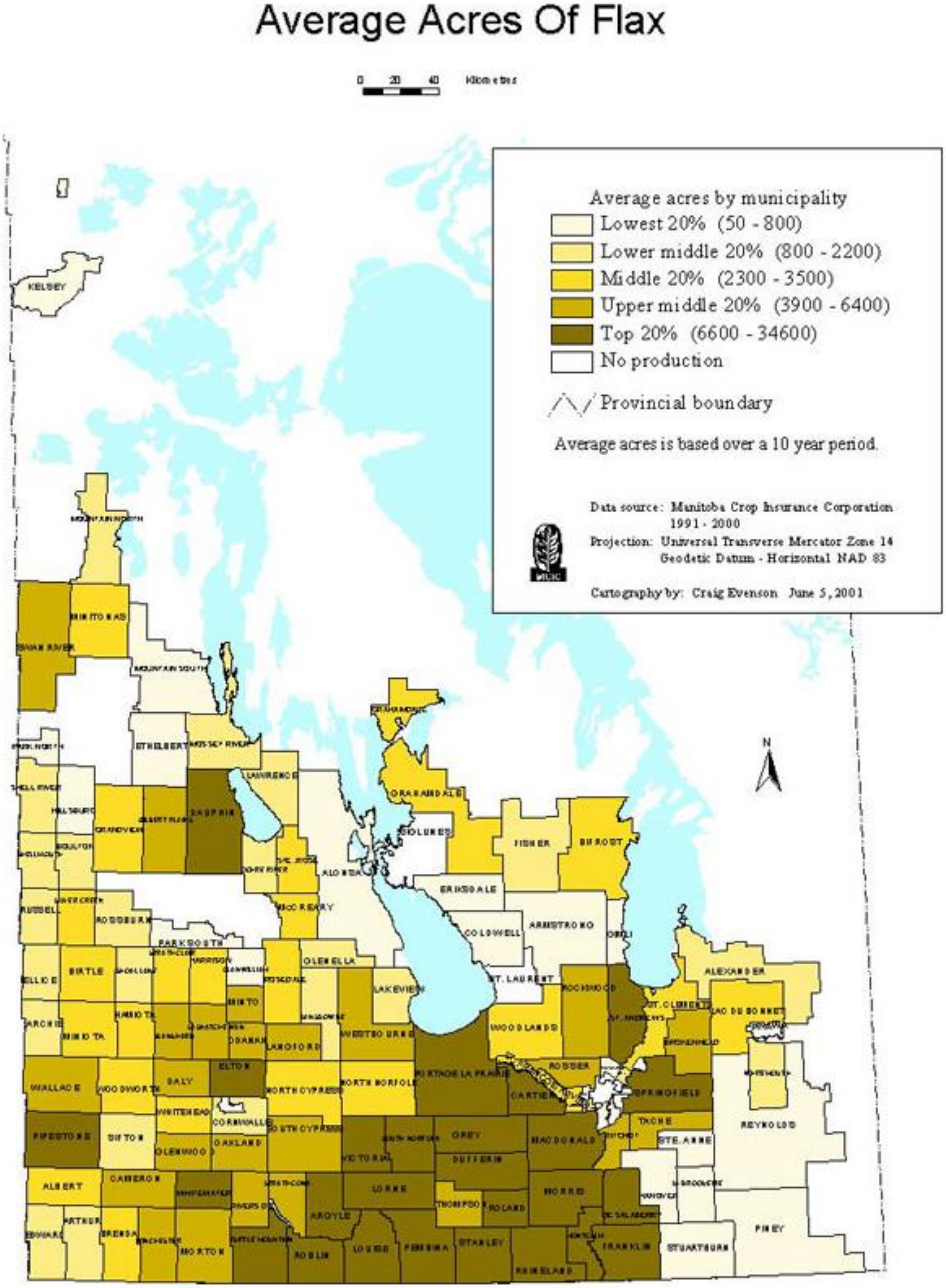
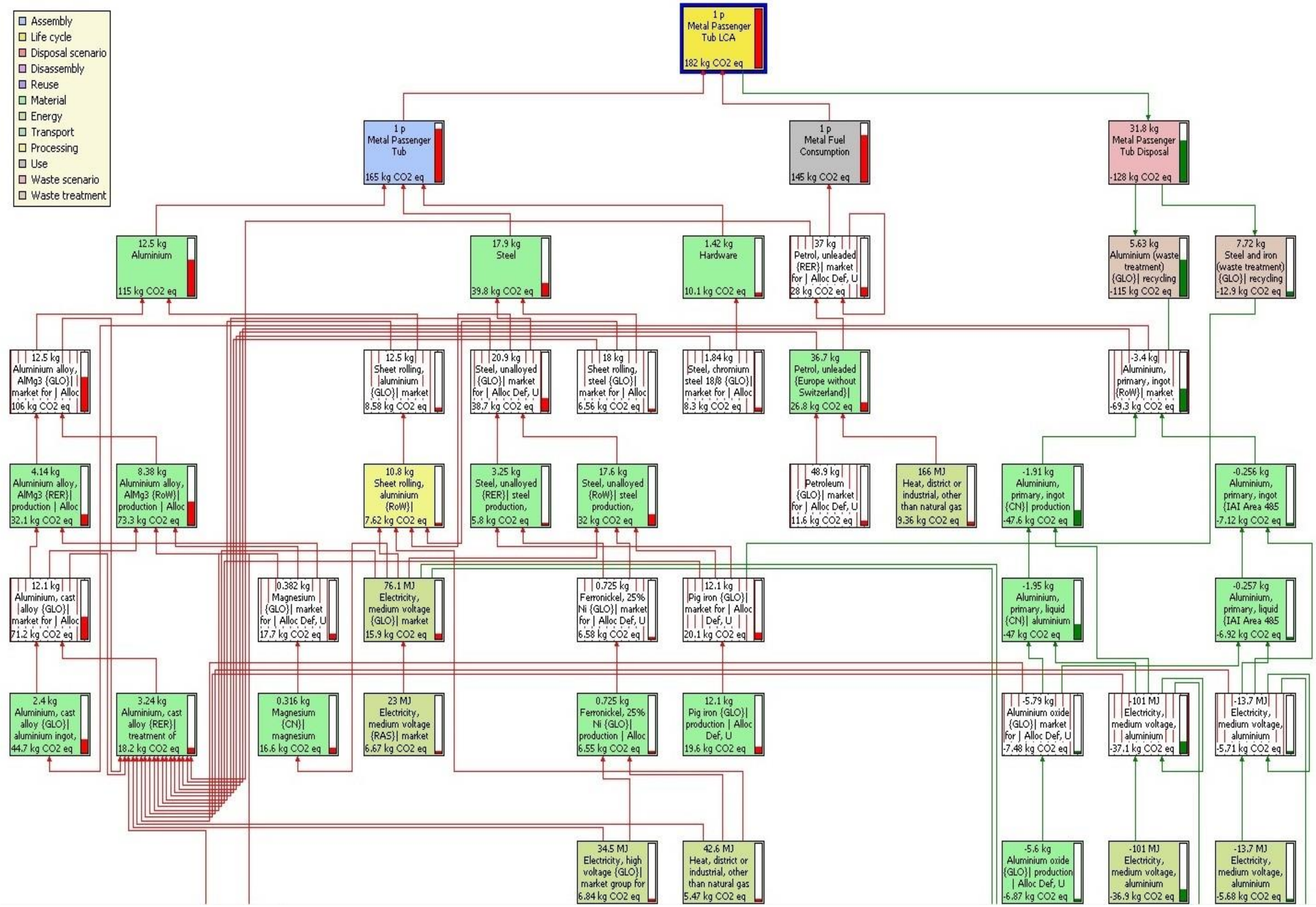
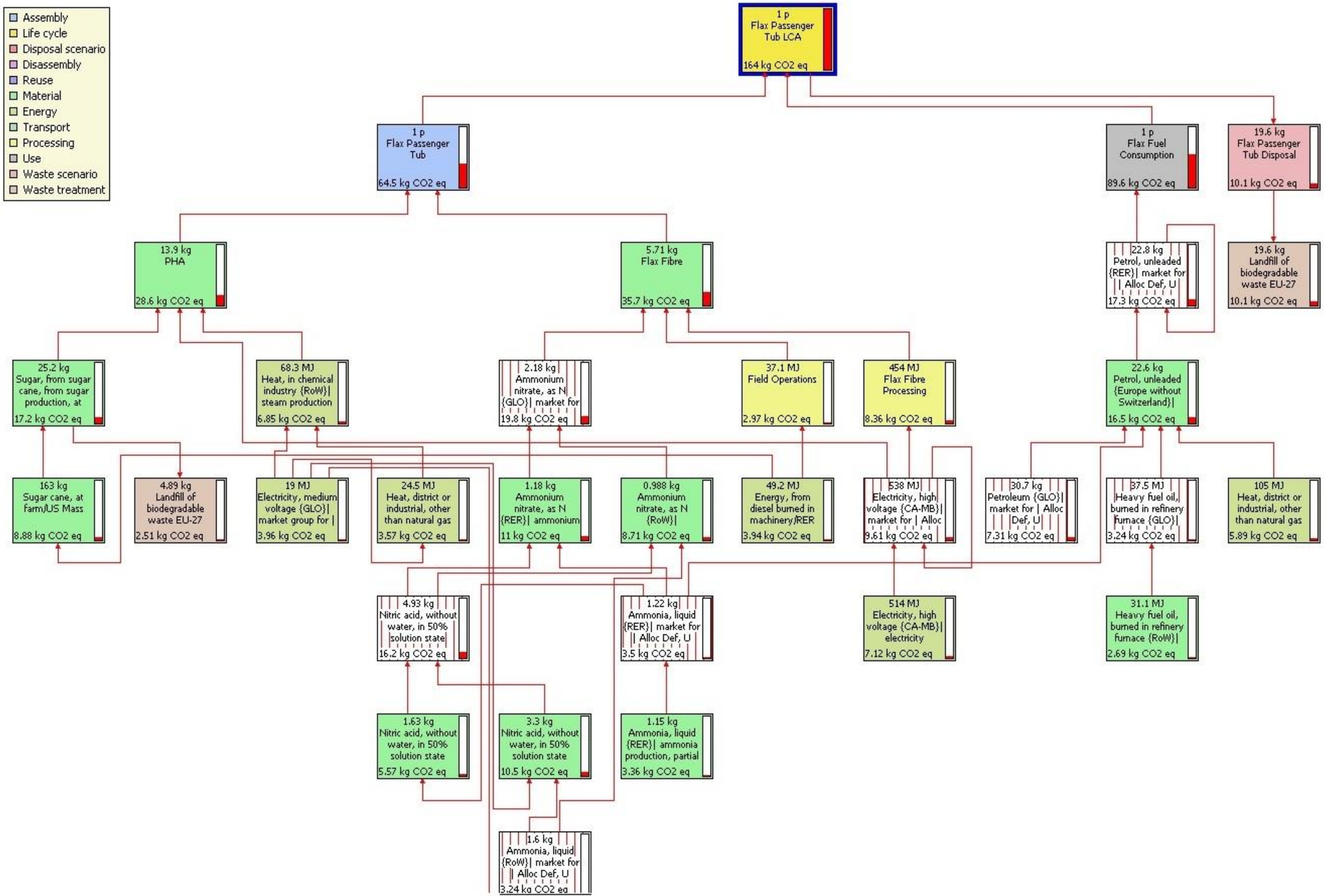
Appendix A – Manitoba Average Acres of Flax 1991-2000



Appendix B – Metal GO-4 Passenger Tub Life Cycle Network [3% cutoff criteria]



Appendix C - Flax GO-4 Passenger Tub Life Cycle Network [1.5% cutoff criteria]



Appendix D – Life Cycle Inventory for the Production of Flax Fibres Using Conventional Tillage and Bio-Retting Method.

	For the production of one tonne of flax sliver	**For the production of one tonne of flax yarn**
Land used	3.12 ha	3.24 ha
Seed	359 kg	373 kg
Lime	2076 kg	2160 kg
Ammonium nitrate	377.5 kg	392 kg
Triple superphosphate	340 kg	353.2 kg
Potassium chloride	259 kg	268.9 kg
Pesticides	8.04 kg	8.4 kg
Crop Production	**Energy (GJ/tonne of sliver)**	**Energy (GJ/tonne of yarn)**
Mouldboard ploughing	1.6	1.7
Harrow – disk	0.6	0.7
Cultivating – disc hiller	0.4	0.4
Fertiliser application	1.9	2
Spray pesticides	0.4	0.4
Harvest – rotary mower	0.7	0.7
Swather	0.5	0.5
Baler	0.4	0.4
Fertiliser & Pesticides		
Lime	3	3.1
Ammonium nitrate	21.6	22.4
Triple superphosphate	4.9	5.1
Potassium chloride	2.3	2.3
Pesticides	1.5	1.6
Fibre Processing		
Post harvest field operations and green scutching	8.97	9.33
Bio-retting, rinsing, drying and mechanical softening	68.36	71.1
Hackling	2.14	2.23
Wet spinning		23.9
Total	**119.3**	**147.9**

Appendix E – Life Cycle Inventory for the Production of PHA

Products			
PHA(kg)	1000		
Feed			
Electricity (MJ)	3942	Sulphates:	
Steam (2.6 MJ/kg) (kg)	4893	$MgSO_4.7H_2O$ (kg)	20.9
Energy equivalent (MJ)	12700	K_2SO_4 (kg)	18.6
Natural gas (MJ)	2123	$(NH_4)_2SO_4$ (kg)	14.8
Air (kg)	290	Na_2SO_4 (kg)	3.0
Process water (m^3)	65.2	$ZnSO4.7H_2O$ (kg)	1.16
Cooling water (m^3)	13.1	$MnSO_4.H_2O$ (kg)	0.92
Sucrose (from cane sugar) (kg)	1810	$FeSO_4.7H_2O$ (kg)	0.82
Acids:		$CuSO_4.5H_2O$ (kg)	0.12
H_2SO_4 (kg)	3.02	$CaCl_2.2H2O$ (kg)	2.3
H_3PO_4 (conc.) (kg)	8.12	K_2HPO_4 (kg)	0.095
H_2O_2 (kg)	52.9	$NaHPO_4$ (kg)	0.078
Optimase L660 (MKC) (kg)	2.4	PPG.EEA 142 antifoam (m^3)	0.005
Synperonic NP8 (ICI Ltd.) (m^3)	0.033		
Waste			
Dilute wastewater (m^3)	65.2	Solid waste (biomass) (kg)	420
COD (te O_2)	0.80		

Appendix F – Life Cycle Inventory for Metal Passenger Tub.

Metal Passenger Tub Ozone Depletion Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg CFC-11 eq	5.53415E-05	2.53169E-05	3.47309E-05	-4.70623E-06
	Remaining substances		kg CFC-11 eq	5.46171E-08	6.51128E-08	6.01518E-10	-1.10972E-08
1	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC-11 eq	1.98556E-06	2.00103E-06	1.5341E-08	-3.08105E-08
2	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	1.13115E-06	1.10428E-06	1.55083E-07	-1.28215E-07
3	Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	6.25397E-07	8.23019E-07	1.20392E-07	-3.18014E-07
4	Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	3.85908E-05	6.88939E-06	3.43586E-05	-2.6572E-06
5	Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	6.3604E-06	6.67154E-06	1.72132E-08	-3.28353E-07
6	Methane, dichlorodifluoro-, CFC-12	Air	kg CFC-11 eq	5.15915E-06	5.20953E-06	2.36676E-08	-7.40467E-08
7	Methane, monochloro-, R-40	Air	kg CFC-11 eq	-1.12985E-07	4.23163E-07	1.15743E-08	-5.47723E-07
8	Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	1.54748E-06	2.1298E-06	2.8445E-08	-6.10768E-07

Metal Passenger Tub Global Warming Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg CO2 eq	182.19452	164.8348141	145.2117	-127.8519941
	Remaining substances		kg CO2 eq	0.338356445	0.759458604	0.039872515	-0.460974673
1	Carbon dioxide, fossil	Air	kg CO2 eq	175.1825899	142.1939728	142.9651428	-109.9765257
2	Carbon dioxide, land transformation	Air	kg CO2 eq	0.333720494	0.597047359	0.010815864	-0.274142729

3	Dinitrogen monoxide	Air	kg CO2 eq	0.662403931	1.172074305	0.110746559	-0.620416933
4	Ethane, hexafluoro-, HFC-116	Air	kg CO2 eq	-0.208745491	0.193279758	0.000143846	-0.402169095
5	Methane, chlorodifluoro-, HCFC-22	Air	kg CO2 eq	0.230246481	0.241509724	0.000623119	-0.011886361
6	Methane, fossil	Air	kg CO2 eq	7.47566933	18.07416955	2.083208663	-12.68170889
7	Methane, tetrafluoro-, CFC-14	Air	kg CO2 eq	-1.819721088	1.603301984	0.001146722	-3.424169793

Metal Passenger Tub Smog Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg O3 eq	4.489448	9.488436	1.920331	-6.91932
	Remaining substances		kg O3 eq	0.029198	0.021625	0.013033	-0.00546
1	Benzene	Air	kg O3 eq	0.011853	0.012997	0.000386	-0.00153
2	Nitrogen dioxide	Air	kg O3 eq	0.012897	0	0	0.012897
3	Nitrogen oxides	Air	kg O3 eq	4.406475	9.446457	1.879911	-6.91989
4	Pentane	Air	kg O3 eq	0.005093	0.00142	0.004231	-0.00056
5	Toluene	Air	kg O3 eq	0.006098	0.001747	0.005199	-0.00085
6	Xylene	Air	kg O3 eq	0.017835	0.00419	0.017571	-0.00393

Metal Passenger Tub Acidification Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg SO2 eq	0.419742	0.941625	0.239136	-0.76102
	Remaining substances		kg SO2 eq	0.000125	0.00013	2.84E-07	-4.7E-06
1	Ammonia	Air	kg SO2 eq	0.010947	0.014626	0.000623	-0.0043
2	Hydrogen chloride	Air	kg SO2 eq	-0.00074	0.015789	0.000771	-0.0173
3	Hydrogen fluoride	Air	kg SO2 eq	-0.01756	0.018982	0.000147	-0.03669
4	Hydrogen sulfide	Air	kg SO2 eq	0.000487	0.000827	3.76E-05	-0.00038
5	Nitrogen dioxide	Air	kg SO2 eq	0.000536	0	0	0.000536
6	Nitrogen oxides	Air	kg SO2 eq	0.124426	0.266741	0.053083	-0.1954
7	Sulfur dioxide	Air	kg SO2 eq	0.301521	0.62453	0.184475	-0.50748

Metal Passenger Tub Eutrophication Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg N eq	0.380381	0.648923	0.072599	-0.34114
	Remaining substances		kg N eq	0.000303	2.64E-05	1.46E-06	0.000275
1	Ammonia	Air	kg N eq	0.000691	0.000923	3.93E-05	-0.00027
2	Ammonium, ion	Water	kg N eq	0.000903	0.000835	0.000177	-0.00011
3	BOD5, Biological Oxygen Demand	Water	kg N eq	0.027878	0.009781	0.02214	-0.00404
4	COD, Chemical Oxygen Demand	Water	kg N eq	0.034163	0.020782	0.022579	-0.0092

5	Nitrate	Water	kg N eq	0.009805	0.020226	0.000836	-0.01126
6	Nitrogen	Water	kg N eq	0.001203	0.001143	0.000114	-5.3E-05
7	Nitrogen oxides	Air	kg N eq	0.007873	0.016877	0.003359	-0.01236
8	Phosphate	Water	kg N eq	0.296783	0.577597	0.023218	-0.30403
9	Phosphorus	Water	kg N eq	0.000779	0.000733	0.000135	-8.8E-05

Metal Passenger Tub Carcinogenic Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		CTUh	1.94E-05	4E-05	7.14E-07	-2.1E-05
	Remaining substances		CTUh	4.71E-08	1.05E-07	9.59E-09	-6.8E-08
1	Arsenic	Water	CTUh	8.11E-08	2.23E-07	7.17E-09	-1.5E-07
2	Chromium	Air	CTUh	3.39E-06	3.4E-06	2.46E-08	-4.2E-08
3	Chromium	Water	CTUh	6.46E-07	6.38E-07	2.21E-08	-1.5E-08
4	Chromium	Soil	CTUh	6.07E-08	6.05E-09	1.54E-08	3.93E-08
5	Chromium VI	Air	CTUh	1.69E-07	1.73E-07	1.28E-09	-5.8E-09
6	Chromium VI	Water	CTUh	1.46E-05	3.49E-05	6.17E-07	-2.1E-05
7	Mercury	Air	CTUh	2.24E-08	5.86E-08	5.69E-09	-4.2E-08
8	Nickel	Water	CTUh	3.88E-07	5.02E-07	1.2E-08	-1.3E-07

Metal Passenger Tub Non-Carcinogenic Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		CTUh	4.19E-05	6.33E-05	3.01E-06	-2.4E-05
	Remaining substances		CTUh	2.7E-07	3.28E-07	5.08E-08	-1.1E-07
1	Antimony	Water	CTUh	5.38E-08	6.06E-08	2.34E-09	-9.1E-09
2	Arsenic	Air	CTUh	6.31E-07	7.73E-07	3.91E-08	-1.8E-07
3	Arsenic	Water	CTUh	6E-06	1.65E-05	5.31E-07	-1.1E-05
4	Arsenic	Soil	CTUh	4.4E-08	3.7E-08	7E-09	-3.7E-11
5	Barium	Water	CTUh	3.39E-07	3.24E-07	2.01E-07	-1.9E-07
6	Cadmium	Air	CTUh	5.54E-07	5.05E-07	1.35E-07	-8.6E-08
7	Cadmium	Water	CTUh	7.25E-08	8.39E-08	2.99E-09	-1.4E-08
8	Carbon disulfide	Air	CTUh	4.95E-08	5.02E-08	1.78E-09	-2.5E-09
9	Chromium	Air	CTUh	6.97E-08	7.01E-08	1.04E-09	-1.4E-09
10	Lead	Air	CTUh	2.3E-06	2.84E-06	9.69E-08	-6.4E-07
11	Lead	Water	CTUh	4.25E-08	4.8E-08	3.04E-09	-8.5E-09
12	Mercury	Air	CTUh	2.65E-06	6.94E-06	6.74E-07	-5E-06
13	Mercury	Water	CTUh	1.62E-07	2.85E-07	1.14E-08	-1.3E-07
14	Vanadium	Water	CTUh	-2.9E-07	4.48E-07	4.44E-09	-7.4E-07
15	Zinc	Air	CTUh	1.43E-05	1.5E-05	2.2E-07	-8.7E-07
16	Zinc	Water	CTUh	1.42E-05	1.86E-05	9.68E-07	-5.4E-06

17	Zinc	Soil	CTUh	4.31E-07	3.82E-07	6.1E-08	-1.2E-08

Metal Passenger Tub Respiratory Effects Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		kg PM2.5 eq	0.109875	0.298776	0.023606	-0.21251
	Remaining substances		kg PM2.5 eq	1.41E-05	9.3E-06	2E-07	4.64E-06
1	Ammonia	Air	kg PM2.5 eq	0.000388	0.000519	2.21E-05	-0.00015
2	Carbon monoxide, fossil	Air	kg PM2.5 eq	0.000174	0.000447	1.31E-05	-0.00029
3	Nitrogen oxides	Air	kg PM2.5 eq	0.001284	0.002752	0.000548	-0.00202
4	Particulates, < 2.5 um	Air	kg PM2.5 eq	0.07542	0.225683	0.011071	-0.16133
5	Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	0.014168	0.031201	0.000679	-0.01771
6	Sulfur dioxide	Air	kg PM2.5 eq	0.018426	0.038166	0.011273	-0.03101

Metal Passenger Tub Ecotoxicity Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		CTUe	959.8502	1956.952	74.10733	-1071.21
	Remaining substances		CTUe	8.481328	8.661028	1.377036	-1.55674
1	Antimony	Air	CTUe	6.546823	7.166286	0.781953	-1.40142
2	Antimony	Water	CTUe	28.0953	31.64108	1.223101	-4.76888
3	Arsenic	Water	CTUe	8.872685	24.43449	0.784384	-16.3462
4	Barium	Water	CTUe	5.280605	5.04007	3.123214	-2.88268

5	Cadmium	Water	CTUe	1.646672	1.906605	0.067262	-0.32719
6	Chromium	Air	CTUe	34.32258	34.49495	0.245448	-0.41782
7	Chromium	Water	CTUe	6.415541	6.357061	0.206481	-0.148
8	Chromium VI	Air	CTUe	1.685424	1.729912	0.012639	-0.05713
9	Chromium VI	Water	CTUe	145.098	345.27	6.10744	-206.279
10	Copper	Air	CTUe	4.58855	4.87029	0.309734	-0.59147
11	Copper	Water	CTUe	269.7717	435.484	21.17345	-186.886
12	Nickel	Water	CTUe	150.8501	195.2493	4.678131	-49.0773
13	Selenium	Water	CTUe	1.184237	2.240771	0.083474	-1.14001
14	Silver	Water	CTUe	3.376159	4.10271	0.585293	-1.31184
15	Vanadium	Air	CTUe	9.30048	9.498268	2.441507	-2.63929
16	Vanadium	Water	CTUe	-169.282	260.7153	2.584184	-432.582
17	Zinc	Air	CTUe	15.18049	15.86523	0.236745	-0.92148
18	Zinc	Water	CTUe	426.1556	561.1646	27.58361	-162.593
19	Zinc	Soil	CTUe	2.280257	1.060398	0.502251	0.717608

Metal Passenger Tub Fossil Fuel Depletion Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Metal Passenger Tub	Metal Fuel Consumption	Metal Passenger Tub Disposal
	Total		MJ surplus	377.0248	113.9184	312.0201	-48.9136
	Remaining substances		MJ surplus	0.449475	0.847891	0.068253	-0.46667
1	Coal, hard	Raw	MJ surplus	4.008009	10.44104	0.235348	-6.66838

2	Gas, mine, off-gas, process, coal mining/m3	Raw	MJ surplus	1.206119	3.496455	0.079977	-2.37031
3	Gas, natural/m3	Raw	MJ surplus	37.28581	43.46021	14.81526	-20.9897
4	Oil, crude	Raw	MJ surplus	334.0754	55.6728	296.8212	-18.4186

Appendix G – Life Cycle Inventory for Flax Passenger Tub.
Flax Passenger Tub Ozone Depletion Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg CFC-11 eq	2.62E-05	4.68E-06	2.14E-05	6.35E-08
	Remaining substances		kg CFC-11 eq	1.28E-08	8.83E-09	3.49E-10	3.59E-09
1	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC-11 eq	1.09E-07	9.99E-08	9.47E-09	5.51E-14
2	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	3.12E-07	1.89E-07	9.57E-08	2.72E-08
3	Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	3.63E-07	2.89E-07	7.43E-08	2.48E-13
4	Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	2.42E-05	3.03E-06	2.12E-05	4.32E-11
5	Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	4.1E-08	3E-08	1.06E-08	3.13E-10
6	Methane, dichlorodifluoro-, CFC-12	Air	kg CFC-11 eq	1.66E-07	1.45E-07	1.46E-08	5.72E-09
7	Methane, monochloro-, R-40	Air	kg CFC-11 eq	3.41E-08	2.7E-08	7.15E-09	6.38E-14
8	Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	8.24E-07	8.06E-07	1.76E-08	6.85E-14
9	Methane, trichlorofluoro-, CFC-11	Air	kg CFC-11 eq	8.5E-08	5.84E-08	2.19E-11	2.66E-08

Flax Passenger Tub Global Warming Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg CO2 eq	164.2123	64.49498	89.6458	10.07147
	Remaining substances		kg CO2 eq	0.074016	0.050913	0.022578	0.000525
1	Carbon dioxide	Air	kg CO2 eq	11.95715	7.648186	0.000163	4.308799
2	Carbon dioxide, fossil	Air	kg CO2 eq	114.9506	26.69158	88.2589	0.000174
3	Carbon dioxide, land transformation	Air	kg CO2 eq	5.599881	5.593204	0.006677	5.13E-08
4	Dinitrogen monoxide	Air	kg CO2 eq	20.74631	20.66205	0.068369	0.015896
5	Methane	Air	kg CO2 eq	7.656586	1.910512	1.97E-07	5.746074
6	Methane, biogenic	Air	kg CO2 eq	0.747015	0.74396	0.003055	2.15E-08
7	Methane, fossil	Air	kg CO2 eq	2.480645	1.194581	1.28606	4.09E-06

Flax Passenger Tub Smog Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg O3 eq	4.733005	3.440145	1.185508	0.107352
	Remaining substances		kg O3 eq	0.034433	0.014363	0.01372	0.00635
1	Chlorine	Air	kg O3 eq	0.006398	0.006011	0.000386	3.36E-07
2	Nitrogen dioxide	Air	kg O3 eq	0.298476	0.197651	0	0.100825
3	Nitrogen oxides	Air	kg O3 eq	4.381832	3.221258	1.160555	1.94E-05
4	Xylene	Air	kg O3 eq	0.011866	0.000862	0.010847	0.000158

Flax Passenger Tub Acidification Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg SO_2 eq	0.487523	0.332906	0.14763	0.006987
	Remaining substances		kg SO_2 eq	0.000736	0.000584	0.000114	3.81E-05
1	Ammonia	Air	kg SO_2 eq	0.112308	0.111916	0.000384	7.62E-06
2	Hydrogen chloride	Air	kg SO_2 eq	0.002412	0.001916	0.000476	2.08E-05
3	Nitrogen dioxide	Air	kg SO_2 eq	0.012403	0.008213	0	0.00419
4	Nitrogen oxides	Air	kg SO_2 eq	0.123731	0.090959	0.032771	5.49E-07
5	Sulfur dioxide	Air	kg SO_2 eq	0.235933	0.119318	0.113885	0.00273

Flax Passenger Tub Eutrophication Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg N eq	0.535971	0.470753	0.044819	0.0204
	Remaining substances		kg N eq	4.88E-06	3.98E-06	9.01E-07	1.67E-11
1	Ammonia	Air	kg N eq	0.007085	0.00706	2.42E-05	4.81E-07
2	Ammonia	Water	kg N eq	0.009688	0.002033	0	0.007655
3	Ammonium, ion	Water	kg N eq	0.00207	0.001961	0.00011	2.62E-10
4	BOD5, Biological Oxygen Demand	Water	kg N eq	0.015631	0.001963	0.013668	3.83E-07
5	COD, Chemical Oxygen Demand	Water	kg N eq	0.018134	0.004177	0.013939	1.78E-05
6	Nitrate	Water	kg N eq	0.371176	0.370656	0.000516	2.9E-06
7	Nitrogen	Water	kg N eq	0.001327	0.001255	7.05E-05	1.73E-06

8	Nitrogen dioxide	Air	kg N eq	0.000785	0.00052	0	0.000265
9	Nitrogen oxides	Air	kg N eq	0.007829	0.005755	0.002073	3.47E-08
10	Phosphate	Water	kg N eq	0.097023	0.070234	0.014333	0.012456
11	Phosphorus	Water	kg N eq	0.005219	0.005135	8.32E-05	2.3E-10

Flax Passenger Tub Carcinogenic Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		CTU h	2.74E-06	2.29E-06	4.41E-07	1.69E-09
	Remaining substances		CTU h	8.9E-09	7E-09	1.81E-09	8.92E-11
1	Arsenic	Water	CTU h	2.92E-08	2.47E-08	4.43E-09	2.23E-11
2	Cadmium	Soil	CTU h	2.74E-09	2.74E-09	2.62E-12	1.58E-14
3	Chromium	Air	CTU h	1.14E-07	9.92E-08	1.52E-08	3.55E-11
4	Chromium	Water	CTU h	4.05E-07	3.91E-07	1.36E-08	7.36E-10
5	Chromium	Soil	CTU h	1.84E-07	1.74E-07	9.49E-09	6.63E-10
6	Chromium VI	Air	CTU h	6.08E-09	5.29E-09	7.9E-10	6.96E-15
7	Chromium VI	Water	CTU h	1.91E-06	1.53E-06	3.81E-07	4.99E-12
8	Chromium VI	Soil	CTU h	8.97E-09	6.21E-09	2.76E-09	1.66E-14
9	Formaldehyde	Air	CTU h	3.22E-09	2.93E-09	2.01E-10	8.36E-11
10	Mercury	Air	CTU h	9.4E-09	5.84E-09	3.51E-09	4.84E-11
11	Mercury	Soil	CTU h	3.93E-09	3.93E-09	1.47E-12	1.19E-15
12	Nickel	Air	CTU h	4.22E-09	3.08E-09	1.14E-09	2.46E-12

13	Nickel	Water	CTU h	4.33E-08	3.59E-08	7.42E-09	5.89E-12
14	Nickel	Soil	CTU h	3.05E-09	3.05E-09	4.38E-12	2.4E-12

Flax Passenger Tub Non-Carcinogenic Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		CTU h	5E-05	4.81E-05	1.86E-06	1.1E-08
	Remaining substances		CTU h	2.29E-07	1.78E-07	5.08E-08	3.95E-10
1	Arsenic	Air	CTU h	1.49E-07	1.25E-07	2.41E-08	3.43E-10
2	Arsenic	Water	CTU h	2.16E-06	1.83E-06	3.28E-07	1.65E-09
3	Barium	Water	CTU h	2E-07	7.57E-08	1.24E-07	2.41E-11
4	Cadmium	Air	CTU h	2.64E-07	1.81E-07	8.35E-08	2.2E-10
5	Cadmium	Soil	CTU h	7.34E-07	7.33E-07	7E-10	4.24E-12
6	Lead	Air	CTU h	3.3E-07	2.7E-07	5.98E-08	5.2E-10
7	Lead	Soil	CTU h	2.72E-07	2.72E-07	7.44E-10	1.79E-13
8	Mercury	Air	CTU h	1.11E-06	6.91E-07	4.16E-07	5.73E-09
9	Mercury	Soil	CTU h	4.66E-07	4.66E-07	1.74E-10	1.4E-13
10	Zinc	Air	CTU h	2.35E-06	2.21E-06	1.36E-07	1.71E-09
11	Zinc	Water	CTU h	3.35E-06	2.76E-06	5.98E-07	2.94E-10
12	Zinc	Soil	CTU h	3.84E-05	3.83E-05	3.77E-08	1.45E-10

Flax Passenger Tub Respiratory Effects Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		kg PM2.5 eq	0.051441	0.034936	0.014573	0.001932
	Remaining substances		kg PM2.5 eq	2.96E-05	1.67E-05	8.11E-06	4.77E-06
1	Ammonia	Air	kg PM2.5 eq	0.003983	0.003969	1.36E-05	2.7E-07
2	Carbon monoxide, biogenic	Air	kg PM2.5 eq	0.000244	0.000244	1.23E-07	1.04E-12
3	Nitrogen dioxide	Air	kg PM2.5 eq	0.000128	8.47E-05	0	4.32E-05
4	Nitrogen oxides	Air	kg PM2.5 eq	0.001277	0.000938	0.000338	5.66E-09
5	Particulates, < 2.5 um	Air	kg PM2.5 eq	0.026674	0.019799	0.006834	4.08E-05
6	Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	0.004687	0.002593	0.000419	0.001676
7	Sulfur dioxide	Air	kg PM2.5 eq	0.014418	0.007292	0.00696	0.000167

Flax Passenger Tub Ecotoxicity Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		CTUe	405.3664	359.5522	45.74983	0.064311
	Remaining substances		CTUe	3.828841	3.137442	0.686787	0.004611
1	Antimony	Air	CTUe	4.885349	4.399736	0.482735	0.002877
2	Antimony	Water	CTUe	6.349753	5.594667	0.755076	1.04E-05
3	Arsenic	Water	CTUe	3.18665	2.700015	0.484236	0.002399
4	Atrazine	Soil	CTUe	10.2774	10.27689	0.00051	4.99E-09

5	Barium	Water	CTUe	3.104862	1.176432	1.928102	0.000328
6	Chloramine	Water	CTUe	1.451638	1.451528	0.00011	6.24E-10
7	Chlorpyrifos	Soil	CTUe	0.466561	0.461212	0.005349	1.87E-08
8	Chromium	Air	CTUe	1.152013	1.000149	0.151526	0.000337
9	Chromium	Water	CTUe	4.024241	3.889504	0.12747	0.007266
10	Chromium	Soil	CTUe	1.812467	1.711351	0.094505	0.00661
11	Chromium VI	Water	CTUe	18.90673	15.13628	3.770401	4.94E-05
12	Copper	Air	CTUe	1.887974	1.696431	0.191213	0.00033
13	Copper	Water	CTUe	172.0028	158.9221	13.07133	0.009451
14	Copper	Soil	CTUe	5.5473	5.530159	0.016454	0.000687
15	Nickel	Air	CTUe	0.475281	0.347468	0.127523	0.00029
16	Nickel	Water	CTUe	16.83934	13.94906	2.888024	0.00226
17	Pendimethalin	Soil	CTUe	2.343653	2.343595	5.76E-05	2.9E-10
18	Silver	Water	CTUe	1.341938	0.980595	0.361328	1.58E-05
19	Tin	Water	CTUe	0.416173	0.396503	0.019669	1.02E-06
20	Vanadium	Air	CTUe	9.641125	8.120136	1.507253	0.013736
21	Vanadium	Water	CTUe	13.02715	11.4289	1.595334	0.002918
22	Zinc	Air	CTUe	2.557547	2.409554	0.146153	0.00184
23	Zinc	Water	CTUe	99.73689	82.70433	17.02862	0.003944
24	Zinc	Soil	CTUe	20.10264	19.78823	0.310063	0.004349

Flax Passenger Tub Fossil Fuel Depletion Inventory [0.1% Cutoff]

No	Substance	Compartment	Unit	Total	Flax Passenger Tub	Flax Fuel Consumption	Flax Passenger Tub Disposal
	Total		MJ surplus	268.5293	73.33456	192.6242	2.57053
	Remaining substances		MJ surplus	0.480912	0.366387	0.091509	0.023016
1	Coal, hard	Raw	MJ surplus	0.635774	0.490482	0.145291	1.2E-06
2	Energy, from gas, natural	Raw	MJ surplus	7.87562	6.224204	0	1.651415
3	Energy, from oil	Raw	MJ surplus	27.94182	27.04612	0	0.895706
4	Gas, natural/m3	Raw	MJ surplus	24.69267	15.54651	9.146134	2.3E-05
5	Oil, crude	Raw	MJ surplus	206.9025	23.66086	183.2413	0.000368