2013

Using bio-based materials in the automotive industry

Simon Che Wen Tseng
University of Windsor

Recommended Citation

Tseng, Simon Che Wen, "Using bio-based materials in the automotive industry" (2013). *Electronic Theses and Dissertations*. 4755.
https://scholar.uwindsor.ca/etd/4755

University of Windsor
thinking forward

POLITECNICO DI TORINO
1859 1906

USING BIO-BASED MATERIALS IN THE AUTOMOTIVE INDUSTRY

By

SIMON CHE WEN TSENG

A Thesis
Submitted to the Faculty of Graduate Studies
through Mechanical Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2012

USING BIO-BASED MATERIALS IN THE AUTOMOTIVE INDUSTRY

by
SIMON CHE WEN TSENG

APPROVED BY:

Dr. P. Henshaw
Department of Environmental Engineering

Dr. D. Green
Department of Mechanical Engineering

Dr. E. Tam, Advisor
Department of Mechanical Engineering

Dr. A. Sobiesiak, Chair of Defense
Faculty of Graduate Studies

7 November, 2012

Author's Declaration of Originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

Abstract

The objective of this research is to evaluate the environmental performance of polylactic acid (PLA) + flax fiber bio-composite against the current in production composite of polypropylene (PP) + wood dust via life cycle analysis (LCA). The system boundary is an extended gate-to-gate LCA that includes the materials production process. In order to complete the LCA set forth, a necessary iterative process of dataset matching was done to convert NatureWorks LLC's Ingeo (PLA) dataset from the USLCI database to the GaBi database in order to model the LCA conducted. The bio-composite of PLA + flax produces less greenhouse gas emissions that contribute to global warming potentials (GWP) largely due to the carbon sequestration of corn production. The current in production composite of PP + wood dust contributes less to both acidification potential (AP) of seawater and photochemical ozone creation potential (POCP) largely due to less agricultural processes. The polymer resin production process is the primary parameter for energy consumption in both composites.

Acknowledgements

First, I would like to thank Dr. Peter Frise and the Auto 21 organization at the University of Windsor for providing me with the unique opportunity to study abroad and conduct researches current and relative to the automotive industry. Their support with the formalities of paperwork and requirements required for graduation, over and above the awarding of partial funding for the research, was greatly appreciated.

I would also like to thank my University of Windsor advisor Dr. Edwin Tam for his patience, guidance and support through the completion of this thesis and other topics of research that has come before.

Many thanks go to Mr. Mohammed Malik for his arranging of resources and partial funding on behalf of the industry partner for this research and his continual support in developing this research topic with Ms. Ewa Lebert.

Thanks are extended overseas to the Italian affiliates of the industry partner for their hospitality for the second phase of my research. I would like to thank Dr. Andrea Pipino, Mr. Francesco Bonino, Mr. Marco Lattore, and Ms. Silvia Lazzari for their guidance and support in the development and implementation of the research methodology.

Thanks are also due to Professor Firrao and Professor Giovanni Belingardi of Politecnico di Torino for their collaboration in developing and supporting this dual degree program and to Ms. Raffaella Fiora for arranging accommodations, meetings, events and aiding in the completion of requirements for obtaining a degree from the institute.

Finally I would like to thank my advisor from the Politecnico di Torino, Professor Marco Sangermano for his resources and knowledge available to me throughout my research.

Table of Contents

List of Tables

List of Equations

List of Figures

List of Abbreviations

USLCI = United States life cycle inventory;
OEM = original equipment manufacturer;
EI = environmental impact;
PU = polyurethane; PUF = polyurethane foam;
LCA = life cycle analysis/assessment;
CAFE = corporate average fuel economy;
VOC = volatile organic compound;
EoL = end-of-life;
HDT = heat deflection temperature;
PLA = polylactic acid;
PP = polypropylene;
PE = polyethylene;
PHA = polyhydroxyalkanoates;
EVA = ethylene vinyl acetate;
NOP = natural oil polyol;
RIM = reaction injection moulding;
P(3HB) or PHB = poly[(R)-3-hydroxybutyrate];
DJSI = Dow Jone Sustainability Index;
GRI = Global Reporting Initiative;
ELV = end-of-life vehicles;
GWP = global warming potential;
LCI = life cycle inventory;
NREL = National Research and Energy Laboratory;
LCIA = life cycle impact assessment;
AP = acidification potential;
POCP = photochemical ozone creation potential;

1 - Introduction

Bio-based materials have been in the market for a very long time, but were not used in significant, practical applications until the late 1990's. The growing global environmental awareness and the sharp rise in oil prices in the past decade have forced plastic and polymer manufacturers to consider alternative sources to replace traditional petroleum in developing various products. Globally, the majority of current bio-based products are in the packaging and disposable or "one-time" use product industries; for example, plastic shopping bags, disposable cups and plastic utensils. Other applications in industries such as medical, bio-mechanical and gardening are being developed as well. This research focuses on bio-polymers (including bio-plastics) for use in the automotive industry.

In the automotive industry, current structural parts are mainly made from steel and constitutes about 70% of the total weight of the vehicle. Thermoplastics account for around 7% and thermosets around 1%. (Brady & Brady, 2007). Taking into account of non-structural parts, such as front and rear bumpers and interior trim components, the plastic contents of an average vehicle can reach as high as 20-25% by weight. Ideally, bio-polymers should be utilized for both exterior and interior components. However, due to the current material property constraints, only interior components are being developed using bio-based materials. The bio-polymer industry is still in its infancy compared to the well established petroleum polymer industry, but future technology and process improvements can enable exterior component applications for bio-polymers.

Both Original Equipment Manufacturers (OEMs) and suppliers at all levels are considering alternative sources for formulating products compared to traditional petroleum-based components. The main reasons for this shift include:

1) Reducing the environmental impact (EI) of the products;
2) Eliminating the dependency on crude oil for component production; and
3) Maintaining a cost competitiveness by utilizing lower cost materials.

Automotive OEMs are under constant pressure from policy makers and customers to become more and more environmentally conscious about their products. This is especially true in the European market because of the various legislations recently implemented. The European Directive on End-of-Life Vehicle 2000/53/EC is based on the concept of *Extended Producer Responsibility*. This waste directive mandates OEMs to design and build vehicles that are simpler to dismantle for reuse and recycle. An abundance of inexpensive crude oil since the beginning of the automotive industry has promoted the extensive use of plastic components in automobiles. The oil crisis in the 1970s and the price spike in 2006 and 2007 along with the realization that there is a finite supply of crude oil, has prompted OEMs and suppliers to develop viable alternatives to petroleum. The main bio-based materials currently under research and development (R&D) include bio-polymers/plastics, bio-composites and bio-polyurethane foam (PUF).

The general consensus of the environmental benefits from utilizing bio-based materials was publicly accepted in the early environmental movement. The concept of sustainability as defined by the Brundtland Commission in 1987:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

This has been influential on current and future industrial developments. Since then, new industries such as bio-fuel, green construction, design for environment, bioplastics and many more have been initiated and developed. However, critics and scholars are challenging the validity of these "green" claims. In order to quantitatively compare bio-based materials and traditional petroleum plastics, life cycle analysis/assessment (LCA) is used. LCA assesses the environmental impacts of a specific product or production process by counting all the inputs and outputs within a predefined scope and boundary based on the needs of the study, and typically compares one alternative against another to derive the preferred one. Actual data are used to the greatest extent possible to ensure accurate representations of the products or systems studied. Analysis, assessment, and interpretation can be done to identify the areas of concern and/or areas of possible improvements. Specifically, in this thesis, the objective is to evaluate the environmental performance of polylactic acid (PLA) + flax fiber bio-composite against the current in production composite of polypropylene (PP) + wood dust using LCA.

2 - Literature Review

2.1 - The Basics

2.1.1 - Polymers

The term *polymers* refer to all long-chain molecules composed of monomers or repeating units of identical structure. Polymers can be naturally occurring, such as cellulose, or synthetic, such as nylon. Typical polymers can be separated into three types: elastomers, fibers, and plastics. Examples of each type are rubber, silk, and polypropylene respectively. Polymer properties depend on the chemical properties of monomers, molecular weight (size of chains), molecular weight distribution, chain orientation and their interactions. There are thousands of polymers currently in production with new additions every day. Polymers can be identified by one of the three following classifications. (Fried, 2003)

2.1.1.1 - Thermoplastics vs. Thermosets

A classification based on polymers' thermal processing behavior. *Thermoplastics* can be softened by increasing their temperature for forming, and repeated reforming is possible by the same heating / forming process. Recycling is also possible due to their recoverability and refabricability. *Thermosets* are polymers cross-linked by chemical reactions where covalent bond links are formed. Once formed, these links are not easily broken thus making methods of recycling more difficult. Thermosets are commonly ground down and reused as fillers or reinforcement materials. However, thermal processes such as fluidised bed heating and pyrolysis can extract fibers and fillers for reuse. (Pickering, 2006)

Thermoplastics can be further classified by structural morphology where polymers are defined as crystalline, amorphous or semi crystalline. A crystalline polymer is one where the atoms and molecules are arranged with a high structural order. Conversely, an amorphous polymer is one that lacks any structural order. Most polymers are defined as semi crystalline where the polymer properties are a mixture of the two extremes.

2.1.1.2 - Addition vs. Condensation

A classification based on polymers' mechanism of polymerization. Additional polymers are formed by the sequential addition of monomers to create a higher molecular weight molecule, such as polyethylene. Condensation polymers are formed by random reaction of two molecules and often occur with the liberation of a small molecule in the form of a gas, water or salt. An example would be nylon-6-6 with the liberation of two H_2O molecules for each repeating unit.

A newly developed classification based on polymerization mechanisms is chain-growth vs. step-growth. The main differentiating factor is when the high molecular weight polymer is formed in the polymerization process. In chain-growth, it is early during the process. In step-growth, the opposite is true.

2.1.1.3 - Homochain vs. Heterochain

A classification based on polymers' chemical structure of the main polymer chain / backbone. A homochain polymer is where the backbone is made up of carbon atoms only. A heterochain polymer is where the backbone is made up of more than one type of atom assembled together into specific types and groups, such as carbonyl groups.

A similar classification that is more commonly used is monopolymer vs. copolymer. A monopolymer is made up of repeating units of the same monomer where a copolymer is made up of different monomer units. However, no differentiation by chain length, orientation, and molecular weight is defined.

Within the three main classifications, the most commonly used classification is thermoplastics vs. thermosets due to its simplicity and relevance to product manufacturing. An in depth knowledge of polymer science is required in order to further differentiate the other two classifications presented above.

2.1.2 - Composites

Composite materials can be naturally occurring or synthesized. They are composed of two, very different materials which exhibit synergistic properties when combined. The major component of a composite is the matrix: the binder for the filler component, which is usually fibers, but can also be particles. Fiber fillers have a high aspect ratio and are used to reinforce polymer properties. Composites have inherently high strength-to-weight ratios. Under stress, most of the load is transferred to the fibers in tension and only a very small portion of the load is sustained by the matrix. Since fibers are lighter and less matrix material is required to obtain the required properties, the overall weight is reduced. The properties of fiber reinforced composites depend on many factors such as: fiber diameter, fiber length, fiber orientation (parallel vs. random), fiber surface roughness, level of consolidation and level of adhesion between matrices and fillers. For example, porous fibers increase sound absorption properties. (Kamath & Bhat, 2005) Automotive industry implementation is driven by regulations and legislations such as the Corporate Average Fuel Economy (CAFE) average vehicle fleet fuel consumption and European Union (EU) landfill regulations for conformity. However, the cost is currently prohibitive for large-scale composite operations. (Brady & Brady, 2007)

2.1.3 - Polyurethane Foam (PUF)

Polyurethane (PU) is a thermosetting polymer that is created in a polyaddition reaction of polyisocyanate and polyalcohol (polyol) groups. A urethane (carbamate) link is formed between the two components as a result of this reaction. Isocyanate is an organic functional group with a alkyl functional group and alcohol is a hydroxyl group bonded to a carbon atom. Polyether or polyester polyol can be utilized for PU production depending on the intended product application. A tertiary amine catalyst is used for the polymerization of PU. The ratio of polyol:polyisocyanate is mainly responsible for determining the PU characteristics other than additives and process controls. The typical ratio is 1:2. The ability to produce both open cell (soft) and closed cell (rigid) foam from PU makes it an important commercial polymer. Blowing agents react with isocyanate and produce CO_2 that forms the cell structure necessary for producing PUF. The most common blowing agent is water. In addition, surfactants are used for cell structure control. Polyether polyols are used for PUF production because of superior properties over polyester polyols such as higher compression modulus, compression set, and abrasion resistance (Harper, 2002). Some of the commonly recognized problems of PUF are hydrolytic instability and fogging. There are 2 types of hydrolytic instabilities: 1) moisture plasticization, a temporary condition where the original properties are lost due to moisture content, but are restored after dehumidification; and 2) hydrolytic (chemical) degradation, a permanent loss of cross-linking due to hydrolysis from moisture accumulation. Fogging is the condensation of volatile organic compounds (VOC) released from PUF onto other components, such as the fogging of an automotive windshield. The cost effectiveness and the ease of manufacturing has positioned PUF as the dominant material in foam applications.

2.1.4 - Life Cycle Analysis/Assessment (LCA)

LCA accounts for all the energy, and materials entering (input), plus all the products, emissions and wastes exiting (output) a predefined system boundary. For a complete environmental impact analysis, the entire life cycle of a product (or a predefined functional unit) is considered. A complete life cycle includes raw materials collection, product manufacturing, usage (product life) and finally product end-of-life (EoL). This is also known as the *cradle-to-grave* approach. The International Standards Organization (ISO) has defined the LCA principles and framework (ISO-14040, 2006) and the requirements and guidelines (ISO-14044, 2006) that have been adopted by industries to evaluate their products and processes. Figure 1 is a flow chart that demonstrates the methodologies defined by ISO.

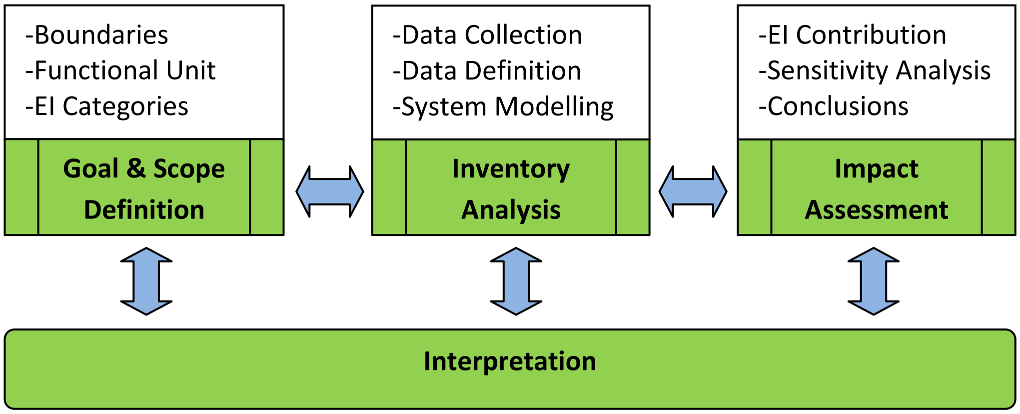


Figure 1 LCA Methodology adapted from ISO 14040 and 14044

2.2 - Bio-based materials and biodegradability

Bio-based materials encompass all raw materials of renewable origins from an anthropological point of view. In the context of bio-polymers, the raw materials are derived from plant matter instead of petroleum. Because of the short growing time for plants and the potential to harvest frequently, these are considered renewable sources. With composites, the matrix, the reinforcement, or both, can be renewable. However, there can be many product variations, and there are currently no standards that define what is or is not a bio-based material. ASTM 6866 defines the methodology of determining a simple product's bio-content based on the carbon dating technique to determine the age of an object. ^{14}C is created by cosmic ray neutron on ^{14}N with a half-life of 5730 years. Therefore, all fossil carbon, which is millions of years old, will have no ^{14}C signature. (Narayan, 2009)

$$\%\,\boldsymbol{Bio-Content} = \frac{\boldsymbol{bio-carbon}}{\boldsymbol{total\ organic\ carbon}} * \mathbf{100\%}$$

where, bio-carbon = is biogenic carbon in part or in whole from biological sources

organic carbon = carbon that is attached to other carbons (ie, H_2, O_2, chains)

ASTM 6866 is the standard used for the *BioPreferred* label in the U.S., which stems from a certification program by the U.S. Environmental Protection Agency (EPA) to promote the development of renewable consumer products.

Biodegradable is the broadest term that encompasses: bioerodable, hydrobiodegradable, photo-biodegradable, oxo-biodegradable and many other types of biodegradability (Nampoothiri, Nair, & John, 2010). Not surprisingly, there are ambiguous definitions and understandings of biodegradability among the general public. In fact, not all bio-based materials are biodegradable and not all biodegradable materials are bio-based. This relationship is not generally understood by the public, which often times assumes one equals the other. A substance is often thought to be biodegradable if it disintegrates into smaller pieces that are no longer perceptible. However, in this definition, the substance still exists in the environment and cannot be utilized by microbial processes: it should actually be termed *bioerodable*. Instead, what is thought of as biodegradable is better classified as *biotic degradable* in which there is a complete chemical or biological dissolution of the substance. Currently, two standards are used for determination of biodegradability under predefined industrial composting conditions: (Hermann, Debeer, Wilde, Blok, & Patel, 2011)

1. EN 13432, where 90% of degradation is completed after 180 days
2. ASTM D6400, where 60% of degradation is completed after 180 days

Industrial composting conditions defined in both EN 13432 and ASTM D6400 can only decompose materials under *Thermophilic* conditions where the temperature is between 50-60°C. In contrast, home composting deals with fluctuating temperatures. This differentiation is important because biodegrable products as defined by EN13432 and ASTM D6400 can only be treated by industrial composters if proper collection infrastructures are present. If not, they will simply increase the amount of landfill waste.

2.3 - Automotive specific bio-based materials

Specific requirements for applications in the automotive industry are more demanding compared to the medical or disposable applications. The biodegradability of the bio-based materials has to be delayed to prolong the use phase of the products. A typical automobile's useful life is between 10-15 years. This is significantly longer than many other industrial applications using bio-based materials. Significant research has been undertaken to develop different formulations, production processes, catalysts and additives to improve the inherently inferior thermal, impact and durability properties of bio-based materials (Kim, Kim, Chun, & Lee, 2011). The industry accepted property standards are heat deflection temperature (HDT) defined by ASTM D648, Izod notched impact strength defined by ASTM D256, and durability scores defined by individual OEM. Table 1 lists the common used standards for material testing, including cross references between ASTM and ISO. Currently, there are significant researches directed to developing polylactic acid (PLA) polymers as replacements for commodity plastics such as polypropylene (PP) and polyethylene (PE), as well as bio-polyols to produce bio-based PUF. A new and promising bio-polymer polyhydroxyalkanoates (PHA) is also being developed, and commercialization of PHA has just begun. However, it will likely be years before it becomes a commodity plastic.

Table 1 Material Properties Standards

Material Properties	ASTM	ISO
Tensile	D638	527
Flexural	D790	178
Heat Deflection Temperature (HDT)	D648	75-1, 75-2
Izod Notch Impact	D256	180
Density*	D792	1183

*not exact equivalents

2.3.1 - Polylactic Acid (PLA)

PLA is a bio-based polymer made from plant starch, primarily from the cultivation of corn or sugar cane. PLA is biodegradable by the recognized standards: EN 13432, ASTM D6400 and D6868. To recycle PLA, the *LOOPLA* process by the Belgian based green chemistry company, Galactic, can be employed. It is a chemical process that depolymerises PLA into lactic acids, the raw material for making PLA resins. This allows repeated feedstock recycling and the use of recycled resin without the penalty of down-cycling, a process to convert waste materials into materials and products of lesser quality, value and usability normal to commodity plastics. The loss of material properties can be minimized. The current limitation on PLA recycling is the lack of infrastructure for collection and sorting. PLA has better mechanical properties compared to commodity plastics such as PP in terms of tensile strength, elongation, and flexural strength. PLA has a higher density as shown by its specific gravity shown in Table 2 compared to PP and ABS adapted from (Kim, Kim, Chun, & Lee, 2011).

Table 2 Mechanical Properties of PLA, PP and ABS

Property	Unit	PLA	PP	ABS
Tensile Strength	MPa	59	30	47
Elongation	%	3	22	30
Flexural Strength	MPa	85	47	78
Flexural Modulus	GPa	2.9	1.6	2.6
Specific Gravity	---	1.2	0.9	1.1
HDT	˚C	56	137	92
Izod Impact Strength	J/m	33.4	61.9	265.2

The barriers for PLA becoming a commodity plastic are cost, poor thermal and impact properties, and hydrolytic instability. The price of typical low cost / commodity thermoplastics is less than \$1.5 / lb. (Stewart, 2011) Price parity depends on the price of crude oil and the price of raw materials. Recent spikes in crude oil price have made PLA an attractive alternative, which costs approximately \$2 / lb. The agricultural production cost of PLA raw materials is more stable compared to crude oil price fluctuation. This is another incentive for considering bio-based materials as an alternative.

PLA has seen applications in the packaging and the bio-medical industry for its biodegradable properties resulting to its ease of disposal. However, for automotive applications, the resin does not have a high enough HDT or Izod impact strength. PLA

HDT depends on the degree of crystallization and its kinetics. With recent research advances, different compatibilizers have been found to improve the crystalinity and thus improve thermal resistance. To increase the Izod impact strength, elastomers such as Ethylene Vinyl Acetate (EVA) are added as additives. These are Toyota's approaches to improve PLA's inherent mechanical weaknesses (Takeshi, Yuichi, & Masatoshi, 2006). FIAT and many other OEMs are experimenting with various PLA blends to improve their impact, thermal and hydrolytic properties. For FIAT, a second generation PLA polymer will be blended with polycarbonate for improved properties that will meet or exceed all production specifications. There are significant, continuous researches into improving PLA for automotive applications.

NatureWorks LLC, the world's biggest PLA producer with its 140,000 tons per annual production plant, has greatly improved PLA production efficiency since its inception in 1999. The manufacturing methodology for Ingeo, the brand name for NatureWorks' PLA polymer, is as follows: (Vink, Rabago, Glassner, & Gruber, 2003) and (Vink, Davies, & Kolstad, 2010)

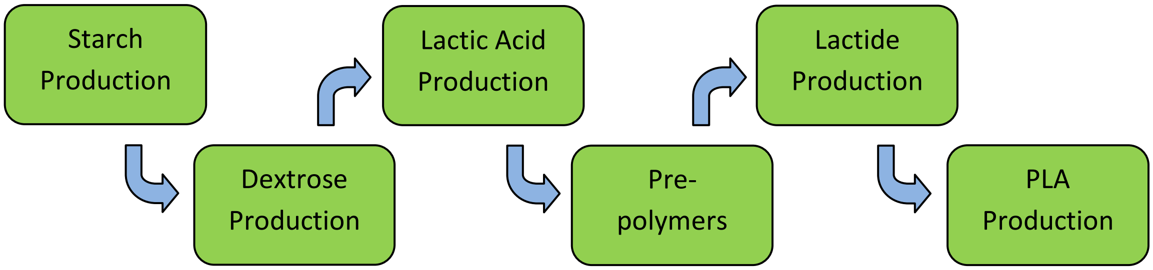


Figure 2 Generalization of NatureWorks PLA Production

PLA resin is still at its infancy even though it has been produced for more than a decade. Process optimizations are constantly being developed, tested and implemented. NatureWorks' peer reviewed public journals have reported a constant reduction in fossil fuel energy consumption and GHG emissions. Ingeo 2009 has an eco profile of 42 MJ/kg polymer and 1.24 kg CO_2 eq/kg polymer respectively. In contrast, the fully optimized production methods of traditional commodity plastics consume more energy and emit more GHG. For example, PP consumes 73 MJ/kg polymer and emits 1.9 kg CO_2 eq/kg polymer.

2.3.1.1 - Automotive Application Manufacturing Process

The production of PLA components is similar to other thermoplastic production for the automotive industry and is done by injection moulding, one of the most important polymer product manufacturing processes. Injection moulding was patented by John and Isaiah Hyatt in 1872 for producing celluloid to replace ivory and other synthetic resin products. An injection moulding machine consists of a mould with fixed and moving parts, an extrusion rod for releasing the parts after moulding, a heated screw cylinder with a discharge nozzle for injecting materials after heating, and a hydraulic plunger/motor for dispensing the materials after pre-production processes such as drying. (Fried, 2003) A mould, even though expensive as an initial investment, can produce thousands of parts before maintenance or replacement is necessary. Due to its continuous production capability for manufacturing components with minimal maintenance and labour, injection moulding is utilized to maximize the economy of scale in the automotive industry. PLA resins are currently being formulated and processed to be compatible with injection moulding in order to reduce the cost of implementation by avoiding changes to the current production infrastructure.

2.3.2 - Bio-Polyurethane Foam (bio-PUF)

The difference between conventional PUF and bio-PUF is the percentage of polyol content replaced by natural oil polyol (NOP) during manufacturing. There is currently no renewable source for polyisocyanate, the other major component in PUF manufacturing. The use of NOP is the only method to reduce the environmental impacts of PUF production. NOP are based on fatty acids or triacylglycerols from the agricultural feedstock material instead of petroleum. Some of the commonly used natural feedstock are soy bean oil, palm oil and castor oil (Yap, Stapleton, & Smolinski, 2011). Hydroxyl groups need to be added to NOP since they are necessary to react with polyisocyanate (with the exception of castor oil). A variety of processes exist for the addition of hydroxyl groups. The choice of a specific method is based on the chemical structure of the vegetable oil (Zhang, Jeon, Malsam, Herrington, & Macosko, 2007). This thesis focuses on soy-bean oil NOP. There are many and varied processes to produce NOP from soybean oil.

1. Air oxidation, which is a simple process that produces raw and lower quality NOP, but with the highest bio content.

2. The addition reaction of methyl-ester groups obtained from soy bean oil, which is a very complex process that produces high quality, but low bio content NOP. (Olari & Cheolas, 2011)

Many other processes exist in between the two above examples. Some of the commonly recognized negative property effects are odour, polyol reactivity, and density control. Zhang et. al, 2007 have found that these affects can be minimized when a ≤ 30% soybean polyol content is maintained. Any significant adverse effect on mechanical properties can be avoided as well.

In North America, more than 2 billion pounds of free rise PUF are produced annually with wide reaching industrial applications in automotive, carpet underlayment, bedding and packaging. Some of the specific automotive applications are seating (cushion and back), armrest and headrest, headliners, sun visors, carpet underlayment and door panels. In particular, the property specification of seat foam is the most stringent in all of PUF in automotive interior applications. (Yap, Stapleton, & Smolinski, 2011)

2.3.2.1 - Automotive Application Manufacturing Process

Both PUF and bio-PUF components are produced by Reaction Injection Moulding (RIM). More than 95% of the total RIM production is used to produce polyurethane. This includes both polyurethane elastomer and PUF. The RIM process is a fairly new process developed in the 1960s to simultaneously process the polymer(s) and mould them in a single operation. The correct proportions of monomers and all other additives and catalysts are carefully metered into a mixer and then injected into the mould immediately after mixing. While in the mould, both polymerization and moulding happen simultaneously as the reactions are carried out and the component cools. However, not all polymers are suitable in RIM: only polymers with favourable polymerization kinetics such as polyurethane can be processed and produced by RIM. (Fried, 2003) The same advantage to maximize the economy of scale exists with RIM and thus it is utilized by the automotive industry. The substitution of bio-polyol with petroleum polyol does not alter the manufacturing process of PUF.

2.3.3 - Polyhydroxyalkanoates (PHA)

PHA has emerged as a promising renewably sourced polymer that is biodegradable. It has been known to accumulate in intracellular inclusions of bacteria, but did not have any commercial value until recent developments. (Ojumu, Yu, & Solomon, 2004) PHA is a natural polyester that can degrade in biological media such as water bodies (river and sea), soil, and compost (residential or industrial). Furthermore, PHA can be biodegraded under both aerobic and anaerobic conditions in all biological media (Volova, et al., 2010) and can thus serve as an all natural alternative to conventional plastics.

PHA is produced from microbial or plant based renewable carbon sources and has thousands of possible monomers depending on the specific application. (Seiichi, Hirofumi, Tomoyasu, Takeharu, Ichiro, & Yoshiharu, 2003) As with the possibility of different monomers, many different types of PHA are available. The most typical and utilized PHA is poly[(R)-3-hydroxybutyrate] (P(3HB) or PHB). It is a short carbon length type monomer that can be copolymered and modified to match the mechanical properties of conventional plastics such as PP. Enzymes utilized for PHA biosynthesis are called PHA synthesaes and are the focus of significant research for potential mass production in the future.

PHA is new in terms of commercial applications. Currently, it is utilized in the packaging and medical industry. (Chen & Wu, 2011) Unfortunately, acceptance and wide-spread application is not currently feasible due to low production capability and high cost; therefore, it is not included in this study. The current price for PHA resin is approximately \$5/lb compared to PP at \$1.5/lb. For future automotive applications, newer production technologies to enable the economy of scale are necessary for mass production. While research continues, PHA is approximately at the same stage of commercialization as PLA 10 years ago.

2.4 - Current Automotive Applications of Bio-based Materials

Before bio-based materials can replace conventional non-renewable materials in the automotive industry, three criteria must be met on top of the environmental benefits in order for the OEMs to implement their usage:

1. Cost;
2. Material properties;
3. Production methodology; and
4. Continuous supply.

Corporate responsibility to the environment has to be achieved in parallel with business economics. The willingness for bio-based materials adaptation by the Automotive OEMs is heavily influenced by these four criteria, which are present for the current conventional materials in use. The cost has to be equivalent or competitive, the material properties have to meet all specifications set forth by each individual OEM, the production methodology has to enable the same mass production capability, and lastly the continuous supply of the bio-based material is essential to avoid disruption to vehicle and/or component production.

Although Henry Ford was the first to introduce bio-based materials[1], soy bean products, to automobiles, the earliest application of bio-based materials in the European automotive industry was pioneered by FIAT. As early as 1982, FIAT introduced wood flour filled door panels in the FIAT Punto and they are now standard equipment in the entire vehicle line-up. In 2003 and 2004, interior trims consisting of 30-40% wood fibers were produced for the FIAT Idea and Lancia Musa respectively. Then in 2011, all FIAT group vehicles started using renewable nylon (PA11) fuel lines made from castor oil. Other automotive OEMs in also started using natural fiber filled components as well. Toyota, in 1999, introduced kenaf fibers as natural reinforcing fibers in PP resin in the Kijang minibus made in India. Since then, the PP/kenaf composite has been employed on numerous Toyota vehicles. A second major automotive bio-based material milestone was in 2003 when Toyota introduced the PLA spare tire cover in the Raum mini MPW. Since then, many automotive OEMs and suppliers have started research and introduced bio-based materials in their vehicles. In 2006, Honda introduced a bio-fabric made of bio-PTT, which replaced 1,3-propandial with a corn based substitute. Bio-fabric is now produced for the 2010 Clarity FCX seat fabric. Ford introduced the first soybean oil based polyol PUF on the 2008 Mustang, a collaboration between Ford and Lear in 2008. By 2011, 75% of Ford's North American built vehicles featured soybean based bio PUF head restraints. (Ford, 2011) Since the completion of NatureWorks' 140,000 ton per year production facility in 2001, PLA has been gaining momentum as the alternative to traditional PP/PE plastics in the automotive industry. In 2009, Hyundai produced a hybrid resin of Ingeo and PP mix for interior trims in the Elentra LPI hybrid. The following model year, Toyota introduced its own version of PLA/PP hybrid resin for interior trims in the Prius hybrid. In 2011, Toyota added Ecological Plastic, bio-PET, which is PET derived from sugar cane starch into its bio-based material list for interior carpet and seat trim applications. Table 3 lists the current OEM applications of bio-based and recycled materials in their vehicle line-up. Recycled material content is generally divided into pre-industrial and post-consumer where the collected materials were created as industrial waste or consumer waste (after some use), respectively.

Apart from OEM developed applications, many suppliers have acknowledged the need for petroleum based plastic alternatives and are offering bio-based materials, parts, and components. Dupont's renewably sourced material family has a series of plastics and elastomers for automotive applications with varying bio content. Hytrel® RS thermoplastic elastomer is 20-60% renewably sourced from plant stock polyol and can be used for hoses, tubing, CV boots, energy dampers, etc. Sorona® EP thermoplastic polymer is 20-37% renewably sourced from corn ethanol and can be used for fabrics, carpets, foams, etc. Zytel® RS is 63-100% renewably sourced from castor or sebacic oil and can be used for fuel lines and under hood covers. Johnson Controls produces WOOD-STOK® door panels made from an extruded thermoplastic sheet with wood dust for the FIAT group since 1982. Natural fibers such as flax, hemp, kenaf, and wood are utilized in its natural material products such as Ecobond, Ecocor, Fibrewood, and Fibrit. Johnson Controls also offers NOP derived from soybean or castor depending on the region of production. Cargill's BiOH bio-polyols derived from soybean oil are used by foam producers worldwide to produce bio PUF for automotive seating applications. In 2011, Molex's Stac64™-e became the automotive industry's first renewable, plant-based resin electrical connector that passes all the OEM specification requirements. Many other suppliers are in the development bio-based materials for commercialization as well. Braskem's Green PE was produced on a commercial scale in September 2010 and its Green PP is expected to do the same in 2013. Both Green PE and PP are derived from sugarcane ethanol and have similar characteristics to their traditional counterparts. However, they are not biodegradable. A direct substitution into existing manufacturing processes makes them valuable alternatives. Various PLA resin blends with different processing methods and/or additives are being developed by a number of companies. For automotive applications, injection moulding is the choice of manufacturing. TeknorApex and Futerro are 2 of the many companies that have developed a PLA blend specifically for injection moulding by perfecting individual proprietary processing technologies and additives. PHA is aslo in development for future automotive commercial use by many companies. Bio-On's MINERV-PHA™ is a linear polyester biosynthesized from sugar that can be characterized to replicate many of the commonly used plastics such as PP, PE, PS, PVC and PET. PHA, although promising, is still years away from wide spread industrial implementation.

Table 3 Summary of recent bio-based and recycled material applications in the automotive industry

OEM	Bio-based materials		Recycled Materials	Model	Year	Components
	Polymer	Filler				
BMW		Flax, sisal		7 Series	2011+	Door panels, linings
Chrysler Group			≥5% foam and trimmings	Grand Cherokee	2011	Seat Cushions
		Wood		Sebring,	----	Door Panels,

		fibers		Stratus, Viper, Cherokee		interior trim pieces
Fiat Group	PA11			All European	2011+	Fuel lines
		Coconut	PET (bottles)	Uno	2010	Interior and exterior trims
		Wood flour		All European	1982+	Door panels
			Plastics	All European	2006+	Wheel well covers
Ford Group	≤25% Soy polyol PUF			75% of line up	2011+	Seat foam, head liner & restraints
			PET (bottles)	Taurus SHO MKZ	2010+	Seat fabric
Ford Group			Jeans and clothes	Focus	2012	Interior sound insulation
		Wheat straws		Flex	2010	Storage bin, door panels
GM		Kenaf fibers	Jeans & carpet	GMC Terrain	2011	Headlining, interior insulations
			Bumpers	Chevy Camaro	2009+	Air inlet panel
			Cardboard	Buick Lacrosse	2010+	Acoustic pads
			Tires	GMC Sierra	2007+	Baffles
Honda	Bio-PTT, PLA			Clarity FCX	2010	Seat fabric, roof & boot lining, carpet
Hyundai	PLA/PP, PA11		PET (bottles)	Blue-Will*	2009	Interior trims, under hood engine cover, headlamps
	PLA/PP			Elentra LPI Hybrid	2009+	Interior trims
Mazda			Bumpers	Biante Minivan	2012	Bumpers
	PLA			Premacy Hydrogen RE Hybrid*	2007	Interior fabrics
MB		Flax, hemp, sisal		A coupe	2007+	Spare wheel well
Mitsubishi		Cotton, bamboo		All	2012+	Interior trims
Toyota	Bio-PET			Sai Hybrid	2011	Carpet, seat trim
	PLA/PP			Prius	2010	Interior trim (non-aesthetic)
VW			Plastics	Golf	2009+	Interior trim

*Not for production concept models

2.5 - Governmental Regulations and Legislations

To become a sustainable business entity, OEMs have to be sustainable in the "triple bottom line" criteria of economical, social, and environmental. All three criteria must be satisfied for sustainable growth as the global movement of better social and environmental business practices evolve beyond economical gains. The *Dow Jones Sustainability Index* (DJSI), a list that judges best-in-class companies in terms of economics, social and environmental performance on a yearly basis has been evaluating automotive OEMs since 1999. Many automotive OEMs strive to get onto or stay on the DJSI list to validate their sustainable practices and boost their business reputation. Another globally recognized standard on corporate sustainability reporting is the *Global Reporting Initiative* (GRI). GRI is a non-profit organization that promotes sustainable growth on the global scale by providing reporting guidelines and frameworks. Both DJSI and GRI are standards automotive OEMs adhere to even though they are not governmental regulations and legislations. As always, the most significant influencing factor is the consumer. The voice of customer is what determines OEM strategic planning and product development, along with regulations and legislation. Individual countries and markets have their own standards; however, the focus of this study will be the standards of the European and the U.S. market.

In the EU, the European directive on end-of-life vehicles (ELV) has defined stringent targets and deadlines for OEMs to comply (EU-ELV, 2000); (Johnson & Wang, 2002).

- 1st July, 2003 – exclusion of lead, mercury, cadmium or hexavalent chromium on new vehicles.
- 2006 – 85% by weight of vehicle must be reused and recycled (material + energy), of which 80% has to be material reuse and recycle.
- 2015 – an increase from 2006 to 95% by weight with 85% to be material reuse and recycle.

The EU directive applies irrespective of how vehicle owners maintain their vehicles. OEMs are ultimately held responsible. This includes aftermarket components that have been installed on the vehicle. Furthermore, the European Emission Standards, which started with EURO 1 in 1993, is becoming increasingly stringent on vehicular tail pipe emissions. Current EURO 5 standards will be superseded by EURO 6 in 2014. The trend of constant reduction of emissions, waste and other pollutants will continue and OEMs need to improve their vehicles for compliance.

Vehicular exhaust emission, above all, is the most critically analyzed and evaluated pollutant for automotive OEMs in terms of governmental and public scrutiny. It is influenced by vehicle weight, which can be lowered with the application of bio-based materials. In the United States, the most stringent tail pipe emission legislation is the California Air Resource Board (CARB) standards. The emission classes are categorized depending on individual vehicular emissions. CARB's low emission vehicle (LEV) program started in 2006 with LEV 1. The current standard is LEV 3, which is adopted by 13 states in the U.S. (Delphi, 2011/2012) All other states have chosen to adopt the federal Clean Air Act, which is less stringent. In addition, the National Highway Traffic and Safety Administration (NHTSA) has issued a CAFE average of 34.1 mpg by May 2016. (NHTSA, 2012) These plus EPA's GHG emission standards can only be met by constant improvements from the OEMs.

3 - Methodology - Goal and Scope Definition

The goal of this study is to: 1) evaluate the environmental performance of PLA + flax fiber composites; and 2) then compare the environmental performance of PLA + flax fiber composites to PP + wood dust composites currently in use for FIAT group of automobiles' interior components. To accomplish this, a comparative LCA study is conducted in Centro Ricerche Fiat (CRF), Fiat Group of Automobiles' central research facility, to evaluate the differences between the two composites.

The *functional unit* is defined as one automotive dashboard trim made of natural fiber reinforced composite. The averaged component weights for PLA + flax short fibers and PP + wood dust are 197.8 g and 159.2 g, respectively. This definition is due to the mould available for component manufacturing. However, the resulting data can broadly apply to all automotive interior trims: the possible applications are many and varied. The currently used natural fiber composite of PP + wood dust consists of 70% PP and 30% wood dust by volume. This composite meets all FIAT specifications such as aesthetics, cost, and various mechanical properties (tensile, elongation, density, and HDT) for automotive interior applications. The bio-composite of PLA + flax being studied consists of 70% PLA and 30% flax fibers by volume. Figures 3 and 4 show photographs of actual composite parts. The PLA resin is a first generation testing material produced by the Politecnico di Pisa that meets all FIAT specifications except aesthetics and thermal resistance. (65˚C compared to the specified 80˚C) A second generation resin material consisting of PLA and PC blend hybrid resin (80:20 by weight) that meets all FIAT specifications including aesthetics and thermal resistance will be tested in the future. All composite pellets used for component manufacturing are processed by extrusion compounding. The final product manufacturing is done by injection moulding.

Figure 3 Current PP + Wood Flour component

Figure 4 PLA + Flax Fibers component

The *system boundary* and *scope* includes the materials production and the manufacturing phases of a LCA study. This is an extension of the typical gate-to-gate LCA that also includes the materials production phase. The use phase is excluded because the difference in fuel consumption due to the utilization of the studied composites is negligible. The weight difference of a single interior trim component is less than 50 g and is deemed negligible and insignificant to the study. The end of life (EoL) phase is also excluded in the study due to the lack of industry data from FIAT. Usually, there is a lack of completeness by the exclusion of the EoL phase due to the different possibilities for EoL treatments mainly recycling, energy and landfilling. However, because of the present lack of PLA recycling infrastructure and the prominence of energy recovery as the main plastic EoL treatment in Europe, the current EoL treatment for both PP and PLA plastics studied are essentially the same. The differences in environmental effects between PP and PLA resins during both the use phase and the EoL phase are therefore excluded. The system boundary is illustrated in Figure 5.

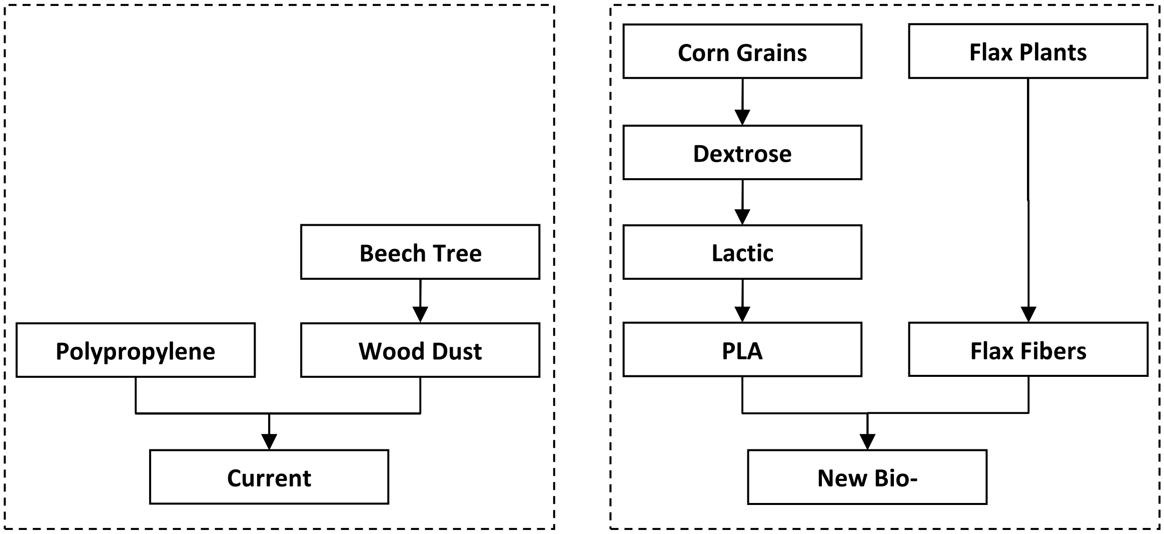


Figure 5 System boundaries: current composite (left) and new bio-composite (right).

For the materials production phase, the agricultural processes necessary to produce flax fiber and corn (raw material for dextrose production in PLA resin manufacturing) are included. Data for the PLA testing material are not available from the Politecnico di Pisa, therefore, NatureWork's PLA data are used as a substitute. Flax cultivation and fiber production data are obtained from GaBi 5 database since flax as a production material has not been utilized nor tested by FIAT. The wood dust utilized for the current composite are manufacturing by-products from other industries such as furniture producers. Wood dust data are obtained from a previously completed LCA project called Forbioplast within FIAT. PP resin production processes from crude oil are included. It is obtained from the eco profiles of commodity plastics created by PlasticEurope included in the GaBi 5 database. Since NatureWork's PLA eco-profile was created conforming to the standards and practices of PlasticEurope, a better consistency of data can be realized by using data from the same source.

Pellets for injection moulding in the manufacturing phase of both composites are made by extrusion compounding. The data for the PP + wood dust extrusion compounding process is adapted from the Forbioplast project in the FIAT database. For the PLA + flax extrusion compounding process, it is assumed to be the same as PP + wood dust.
The component manufacturing phase took place in FIAT's research facility, Centro Ricerche FIAT (CRF), located at Orbassano, Piedmonte, Italy. A Sandretto Serin Otto 330 injection moulding machine is used for moulding both composites. It is a 310 ton injection moulding machine with water cooled moulds and an electrically heated barrel. For PLA + flax component manufacturing, the mould temperature is kept at 25˚C by a Piovan TH9/W Thermovan to enable continuous production of components.

The barrel is divided into five zones and heated to different temperatures to maximize injection moulding efficiency. The zones are nozzle, end zone, secondary zone, primary zone, and material input zone with respective temperatures 170˚C, 180˚C, 175˚C, 170˚C, and 165˚C. Prior to injection moulding, the pellets are processed in a Piovan DSN 508 dryer for 3 hours. All process energy consumption data are collected using FLUKE's 435 Power Quality Analyzer and relevant software connected directly to the Serin Otto 330 injection moulding machine. The PP + wood dust composite data were collected using the same methodologies by the Forbioplast project team in 2011.

Due to the lack of FIAT data, the EoL phase cannot be quantitatively assessed, but a qualitative review was undertaken. The EoL phase is separated into 3 process levels based on the European automotive EoL practices.

1. The ***first level*** is recycling where both composite components are removed from the vehicles for reprocessing into either new virgin material and/or down cycled raw material for other products. Recycled PP can be reused to make new interior trims, but only in a limited percentage. For the most part, recycled PP will become raw materials for products such as insulation fillers. PLA, unlike PP, can be chemically recycled and reused as new virgin material indefinitely without any loss of mechanical properties. However, there is a lack of infrastructure to recycle PLA efficiently.

2. The ***second level*** is energy recovery by incineration. This method is a very common practice in Europe due to the limited space for landfills and the EU ELV regulation which permits a percentage of mass-to-energy recovery. Dismantled plastics are used as fuel to generate electricity.

3. The ***third level*** is landfilling where dismantled plastics are buried at industrial landfills with other automotive shredder residues as an EoL treatment.

The distribution of the composite components into the three process levels depends on each OEM's corporate strategy and mandate, and the plastic part itself. Research into EU regulations and FIAT's database of vehicle EoL treatments revealed there is no one accepted best practice or standard of practice currently implemented in the European automotive industry. These standards and practices are necessary to designate the correct percentage of each EoL process for both the PP + wood flour composite and the PLA + flax fiber composite.

To evaluate the environmental performance of both composites, several environmental impacts are chosen for evaluation:

- non-renewable energy;
- global warming potential (GWP);
- acidification; and
- photochemical smog formation.

The non-renewable energy includes fossil energy and nuclear energy in terms of energy production facilities, including all fuels/energy necessary to power machinery, related infrastructure, and transportation needs. The GWP includes carbon dioxide, methane, nitrous oxide and many other relevant green house gases available from the data collected. Carbon content within biomass is included because it is sequestrated and released back into the environment slowly after EoL processes. The biomass included are: corn grains, wood dust, and flax fibers. Soil carbon sequestration, a process that captures and stores carbon dioxide (CO_2) from the atmopshere, is not included due to the unavailability of the necessary software for accurate calculations instead of rough estimates. The environmental impacts (GWP, acidification and photochemical smog) are calculated by the GaBi software based on collected data. Both non-renewable and renewable energy consumption are scoped out of the study by default because the values are given within the databases (USLCI and GaBi 5) and cannot be manipulated. However, the calculated resulting energy consumption is included within this study as complementary information to the EI categories.

The GaBi software calculates the environmental impact potentials, total energy consumed (renewal and/or non renewable), total air emissions, total water emission, and other resultant quantities of a product system based on plans that can be created within the software. In a plan, the modeled system is created by adding various processes and flows. In LCA terms, system boundaries are represented by plans, actual studied processes are represented by processes, and all system related inputs and outputs are represented by flows. The flows connect plans and/or processes within the modeled system or define the input / output flows.

The input and output flows are the most important information in GaBi. Flows are characterized differently with their respective quantities by mass, energy, volume, cost and many others. These quantities can be thought as the properties of the flows. Flows that enter or leave the studied system from the natural world (ie, coal or CO_2 emission respectively) are defined as elementary flows. The life cycle inventory (LCI) is this list of input and output flows. The importance of LCI is emphasized by the detailed description of the Ingeo (PLA) process data conversion section.

3.1 - Ingeo (PLA) Process Data Conversion

LCA software can vary considerably in terms of their assumptions and model development, and there is no single agreed upon “correct” model. A variety of different methodologies have been developed by various academic institutions and private companies. Some of the most commonly used LCA databases are GaBi, EcoInvent, and the US Life Cycle Inventory (USLCI). Each database's application depends on and is influenced by geographical markets. GaBi is mainly utilized in the European market and USLCI is more utilized in the North American market. EcoInvent is a more encompassing, but general database. As stated in the study scope, the entire PLA production process is to be included in the system boundary. NatureWorks LLC has published Ingeo's process LCI as a data set in the USLCI database. Since the PLA + flax fiber resin under study is Ingeo prior to the extrusion process, the USLCI PLA process data set will be utilized for this part of the study.

USLCI database is a public LCI database for the US that was created by the National Research and Energy Laboratory (NREL). The database format is based on Ecospold 2.1 xml format that emphasizes unit processes. These unit processes are predominantly gate-to-gate. The methodology between the USLCI and GaBi databases are different. USLCI calculates the resultant environmental impacts based on the unit processes. GaBi, on the other hand, bases its calculations on the input and output flows. The two methodologies have different assumptions and procedures in creating the respective databases. USLCI calculates the environment performance based on the unit process results instead of calculating based on all inputs and outputs. Due to these differences, the USLCI process data of PLA needs to be converted to a GaBi compatible format in order to be utilized in simulation model created in the study. Both databases are assumed to have considered all related parameters. The following steps were taken to properly convert USLCI process data so that they are compatible in the GaBi software.

Data matching is crucial in LCA to ensure the model represents the scope, research data, and the studied location as accurately as possible. This is especially true in situations where LCI databases of different methodologies are combined together, as it is the case here. Ecospold and GaBi also uses different terminologies for the studies input and output flows that need to be clarified and matched to ensure data correctness. Some examples of such conversion are presented here:

1. Calcite is an input in USLCI, but it is not present in GaBi. After reviewing all the available inputs similar to calcite in GaBi and background research on the importance of calcite within the study, it is determined that limestone is the best matched equivalent.

2. Water emissions are not differentiated between fresh and sea water in Ecopold, but such differentiation is necessary in GaBi. Since the environmental impact categories of global warming potential and acidification potential concern sea water for CO_2 and excess H^+ ions, all USLCI water related inputs and outputs are converted to sea water in GaBi.

3. Coal, as an energy input is given as bituminous with an energy value of 24.8MJ/kg in USCLI. However, GaBi has the ability to differentiate coals produced from different geographical regions in addition to type and energy value. Since PLA is produced in NatureWorks plant in Blair, Nebraska, USA, hard coal USA was chosen as the replacement in GaBi. The difference in energy

values between 24.8MJ/kg and 27.7MJ/kg are also taken into account by modifying the amount of coals used by a factor of 0.895.

Conversions similar to the three given examples were undertaken for all data entries of the USLCI PLA dataset. The complete list of the original USLCI data set can be found in Appendix A1. This step of data matching and conversion is essential to improve the analysis method by refining the acquired data and LCA modeling to represent the study boundary and scope more accurately. Table 4 demonstrates the different terminologies and flow data conversions necessary to implement USLCI data in GaBi.

Table 4 Dataset conversion from USLCI to GaBi

USLCI / Ecospold		GaBi	Significance
Elementary Flow	**Converts Into**	Input Flow	Input data of a process
Product Flow		Output Flow	Output data of a process
Root Flow		Tracked Flow	Input or output to be connected to another process within the model

3.1.1 - Importing USLCI Ecospold xml file into GaBi

The Ecospold xml file was downloaded from NREL's website. It is then imported into GaBi and an initial check was performed to eliminate discrepancies between the website listed exchanges (input and output flows) and the input and output flows in GaBi. (Vink E. , 2012) The process data set imported is considered more accurate in case of discrepancies because it is an updated version since its original publication on USLCI. Several duplicate entries were deleted.

3.1.2 - Elemental flows, characterization and normalization matching

After importation, all elemental and product flows of the USLCI Polylactide Biopolymer Resin, at plant process, are separated into input or output streams in GaBi. However, all entries are not linked to the GaBi database. Manually matching data subsets is necessary to convert and connect all the elemental flows with GaBi database equivalents. Most entries have direct equivalents within GaBi; however, some required in depth research to determine the most accurate substitutes. These substitutions with their associated reasoning are listed below:

3.1.2.1 - Input

1. ***Barite, in ground → Barium Sulphate***

   Barite or baryte is a mineral consisting of barium sulphate minerals. A direct equivalent replacement is possible.

2. ***Calcite, in ground → Limestone***

   Calcite is a carbonate mineral and is a common constituent of limestone. Since calcite is not present in GaBi, limestone is used as a substitute. Furthermore, it is combined with the additional entry of limestone.

$$\text{(USLCI) Calcite} + \text{Limestone} = \text{Limeston (GaBi)}$$

$$3.44\text{e} - 2\ [\text{kg}] + 1.01\text{e} - 1\ [\text{kg}] = 0.1354\ [\text{kg}]$$

3. ***Coal, bituminous, 24.8 MJ/kg, in ground → Hard Coal USA***

   Hard coal USA in GaBi has a caloric value of 24.8 MJ/kg. The amount after substitution is modified as shown since the original value is 27.7 MJ/kg.

$$\frac{24.8\ [\frac{\text{MJ}}{\text{kg}}]}{27.7\ [\frac{\text{MJ}}{\text{kg}}]} * 1.73\text{e} - 2\ [\text{kg}]\ (\text{USLCI}) \ = 0.0155\ [\text{kg}]\ (\text{GaBi})$$

   where, 1.73e-2 [kg] is the mass of Coal from the USLCI PLA dataset

4. ***Copper ore, in ground → Copper Ore 1%***

   1% is chosen among the possible choices because it is the most common assuming the copper is mined in the U.S.

5. ***Iron ore, in ground → Iron Ore (56.86%)***

   56.86% is chosen among the possible choices since most of the iron deposits of 60% or greater have been mostly depleted worldwide.

6. ***3 entries of Occupation***

   Units are changed from [m^2] to [m^2*year] and then converted to [kg] for a single input to GaBi.

7. ***Water, cooling (river)***
   Water, irrigation (river) → Water (River Water)
   Water, process (river)

   GaBi does not have separate elemental flows for different purposes of water. Hence all 3 river water usages are combined into a single flow.

8. ***Water, irrigation (ground) → Water (Ground Water)***
   Water (Surface Water)

   Irrigation water from ground water sources are divided into 2 parts (96% ground water and 4% surface water) as per the comment on the NREL website where the USLCI dataset was obtained.

$$\text{Water (ground)} = 20\ [\text{kg}] * .96 = 19.214\ [\text{kg}]$$
$$\text{Water (surface)} = 20\ [\text{kg}] * .04 = 0.801\ [\text{kg}]$$

where, 20 [kg] is the mass of irrigation water from the USLCI PLA dataset

3.1.2.2 - Output

*All water emissions are converted to seawater emissions rather than fresh water emissions since the EI category of AP measures the pH level of seawater.

1. ***2,4-D → 2,4-Dichlorophenoxyacetic acid***

   Emission to soil assumed to be pesticide related since 2,4-Dicholrophenoxyacetic acid is a chemical used in pesticides.

2. ***Aluminum compounds, unspecified → Metals (Unspecified)***

   Aluminum compounds in water emission is not present. Metal (unspecified) to fresh water is substituted in as an equivalent.

3. ***Arsenicum compounds, unspecified → Arsenic Trioxide***

   Arsenic trioxide, a air chemical emission, is substituted as an equivalent for arsenicum compounds, which is a chemical of pesticides.

4. ***Calcium compounds, unspecified → Calcium Nitrate***

   $Ca(NO_3)_2$ is a calcium compound that is released as a water emission from the use of fertilizers.

5. ***Chlorine***

   Organo-Chlorine → Chlorine

   Both chlorine and organo-chloride are air emissions. Since organo-chlorine is not available in GaBi, it is combined into chlorine.

$$\text{(USLCI) Chlorine} + \text{Organo} - \text{Chlorine} = \text{Chlorine (GaBi)}$$
$$1.6\text{e} - 7\ [\text{kg}] + 1.02\text{e} - 5\ [\text{kg}]\ = 1.023\text{e} - 5\ [\text{kg}]$$

6. ***Chlorpyrifos → Unspecified Pesticides (Hazardous)***

   Chlorpyrifos is a organophosphate pesticide used in farming. Since it is unavailable in GaBi, the unspecified pesticides entry is substituted as an equivalent.

7. ***Copper compounds, unspecified (water) → Copper (+II/+III) Emission***
   Copper compounds, unspecified (air) → +II Heavy Metal Emission
   Copper (+II/+III) is substituted as copper compound water emission equivalent, but +II is used air emission equivalent instead of +III because Cu(II) is more common and is often seen in the form of salts.

8. ***Dinitrogen monoxide → User Created Flow (1 kg = 2.96e+2 kg CO_2 equivalent)***
   An important global warming potential (GWP) air emission that is not available in the GaBi database. The value of 1 kg = 296 kg CO_2 equivalent is obtained from Leiden University's Institute of of Environmental Science (CML)'s published impact analysis data under GWPs Houghton, 1994, 1995, 2001. (Houghton, 2011)

9. ***Magnesium compounds, unspecified → Magnesium +II***
   A common alkaline earth metal with an oxidation number of +II, Mg (+II) is one of the most abundant element on Earth that finds application in the agricultural industry among others.

10. ***Nickel compounds, unspecified → Nickel +II (Heavy Metal Emission)***
    Nickel +II is substituted because it is the most common oxidation state of nickel.

11. ***Nitrogen compounds, unspecified → Nitrogen (as total N)***
    Total nitrogen from GaBi database is substituted to encompass all nitrogen compounds emitted since a specified entry is unavailable.

12. ***Particulates, <2.5 um → Dust (PM 2.5)***
    Particulates, >2.5 um and <10 um → Dust (PM 2.5 - PM 10)
    Particulates, >10 um → Dust (> PM 10)
    A simple conversion from different naming schemes.

13. ***Sodium Compounds → Sodium Nitrate***
    Sodium nitrate is equivalent substitute because it is commonly used in the production of fertilizers and is released as water emissions due to rain.

14. ***Suspended solids, unspecified → Gypsum Suspension***
    Insoluble solids as water emission. Because a specific entry is not available in GaBi, gypsum suspension is substituted as equivalent.

3.1.3 - Root/Tracked product flow matching for GaBi compatibility

Similar to elemental flow matching, all Ecospold root flows need to be converted into tracked product flows in GaBi to enable software modeling. GaBi requires product flows that are tracked. GaBi tracked flows are input and output flows within a process that are to be connected to other processes within the model. A good example is natural gas. Natural gas is an input flow in the PLA production process and can be different depending on geographical location of resin production. For NatureWorks' Ingeo, it would be *Nature Gas, USA*. Some Ecospold root flows, however, remain untracked and are not connected to other processes.

A special note on dummy flows is necessary to understand their presence in the process dataset when converting from USLCI to GaBi. According to GaBi, "... many of the datasets included placeholder flows when minor inputs (below the cut-off criteria) were not available in the USLCI database; these placeholder flows are marked with the prefix Dummy... " Dummy flows are not matched/linked in GaBi, but future data incorporations and additions will enable GaBi to replace the dummy flows with appropriate product flows. Because of their importance in GaBi software modeling, all tracked product flow conversions will be listed below with their associated reasoning:

3.1.3.1 - Input

1. ***Electricity, as grid, US, 2008 → Electricity***

   No U.S. specific electric power product flow is available in the GaBi database; only a generic electricity value from GaBi can be used. Since the production of Ingeo PLA biopolymer is an industrial process using industrial rated power of 480V and 60 Hz in the U.S., an adjusted quantity is necessary to create an equivalent tracked product flow. It is not possible to obtain an exact conversion factor without an extensive analysis into the differences of power distribution systems between the U.S. and Italy. Therefore, an approximated conversion factor of 2.1 was used after consulting previous FIAT bio-based project datasets. This value was deemed acceptable because this thesis study is a preliminary study to discover any trends in the usage PLA bio-based resin.

2. ***Natural gas, combusted in industrial boiler***
   Natural gas, combusted in industrial equipment → Natural Gas USA
   Gas, natural, in ground

   GaBi does not allow duplicate entries in either the input or the output flow entries. Duplicate entries prompt error messages when practitioners try to run the model and calculate the environmental impacts. A combination of both natural gas root flows from the Ecospold format and the elemental flow of in ground natural gas is performed to consolidate all 3 entries into a single tracked product flow.

   Furthermore, a unit conversion is necessary from MJ/m^3 to MJ/kg since GaBi's reference unit is in mass. To determine the ratio for volume to mass conversion of natural gas, one needs to apply the ideal gas law ($PV = nRT$) at standard temperature and pressure (0˚C and 1 atm respectively) along with a molar analysis of methane ($CH_4 = 12+1+1+1+1 = 16$ g/mol), the main component in natural gas. Note that 22.4 litres of any gas is equal to 1 mole at standard temperature and pressure.

$$\frac{16\ [\mathrm{g}]}{\mathrm{mol}} * \frac{1000\ [\mathrm{L}]}{[\mathrm{m}^3]} * \frac{\mathrm{mol}}{22.4\ [\mathrm{L}]} = 714 \frac{[\mathrm{g}]}{[\mathrm{m}^3]} \text{ or } 0.714 \frac{[\mathrm{kg}]}{[\mathrm{m}^3]}$$

Therefore, the combined and unit converted quantity of natural gas is:

$$(0.224 + 0.154 + 0.0479)\ [\mathrm{m}^3]\ * 0.714\ \frac{[\mathrm{kg}]}{[\mathrm{m}^3]} = 0.270\ [\mathrm{kg}]$$

where, 0.224 [m^3] is the mass of natural gas (industrial boiler);
0.154 [m^3] is the mass of natural gas (industrial equipment); and
0.0479 [m^3] is the mass of gas, natural (in ground) from USCLI dataset

However, the same ratio needs to be applied in reverse to convert the energy unit from MJ/m^3 to MJ/kg. As a check, the original amount is verified to be unchanged in the amount of 0.4259 kg.

3. ***Coal, bituminous, in ground → Hard Coal (USA)***
   Ecospold's coal has a caloric value of 24.8 MJ/kg and hard coal (USA) has a value of 27.7 MJ/kg. Therefore, an adjusted quantity is necessary to create an equivalent tracked product flow:

$$1.73\mathrm{e} - 2 * \frac{24.8 \left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right]}{27.7 \left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right]} = 0.0155\ [\mathrm{kg}]$$

4. ***Oil, crude, in ground → Crude Oil (USA)***
   An input that is required to be tracked instead of an elemental flow as it was categorized in the Ecospold format.

5. ***RNA: Transport, Combination Truck, Diesel Powered***
   Unit was given in t*km, a standard unit for the Ecospold format. A user created flow is created with a conversion factor of 1000 kgkm = 1 t*km.

3.1.3.2 - Output

1. ***Ingeo Polylactide (PLA) Biopolymer (by NatureWorks LLC)***

   The end product from the industrial process that has been converted from USLCI's Ecospold format into a GaBi compatible process.

Please see Appendix A1 for the complete list of elemental flows and tracked production flows prior to database matching and Appendix A2 for after database matching.

3.1.4 - Dataset Conversion Verification

After completion of elemental and track product flows matching, a new plan was created in GaBi to complete the process with the necessary inputs to model the production of 1 kg of Ingeo Polylactide Biopolymer (PLA). As described in the tracked product flows matching section, the five necessary inputs are shown in Figure 6.

Figure 6 PLA (Ingeo) production plan model in GaBi after dataset conversion

A balance calculation is then performed to generate results for comparison with literature data published by NatureWorks LLC. The eco-profile of Ingeo 2009 published focuses on the energy required and the GHG emission released by the production of 1 kg of Ingeo. These values are 67.83 MJ of total energy and a net GHG emission of 1.24 kg CO_2/kg Ingeo respectively. (Vink E. , 2012) To check the validity of the converted dataset in GaBi, these values will be compared to the values generated by the balance calculation. The model generated data are 65.032 MJ of total energy and a net GHG emission of 1.12 kg CO_2/kg Ingeo. Please see Appendix A3 and A4 for details. With respect to energy required for producing 1 kg of Ingeo, the converted GaBi process generated a value that is very close to the published data. The values for GHG emission have a discrepancy of 0.12 kg CO_2/kg Ingeo. This discrepancy is undesirable due to the methodological differences between eco-profile and GaBi. Considering the number of conversions necessary for the USLCI to GaBi database conversion, this discrepancy is deemed acceptable because of the first iteration laboratory material status of the PLA + flax fibers. Please see Table 5 for the compared data values.

Table 5 PLA (Ingeo) data comparison: eco-profile vs. GaBi

	Unit	Eco-Profile	GaBi	Difference	Discrepancy [%]
Total Energy	[MJ/kg Ingeo]	67.834	65.032	2.802	4.1
GHG	[Kg CO_2/kg Ingeo]	1.24	1.12	0.12	9.7

A user created and verified GaBi process can now be implemented to complete the PLA + flax dashboard component modeling. The single output tracked production flow of the Ingeo process will become part of the input for the extrusion process that compounds flax short fibers with NatureWork's Ingeo PLA.

3.2 - GaBi 5 Life Cycle Assessment Model Creation

Both studied composites have a 30% content of natural fibers by volume. Both wood dust and flax fiber utilized for the thesis study have densities of < 100 kg/m^3, which are much lower than both the polypropylene and PLA resins utilized at ≥ 1000 kg/m^3. It is assumed that a 30% displacement in volume equals a 30% displacement in weight of the extrusion compounded composite pellets. This is necessary because mass measurements are used for all material inputs and outputs in the modeled systems.

The mould utilized for producing the dashboard trim component was made for PP + wood dust composite pellets. The same mould is used for producing the PLA + flax component as well. Since the functional unit is one dashboard trim part, the injection moulding process is based on per component weight instead of per unit weight; for example, per 1 kg of composite material. The weights of the components are 159.2 g for PP + wood dust and 197.8 g for PLA + flax. These values are obtained by averaging 10 injection moulded components. Please see Appendix B1 for detailed calculations.

3.2.1 - Polypropylene Resin + Wood Dust

The composite of PP + wood dust is currently utilized for interior components in the product line-up of FIAT group of automobiles. This composite is the reference material for comparing environmental impacts through an LCA against the bio-composite of PLA + flax. The majority of the LCI data were adapted from the previous FIAT project, Forbioplast. The completed LCA model for PP + wood dust is shown in Figure 7. The plan is composed of four main processes: wood dust drying, extrusion compounding, pellet drying, and injection moulding. Each main process has sub-process inputs and outputs that make up the LCA model. The process sequence starts from wood dust production, followed by the drying of wood dust and extrusion compounding of composite pellets. Then after transporting the pellets to Centro Ricerche Fiat (CRF), an additional drying process to remove the moisture content in the pellets is performed before injection moulding to produce the final dashboard trim component.

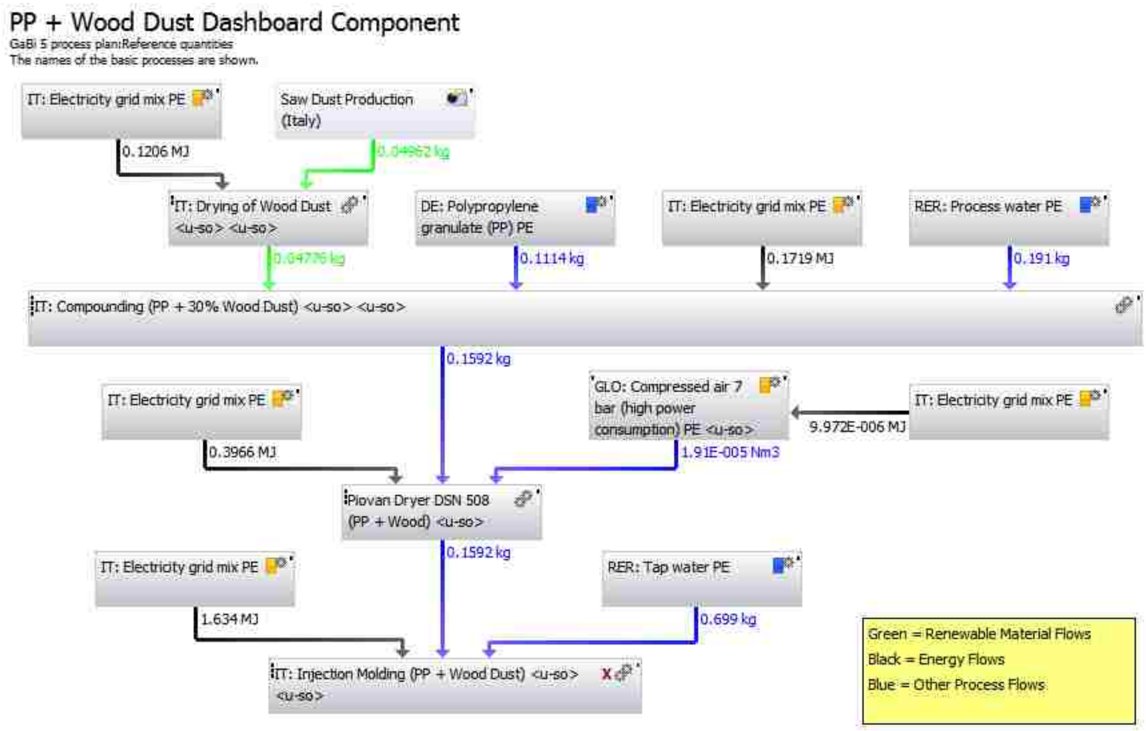


Figure 7 model of PP + wood dust dashboard component

3.2.1.1 - Wood Dust Drying

Wood dust production LCI data was adapted from the Forbioplast project. Forbioplast project was a multi-company collaboration on the usage of bio-materials in polymer production to reduce component weight while maintaining all necessary specifications. The component produced was a PP + wood dust seat pan to be compared with an identical part made entirely of PP. Since the wood dust used was produced in Italy, the same process LCI data was adapted in this study. Please see Appendix B2 for the LCA model and LCI model data adapted from the Forbioplast project.

Similar to wood dust production, wood dust drying process LCI data is also adapted from the Forbioplast project. Wood dust typically has a moisture content between 50% - 65%. (Magelli, Boucher, Bi, Melin, & Bonoli, 2009) The wood dust was dried in an oven for 10 hours at 80˚C to lower the moisture content to around 10% before the extrusion compounding process. The energy required per 1 kg of wood dust was determined to be 2.525 MJ. Please see Appendix B3 for wood dust drying process adapted from the Forbioplast project.

3.2.1.2 - Extrusion Compounding

In the Forbioplast project, the extrusion compounding process occurred in a laboratory in Hungary rather than in Italy. After completion, the produced composite pellets were transported by truck to CRF in Italy. The PP used consisted of both virgin and recycled materials. This is not the case for the study presented here, which uses only virgin PP. Electric energy, lubricants and process water are also consumed during the process. Please see Appendix B4 for the Forbioplast compounding process. To adapt the Forbioplast compounding process for application in the study, all PP utilized are changed to virgin materials as no recycled PP was utilized for the PLA + flax component production. All relevant process input and output flows such as energy and water consumption are modified to fit the study. Please see Appendix B5 for the adapted extrusion compounding process.

3.2.1.3 - Pellet Drying

A moisture removal process is necessary before injection moulding. This is necessary to ensure the quality of the produced parts by maintaining a consistent density throughout the component without the presence of air pockets. Piovan DSN 508 with 400V / 50 Hz dryer is utilized for this process. The power consumption is calculated to be 3.46 kW. Please see Appendix B6 for the data sheet provided by Piovan. For the PP and wood dust composite pellets, the required drying time is 4 hours. 20 kg of pellets were also employed for the production run of the interior dashboard trim study. The amount of energy consumed is:

$$Energy\ per\ part\ = \frac{3.46\ [kW] * 4[h]}{20[kg]} * \frac{0.1592[kg]}{part} = 0.1102\ \frac{[kWh]}{part}$$

3.2.1.4 - Injection Moulding - Polypropylene (PP) + Wood Dust

The same injection moulding process produces the final product of the interior dashboard trim component being studied for both composites. For PP + wood dust, the injection moulding process was done years ago during the completion of the Forbioplast project and was not data logged, but the process was completed at CRF using the Sandretto Serin

Otto 330 injection moulding machine. The same machine was used in the PLA + flax case where data were logged by external experts from Fluke. By comparing the mechanical and injection moulding properties of both PP + wood dust and PLA + flax composites, both composites have similar suggested injection temperatures (190˚C and 180˚C respectively) and similar suggested mould temperatures (50˚C and 60˚C). Please see Appendix B7 for the property tables. Both injection moulding processes were assumed to consume the same amount of energy. Water consumption is 0.699 kg per part with a component weight of 0.1578 kg. A detailed description of the injection moulding process modeling is given in the PLA + flax LCA model section.

3.2.2 - Polylactic Acid Resin + Flax Short Fibers (with 8% H_2O content)

The completed LCA model for PLA + flax is shown below in Figure 8. The plan is composed of 3 main processes: 1) extrusion compounding; 2) pellet drying; and 3) injection moulding. Each main process has sub-process inputs and outputs that make up the LCA model. The process sequence starts with raw material production, which includes Ingeo PLA resin and short flax fibers. Extrusion compounding then follows to produce the composite pellets. Lastly, pellet drying is performed prior to injection moulding to produce the end dashboard trim component.

3.2.2.1 - Extrusion Compounding

Extrusion compounding of PLA and flax fibers produces the composite pellets for injection moulding. There are four inputs to this process: electric power, process water, PLA resin and flax short fibers. Both electric power and process water necessary for extrusion compounding are represented by GaBi 5 database LCI data because of matching parameters to the actual process. PLA resin data were described in detail previously in the Ingeo PLA Process Data Conversion section. Due to a lack of industry data within the FIAT database, data substitution was necessary. After internal reviews at CRF, it was decided that flax fiber data within the GaBi database can be used as an equivalent in completing the LCI. Another option was to assume bamboo fiber data as flax fiber equivalent and collect the relevant LCI data from literature. This was proposed because of future FIAT projects that will be utilizing bamboo fibers as composite reinforcements.

After some initial literature review, this option was determined to be unfeasible due to validity and time constraints. Finally, GaBi 5's flax short fiber with 8% H_2O content process was chosen to represent the natural fiber reinforcement in the modeled system due the similarities in material properties.

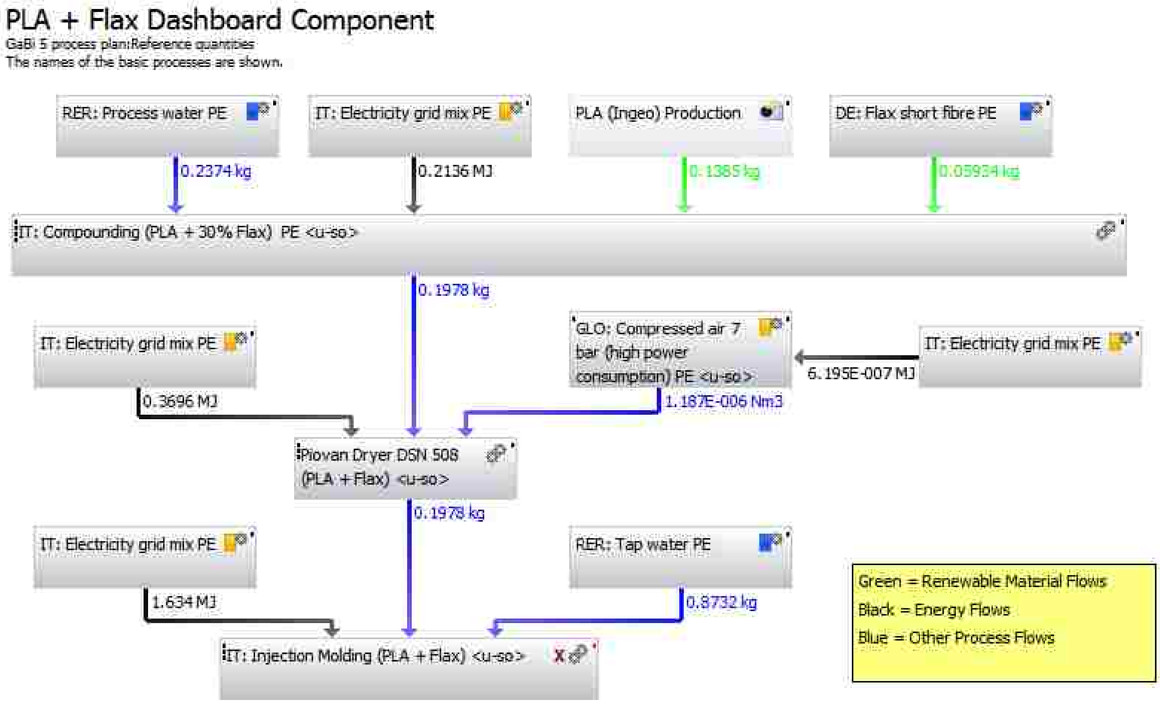


Figure 8 LCA model of PLA + flax dashboard component

Energy consumption required for the extrusion compounding process is assumed to be the same for PP + wood dust due to a lack of data from Politecnico di Pisa, the producer of the composite pellets. This assumption is reasonable because all datasets collected on previous extrusion compounding processes involving polymer resins and natural fiber reinforcement within FIAT were very similar in energy consumption with regards to machine operation and mould cooling. This same reasoning is applied to the process water consumed.

3.2.2.2 - Pellet Drying

A similar moisture removal process is necessary before injection moulding of PLA + flax components. The same Piovan DSN 508 with 400V / 50 Hz dryer is utilized for this process. For the PLA and flax composite pellets, the required drying time is 3 hours, and 20 kg of pellets were used for the production un to produce the interior dashboard trim. The following energy was consumed:

$$Energy\ per\ part\ = \frac{3.46\ [kW] * 3[h]}{20[kg]} * \frac{0.197.8[kg]}{part} = 0.1027\ \frac{[kWh]}{part}$$

3.2.2.3 - Injection Moulding - Polylactic Acid (PLA) + Flax

GaBi 5's injection moulding for plastic part process was selected as the base for modifications to represent the energy and water consumption data collected. Data collection was done externally rather than internally by experts from Fluke using Fluke's 435 power quality analyzer to maintain the objectivity of this research study. Potentiometers were placed on both the injection moulding machine and the water cooling system that maintains the mould temperature during the injection moulding process. For PLA + flax, the injection temperature is between 170˚C to 180˚C depending on which zone was being measured on the injection barrel. The mould temperature was kept at around 25˚C instead of the suggested 60˚C provided by the Politecnico di Pisa to prevent burning of the flax fiber, which if not prevented produces a burnt smell.

The entire injection moulding cycle per part took 74 seconds to complete and the energy consumption data was collected in two second intervals. The measured data was transformed to obtain the unit of [kWh] required for GaBi 5 modeling. First, every data point was multiplied by 2 and then divided by a factor of 1000 to obtain a unit of [kWs]. This is followed by a multiplication of 3600 to convert seconds to hours, to obtain the desired unit of [kWh]. Please see Appendix B8 for graphical representation of energy consumption data collected and Appendix B9 for the calculations done in a Microsoft Excel worksheet.

Water consumption data is represented by GaBi 5's injection moulding for plastic part process at 4.41 kg of water per kg of part produced. This amount is proportionally reduced to 0.8732 kg per part since the PLA + flax component's averaged weight is 0.1592 kg.

4 - Results & Life Cycle Impact Assessment (LCIA)

A life cycle impact assessment (LCIA) was undertaken within GaBi 5 to evaluate the possible environmental impacts of the studied composites. The differences in environmental impacts between the PP + wood dust composite and the PLA + flax composite are compared. The categories to be analyzed are:

1. Global Warming Potential - 100 years (GWP);
2. Acidification Potential (AP); and
3. Photochemical Ozone Creation Potential (POCP).

The 3 chosen EI categories have fundamental impacts to Earth's eco-system and are widely accepted by LCA practitioners. Furthermore, all 3 EI categories are especially important to the automotive industry as they correlates to CO_2 and tail pipe emissions.

Many different LCA practice standards exist around the world. The standard used for the study is CML 2001 (Nov 2009) created by the Institute of Environmental Sciences (CML), University of Leiden, Nederland in 2001. This latest revision is used in GaBi 5 for all LCIA calculations.

In addition to the three selected environmental impact categories, the amount of *non-renewable energy* consumed to produce the functional unit is also analyzed as it closely relates to production cost for the OEM. Even though non-renewable energy within GaBi 5 also includes non fossil fuel energy sources such as nuclear power, the values enable researchers to compare the amount of fossil fuels consumed within the system scope and boundary.

4.1 - Reference Material - Polypropylene + Wood Dust

The contributions from each main production process are presented graphically to better understand which process within the system boundary has the greatest environmental impacts. For the PP + wood dust reference composite, the main processes are: wood dust production, wood dust drying, polypropylene granulates production, extrusion compounding, pellet drying and injection moulding. In the following graphs, a total value is shown along with the breakdown of the main contributing processes for each of the four environmental impacts.

4.1.1 - Global Warming Potential - 100 Years

The global warming potential (GWP) correlates the ability of various green house gases to absorb and trap infrared energy in the atmosphere. It compares the amount of heat energy trapped by a certain gas of a given mass to the similar mass of the reference gas, carbon dioxide. GWP is calculated over specific time intervals such as 20, 50, 100 or 500 years. The interval chosen for the study is 100 years, which is the most commonly used interval. The total GWP per functional unit of one interior dashboard trim component is 0.5546 kg CO_2-equivalent as shown in Figure 9.

4.1.2 - Acidification Potential

Acidification potential (AP) is the measure of H^+ ion levels that decreases pH levels in water. The increase of H^+ levels in water is due to the uptake of atmospheric CO_2 of anthropogenic origin. As more CO_2 is released into the atmosphere, more are dissolved by the world's oceans in the form of carbonic acid. Acidification is present in both fresh water (lakes and rivers) and seawater (oceans). The acidification of seawater is represented in the study. As shown in Figure 10, the total AP per functional unit is 1.214e-3 kg SO_2-equivalent.

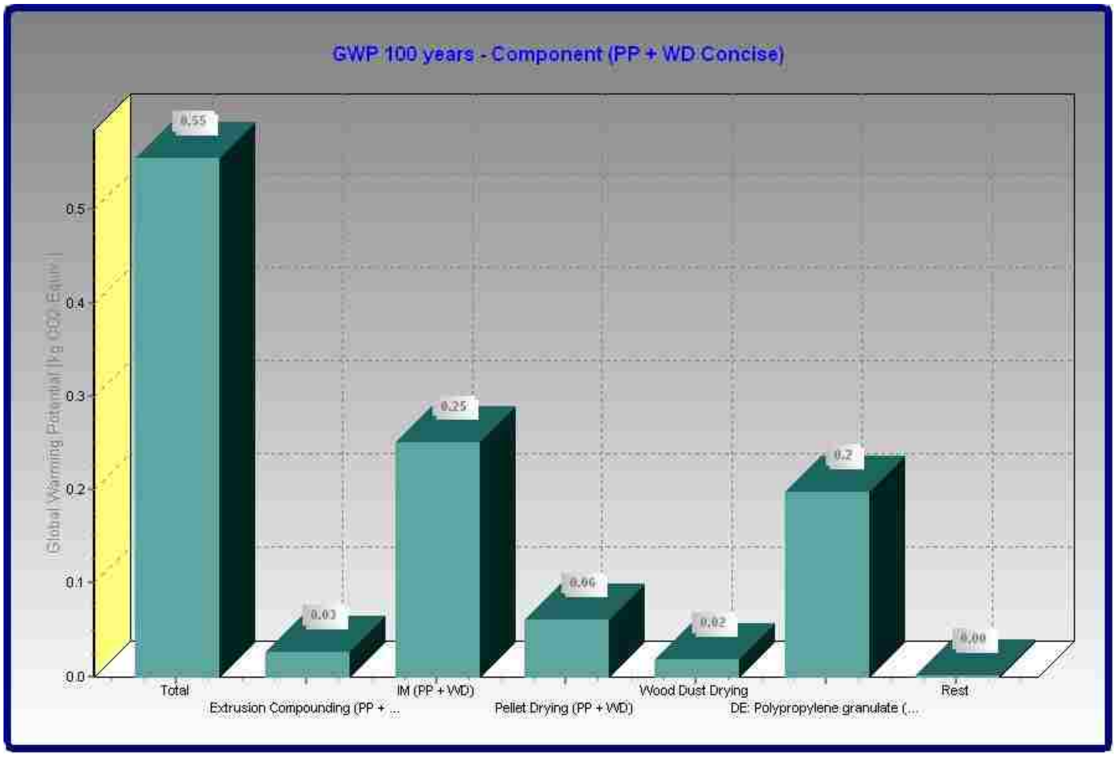


Figure 9 Global Warming Potential - 100 years for PP + Wood Dust

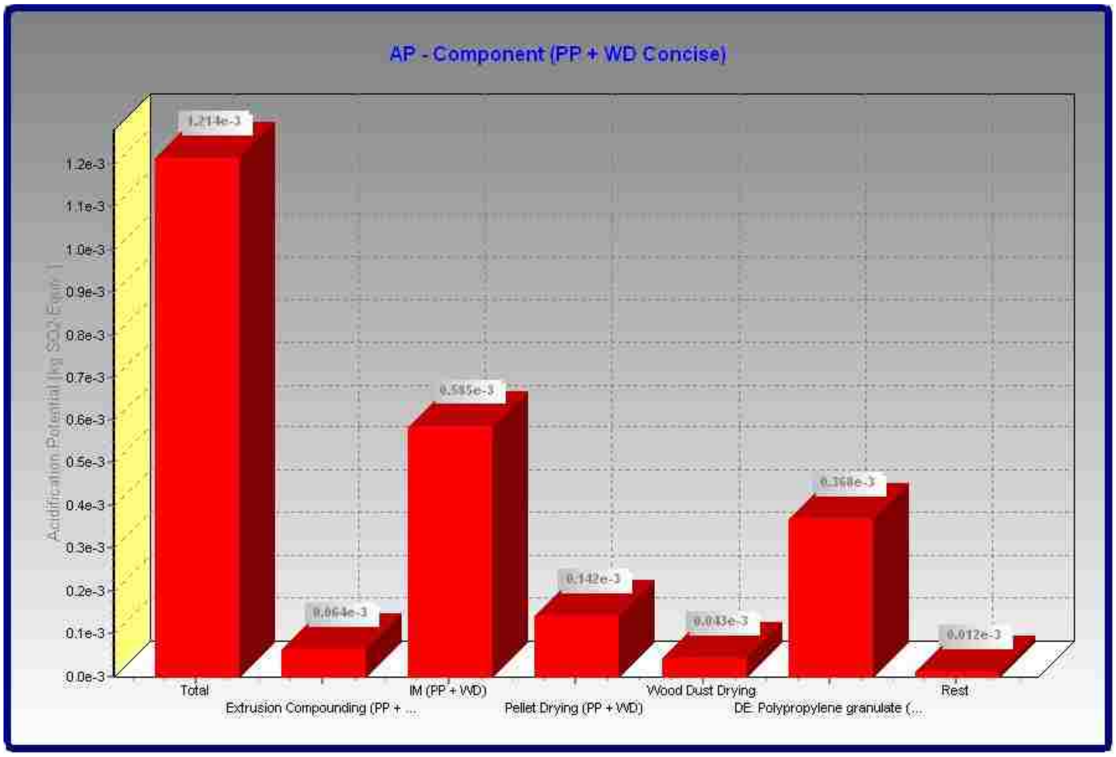


Figure 10 Acidification Potential for PP + Wood Dust

4.1.3 - Photochemical Ozone Creation Potential

Commonly known as smog, a term used to describe air that is both smoky and foggy, the photochemical ozone creation potential (POCP) measures the amount of air pollutants and ground level ozone created from the reaction between sunlight, nitrogen oxides and VOC of anthropogenic origins suspended in the air. As shown in Figure 11, the total POCP per functional unit is 1.38e-4 kg ethene-equivalent.

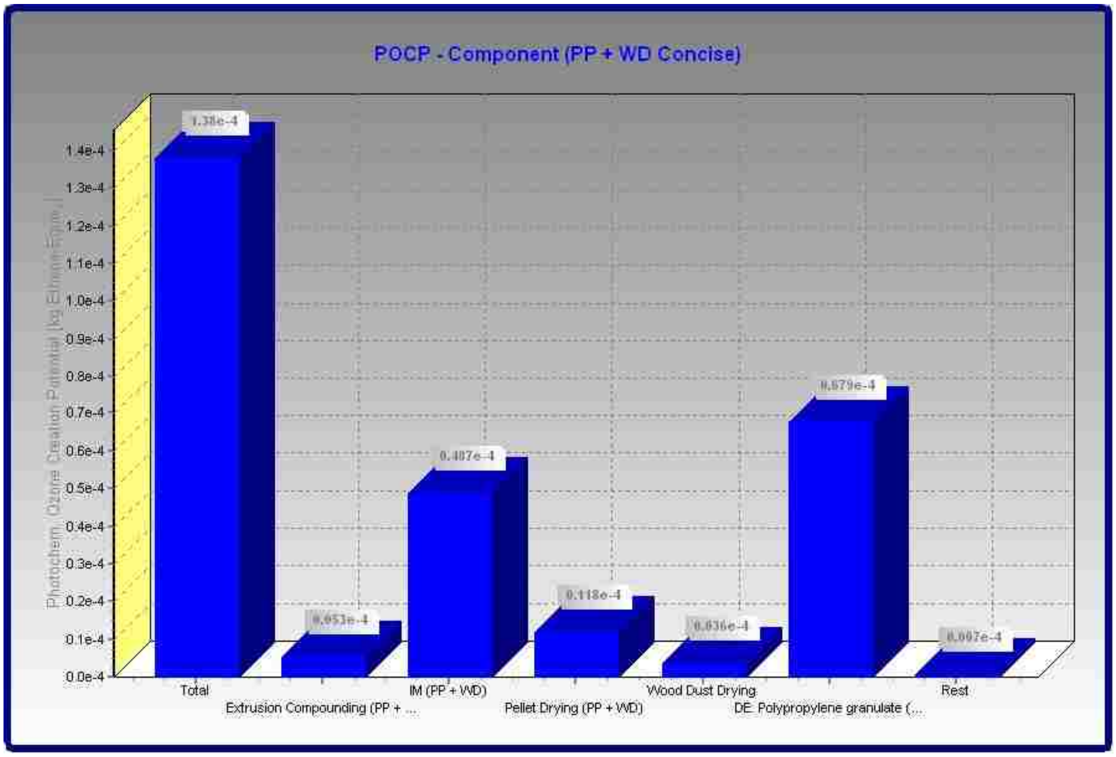


Figure 11 Photochemical Ozone Creation Potential for PP + Wood Dust

4.2 - Bio-based Material - Polylactic Acid Resin (PLA) + Flax Fibers

Using the same categorization method as the reference material, the environmental impact potentials for the main production processes for PLA + flax components are also evaluated. These processes are: flax short fibers production, Ingeo (PLA) production, extrusion compounding, pellet drying and injection moulding. A total value is shown along with the breakdown of the main contributing processes for each of the three environmental impacts for all resultant graphs. Figures 12, 13, and 14 shows the resulting graphs for GWP, AP, and POCP respectively.

4.2.1 - Global Warming Potential - 100 Years

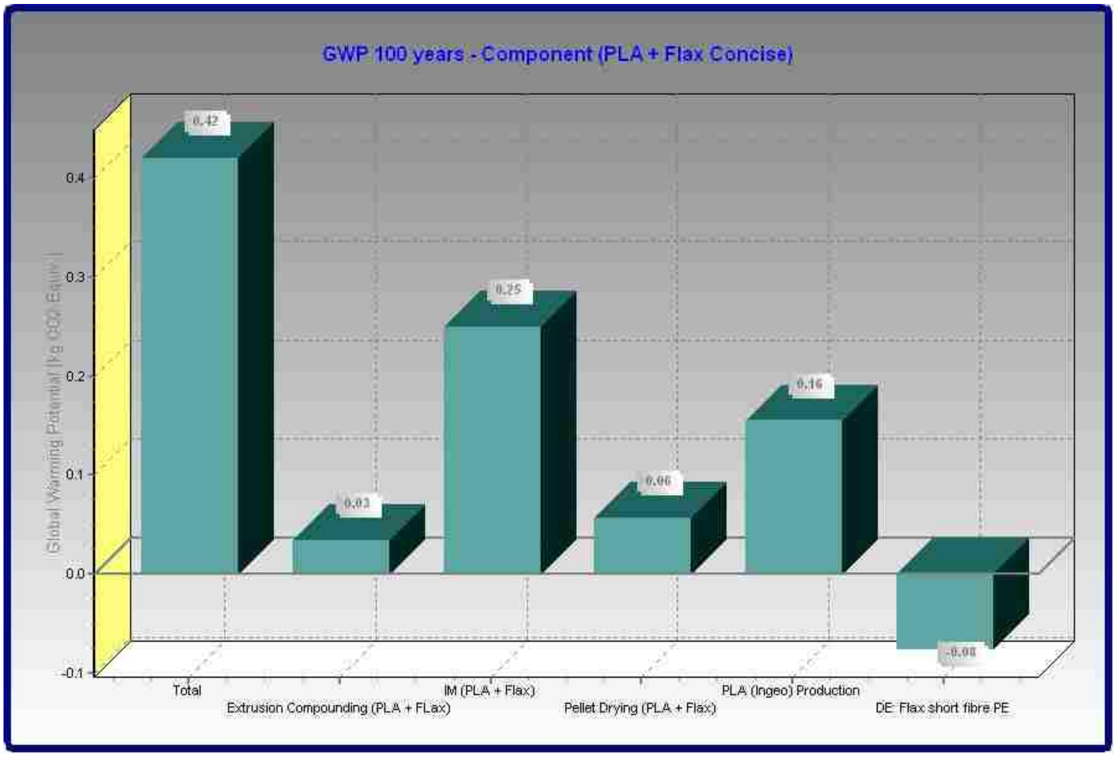


Figure 12 Global Warming Potential - 100 Years for PLA + Flax

4.2.2 - Acidification Potential

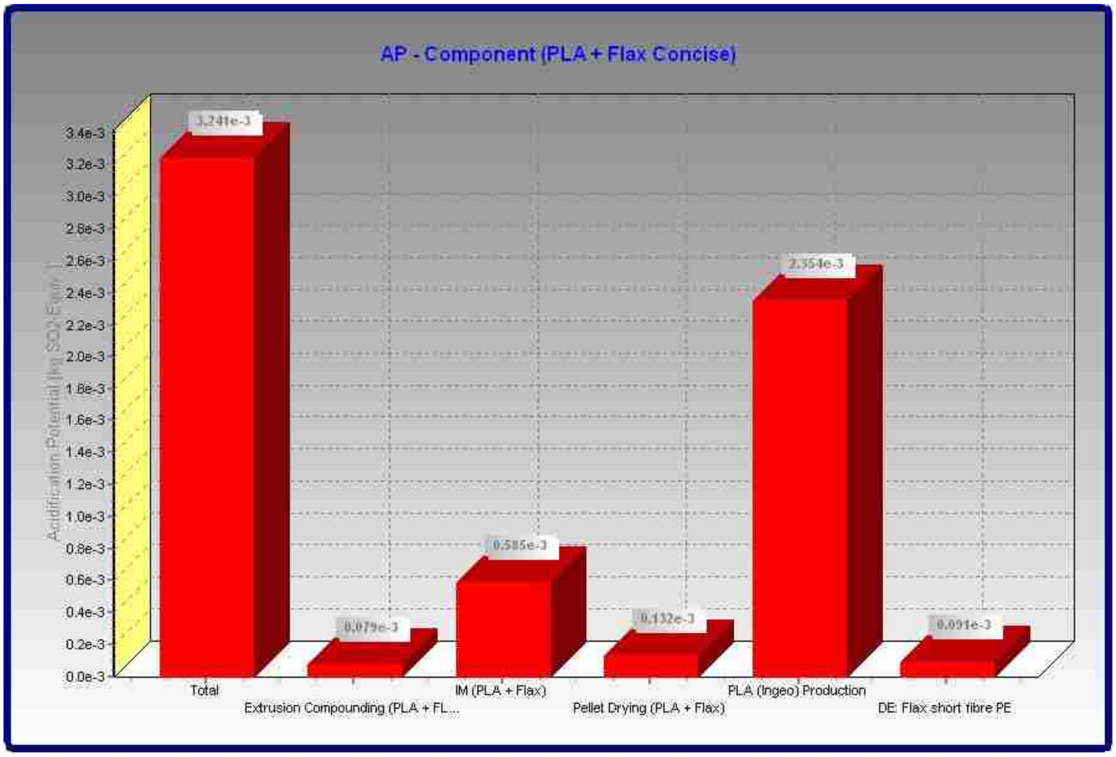


Figure 13 Acidification Potential for PLA + Flax

4.2.3 - Photochemical Ozone Creation Potential

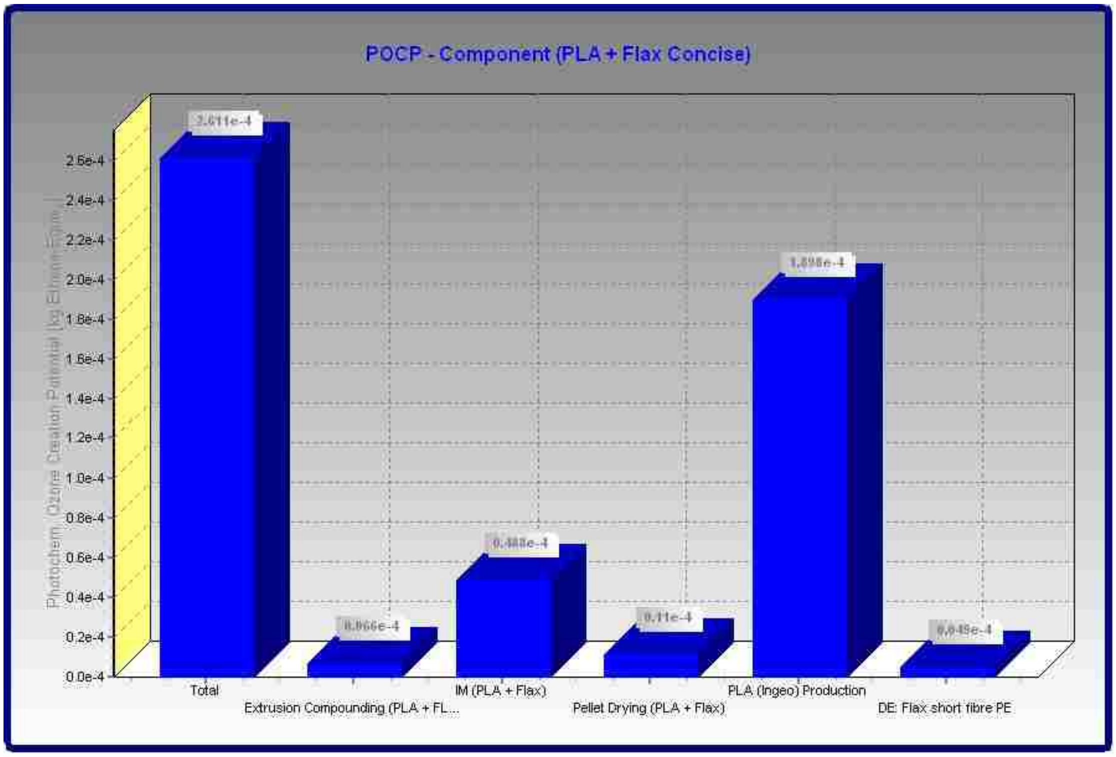


Figure 14 Photochemical Ozone Creation Potential for PLA + Flax

4.3 - Life Cycle Impact Assessment (LCIA)

The 100 year global warming potential for both the PP + wood dust composite and PLA + flax are shown in Figures 9 and 12 respectively. For each functional unit produced, the PP + wood dust composite releases a total of 0.5546 kg CO_2-equivalent compared to 0.4205 kg CO_2-equivalent released by the PLA + flax composite. The biggest contributors to GWP are the same for both composites: polymer resin production (both PP and PLA) and injection moulding. The injection moulding process, being the greatest contributor, requires a significant amount of electrical energy to mould the components and regulate the mould temperature. In Italy, electricity is produced mainly through fossil fuel consumption. PP, unlike PLA, is a product of crude oil and therefore contributes greatly to GWP. One point to emphasize is the sequestration of GWP in the flax production process. This is due to bio-mass CO_2 sequestration in flax short fiber production.

For acidification potential, PP + wood dust composite releases 1.214e-3 kg SO_2-equivalent compared to 3.241e-3 kg SO_2-quivalent released by PLA + flax composite per functional unit produced. The injection moulding process is a main contributor and is the same for both composites. This is to be expected since the injection moulding process of PP + wood dust was assumed to be the same for PLA + flax. Another significant contributor is the polymer production process for both PP granulate production and PLA resin production. PLA (Ingeo) resin production is more important in terms of AP compared to PP because PLA is produced from agricultural corn, which consumes fossil fuel energy for both corn production and resin production. No biomass production is necessary for PP. This is clearly demonstrated by the AP graphs of the composites in Figures 10 and 13.

Photochemical ozone creation potential for the PP + wood dust composite is calculated to be 1.38e-4 kg Ethene-equivalent. For the PLA + flax composite, the value is 2.611e-4 kg Ethene-equivalent. Similar to other environmental impacts, the two largest contributing processes are injection moulding and polymer resin production. Continuing the trend from AP, PLA production produces more POCP per functional unit compared to PP production.

There are two primary sources for the local environmental impacts (acidification and photochemical ozone creation) considered in the study. The first source is the fossil fuels consumed during production and agricultural processes. This includes the release of sulphuric oxides from the production of electricity because Italian power generation depends heavily on fossil fuel combustion. The second source is the fertilizers used during biomass production for both wood dust and flax short fibers. The main detrimental environmental impact source from agricultural practices are CO_2, methane and nitrogen oxide emissions.

Both composites consume roughly the same amount of non-renewable energy for component production. The PP + wood dust composite consumes 13.91 MJ per component and the PLA + flax composite consumes 13.98 MJ. This result was not expected from initial study formulation. The trend continues when examining total energy consumption. The total energy consumption for the reference composite is 14.94 MJ compared to 16.28 MJ for the bio-material composite, which is unexpectedly higher than initial estimate.

5 - Conclusion and Recommendation

This research compared the reference material, polypropylene (PP) + wood dust, which is already in use within the FIAT group of automobiles to a new laboratory bio-composite material of polylactic acid (PLA) + flax to determine which material, over its life cycle, posed the lowest overall environmental impacts.

After data collection, a data matching/conversion process is necessary before life cycle assessment (LCA) software modeling can start. Due to the lack of compliant dataset for the GaBi software, the PLA resin production's life cycle inventory (LCI) dataset has to be imported from United States Life Cycle Inventory (USLCI). A direct software to software database conversion is not possible due to the difference in LCA methodologies. Therefore, manual data matching is required on all data entries where direct substitution is not possible. What follows is the iterative process of background research on all data entries between the two databases to produce conversion factors and equivalent substitutes based on various parameters such as geographical region (electricity grid mix from USA vs. Italy), specific types of resources (coal vs. lignite), and caloric values. This conversion process has become a secondary objective that is pre-requisite to the main LCA objectives stated at the start of the conducted study.

CO_2 emission reduction is currently the main focus for automotive OEM to comply with present and future government legislations and to gain positive corporate image from the consumers. The new bio-composite of PLA + flax out performs the current PP + wood dust composite in terms global warming potentials (GWP), but not with regards to local environmental performance. Furthermore, the first generation laboratory PLA + flax bio-composite consumes more energy per component, which translates into a higher cost for production. The LCA results suggest to therefore continue using the current PP + wood dust composite for current mass produced components. Bio-based material composites, namely PLA + flax, can be a feasible alternative with further advancement in production methodologies and enhancement in material properties.

The PLA resin reinforced with flax short fibers component production offers environmental advantages over PP resin reinforced with wood dust in terms of 100 year global warming potentials. In terms of local environmental impacts, however, the PLA + flax composite produces more pollutants that contribute to acidification and photochemical ozone creation. This is due to a total emission to air that is four times greater when compared to PP + wood dust component production. This is because of the agricultural practices in producing the corn feedstock necessary for PLA production. Many existing agricultural practices can be implemented to decrease the amount of CO_2 released from corn production. One example is off season or winter crops agriculture. It can be implemented to increase the organic carbon level in the soil by providing cover crops as protection to offset the CO_2 released. (Kim, Dale, Drzal, & Misra, 2008) Please see Appendices C1 and C2 for the detailed breakdown of emissions to air between the two composites.

For the non-renewable energy consumption and the resulting environmental impact from GWP, the processes that contribute the most are polymer resin manufacturing and the final component injection moulding. For injection moulding, more energy efficient machineries and production methods are recommended for both composites to lower the energy consumption and thus GWP. With respect to polymer resin production, NatureWorks LLC is currently using the third iteration of its PLA (Ingeo) production process to lower the energy consumption and environmental impacts. As PLA production is still a new industrial process, there is more room for improvement. For PP production, *Green PP*, a renewable PP resin from Braskem is a promising alternative for petroleum based PP to lower GWP. More LCA studies on such alternatives would help to determine more sustainable sources of PP.

The PLA + flax composite utilized for the study is a first generation laboratory material being tested for material specification validation and to assess any trends in using bio-based materials. As such, the data interpretations of the practitioner are acknowledged as is and a sensitivity analysis is not conducted to statistically analyze the resultant EI's. A more in depth LCA study will be conducted as the material progresses towards the replacement of the reference composite of PP + wood dust.

The injection moulding equipment at FIAT is only for experimental and testing purposes. Production efficiency optimization that would have been performed in a mass production scenario was not done for the study. As the material matures and greater economies-of-scale can be achieved, a more energy efficient and more environmentally friendly injection moulding process will be implemented and evaluated prior to mass production as that is FIAT's corporate mandate.

Existing data from Forbioplast, a previously completed LCA study on the reference material was adapted as the basis for comparison. However, the main focuses of LCA studies for automotive OEM are energy consumption and CO_2 emission from production cost and environmental legislation perspectives. This focus sometimes reduces the data accuracy of other environmental impacts to be studied. For example, the beech tree sub-process within the wood dust production process of Forbioplast is simplified as a renewable energy source. A complete LCI data collection was not performed to include the wood harvesting process as was done for the flax short fibers production process. As a consequence, the most accurate representation of LCI within the study is the non-renewable energy consumption and the 100 years global warming potentials.

For future studies, some recommendations can be given to overcome the deficiencies encountered.

1. Collect more complete LCI database on all processes within the scope of the study. This includes all raw and secondary materials used in production, all transportation energies consumed, all process inputs (electricity, water, air,

additives and others) and outputs (air emissions, water emissions, and waste materials), and all secondary processes within the scope and boundary such as waste heat.

2. Utilize datasets from the same databases and/or data formats wherever possible to avoid the need for data conversions. This will shorten the LCI collection time and minimize data discrepancies.

Depending on the scope and boundary of the intended future study, these recommendations will ensure the creation of a more representative LCA model. For any LCA study, the resultant analyses are only as good as its data collected.

Appendices

Appendix A

Appendix A1 - USLCI Ecospold Ingeo (PLA) Process Flows Data

Inputs				
Flow	**Quantity**	**Amount**	**Unit**	**Tracked**
RNA: Dummy_Disposal, chemical waste, unspecified, to residual materials landfill [Flows]	Mass	0.000623	kg	X
RNA: Dummy_Disposal, chemical waste, unspecified, to sanitary landfill [Flows]	Mass	0.001011	kg	X
RNA: Dummy_Disposal, inert solid waste, to inert material landfill [Flows]	Mass	0.001665	kg	X
RNA: Dummy_Disposal, mineral waste, underground deposit [Flows]	Mass	0.01694	kg	X
RNA: Dummy_Disposal, mining waste, underground deposit [Flows]	Mass	0.003381	kg	X
RNA: Dummy_Disposal, slags & ash waste, unspecified reuse [Flows]	Mass	0.001417	kg	X
RNA: Dummy_Disposal, tailings waste, underground deposit [Flows]	Mass	0.001259	kg	X
RNA: Electricity, as grid, US, 2008 [Flows]	Energy	5.857153	MJ	X
RNA: Natural gas, combusted in industrial boiler [Flows]	Energy	0.224	MJ	X
RNA: Natural gas, combusted in industrial equipment [Flows]	Volume	0.154	m3	X
RNA: Transport, combination truck, diesel powered [Flows]	kgkm	126.76	kgkm	X
Coal, bituminous, 24.8 MJ/kg, in ground [in ground]	Mass	0.017333	kg	
UNSPECFIED: Air [in air]	Mass	0.254319	kg	
UNSPECFIED: Barite, in ground [in ground]	Mass	7.25E-05	kg	
UNSPECFIED: Bauxite ore, in ground [in ground]	Mass	5.04E-06	kg	
UNSPECFIED: Calcite, in ground [in ground]	Mass	0.101051	kg	
UNSPECFIED: Calcium sulphate, in ground [in ground]	Mass	2.69E-08	kg	
UNSPECFIED: Carbon dioxide, biogenic [unspecified]	Mass	1.833	kg	
UNSPECFIED: Clay, bentonite, in ground [in ground]	Mass	5.34E-06	kg	
UNSPECFIED: Coal, lignite, in ground [in ground]	Mass	2.56E-05	kg	
UNSPECFIED: Coal, metallurgical, in ground [in ground]	Mass	2.27E-05	kg	
UNSPECFIED: Copper ore in ground [in ground]	Mass	1.72E-11	kg	
UNSPECFIED: Dolomite, in ground [in ground]	Mass	6.93E-07	kg	

UNSPECFIED: Ferromanganese, in ground [in ground]	Mass	5.06E-08	kg	
UNSPECFIED: Fluorspar, 92%, in ground [in ground]	Mass	9.17E-08	kg	
UNSPECFIED: Gas, natural, in ground [in ground]	Mass	0.047945	kg	
UNSPECFIED: Gravel, in ground [in ground]	Mass	2.06E-07	kg	
UNSPECFIED: Iron ore, in ground [in ground]	Mass	5.58E-05	kg	
UNSPECFIED: Lead ore, in ground [in ground]	Mass	3.15E-07	kg	
UNSPECFIED: Limestone, in ground [in ground]	Mass	0.034381	kg	
UNSPECFIED: Nitrogen, in air [in air]	Mass	0.001111	kg	
UNSPECFIED: Occupation, arable, conservation tillage [unspecified]	Area	1.0368	sqm	
UNSPECFIED: Occupation, arable, reduced tillage [unspecified]	Area	0.421632	sqm	
UNSPECFIED: Occupational, arable, conventional tillage [unspecified]	Area	0.266112	sqm	
UNSPECFIED: Oil, crude, in ground [in ground]	Mass	0.046623	kg	
UNSPECFIED: Olivine, in ground [in ground]	Mass	5.23E-07	kg	
UNSPECFIED: Oxygen, in air [in air]	Mass	0.000173	kg	
UNSPECFIED: Phosphate as P2O5, phosphate rock, in ground [in ground]	Mass	0.003221	kg	
UNSPECFIED: Potassium chloride, in ground [in ground]	Mass	0.014802	kg	
UNSPECFIED: Sand, unspecified, in ground [in ground]	Mass	0.004446	kg	
UNSPECFIED: Shale, in ground [in ground]	Mass	7.60E-08	kg	
UNSPECFIED: Sodium chloride, in ground [in ground]	Mass	0.081453	kg	
UNSPECFIED: Sulfur, in ground [in ground]	Mass	0.040642	kg	
UNSPECFIED: Water, cooling [river]	Mass	10.74452	kg	
UNSPECFIED: Water, irrigation [river]	Mass	0.833957	kg	
UNSPECFIED: Water, irrigation [ground-]	Mass	20.01496	kg	
UNSPECFIED: Water,process [river]	Mass	16.12689	kg	
UNSPECFIED: Zinc ore, in ground [in ground]	Mass	1.15E-08	kg	

Outputs				
Flow	**Quantity**	**Amount**	**Unit**	**Tracked**
RNA: Polylactide Biopolymer Resin, at plant [Flows]	Mass	1	kg	X
UNSPECFIED: 2,4-D [unspecified]	Mass	3.58E-06	kg	
UNSPECFIED: Acetamide [unspecified]	Mass	1.19E-06	kg	
UNSPECFIED: Acetochlor [unspecified]	Mass	6.99E-05	kg	
UNSPECFIED: Alachlor [unspecified]	Mass	4.87E-06	kg	
UNSPECFIED: Aluminum compounds,	Mass	1.28E-08	kg	

unspecified [low population density, long-term]				
UNSPECFIED: Ammonia [low population density, long-term]	Mass	4.79E-06	kg	
UNSPECFIED: Ammonium, ion [low population density, long-term]	Mass	3.51E-07	kg	
UNSPECFIED: Antimony compounds, unspecified [low population density, long-term]	Mass	3.24E-11	kg	
UNSPECFIED: Arsenic compounds [low population density, long-term]	Mass	7.65E-11	kg	
UNSPECFIED: Arsenicum compounds, unspecified [low population density, long-term]	Mass	1.23E-10	kg	
UNSPECFIED: Atrazine [unspecified]	Mass	0.000109	kg	
UNSPECFIED: Barium [low population density, long-term]	Mass	4.55E-08	kg	
UNSPECFIED: Barium compounds, unspecified [low population density, long-term]	Mass	1.00E-09	kg	
UNSPECFIED: Barium compounds, unspecified [low population density, long-term]	Mass	6.56E-10	kg	
UNSPECFIED: Berylium [low population density, long-term]	Mass	1.01E-12	kg	
UNSPECFIED: Bifenthrin [unspecified]	Mass	2.55E-07	kg	
UNSPECFIED: BOD5, Biological Oxygen Demand [low population density, long-term]	Mass	2.70E-06	kg	
UNSPECFIED: Bromate [low population density, long-term]	Mass	2.64E-10	kg	
UNSPECFIED: Bromine [low population density, long-term]	Mass	5.47E-10	kg	
UNSPECFIED: Bromoxynil [unspecified]	Mass	7.65E-07	kg	
UNSPECFIED: Cadmium compounds, unspecified [low population density, long-term]	Mass	2.66E-11	kg	
UNSPECFIED: Cadmium compounds, unspecified [low population density, long-term]	Mass	3.10E-11	kg	
UNSPECFIED: Calcium compounds, unspecified [low population density, long-term]	Mass	0.000128	kg	
UNSPECFIED: Calcium, ion [low population density, long-term]	Mass	0.000252	kg	
UNSPECFIED: Carbon dioxide, fossil [low population density, long-term]	Mass	0.265033	kg	
UNSPECFIED: Carbon disulfide [low	Mass	6.04E-12	kg	

population density, long-term]				
UNSPECFIED: Carbon monoxide, fossil [low population density, long-term]	Mass	0.001307	kg	
UNSPECFIED: Carbonate [low population density, long-term]	Mass	2.48E-07	kg	
UNSPECFIED: Chlorate [low population density, long-term]	Mass	5.97E-08	kg	
UNSPECFIED: Chloride [low population density, long-term]	Mass	0.001253	kg	
UNSPECFIED: Chlorine [low population density, long-term]	Mass	1.80E-09	kg	
UNSPECFIED: Chlorine [low population density, long-term]	Mass	1.60E-07	kg	
UNSPECFIED: Chlorpyrifos [unspecified]	Mass	5.66E-06	kg	
UNSPECFIED: Chromium compounds, unspecified [low population density, long-term]	Mass	3.93E-11	kg	
UNSPECFIED: Chromium III [low population density, long-term]	Mass	9.99E-10	kg	
UNSPECFIED: Chromium VI [low population density, long-term]	Mass	6.44E-11	kg	
UNSPECFIED: Cobalt compounds, unspecified [low population density, long-term]	Mass	2.61E-11	kg	
UNSPECFIED: COD, Chemical Oxygen Demand [low population density, long-term]	Mass	0.004895	kg	
UNSPECFIED: Copper compounds, unspecified [low population density, long-term]	Mass	3.94E-10	kg	
UNSPECFIED: Copper compounds, unspecified [low population density, long-term]	Mass	4.73E-11	kg	
UNSPECFIED: Corn dust (biomass) [low population density, long-term]	Mass	7.64E-05	kg	
UNSPECFIED: Cyanide [low population density, long-term]	Mass	6.25E-11	kg	
UNSPECFIED: Cyanide compounds, unspecified [low population density, long-term]	Mass	1.19E-10	kg	
UNSPECFIED: Cyfluthrin [unspecified]	Mass	5.95E-08	kg	
UNSPECFIED: Cypermethrin [unspecified]	Mass	4.41E-08	kg	
UNSPECFIED: Detergents, unspecified [low population density, long-term]	Mass	4.70E-08	kg	
UNSPECFIED: Dicamba [unspecified]	Mass	2.04E-06	kg	
UNSPECFIED: Diflufenzopyr-sodium [unspecified]	Mass	2.27E-07	kg	
UNSPECFIED: Dimethenamid [unspecified]	Mass	5.92E-06	kg	

UNSPECFIED: Dinitrogen monoxide [low population density, long-term]	Mass	0.000371	kg	
UNSPECFIED: Dissolved solids [low population density, long-term]	Mass	3.68E-06	kg	
UNSPECFIED: Ethene [low population density, long-term]	Mass	3.83E-12	kg	
UNSPECFIED: Fipronil [unspecified]	Mass	3.40E-07	kg	
UNSPECFIED: Flumetsulam [unspecified]	Mass	3.96E-07	kg	
UNSPECFIED: Fluoride [low population density, long-term]	Mass	5.05E-07	kg	
UNSPECFIED: Fluoride compounds, unspecified [low population density, long-term]	Mass	2.11E-11	kg	
UNSPECFIED: Fluorine [low population density, long-term]	Mass	1.55E-10	kg	
UNSPECFIED: Foramsulfuron [unspecified]	Mass	4.25E-08	kg	
UNSPECFIED: Glufosinate [unspecified]	Mass	1.40E-06	kg	
UNSPECFIED: Glyphosate [unspecified]	Mass	2.32E-05	kg	
UNSPECFIED: Helium [low population density, long-term]	Mass	4.94E-08	kg	
UNSPECFIED: hydrocarbons, unspecified [low population density, long-term]	Mass	2.37E-07	kg	
UNSPECFIED: Hydrogen [low population density, long-term]	Mass	9.03E-05	kg	
UNSPECFIED: Hydrogen chloride [low population density, long-term]	Mass	9.82E-06	kg	
UNSPECFIED: Hydrogen cyanide [low population density, long-term]	Mass	1.65E-35	kg	
UNSPECFIED: Hydrogen fluoride [low population density, long-term]	Mass	3.74E-07	kg	
UNSPECFIED: Hydrogen sulfide [low population density, long-term]	Mass	1.35E-07	kg	
UNSPECFIED: Imazapyr [unspecified]	Mass	5.66E-09	kg	
UNSPECFIED: Imazethapyr [unspecified]	Mass	1.98E-08	kg	
UNSPECFIED: Iron compounds, unspecified [low population density, long-term]	Mass	1.26E-05	kg	
UNSPECFIED: Iron compounds, unspecified [low population density, long-term]	Mass	2.93E-10	kg	
UNSPECFIED: Isoxaflutole [unspecified]	Mass	6.80E-07	kg	
UNSPECFIED: Lambda-cyhalothrin [unspecified]	Mass	2.83E-08	kg	
UNSPECFIED: Lead compounds, unspecified [low population density, long-term]	Mass	5.62E-11	kg	
UNSPECFIED: Lead compounds, unspecified [low population density, long-term]	Mass	1.34E-10	kg	
UNSPECFIED: Magnesium compounds,	Mass	9.48E-07	kg	

unspecified [low population density, long-term]				
UNSPECFIED: Manganese [low population density, long-term]	Mass	7.14E-11	kg	
UNSPECFIED: Manganese compounds, unspecified [low population density, long-term]	Mass	3.62E-09	kg	
UNSPECFIED: Mercury compounds, unspecified [low population density, long-term]	Mass	1.19E-11	kg	
UNSPECFIED: Mercury compounds, unspecified [low population density, long-term]	Mass	1.37E-10	kg	
UNSPECFIED: Mesotrione [unspecified]	Mass	1.84E-06	kg	
UNSPECFIED: Methane, fossil [low population density, long-term]	Mass	0.001302	kg	
UNSPECFIED: Metolachlor [unspecified]	Mass	5.05E-05	kg	
UNSPECFIED: Molybdenum [low population density, long-term]	Mass	1.31E-11	kg	
UNSPECFIED: Molybdenum [low population density, long-term]	Mass	1.01E-11	kg	
UNSPECFIED: Nickel compounds, unspecified [low population density, long-term]	Mass	3.41E-10	kg	
UNSPECFIED: Nickel compounds, unspecified [low population density, long-term]	Mass	4.23E-10	kg	
UNSPECFIED: Nicosulfuron [unspecified]	Mass	3.11E-07	kg	
UNSPECFIED: Nitrate [low population density, long-term]	Mass	0.001227	kg	
UNSPECFIED: Nitrogen compounds, unspecified [low population density, long-term]	Mass	0.000133	kg	
UNSPECFIED: Nitrogen oxides [low population density, long-term]	Mass	0.005362	kg	
UNSPECFIED: NMVOC, non-methane volatile organic compounds, unspecified origin [low population density, long-term]	Mass	0.000743	kg	
UNSPECFIED: organo-chlorine, unspecified [low population density, long-term]	Mass	1.02E-05	kg	
UNSPECFIED: Paraquat [unspecified]	Mass	7.22E-07	kg	
UNSPECFIED: Particulates, < 2.5 um [low population density, long-term]	Mass	-1.13E-05	kg	
UNSPECFIED: Particulates, > 10 um [low population density, long-term]	Mass	-0.00014	kg	
UNSPECFIED: Particulates, > 2.5 um, and < 10um [low population density, long-term]	Mass	-0.00012	kg	
UNSPECFIED: Particulates, unspecified [low population density, long-term]	Mass	0.00024	kg	

UNSPECFIED: Pendimethalin [unspecified]	Mass	2.92E-06	kg	
UNSPECFIED: Permethrin [unspecified]	Mass	1.27E-07	kg	
UNSPECFIED: Phenol [low population density, [long-term]	Mass	6.76E-09	kg	
UNSPECFIED: Phosphate [low population density, long-term]	Mass	3.15E-08	kg	
UNSPECFIED: Phosphorus compounds, unspecified [low population density, long-term]	Mass	1.22E-05	kg	
UNSPECFIED: Potassium compounds, unspecified [low population density, long-term]	Mass	1.72E-07	kg	
UNSPECFIED: Primisulfuron [unspecified]	Mass	1.42E-07	kg	
UNSPECFIED: Prosulfuron [unspecified]	Mass	2.55E-08	kg	
UNSPECFIED: Rimsulfuron [unspecified]	Mass	1.42E-07	kg	
UNSPECFIED: Selenium [low population density, long-term]	Mass	2.01E-12	kg	
UNSPECFIED: Selenium compounds, unspecified [low population density, long-term]	Mass	6.03E-11	kg	
UNSPECFIED: Silver compounds, unspecified [low population density, long-term]	Mass	4.43E-11	kg	
UNSPECFIED: Simazine [unspecified]	Mass	2.86E-06	kg	
UNSPECFIED: Sodium compounds, unspecified [low population density, long-term]	Mass	0.000616	kg	
UNSPECFIED: Strontium [low population density, long-term]	Mass	4.02E-12	kg	
UNSPECFIED: Strontium compounds, unspecified [low population density, long-term]	Mass	3.66E-09	kg	
UNSPECFIED: Sulfate [low population density, long-term]	Mass	0.000137	kg	
UNSPECFIED: Sulfur dioxide [low population density, long-term]	Mass	0.001364	kg	
UNSPECFIED: Sulfuric acid [low population density, long-term]	Mass	1.38E-08	kg	
UNSPECFIED: Suspended solids, unspecified [low population density, long-term]	Mass	0.002369	kg	
UNSPECFIED: Tebupirimphos [unspecified]	Mass	1.19E-06	kg	
UNSPECFIED: Tefluthrin [unspecified]	Mass	9.34E-07	kg	
UNSPECFIED: Terbufos [unspecified]	Mass	3.17E-06	kg	
UNSPECFIED: Tin [low population density, long-term]	Mass	6.34E-11	kg	
UNSPECFIED: Titanium [low population density, long-term]	Mass	2.01E-12	kg	

UNSPECFIED: Titanium [low population density, long-term]	Mass	1.11E-11	kg	
UNSPECFIED: TOC, Total Organic Carbon [low population density, long-term]	Mass	1.12E-05	kg	
UNSPECFIED: Vanadium compounds, unspecified [low population density, long-term]	Mass	5.03E-12	kg	
UNSPECFIED: Vanadium compounds, unspecified [low population density, long-term]	Mass	1.56E-09	kg	
UNSPECFIED: Zinc compounds, unspecified [low population density, long-term]	Mass	4.80E-10	kg	
UNSPECFIED: Zinc compounds, unspecified [low population density, long-term]	Mass	2.62E-10	kg	

Appendix A2 - Converted Ingeo (PLA) Process Flows Data for GaBi 5

Inputs				
Flow	**Quantity**	**Amount**	**Unit**	**Tracked**
Crude oil USA [Crude oil (resource)]	Mass	0.046623	kg	X
Electricity [Electric power]	Energy	12.2471	MJ	X
Hard coal USA [Hard coal (resource)]	Mass	0.0155	kg	X
Natural gas USA [Natural gas (resource)]	Mass	0.4259	kg	X
RNA: Transport, combination truck, diesel powered [Flows]	kgkm	127	kgkm	X
Waste in landfill (inert material, sanitary and residual material landfill) [Consumer waste]	Mass	0.003293	kg	*
Waste in underground deposit [Hazardous waste]	Mass	0.02154	kg	*
Air [Renewable resources]	Mass	0.254319	kg	
Barium sulphate [Non renewable resources]	Mass	7.25E-05	kg	
Bauxite [Non renewable resources]	Mass	5.04E-06	kg	
Bentonit clay [Non renewable resources]	Mass	5.34E-06	kg	
Calcium Sulphate (CaSO4, ore) [Non renewable resources]	Mass	2.69E-08	kg	
Carbon dioxide [Renewable resources]	Mass	1.833	kg	
Copper ore (1 %) [Non renewable resources]	Mass	1.72E-11	kg	
Dolomite [Non renewable resources]	Mass	6.93E-07	kg	
Ferro manganese [Non renewable resources]	Mass	5.06E-08	kg	
Fluorspar (calcium fluoride; fluorite) [Non renewable]	Mass	9.17E-08	kg	
Gravel [Non renewable resources]	Mass	2.06E-07	kg	
Hazardous waste (unspec.) [Hazardous waste]	Mass	0.001417	kg	
Iron ore (56,86%) [Non renewable resources]	Mass	5.58E-05	kg	
Lead ore (5%) [Non renewable resources]	Mass	3.15E-07	kg	
Lignite USA [Lignite (resource)]	Mass	2.56E-05	kg	
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.1354	kg	
Metallurgical coal [Non renewable resources]	Mass	2.27E-05	kg	
Nitrogen [Renewable resources]	Mass	0.001111	kg	
Occupation, arable, conservation tillage [Hemeroby]	Mass	1.0368	kg	
Occupation, arable, conventional tillage [Hemeroby]	Mass	0.266112	kg	
Occupation, arable, reduced tillage [Hemeroby]	Mass	0.421632	kg	
Olivine [Non renewable resources]	Mass	5.23E-07	kg	
Oxygen [Renewable resources]	Mass	0.000173	kg	
Phosphate (P2O5) [Non renewable resources]	Mass	0.003221	kg	
Potassium chloride [Non renewable resources]	Mass	0.014802	kg	
Sand [Non renewable resources]	Mass	0.004446	kg	
Shale [Non renewable resources]	Mass	7.60E-08	kg	

Sodium chloride (rock salt) [Non renewable resources]	Mass	0.081453	kg	
Sulphur [Non renewable elements]	Mass	0.040642	kg	
Water (ground water) [Water]	Mass	19.2143	kg	
Water (river water) [Water]	Mass	27.7052	kg	
Water (surface water) [Water]	Mass	0.8005	kg	
Zinc [Non renewable elements]	Mass	1.15E-08	kg	

Outputs				
Flow	**Quantity**	**Amount**	**Unit**	**Tracked**
Ingeo Polylactide (PLA) biopolymer (by NatureWorks LLC) [Plastics]	Mass	1	kg	X
Pesticides, unspecified [Hazardous waste]	Mass	5.66E-06	kg	*
Unspecified biomass [Consumer waste]	Mass	7.64E-05	kg	*
2,4-Dichlorophenoxyacetic acid (2,4-D) [Pesticides to agricultural soil]	Mass	3.58E-06	kg	
Acetamide [Pesticides to agricultural soil]	Mass	1.19E-06	kg	
Acetochlor [Pesticides to agricultural soil]	Mass	6.99E-05	kg	
Alachlor [Pesticides to agricultural soil]	Mass	4.87E-06	kg	
Ammonia [Inorganic emissions to air]	Mass	4.79E-06	kg	
Ammonium / ammonia [Inorganic emissions to sea water]	Mass	3.51E-07	kg	
Antimony [Heavy metals to air]	Mass	3.24E-11	kg	
Arsenic (+V) [Heavy metals to fresh water]	Mass	7.65E-11	kg	
Arsenic trioxide [Heavy metals to air]	Mass	1.23E-10	kg	
Atrazine [Pesticides to agricultural soil]	Mass	0.000109	kg	
Barium [Inorganic emissions to air]	Mass	4.55E-08	kg	
Barium [Inorganic emissions to fresh water]	Mass	6.56E-10	kg	
Barium compounds (unspecified; rel. to Ba) [Inorganic emissions to air]	Mass	1.00E-09	kg	
Beryllium [Inorganic emissions to air]	Mass	1.01E-12	kg	
Bifenthrin [Pesticides to agricultural soil]	Mass	2.55E-07	kg	
Biological oxygen demand (BOD) [Analytical measures to fresh water]	Mass	2.70E-06	kg	
Bromate [Inorganic emissions to fresh water]	Mass	2.64E-10	kg	
Bromine [Inorganic emissions to air]	Mass	5.47E-10	kg	
Bromoxynil [Organic emissions to agricultural soil]	Mass	7.65E-07	kg	
Cadmium (+II) [Heavy metals to air]	Mass	2.66E-11	kg	
Cadmium (+II) [Heavy metals to fresh water]	Mass	3.10E-11	kg	
Calcium (+II) [Inorganic emissions to fresh water]	Mass	0.000252	kg	
Calcium nitrate (Ca(NO3)2) [Inorganic emissions to fresh water]	Mass	0.000128	kg	
Carbon dioxide [Inorganic emissions to air]	Mass	0.265033	kg	
Carbon disulphide [Inorganic emissions to air]	Mass	6.04E-12	kg	

Carbon monoxide [Inorganic emissions to air]	Mass	0.001307	kg	
Carbonate [Inorganic emissions to fresh water]	Mass	2.48E-07	kg	
Chemical oxygen demand (COD) [Analytical measures to fresh water]	Mass	0.004895	kg	
Chlorate [Inorganic emissions to fresh water]	Mass	5.97E-08	kg	
Chloride [Inorganic emissions to fresh water]	Mass	0.001253	kg	
Chlorine [Inorganic emissions to air]	Mass	1.02E-05	kg	
Chlorine (dissolved) [Inorganic emissions to fresh water]	Mass	1.60E-07	kg	
Chromium (+III) [Heavy metals to fresh water]	Mass	9.99E-10	kg	
Chromium (+VI) [Heavy metals to fresh water]	Mass	6.44E-11	kg	
Chromium (unspecified) [Heavy metals to air]	Mass	3.93E-11	kg	
Cobalt [Heavy metals to air]	Mass	2.61E-11	kg	
Copper (+II) [Heavy metals to air]	Mass	4.73E-11	kg	
Copper ion (+II/+III) [Inorganic emissions to fresh water]	Mass	3.94E-10	kg	
Cyanide [Inorganic emissions to fresh water]	Mass	6.25E-11	kg	
Cyanide (unspecified) [Inorganic emissions to air]	Mass	1.19E-10	kg	
Cyfluthrin [Pesticides to agricultural soil]	Mass	5.95E-08	kg	
Cypermethrin [Pesticides to agricultural soil]	Mass	4.41E-08	kg	
Detergent (unspecified) [Other emissions to fresh water]	Mass	4.70E-08	kg	
Dicamba [Pesticides to agricultural soil]	Mass	2.04E-06	kg	
Diflufenzopyr-sodium [Pesticides to agricultural soil]	Mass	2.27E-07	kg	
Dimethenamid [Pesticides to agricultural soil]	Mass	5.92E-06	kg	
Dinitrogen Oxide [Inorganic emissions to air]	Mass	0.000371	kg	
Dust (> PM10) [Particles to air]	Mass	-0.00014	kg	
Dust (PM2,5 - PM10) [Particles to air]	Mass	-0.00012	kg	
Dust (PM2.5) [Particles to air]	Mass	-1.13E-05	kg	
Dust (unspecified) [Particles to air]	Mass	0.00024	kg	
Ethene (ethylene) [Group NMVOC to air]	Mass	3.83E-12	kg	
Fipronil [Pesticides to agricultural soil]	Mass	3.40E-07	kg	
Flumetsulam [Pesticides to agricultural soil]	Mass	3.96E-07	kg	
Fluoride [Inorganic emissions to fresh water]	Mass	5.05E-07	kg	
Fluorides [Inorganic emissions to air]	Mass	2.11E-11	kg	
Fluorine [Inorganic emissions to fresh water]	Mass	1.55E-10	kg	
Foramsulfuron [Pesticides to agricultural soil]	Mass	4.25E-08	kg	
Glufosinate [Pesticides to agricultural soil]	Mass	1.40E-06	kg	
Glyphosate [Pesticides to agricultural soil]	Mass	2.32E-05	kg	
Gypsum suspension [Others]	Mass	0.002369	kg	
Helium [Inorganic emissions to air]	Mass	4.94E-08	kg	
Hydrocarbons (unspecified) [Organic emissions to air (group VOC)]	Mass	2.37E-07	kg	

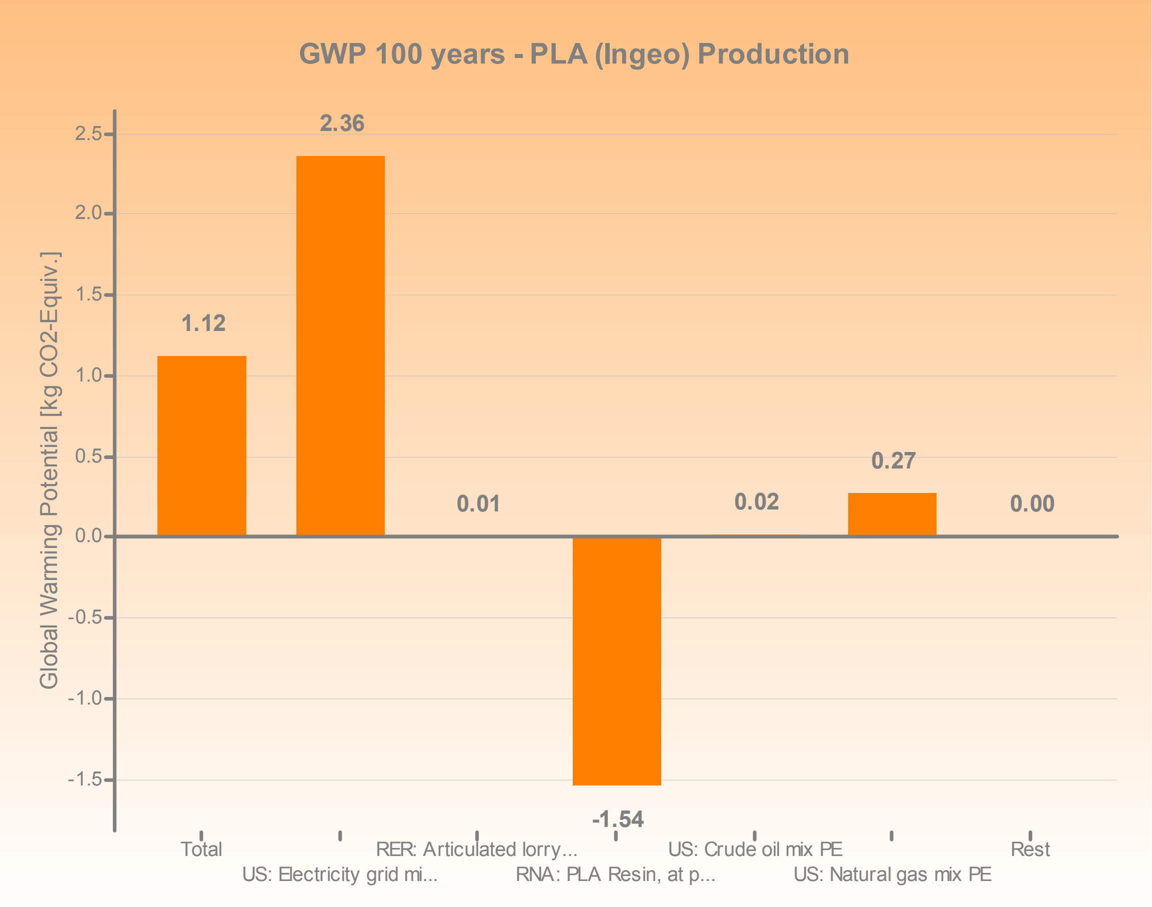
Hydrogen [Inorganic emissions to air]	Mass	9.03E-05	kg	
Hydrogen chloride [Inorganic emissions to air]	Mass	9.82E-06	kg	
Hydrogen cyanide (prussic acid) [Inorganic emissions to air]	Mass	1.65E-35	kg	
Hydrogen fluoride [Inorganic emissions to air]	Mass	3.74E-07	kg	
Hydrogen sulphide [Inorganic emissions to air]	Mass	1.35E-07	kg	
Imazapyr [Pesticides to agricultural soil]	Mass	5.66E-09	kg	
Imazethapyr [Pesticides to agricultural soil]	Mass	1.98E-08	kg	
Iron [Heavy metals to fresh water]	Mass	1.26E-05	kg	
Iron [Heavy metals to air]	Mass	2.93E-10	kg	
Isoxaflutole [Pesticides to agricultural soil]	Mass	6.80E-07	kg	
Lambda cyhalothrin [Pesticides to agricultural soil]	Mass	2.83E-08	kg	
Lead (+II) [Heavy metals to air]	Mass	1.34E-10	kg	
Lead (+II) [Heavy metals to fresh water]	Mass	5.62E-11	kg	
Magnesium ion (+II) [Inorganic emissions to fresh water]	Mass	9.48E-07	kg	
Manganese (+II) [Heavy metals to air]	Mass	7.14E-11	kg	
Manganese (+II) [Heavy metals to fresh water]	Mass	3.62E-09	kg	
Mercury (+II) [Heavy metals to air]	Mass	1.37E-10	kg	
Mercury (+II) [Heavy metals to fresh water]	Mass	1.19E-11	kg	
Mesotrione [Pesticides to agricultural soil]	Mass	1.84E-06	kg	
Metals (unspecified) [Particles to fresh water]	Mass	1.28E-08	kg	
Methane [Organic emissions to air (group VOC)]	Mass	0.001302	kg	
Metolachlor [Pesticides to agricultural soil]	Mass	5.05E-05	kg	
Molybdenum [Heavy metals to air]	Mass	1.01E-11	kg	
Molybdenum [Heavy metals to fresh water]	Mass	1.31E-11	kg	
Nickel (+II) [Heavy metals to air]	Mass	4.23E-10	kg	
Nickel (+II) [Heavy metals to fresh water]	Mass	3.41E-10	kg	
Nicosulfuron [Pesticides to agricultural soil]	Mass	3.11E-07	kg	
Nitrate [Inorganic emissions to fresh water]	Mass	0.001227	kg	
Nitrogen (as total N) [Inorganic emissions to fresh water]	Mass	0.000133	kg	
Nitrogen oxides [Inorganic emissions to air]	Mass	0.005362	kg	
NMVOC (unspecified) [Group NMVOC to air]	Mass	0.000743	kg	
Paraquat [Pesticides to agricultural soil]	Mass	7.22E-07	kg	
Pendimethalin [Pesticides to agricultural soil]	Mass	2.92E-06	kg	
Permethrin [Pesticides to agricultural soil]	Mass	1.27E-07	kg	
Phenol (hydroxy benzene) [Hydrocarbons to fresh water]	Mass	6.76E-09	kg	
Phosphate [Inorganic emissions to fresh water]	Mass	3.15E-08	kg	
Phosphorus [Inorganic emissions to fresh water]	Mass	1.22E-05	kg	
Potassium [Inorganic emissions to fresh water]	Mass	1.72E-07	kg	
Primisulfuron [Pesticides to agricultural soil]	Mass	1.42E-07	kg	

Prosulfuron [Pesticides to agricultural soil]	Mass	2.55E-08	kg	
Rimsulfuron [Pesticides to agricultural soil]	Mass	1.42E-07	kg	
Selenium [Heavy metals to fresh water]	Mass	2.01E-12	kg	
Selenium [Heavy metals to air]	Mass	6.03E-11	kg	
Silver [Heavy metals to sea water]	Mass	4.43E-11	kg	
Simazine [Pesticides to agricultural soil]	Mass	2.86E-06	kg	
Sodium nitrate [Inorganic emissions to fresh water]	Mass	0.000616	kg	
Solids (dissolved) [Analytical measures to fresh water]	Mass	3.68E-06	kg	
Strontium [Heavy metals to fresh water]	Mass	3.66E-09	kg	
Strontium [Inorganic emissions to air]	Mass	4.02E-12	kg	
Sulphate [Inorganic emissions to fresh water]	Mass	0.000137	kg	
Sulphur dioxide [Inorganic emissions to air]	Mass	0.001364	kg	
Sulphuric acid [Inorganic emissions to air]	Mass	1.38E-08	kg	
Tebupirimphos [Pesticides to agricultural soil]	Mass	1.19E-06	kg	
Tefluthrin [Pesticides to agricultural soil]	Mass	9.34E-07	kg	
Terbufos [Pesticides to agricultural soil]	Mass	3.17E-06	kg	
Tin (+IV) [Heavy metals to air]	Mass	6.34E-11	kg	
Titanium [Heavy metals to fresh water]	Mass	1.11E-11	kg	
Titanium [Heavy metals to air]	Mass	2.01E-12	kg	
Total organic carbon [Other emissions to air]	Mass	1.12E-05	kg	
Vanadium (+III) [Heavy metals to fresh water]	Mass	5.03E-12	kg	
Vanadium (+III) [Heavy metals to air]	Mass	1.56E-09	kg	
Zinc (+II) [Heavy metals to fresh water]	Mass	2.62E-10	kg	
Zinc (+II) [Heavy metals to air]	Mass	4.80E-10	kg	

Appendix A3 - Exported Quantities View from GaBi Balance

	PLA (Ingeo) Production
Quantities	0
Economic quantities	0
Environmental quantities	0
CML 1996	0
CML 2001	0
CML 2001 - Dec. 2007	0
CML 2001 - Nov. 2009	0
CML 2001 - Nov. 2010	0
Eco-Indicator 95	0
Eco-Indicator 99	0
EDIP 1997	0
EDIP 2003	0
Impact 2002+	0
ReCiPe	0
TRACI	0
TRACI 2.0	0
UBP	0
USEtox	0
Primary energy demand from ren. & non ren. resources (gross cal. value) [MJ]	65.03210698
Primary energy demand from ren. & non ren. resources (net cal. value) [MJ]	60.93171436
Primary energy from renewable raw materials (gross cal. value) [MJ]	4.236733595
Primary energy from renewable raw materials (net cal. value) [MJ]	4.236733593
Primary energy from resources (gross cal. value) [MJ]	60.79537338
Primary energy from resources (net cal. value) [MJ]	56.69498076
Land use quantities	0
Technical quantities	0
Polylactic Acid [kg]	0

Appendix A4 - LCIA CML 2001 (Nov. 09) Graph of GHG from GaBi Balance

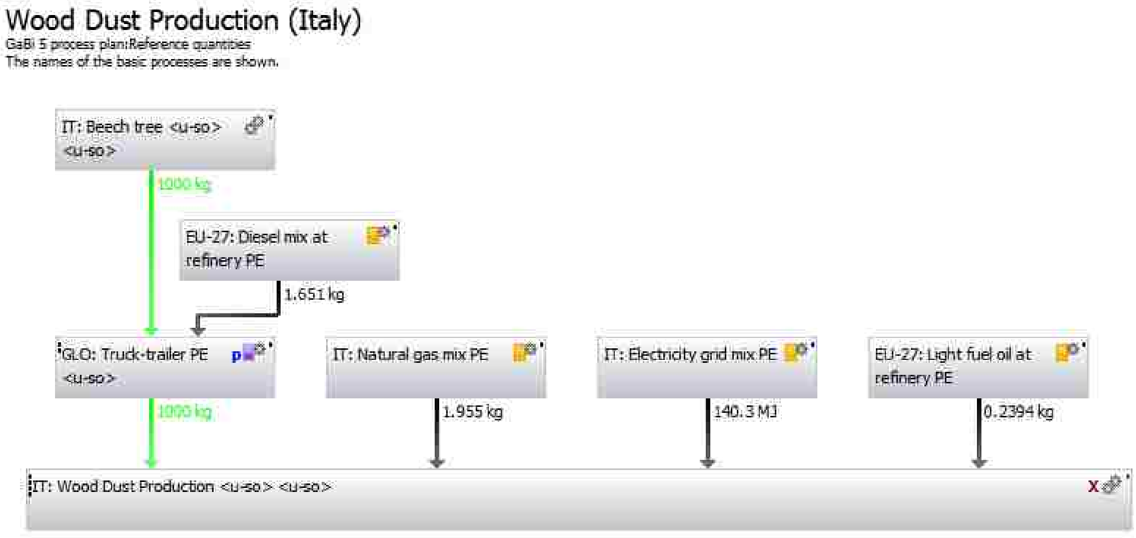


Appendix B

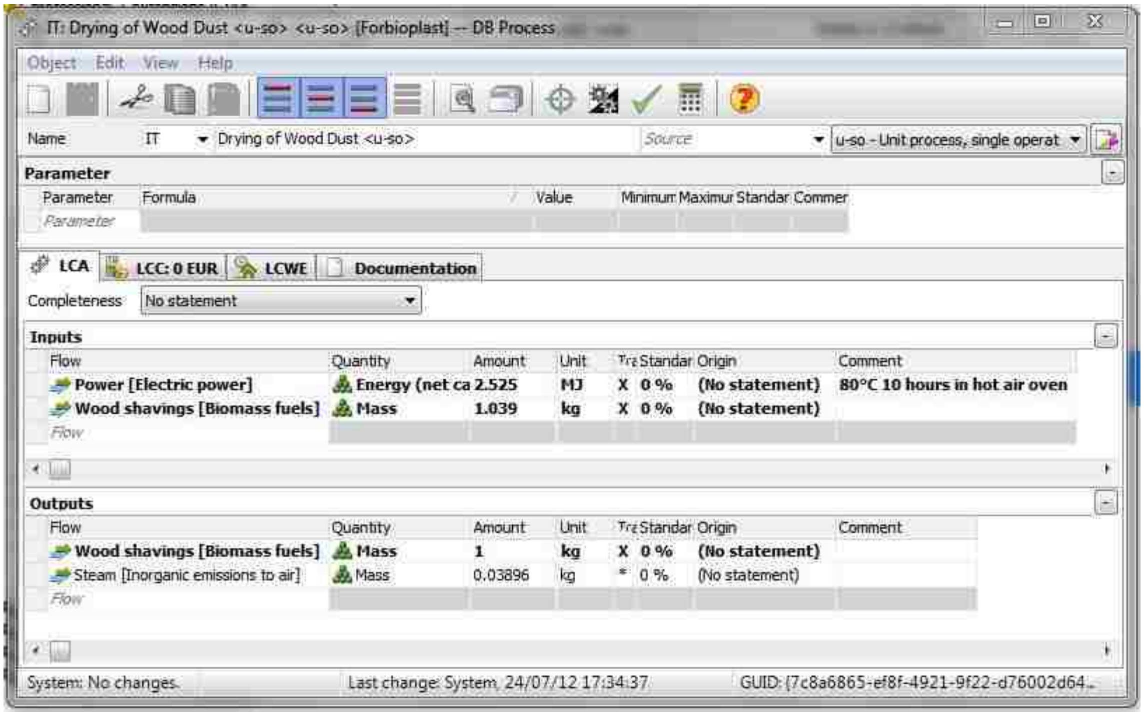
Appendix B1 - Component Average Weight Calculations

PP + Wood Dust		PLA + Flax	
Component	**Weight**	**Component**	**Weight**
1	160.2	1	199.3
2	160.1	2	198.1
3	159.7	3	198.2
4	159.8	4	197.8
5	158.5	5	197.7
6	159.1	6	197.5
7	158.7	7	197.3
8	158.8	8	197.2
9	158.3	9	197.7
10	158.6	10	197.4
Average	**159.2**		**197.8**

Appendix B2 - GaBi Model of Wood Dust Production Adapted from Forbioplast



Appendix B3 - GaBi Process of Wood Dust Drying Adapted from Forbioplast



IT: Drying of Wood Dust <u-so> <u-so> [Forbioplast] -- DB Process

Name IT Drying of Wood Dust <u-so> Source u-so - Unit process, single operat

Parameter

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

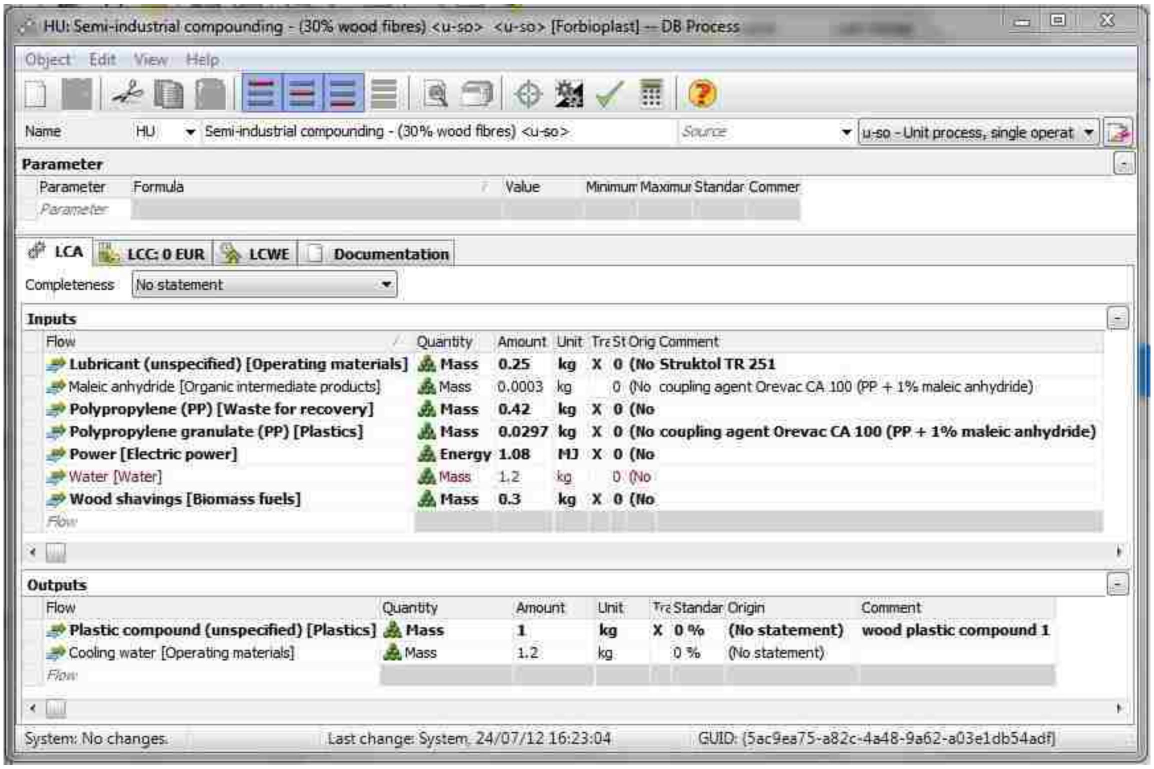
Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Power [Electric power]	**Energy (net ca**	**2.525**	**MJ**	**X**	**0 %**	**(No statement)**	**80°C 10 hours in hot air oven**
Wood shavings [Biomass fuels]	**Mass**	**1.039**	**kg**	**X**	**0 %**	**(No statement)**	
Flow							

Outputs

Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Wood shavings [Biomass fuels]	**Mass**	**1**	**kg**	**X**	**0 %**	**(No statement)**	
Steam [Inorganic emissions to air]	Mass	0.03896	kg	*	0 %	(No statement)	
Flow							

System: No changes. Last change: System, 24/07/12 17:34:37 GUID: {7c8a6865-ef8f-4921-9f22-d76002d64...

Appendix B4 - Forbioplast Compounding Process



HU: Semi-industrial compounding - (30% wood fibres) <u-so> <u-so> [Forbioplast] -- DB Process

Name HU Semi-industrial compounding - (30% wood fibres) <u-so> Source u-so - Unit process, single operat

Parameter

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

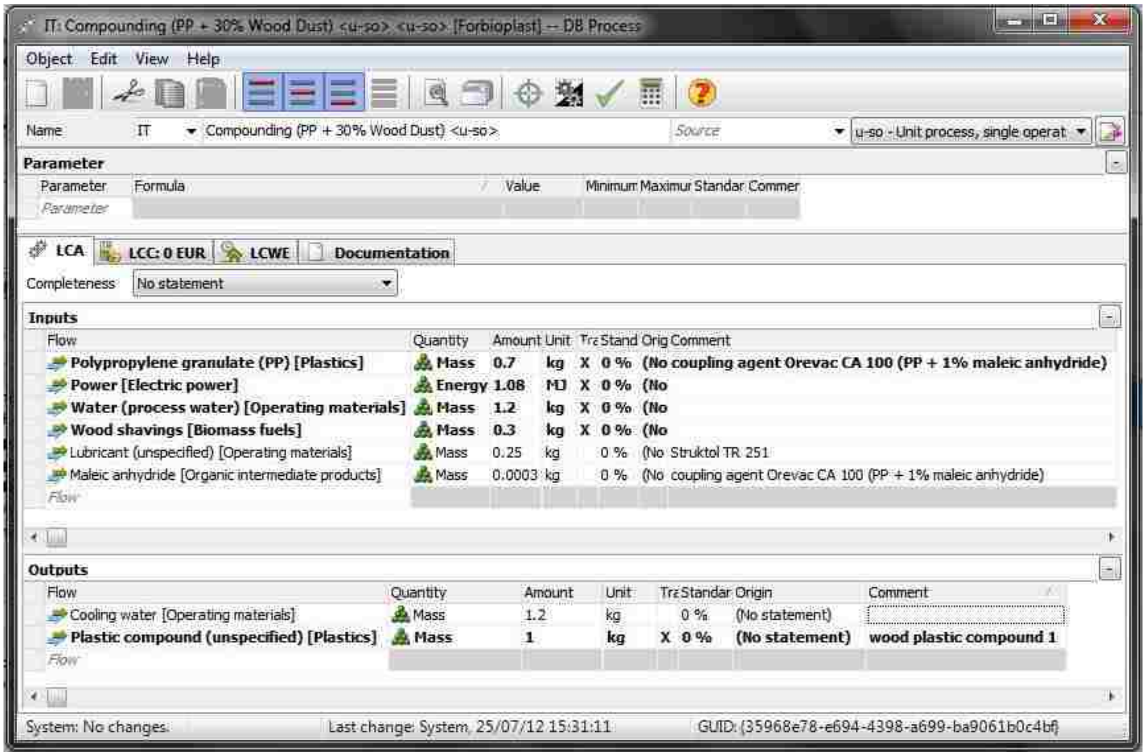
Flow	Quantity	Amount	Unit	Tra	St	Orig	Comment
Lubricant (unspecified) [Operating materials]	**Mass**	**0.25**	**kg**	**X**	**0**	**(No**	**Struktol TR 251**
Maleic anhydride [Organic intermediate products]	Mass	0.0003	kg		0	(No	coupling agent Orevac CA 100 (PP + 1% maleic anhydride)
Polypropylene (PP) [Waste for recovery]	**Mass**	**0.42**	**kg**	**X**	**0**	**(No**	
Polypropylene granulate (PP) [Plastics]	**Mass**	**0.0297**	**kg**	**X**	**0**	**(No**	**coupling agent Orevac CA 100 (PP + 1% maleic anhydride)**
Power [Electric power]	**Energy**	**1.08**	**MJ**	**X**	**0**	**(No**	
Water [Water]	Mass	1.2	kg		0	(No	
Wood shavings [Biomass fuels]	**Mass**	**0.3**	**kg**	**X**	**0**	**(No**	
Flow							

Outputs

Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Plastic compound (unspecified) [Plastics]	**Mass**	**1**	**kg**	**X**	**0 %**	**(No statement)**	**wood plastic compound 1**
Cooling water [Operating materials]	Mass	1.2	kg		0 %	(No statement)	
Flow							

System: No changes. Last change: System, 24/07/12 16:23:04 GUID: {5ac9ea75-a82c-4a48-9a62-a03e1db54adf}

Appendix B5 - PP + Wood Dust Extrusion Compounding Process



IT: Compounding (PP + 30% Wood Dust) <u-so> <u-so> [Forbioplast] -- DB Process

Name IT Compounding (PP + 30% Wood Dust) <u-so> Source u-so - Unit process, single operat

Parameter

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

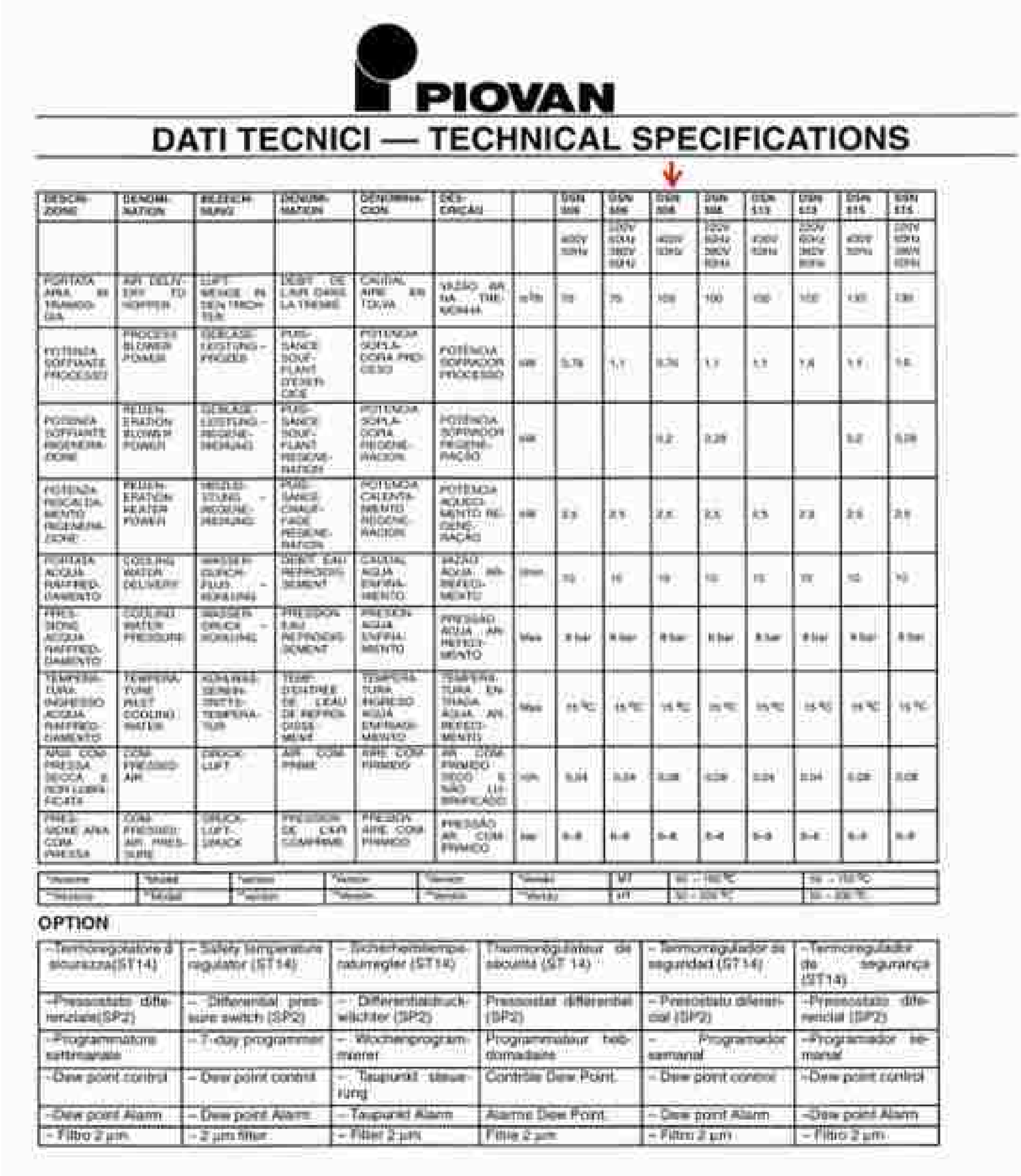
Flow	Quantity	Amount	Unit	Tra	Stand	Orig	Comment
Polypropylene granulate (PP) [Plastics]	**Mass**	**0.7**	**kg**	**X**	**0 %**	**(No**	**coupling agent Orevac CA 100 (PP + 1% maleic anhydride)**
Power [Electric power]	**Energy**	**1.08**	**MJ**	**X**	**0 %**	**(No**	
Water (process water) [Operating materials]	**Mass**	**1.2**	**kg**	**X**	**0 %**	**(No**	
Wood shavings [Biomass fuels]	**Mass**	**0.3**	**kg**	**X**	**0 %**	**(No**	
Lubricant (unspecified) [Operating materials]	Mass	0.25	kg		0 %	(No	Struktol TR 251
Maleic anhydride [Organic intermediate products]	Mass	0.0003	kg		0 %	(No	coupling agent Orevac CA 100 (PP + 1% maleic anhydride)
Flow							

Outputs

Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Cooling water [Operating materials]	Mass	1.2	kg		0 %	(No statement)	
Plastic compound (unspecified) [Plastics]	**Mass**	**1**	**kg**	**X**	**0 %**	**(No statement)**	**wood plastic compound 1**
Flow							

System: No changes. Last change: System, 25/07/12 15:31:11 GUID: {35968e78-e694-4398-a699-ba9061b0c4bf}

Appendix B6 - Piovan Dryer Data Sheet



PIOVAN

DATI TECNICI — TECHNICAL SPECIFICATIONS

OPTION

-Termoregolatore di sicurezza(ST14)	– Safety temperature regulator (ST14)	– Sicherheitstemperaturregler (ST14)	Thermorégulateur de sécurité (ST 14)	– Termoregulador de seguridad (ST14)	-Termoregulador de segurança (ST14)
-Pressostato differenziale(SP2)	– Differential pressure switch (SP2)	– Differentialdruckwächter (SP2)	Pressostat différentiel (SP2)	– Presostato diferencial (SP2)	-Pressostato diferencial (SP2)
-Programmatore settimanale	– 7-day programmer	– Wochenprogrammierer	Programmateur hebdomadaire	– Programador semanal	-Programador semanal
-Dew point control	– Dew point control	– Taupunkt steuerung	Contrôle Dew Point	– Dew point control	-Dew point control
-Dew point Alarm	– Dew point Alarm	– Taupunkt Alarm	Alarme Dew Point	– Dew point Alarm	-Dew point Alarm
– Filtro 2 µm	– 2 µm filter	– Filter 2 µm	Filtre 2 µm	– Filtro 2 µm	– Filtro 2 µm

Appendix B7 - Mechanical and Injection Properties Tables

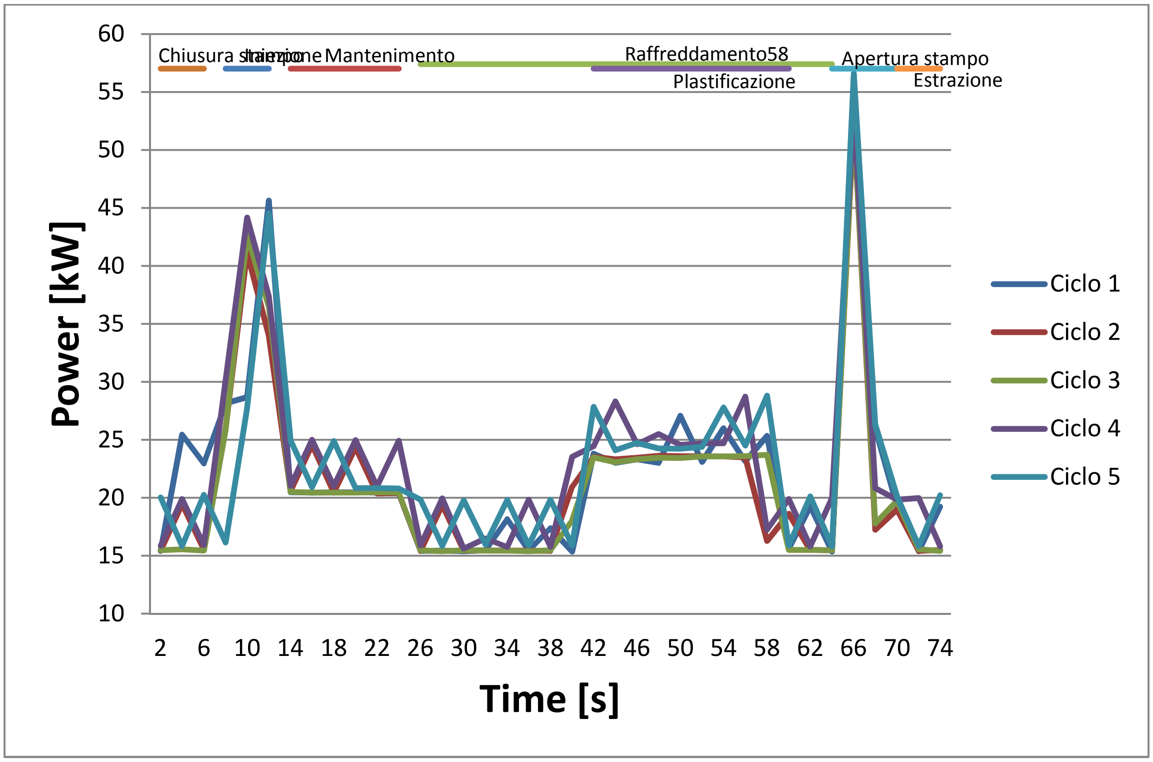
Polypropylene + Wood Dust

Mechanical Property:	**Values:**
Density	1080 [kg/m3]
Elastic Modulus	3000 [MPa]
Tensile Strength	32 [MPa]
Elongation	2 [%]
Deflection Temperature	100 [˚C]
Process Properties:	**Values:**
Injection Temperature	190 [˚C]
Mould Temperature	50 [˚C]

Polylactic Acid + Flax Fibers

Mechanical Property:	**Values:**
Density	1260 [kg/m3]
Elastic Modulus	4200 [MPa]
Tensile Strength	42 [MPa]
Elongation	3 [%]
Deflection Temperature	68 [˚C]
Process Properties:	**Values:**
Injection Temperature	180 [˚C]
Mould Temperature	60 [˚C]

Appendix B8 - Graph of Energy Collected By External Experts



Appendix B9 - PLA + Flax Injection Moulding Energy Conversion Data Table

Tempo [s]	Ciclo 1	Ciclo 2	Ciclo 3	Ciclo 4	Ciclo 5	Cycle Avg	kW*s	kW*h
2	15420	15460	15490	15870	20040	16456	32.912	0.0091
4	25460	19460	15570	19890	15840	19244	38.488	0.0107
6	22970	15540	15460	15920	20270	18032	36.064	0.0100
8	28150	26040	25880	30170	16150	25278	50.556	0.0140
10	28680	41150	42650	44180	27710	36874	73.748	0.0205
12	45640	33990	36530	37370	44520	39610	79.22	0.0220
14	20470	20580	20500	21020	24960	21506	43.012	0.0119
16	20440	24550	20450	25010	20930	22276	44.552	0.0124
18	20490	20440	20460	21000	24900	21458	42.916	0.0119
20	20470	24330	20440	24990	20830	22212	44.424	0.0123
22	20440	20370	20490	20970	20850	20624	41.248	0.0115
24	20380	20400	20450	24930	20800	21392	42.784	0.0119
26	15430	15430	15480	15890	19840	16414	32.828	0.0091
28	15460	19360	15410	19940	15860	17206	34.412	0.0096
30	15410	15460	15490	15630	19800	16358	32.716	0.0091
32	15480	15450	15440	16500	15970	15768	31.536	0.0088
34	18160	15440	15460	15770	19810	16928	33.856	0.0094
36	15450	15450	15390	19830	15900	16404	32.808	0.0091
38	17390	15430	15470	15780	19850	16784	33.568	0.0093
40	15360	20950	18040	23540	15890	18756	37.512	0.0104
42	23820	23540	23490	24460	27860	24634	49.268	0.0137
44	23020	23320	23060	28310	24090	24360	48.72	0.0135
46	23310	23460	23330	24610	24740	23890	47.78	0.0133
48	23010	23630	23450	25500	24260	23970	47.94	0.0133
50	27080	23600	23440	24560	24240	24584	49.168	0.0137
52	23100	23570	23570	24690	24390	23864	47.728	0.0133
54	25990	23570	23560	24690	27790	25120	50.24	0.0140
56	23150	23480	23610	28720	24510	24694	49.388	0.0137
58	25350	16290	23700	17250	28820	22282	44.564	0.0124
60	15630	18640	15510	19900	15890	17114	34.228	0.0095
62	19260	15510	15520	15820	20120	17246	34.492	0.0096
64	15380	15470	15470	20020	15800	16428	32.856	0.0091
66	56310	52650	52920	53580	56590	54410	108.82	0.0302
68	25990	17260	17780	20830	26300	21632	43.264	0.0120
70	19310	18990	19740	19850	20110	19600	39.2	0.0109
72	15410	15430	15570	19980	15840	16446	32.892	0.0091
74	19230	15510	15430	15810	20240	17244	34.488	0.0096
						per part	**Total [kWh]**	0.4539
							Total [MJ]	1.6342

Appendix B10 - Per Component Basis of Energy Consumption

Component (PP + WD)	
Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	14.93765
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	13.86289
Primary energy from renewable raw materials (gross cal. value) [MJ]	1.025286
Primary energy from renewable raw materials (net cal. value) [MJ]	1.025286
Primary energy from resources (gross cal. value) [MJ]	13.91236
Primary energy from resources (net cal. value) [MJ]	12.8376
Component (PLA + Flax)	
Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	16.28035
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	15.30392
Primary energy from renewable raw materials (gross cal. value) [MJ]	2.296104
Primary energy from renewable raw materials (net cal. value) [MJ]	2.296104
Primary energy from resources (gross cal. value) [MJ]	13.98425
Primary energy from resources (net cal. value) [MJ]	13.00782

Appendix C

Appendix C1 - Emissions to Air for Polypropylene + Wood Dust

Component - Polyproplene + Wood Dust	
_	**[kg]**
Flows	3922.816544
Resources	1950.223469
Emissions to air	7.291817107
Heavy metals to air	9.11E-07
Inorganic emissions to air	4.418455803
Ammonia	3.59E-06
Ammonium	3.81E-10
Ammonium nitrate	1.77E-15
Argon	3.64E-08
Barium	2.89E-08
Beryllium	3.42E-10
Boron	4.26E-14
Boron compounds (unspecified)	3.15E-07
Bromine	8.54E-08
Carbon dioxide	0.507653208
Carbon dioxide (biotic)	0.027967597
Carbon disulphide	2.96E-15
Carbon monoxide	0.000240158
Chloride (unspecified)	1.79E-07
Chlorine	2.56E-08
Cyanide (unspecified)	4.12E-09
Fluoride	4.13E-08
Fluorides	2.41E-10
Fluorine	7.38E-11
Helium	5.29E-11
Hydrogen	4.10E-08
Hydrogen bromine (hydrobromic acid)	3.19E-12
Hydrogen chloride	3.28E-06
Hydrogen cyanide (prussic acid)	9.64E-12
Hydrogen fluoride	3.26E-07
Hydrogen iodide	1.07E-16
Hydrogen phosphorous	6.80E-13
Hydrogen sulphide	6.72E-05
Lead dioxide	3.40E-15
Nitrogen (atmospheric nitrogen)	0.005107639

Nitrogen dioxide	1.47E-05
Nitrogen monoxide	6.00E-07
Nitrogen oxides	0.000597692
Nitrogentriflouride	1.69E-12
Nitrous oxide (laughing gas)	7.41E-06
Oxygen	4.26E-06
Scandium	1.13E-15
Silicium tetrafluoride	2.97E-13
Strontium	4.30E-14
Sulphur	3.97E-10
Sulphur dioxide	0.000659339
Sulphur hexafluoride	3.26E-12
Sulphur trioxide	6.00E-14
Sulphuric acid	2.52E-10
Tin oxide	3.94E-18
Water (evapotranspiration)	0.055830487
Water vapour	3.820297603
Zinc oxide	7.88E-18
Zinc sulphate	8.99E-11
Organic emissions to air (group VOC)	0.002067455
Group NMVOC to air	0.00027192
Hydrocarbons (unspecified)	8.12E-08
Methane	0.001795226
Organic chlorine compounds	1.58E-12
Polycyclic hydrocarbons	3.37E-30
VOC (unspecified)	2.28E-07
Other emissions to air	2.871234226
Particles to air	5.87E-05
Radioactive emissions to air	2.77E-12

Appendix C2 - Emissions to Air for Polylactic Acid + Flax

Component - PLA + Flax	
_	**[kg]**
Flows	3963.267574
Resources	1960.890278
Emissions to air	32.67457621
Heavy metals to air	1.29E-06
Inorganic emissions to air	29.21667504
Ammonia	2.97E-05
Ammonium	4.25E-10
Ammonium nitrate	1.70E-15
Argon	2.69E-08
Barium	8.09E-08
Barium compounds (unspecified; rel. to Ba)	1.39E-10
Beryllium	8.80E-10
Boron	1.28E-13
Boron compounds (unspecified)	7.48E-07
Bromine	2.87E-07
Carbon dioxide	0.711840693
Carbon dioxide (biotic)	2.19E-11
Carbon dioxide (biotic)	0.066267487
Carbon disulphide	8.37E-13
Carbon monoxide	0.000652205
Chloride (unspecified)	6.67E-08
Chlorine	1.43E-06
Cyanide (unspecified)	2.26E-09
Dinitrogen Oxide	5.14E-05
Fluoride	1.38E-07
Fluorides	1.13E-08
Fluorine	6.53E-11
Helium	6.89E-09
Hydrogen	1.44E-05
Hydrogen bromine (hydrobromic acid)	3.84E-12
Hydrogen chloride	3.09E-05
Hydrogen cyanide (prussic acid)	1.84E-11
Hydrogen fluoride	1.34E-06
Hydrogen iodide	7.45E-17
Hydrogen phosphorous	6.00E-13
Hydrogen sulphide	6.38E-05
Lead dioxide	3.76E-15
Nitrogen (atmospheric nitrogen)	0.000136463

Nitrogen dioxide	4.06E-08
Nitrogen monoxide	2.53E-06
Nitrogen oxides	0.00180188
Nitrogentriflouride	1.57E-12
Nitrous oxide (laughing gas)	2.25E-05
Oxygen	6.60E-06
Scandium	1.08E-15
Silicium tetrafluoride	2.76E-13
Strontium	5.98E-13
Sulphur	8.68E-10
Sulphur dioxide	0.001803243
Sulphur hexafluoride	2.67E-12
Sulphur trioxide	2.97E-14
Sulphuric acid	2.61E-09
Tin oxide	2.48E-18
Water (evapotranspiration)	23.87615826
Water vapour	4.55778881
Zinc oxide	4.96E-18
Zinc sulphate	2.72E-10
Organic emissions to air (group VOC)	0.002310292
Group NMVOC to air	0.000304717
Hydrocarbons (unspecified)	6.68E-06
Methane	0.001998899
Organic chlorine compounds	7.86E-13
VOC (unspecified)	9.25E-11
Other emissions to air	3.455472329
Particles to air	0.000117262
Radioactive emissions to air	2.51E-12

References

Brady, M., & Brady, P. (2007). Automotive Composites: Which way are we going? *Reinforced Plastics* , 32-35.

Chen, G., & Wu, Q. (2011). 3.21 - PHA/PHB. *Comprehensive Biotechnology (2nd Edition), Volume 3* , 217-227.

Delphi. (2011/2012). *Worldwide Emissions Standards - Passengers Cars and Light Duty Vehicles.* Troy, Michigan: Delphi.

EU-ELV. (2000). Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles. *European Directive* .

Ford. (2011 йил 31-August). *Ford Media.* Retrieved 2012 йил 5-March from Ford.com: media.ford.com/article_print.cfm?article_id=35137

Fried, J. R. (2003). *Polymer Science and Technology.* Upper Saddle River, NJ 07458: Pearson Education Inc.

Harper, C. A. (2002). *Handbook of Plastics, Elastomers and Composites - 4th Edition.* New York, NY: McGraw-Hill Book Co.

Hermann, B., Debeer, L., Wilde, B. D., Blok, K., & Patel, M. (2011). To compost or not to compost: carbon and energy footprints of biodegradable biomaterials' waste management. *Polymer Degrdation and Stability 96* , 1159-1171.

Houghton. (2011 йил 28-03). *CML-IA Characterisation Factors.* Retrieved 2012 йил 15-06 from University of Leiden - Institute of Environmental Sciences (CML): http://cml.leiden.edu/software/data-cmlia.html

ISO-14040. (2006). Life Cycle Assessment: Principles and Frameworks. *International Standard* .

ISO-14044. (2006). Life Cycle Assessment: Requirements and Guidelines. *International Standard* .

Johnson, M., & Wang, M. (2002). Evaluation polcies and automotive recovery options according to the European Directive of end-of-life vehicles (ELV). *Proc Instn Mech Engrs Vol 216, part D: J Automotive Engineering* , 723-739.

Kamath, M., & Bhat, G. S. (2005). Biodegradable / Compostable Composites from Lingo-Cellulosic Fibers for Automotive Applications. *SAE Technical Paper Series (2005-01-3338)* .

Kim, S., Dale, B. E., Drzal, L. T., & Misra, M. (2008). Life Cycle Assessment of Kenaf Fiber Reinforced Biocomposite. *Journal of Biobased Materials and Bioenergy* , vol. 2, 85-93.

Kim, S., Kim, O., Chun, Y., & Lee, W. (2011). Research on the Development of the Bio Composites for Automotive Interior Parts. *SAE Technical Paper Series (2011-28-0006)* .

Magelli, F., Boucher, K., Bi, H. T., Melin, S., & Bonoli, A. (2009). An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy 33* , 434-441.

Nampoothiri, K. M., Nair, N. R., & John, R. P. (2010). An Overview of the Recent Development in Polylactide (PLA) Research. *Bioresource Technology 101* , 8493-8501.

Narayan, R. (2009). Biobased & biodegradable plastics for reducing carbon and environmental footprint. *Department of Chemical Engineering & Material Science* .

NHTSA. (2012). *CAFE GHG Fact Sheet.* Retrieved 2012 йил 2-April from www.nhtsa.gov: www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE-GHG_Fact_Sheet.pdf

Ojumu, T., Yu, J., & Solomon, B. (2004). Production of Polyhydroxyalkanoates, A Bacterial Biodegradable Polymer. *African Journal of Biotechnology Vol. 3(1)* , 18 - 24.

Olari, J., & Cheolas, E. (2011). The Use of Soy Polyols in Automotive Acoustical Foams. *SAE Technical Paper Series (2011-01-1257)* .

Pickering, S. (2006). Recycling Technologies for Thermoset Composite Materials - Current Status. *Composites Part A: Applied Science and Manufacturing* , 1206 - 1215.

Seiichi, T., Hirofumi, N., Tomoyasu, K., Takeharu, T., Ichiro, Y., & Yoshiharu, D. (2003). Production of polyhydroxyalkanoate (PHA) from renewable carbon sources in recombinant Ralstonia eutropha using mutants of original PHA synthase. *Biochemical Engineering Journal, Volume 16, Issue 2* , 107-113.

Stewart, R. (2011). Thermoplastic Composites - Recyclable and Fast to Process. *Reinforced Plastics* , 22-28.

Takeshi, S., Yuichi, M., & Masatoshi, M. (2006). Performance Improvement of Eco Plastics / Poly Lactic Acid. *SAE Technical Paper Series* .

Vink, E. T., Davies, S., & Kolstad, F. J. (2010). The eco-profile for current Ingeo polylactide production. *Industrial Biotechnology* , 212-224.

Vink, E. T., Rabago, K. R., Glassner, D. A., & Gruber, P. R. (2003). Applications of life cycle assessment to NaturelWorks polylactide (PLA) production. *Polymer Degradation and Stability 80* , 403-419.

Vink, E. (2012 йил 30-May). *U.S. Life-Cycle Inventory Database - Polylatide Biopolymer Resin, at plant.* Retrieved 2012 йил 14-June from National Research and Energy Laboratory (NREL): https://www.lcacommons.gov/nrel/process/show/98771b3d-cf03-495d-bcb1-79c458a41a02

Volova, T., Boyandin, A., Vasillev, A., Karpov, V., Prudnikova, S., Mishukova, O., et al. (2010). Biodegradation of polyhydroxyalkanoates (PHAs) in tropical costal waters and identification of PHA-degrading bacteria. *Polymer Degradation and Stability, Volume 95, Issue 12* , 2350-2359.

Yap, C., Stapleton, R., & Smolinski, R. (2011). Natural Oil Polyol (NOP) Based Polyurethane Slabstock for Automotive Interior Foam-Fabric / Vinyl Laminate Construction. *SAE Technical Paper Series (2011-01-0459)* .

Zhang, L., Jeon, H. K., Malsam, J., Herrington, R., & Macosko, C. W. (2007). Substituting soybean-oil based polyol into polyurethane flexible foams. *Polymer 48* , 6656-6667.

Vita Auctoris

NAME: Simon Che Wen Tseng

PLACE OF BIRTH: Taipei, Taiwan

YEAR OF BIRTH: 1982

EDUCATION: Centennial College, Scarborough, Ontario
2002 - 2004
University of Windsor, Windsor, Ontario
2006 - 2010 BASc.
Politecnico di Torino, Torino, Piedmonte, Italy
2011 - 2012 Laurea Magistrale