**Financial Cost Comparison of Acrylonitrile Butadiene Styrene (ABS) and
BioABS**

by

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ABSTRACT

FINANCIAL COST COMPARISON OF ACRYLONITRILE BUTADIENE STYRENE (ABS) AND BIOABS

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BioABS, which is a light-weight, recyclable green composite made from engineered soybean hulls, is a potential replacement for the petroleum-based plastic Acrylonitrile Butadiene Styrene (ABS). The purpose of this study is to assess the financial feasibility of BioABS relative to ABS. ABS and BioABS are substitute outputs sold for the same price and the production processes are essentially the same. Thus, the differences in net returns are based on differences in variable costs. ABS consists of 25% acrylonitrile, 20% butadiene, and 55% styrene, while BioABS is made up of 6.75% acrylonitrile, 5.4% butadiene, 14.85% styrene, 63% PLA, which is made from corn, sugar beets or rice, and 10% soybean hulls. The variable cost of producing BioABS is \$1896.55/t, which is 4% higher than traditional ABS. If the price of styrene increases by 12.5% or if the price of PLA falls by 5.7%, BioABS then can be produced cheaper than ABS.

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Chapter 1: Introduction

1.1 Background

Worldwide environmental concerns and sustainable development are driving forces to conserve petroleum resources (1). Climate change, a consequence of greenhouse gas emission mainly from fossil fuel combustion, has become a serious environmental issue. As a result, many attempts have been carried to reduce the impacts of petroleum-based products and bio-based products are recognized as new wave in green industrial development. A bio-based product is a “commercial or industrial product (other than food or feed) that is composed in whole or in significant part of biological products, including renewable domestic agricultural and forestry materials, or an intermediate ingredient of feedstock” (2). Bio-based materials are industrial products made from renewable agricultural and forestry feedstocks. These feedstocks can include wood, grasses, and crops, as well as waste and residues(3) and may replace fabrics, adhesives, reinforcement fibres, polymers, and other conventional materials. Bio-based materials have been used broadly in the food and medical industries. Food-related applications include beverage bottles, containers, cups, disposable tableware, and packing. Medical applications include the production of disposable equipment and tools designed for easy decomposition(4). In 2007, 65% of bio-based plastics were used in packing and food related applications. This share is estimates to shrink to about 40%, as automotive and electronics applications, which have a higher profit potential than packaging and food industries, are expected to gain market share, reaching over 25% by 2050(5).

Since early human ancestors started smelting ore and shaping it into tools, material choices have been the foundation for functionality in design. The material industry underwent a large

transformation with the advent of polymer materials. Polymers are building blocks of molecules that link together to form long chains that can be used to make plastics. Polymers are mostly derived from petroleum reserves and are relatively inexpensive to produce. In addition, they are easily processed using methods perfected in the middle of the twentieth century.

Generally, plastic is mouldable, easy to manufacture, imperviousness to water, and can be made at a low cost. It plays an essential role in modern industry since it is used to make a wide range of products, from paper clips to spaceships. Five main polymers currently dominate the industry: polypropylene (PP), polystyrene (PS), polyethylene (PE), poly(vinyl chloride) (PVC), and poly(ethylene terephthalate) (PET)(6). The properties required in the product and costs determine which polymer is used for different applications. These five polymers have properties that range from relatively low to high strength, poor to excellent barrier properties, and low to high heat capabilities, among others.

Traditional plastic is derived from petroleum. The fact that a plastic is petroleum-based refers to the carbon source from which it is obtained. Since traditional plastics are made from a non-renewable resource, there are concerns about the sustainability of its use. The price of making petroleum-based plastics would increase with increases in the price of fossil fuel as this resource becomes scarcer.

An additional concern associated with traditional plastics is their lack of degradability. The growing use of plastics takes up an increasing amount of landfills. According to the United Nations Environmental Programme, global plastic consumption has gone from 5.5 million tons in the 1950s to 110 million tons in 2009(7). Today Americans discard about 33.6 million tons of plastic each year, but only 6.5 percent of it is recycled and 7.7 percent is combusted in waste-to-

energy facilities, which create electricity or heat from garbage. The rest ends up in landfills where it may take up to 1,000 years to decompose, and potentially leak pollutants into the soil and water(8).

If the carbon source that it is obtained is not from petro-chemicals, and instead from an agricultural or other bio-feedstock, the plastic is considered bio-based. Bio-based plastics rely on renewable, rather than non-renewable, resources. The second sustainable property that is an advantage for bio-based plastics is its biodegradability. Bio-based plastics are made using renewable resources, such as plant biomass, and will biodegrade under certain environmental conditions. These materials are suitable for disposable items, such as packaging, drink bottles, single-use food containers and cutlery. They are more sustainable because they save fossil fuel resources and, if disposed of appropriately, support further plant growth.

As a result of the aforementioned economic and environmental shifts, there is an increasing interest in the use of bio-based materials to replace currently used petroleum-based materials. Biopolymers are diverse and versatile materials that have potential applications in virtually all sectors of the economy. For example, they can be used as adhesives, absorbents, lubricants, soil conditioners, cosmetics, drug delivery, vehicles, textiles, high-strength structural materials, and even computational switching devices(9). Currently, many biopolymers are still in the developmental stage, but important applications are beginning to emerge in the areas of packing, food production, medicine and automotive. Table 1.1 displays some examples of bio-based materials in automotive applications(10). Another promising area is that of nanocomposites and electrospinning of nanofibers(11).

Table 1. 1 Selected bio-based automotive components

Model(s)	Feedstock	Material	Application
Cadillac DeVille	Wood	Polypropylene	Seatbacks
Chevrolet Impala	Flax	Polypropylene	Trim, rear shelf
Ford Flex	Wheat straw	Polypropylene	Interior storage bins
Ford Focus BEV	Coconut	Polypropylene	Loadfloor
Ford vehicles (Multiple)	Soy	Polyurethane	Foam seating, headrests, headliner
GMC Terrain	Cotton, kenaf	Polyester	Acoustic insulator, ceiling liner
Honda Pilot	Wood	N/A	Floor area parts
Lexus CT200h	Bamboo, corn	Polyethylene terephthalate, Sorona	Luggage-compartment, speakers, floor mats
Mazda 5 Hydrogen RE Hybrid	Corn	Polylactic acid	Console, seat fabric
Mercedes-Benz A-Class	Abaca/banana, flax, other natural fibers	Composite material	Underbody panels, seatbacks, spare tire cover
Mercedes-Benz C- and A-Class	Flax	Polyethylene	Engine and transmission cover, underbody panels
Toyota Prius	Corn	Sorona EP	Instrument-panel, air-conditioning vent
Toyota Raum	Kenaf, starch	Composite material	Floor mats, spare tire cover

Source: CAR 2011

Figure 1. 1 Composites supply and demand

1.2 Economic Problem

The polymer materials industry is heavily dependent on the use of petroleum-based plastics. The reliance on fossil fuels has financial and environmental complications for sectors using plastics.

As a result, there is a drive for low cost, green materials to replace the existing products.

Composites from engineered soy hull and BioABS are potential alternatives for transportation applications. While these green bio-based plastics are technically feasible, it is not known if they are financially feasible compared to petroleum-based plastics. There is no information on how price changes will influence the relative profitability of the two methods. Thus, the material industry is faced with the economic problem of making decisions whether these bio-based composites are commercially feasible.

The economic problem is illustrated by Figure 1.1. There is a single demand for polymers represented by the demand curve D . This demand can be supplied by two markets; petroleum-based (S_T) and bio-based (S_B). The market price is determined by total supply and demand (Figure 1.1). Total supply (S) is the horizontal sum of bio-based composite supply (S_B) and traditional composite supply (S_T). If demand intersects total supply at a point where the equilibrium quantity is less than Q_3 and equilibrium price is less than P_b , bio-based polymers will not be produced. Bio-based polymers maybe technically feasible to produce but will not be commercially feasible unless the polymer price is greater than the bio-based composite shutdown price. Whether bio-based polymers are commercially feasible thus depends on the relative location of the cost curves, which in turn depend on the relative efficiencies of production and relative prices of inputs.

1.3 Research Problem

Currently, industry uses plastics that are mainly derived from petroleum. The nature of the source is that it takes millions years to produce. The diminishment of reserves and supply problems attract more attention. Therefore, there is an increasing importance in the use of bio-based materials to substitute petroleum-based ones. Composites from engineered soy hull and BioABS are new materials, so whether they possess commercial viability for automotive applications is unknown. To determine the economic feasibility of composites from engineered soy hull and BioABS, it is important to know the costs and benefits of this new technology. Hence, a cost modelling tool is described such that the process of cost estimation can be understood.

Cost modelling for composites can be approached in a variety of ways depending on what specific information is required. Popular approaches include activity based comparative techniques(12), process-oriented cost models(13), parametric cost models(14), and process flow simulations(15).

Activity based comparative techniques based upon historical data, so it is of limited use when new processes are considered. Process-oriented cost models require in-depth knowledge of the manufacturing process and part geometry. Parametric cost models offer flexibility together with easy manipulation of process and economic factors for sensitivity studies(16).

The current trend for cost modelling approached for polymer composites is technical cost modelling (TCM), which is based on an activity based costing (ABS) approach, but use engineering, technical and economic characteristics associated with each manufacturing activity to evaluate its cost. The technical cost modelling approach is shown in Figure 1.2(17).

Figure 1. 2 Technical cost modelling approach

TCM is a combined parametric and process flow simulation method used widely throughout the manufacturing industries where historical data is either not available or does not exist. A production process is first identified. Then the process is divided into the contributing process steps. Costs of each operation are then combined to give a total cost for the production process. Therefore, the complex problem of cost analysis is reduced to a series of simpler estimating problems(18). The costs of these elements are derived from inputs including process parameters and production factors, such as labour and capital requirements, production volumes, energy use and so on. These elements are calculated based on engineering principles, economic relationships, and manufacturing variables.

Because the composite is new material, there is a lack of information about economic assessment of it. This study will use technical cost model(18) to estimate the costs of the new material.

1.4 Purpose and Objectives

The purpose of this study is to assess the financial feasibility of composites made from engineered soy hull and BioABS for automotive applications, relative to the petroleum-based composites. To achieve the general purpose, the following objectives are specified;

1. To describe the production process of bio-based composites for automotive applications by reviewing previous researches.
2. To estimate the cost of the biocomposites production by using a technical cost model, which is based upon an activity based costing approach.
3. To compare the cost of bio-based composites with their petroleum-based counterparts.

1.5 Chapter Outlines

The next chapter of the thesis reviews the physical basics of polymers and fibers and describe the differences between traditional and bio-based approaches. Chapter 3 outlines the model used to determine the cost of producing polymers using the two approaches. It will also explain the need for a sensitivity analysis. The results of the model are pretended in Chapter 4 along with a sensitivity analysis of relative costs changing in prices and other parameters. The thesis concludes with a summary of the results and their implications in Chapter 5.

Chapter 2: Literature Review of Bio-based Polymers

2.1 Introduction

The purpose of this chapter is to review the physical basics of polymers and fibres. It begins with a discussion of traditional polymers in terms of definitions, types and uses of polymers followed by the distinction with bio-based polymers. A similar format is followed for a description of traditional and bio-based fibres. The review provides the necessary background to determine the costs and benefits of bio-based polymers and fibres compared to traditional petroleum-based polymers. The next chapter highlights the inputs and outputs of the production process for both methods.

2.2 Traditional Polymers

2.2.1 What is a Polymer?

Polymers are a class of “giant” molecules consisting of discrete building blocks linked together to form long chains(9). There are natural polymeric materials such as wool, silk and amber and synthetic polymers including polystyrene (PS), polyethylene (PE) and so on(19).

2.2.2 Types and Uses of Polymers

Traditional plastic, mainly derived from petroleum, is easy to manufacture and shape, and has low cost and imperviousness to water. It plays essential role on modern industry with a wide range of applications, from paper clips to spaceships. Five main polymers dominate the current industry: polypropylene (PP), polystyrene (PS), polyethylene (PE), poly(vinyl chloride) (PVC), and poly(ethylene terephthalate) (PET)(6). Different properties and cost determine each is used for different applications. Best performance to cost ratio of many of the currently available

plastics makes them be considered commodity plastics. These five polymers have properties that range from relatively low to high strength, poor to excellent barrier properties, and low to high heat capabilities, among others. Mainly, their properties are inferior to non-commodity polymers.

PE has the simplest molecular formula and is the least costly of addition polymers(6). It can be separated into two categories, high-density and low-density. High-density polyethylene (HDPE) has a low degree of branching and thus low intermolecular forces and tensile strength. It is used when clarity is not of great importance for its strength. Applications such as milk jugs, detergent bottles, butter tubs, and water pipes use HDPE(20).

Low-density polyethylene (LDPE) is fairly transparent, flexible, strong, tough, and moisture resistant. LDPE is a good candidate for use in both rigid containers and plastic film applications such as plastic bags and film wrap(20).

PP is harder, denser, and more transparent than PE and has good resistance to fatigue(6). It used in a wide variety of applications including packaging and labeling, stationery, plastic parts and reusable containers of various types, laboratory equipment, loudspeakers, automotive components, and polymer banknotes(21).

PS is a synthetic aromatic polymer made from monomer styrene, which is a liquid petrochemical. Uses include protective packaging (such as packing peanuts and CD and DVD cases), containers (such as "clamshells"), lids, bottles, trays, tumblers, and disposable cutlery(22).

PVC is the third-most widely produced plastic, after PE and PP. PVC is used in construction because it is more effective than traditional materials such as copper, iron or wood in pipe and

profile applications. It is also used in clothing and upholstery, electrical cable insulation, inflatable products and many applications in which it replaces rubber(23).

PET has a glass-like transparency good gas barrier to carbonation, strong, lightweight and tough. Plastic bottles made from PET are widely used for soft drinks. It is also used for peanut butter jars, plastic film, and microwavable packaging(24).

2.3 Bio-based Polymers

The term “bio-based polymers” is used to describe a variety of materials. Bio-based polymers fall into two principal categories: (1) polymers that are produced by biological systems such as microorganisms, plants, and animals; (2) polymers that are synthesized chemically but are derived from biological starting materials such as amino acids, sugars natural fats, or oils(9). In common, renewability is most important in defining bio-based polymers.

2.4 Natural Fibers

2.4.1 Why Include Fibres?

There is a growing interest to use fibers as reinforces in plastics composites mainly due to their sustainability, low weight, highly specific strength and stiffness(25). They have good potential for use in waste management because of their biodegradability and their much lower production of ash during incineration. Their low cost and worldwide availability make them attractive(11). It also causes value addition to agriculture.

Natural fiber fillers and reinforcements are the fastest growing polymer additive(26). In the past 15 years, natural-fiber composites have been adopted by the European automotive industry(27);

in recent years, these materials have been gaining traction in the United States. Use of castor and soy-based polymers for interior foams has now become more widespread as well.

2.4.2 Types

The natural fibres can be divided into two groups: animal fibres and plant fibres. Examples for animal fibres are red algae, spider silk, and hair such as cashmere wool, mohair and angora, fur such as sheepskin, rabbit, mink, fox, etc. The plants category contains wood and non-wood. The latter has five basic types: straw fibers (wheat, corn, and rice), bast fibers (jute, flax, hemp, and ramie), leaf fibers (sisal, and pineapple leaf), seed/fruit fibers (cotton, coir, and kapok) and grass fibers (bamboo, switch grass, and elephant grass)(28).

Fibers can be derived not only from both wood and crop, but also a number of non-traditional agricultural sources. These include source like seed hulls and husks, as well as agricultural crop processing by-products such as residues from corn or sugar processing(29). This study will focus on soy hull.

2.5 Summary

This chapter introduces the physical basics of polymers and fibres. It starts with a discussion of traditional polymers in terms of defining, types and uses, followed by the distinction with bio-based polymers. Then it explains the necessity of using fibers in plastics composites and fiber types. The review provides the background to help determine the costs of composites in bio-based method compared with traditional method. The next chapter highlights physical production

process of two approaches and outlines the model used to determine the costs of producing composites in the two methods.

Chapter 3: Conceptual Framework

3.1 Introduction

This chapter begins with explaining why we focus on ABS and BioABS. Then it defines the composites' physical production process for the traditional approach and the bio-based approach. After that it outlines the technical cost model to determine the cost of producing composites in two approaches respectively. It also explains the need for a sensitivity analysis.

3.2 Physical Production Process of Two Approaches

3.2.1 ABS and its production process

Much of the plastic used in the automotive industry is in the form of acrylonitrile butadiene styrene (ABS). ABS is a durable thermoplastic, resistant to weather and some chemicals(30). Traditionally, it has been positioned between commodity plastics, such as polystyrene (PS) and polypropylene (PP), and the higher-performing engineering thermoplastics, for example, polycarbonate and polyurethane. ABS resins are composed of over 50% styrene and varying amounts of butadiene and acrylonitrile. Due to the flexibility in composition and structure, the petroleum-based plastic is widely used in automobile sector including instrument panels, consoles, radiator grills, headlight housings and interior trim parts(31).

ABS polymerisation can be carried out using a liquid phase, suspension or emulsion process; emulsion polymerisation is the world's most applied process(32). First, butadiene is polymerised to polybutadiene, and then acrylonitrile and styrene are added to it to form the ABS polymer.

The share of acrylonitrile, butadiene and styrene can be varied with 25% acrylonitrile, 20% butadiene, and 55% styrene as the typical composition(32).

The process scheme is shown in Figure 3.1.

Figure 3. 1 Process scheme of ABS production

Source: Joosten, 1998

Left line in Figure 3.1 shows acrylonitrile production. It is based on Sohio process. Ammonia, propylene and oxygen are catalytically converted to acrylonitrile by using a fluidized bed reactor.

Hydrogen cyanide (HCN) is one major by-product. Ammonia is produced primarily steam reforming of natural gas. Natural gas is fed with steam into a tubular furnace where the reaction over a nickel reforming catalyst produces hydrogen (H_2) and carbon oxides. The primary reformer products are then mixed with preheated air and reacted in a secondary reformer to produce the nitrogen (N_2) needed in ammonia synthesis. The gas is then cooled to a lower temperature and subjected to the water shift reaction in which carbon monoxide and steam are reacted to form carbon dioxide (CO_2) and H_2 . The CO_2 is removed from the shifted gas in an absorbent solution. H_2 and N_2 are reacted in a synthesis converter to form ammonia.

For the middle line, it is polybutadiene production. Butadiene is extracted from the C_4 fraction of steamcrackers. Then through polymerisation, butadiene converts to polybutadiene.

Right line in Figure 1 indicates styrene production. Styrene is produced from ethylene and benzene, and benzene is extracted from the pyrolysis gasoline (BTX) fraction of steamcrackers. One of major coproducts is toluene.

We do not discuss each process separately. Instead, we focus on data for the combination of process to produce ABS. Table 3.1 represents the data of ABS production.

In total, to produce 1 ton ABS, the combined processes need 0.256 ton acrylonitrile, 0.205 ton butadiene and 0.564 ton styrene (the ratio is about 25%, 20%, 55%). For input materials, there need 0.564 ton styrene, 0.279 ton propylene, 0.113 ton ammonia and 0.205 ton C_4 fraction, as well as some steam and air. At the same time, 0.026t hydrogen cyanide (HCN) and 0.023t toluene are produced as main coproducts.

Table 3. 1 Data of ABS production

	Unit	Amount
Input		
Styrene	[t]	0.56
Propylene	[t]	0.28
C ₄	[t]	0.21
Ammonia	[t]	0.11
Electricity	[GJ _e]	2.0
Fuel oil	[GJ]	0.5
Natural gas	[GJ]	0.4
Steam	[GJ]	1.2
Output		
ABS	[t]	1
HCN	[t]	0.03
Toluene	[t]	0.02
CO ₂	[t]	0.11
Costs		
Investment	[ECU ₁₉₉₄ /t ABS cap.]	1202
Fixed	[ECU ₁₉₉₄ /t ABS cap. year]	48
including labour	[ECU ₁₉₉₄ /t ABS cap. year]	24
Variable	[ECU ₁₉₉₄ /t ABS]	52
including labour	[ECU ₁₉₉₄ /t ABS]	21
Lifetime	[year]	25
Availability factor	[-]	0.95
Residual capacity	[kton ABS/year]	2800

Source: MATTER Datasheet

The energy required for the individual processes are estimated by Heijningen and Chauvel(32) and include acrylonitrile production, butadiene extraction, butadiene polymerisation and ABS polymerisation. Benzene extraction, styrene production and ammonia production are not included.

Cost data were calculated from data on acrylonitrile production and butadiene extraction and estimates for ABS polymerisation costs (based on PS polymerisation). Chauvel's investment values were multiplied by 1.4 in order to include offsite costs(32).

After ABS is made, it needs some processing methods to form finished products, such as instrument panels, headlight housings and other automobile interior parts. There are 4 steps in the process.

(1)Drying

All polymers are obtained in pellet form. They are hygroscopic. Residual moisture content in those materials that were not properly dried can lead to bubbles inside the part, flash and poor surface quality(33). Before any polymer processing can occur, the moisture level in the polymer must be decreased below 100 ppm, so the polymer pellets are dried in a convection oven for at least 4 hours at 80°C(34).

(2)Extrusion

The most important polymer process is extrusion. Polymer blending and compounding is traditionally done using a twin-screw extruder. It is the fundamental method for blending polymers, and it is also the preferred method of conveying molten polymer as part of many other methods of polymer processing. Extrusion is used in injection molding, cast film, blow molding, and among others(35). Plastic pellets or granules are first loaded into a hopper, then fed into an extruder, which is a long heated barrel, through which it is moved by the action of a continuously revolving screw. At the final stage, these screws push the molten polymer out a small opening or die(36). These are three sections of the barrel, the feed, transition, and metering, shown as in Figure 3.2.

Figure 3. 2 Schematic of the screw cross section in a twin-screw extruder

When thermoplastic polymers are extruded, it is necessary to cool the extrudate below T_m (melting temperature) or T_g (glass transition temperature) to impart dimensional stability. This cooling can often be done simply by running the product through a tank of water, by spraying cold water, or by air cooling(37).

Extruders are also used for compounding plastics (i.e., adding various ingredients to a resin mix) and for converting plastics into pellet shape commonly used in processing. In this last operation specialized equipment, such as the die plate-cutter assembly, is installed in place of the die and an extrusion-type screw is used to provide plasticated melt for various injection-moulding processes(37) .

(3)Drying

Just as mentioned above, before injection molding, to decrease the moisture, especially cooling by cold water in extrusion process, polymers also need to be dried.

(4)Injection molding

ABS pellets fall from the hopper into the barrel when the plunger is withdrawn. The plunger then pushes the material into the heating zone, where it is heated and softened. Rapid heating takes place due to spreading of the polymer into a thin film around a torpedo. The already molten polymer displaced by this new material is pushed forward through the nozzle, which is in intimate contact with the mold. The molten polymer flows through the sprue opening in the die, down the runners, past the gate, and into the mold cavity. The mold is held tightly closed by clamping action of the press platen. The molten polymer is thus forced into all parts of the mold cavities, giving a perfect reproduction of the mold. The mold must be cooled under pressure below T_m or T_g before the mold is opened and the molded part is ejected. The plunger is then withdrawn, a fresh charge of materials drops down, the mold is closed under a locking force, and the entire cycle is repeated(38). In short, the cycle starts with closing the mold, followed by the injection of the polymer into the mold cavity, cools the polymer, opens the mold and ends with releasing the molded part(39).

3.2.2 BioABS and its production process

The best chance to develop a bio-based plastic that is close to the performance of ABS is to use ABS as the base plastics in the formulation and supplement it with a bio-based material. We want to mimic ABS because it is so heavily used in the automotive and electronics industries due to its cost and its performance and a range of demands.

Poly lactide or polylactic acid (PLA) is an aliphatic polyester thermoplastic that is biodegradable and non-toxic(40). PLA is a versatile new compostable polymer that is made from 100% renewable resources like corn, sugar beets or rice(41). It is being used in manufacturing fresh food packaging and food service ware such as disposable cups, rigid packaging, food containers,

cutlery, films and plates. PLA can also be blended with other petroleum-based polymers to make them partially bio-based or biodegradable with high toughness(42). PLA is chosen to blend with ABS, also because it is the only commercially produced bio-based polymer suitable for bulk application(43). PLA production starts with a crop (typically corn) growing, harvesting, and milling to separate out its starch. This starch is hydrolyzed into dextrose, which in turn is converted to lactic acid using microorganisms. After some more chemical treatment, the lactic acid forms into long polymer chains, becoming PLA resin(44).

NatureWorks started to produce Ingeo PLA resin in its 140000 tonne-per-year manufacturing facility in Blair, Nebraska, USA in 2001. In 2002 NatureWorks began to produce lactic acid in its 180000 tonne-per-year manufacturing facility located next to the polymer plant. Today, these two plants are the only large-scale commercial production facilities for PLA worldwide(45).

The simplified flow diagram for the production of virgin Ingeo PLA is presented in Figure 3.3(41). The primary inputs to these major steps are listed on the left and right in Figure 3.3. In the final eco-profiles data, these primary inputs are traced back to the extraction of the raw materials from the earth. The following data (eco-profiles) in Table 3.2-3.4 represents Ingeo 2009 manufacturing system. All data is given per kilogram of Ingeo (at factory gate). To get 1 kg PLA, 1.5319 kg corn is needed. Table 3.2 shows the energy data expressed as masses of fuels. Table 3.3 indicates the demand for water. The “Unspecified” in the “Use for processing column” mainly represents the irrigation water use during corn production. Table 3.4 shows the raw materials requirements. The bottom entry gives “Land use”. The net land use is 1.7 m²/kg Ingeo.

Figure 3. 3 Flow diagram of the manufacture of Ingeo polylactide (PLA)

Source: Vink et al., 2003

Table 3. 2 Gross primary fuels used to produce 1 kg Ingeo 2009, expressed as mass

Fuel type	Input (mg)
Crude oil	60300
Gas/condensate	378876
Coal	577430
Metallurgical coal	182
Lignite	26
Peat	1
Wood	1

Table 3. 3 Gross water consumption required for production of 1 kg Ingeo 2009

Source	Use for processing (mg)	Use for cooling (mg)	Totals (mg)
Public supply	16495064	7205585	23700649
River canal	1831	461049	462880
Sea	1062	12149	13211
Well	48240	0	48240
Unspecified	21341920	3220774	24562694
Totals	37888117	10899557	48787674

Table 3. 4 Gross raw materials required to produce 1 kg Ingeo 2009

Raw material	Input (mg)
Barytes	73
Bauxite	7
Sodium chloride (NaCl)	81716
Chalk (CaCO ₂)	101703
Clay	28593
Fe	451
Pb	3
Limestone (CaCO ₂)	35108
Sand (SiO ₂)	10289
Phosphate as P ₂ O ₅	7454
S (elemental)	7756
Dolomite	6
O ₂	180
N ₂	9152
Air	285690
Bentonite	6
Gravel	2
Olivine	4
Potassium chloride (KCl)	14802
S (bonded)	33038
Biomass (including water)	314
Land use (x E-06 m ²)	1727693

Source: NatureWorks, 2010

After ABS and PLA are manufactured, separately, we can produce BioABS. In short, BioABS is made from ABS blending with PLA and using soy hull as additives to alter properties. 70:30 PLA:ABS blend is chosen as the most viable ratio because it has the best balance of bio-based

content and potential properties(34). BioABS processing is similar with ABS. The machines they use are the same. They both use twin-screw extruders and injections moulders. The differences are input materials and the machines operation situation. For BioABS, when doing extrusion, ABS, PLA and additives are put into the hopper at the same time. Other steps are almost the same except the temperature and cycle time. ABS and PLA have different melting temperature. ABS has a generally higher melting point of PLA. As a result, input materials are focused on. Table 3.5 shows the difference of input materials between producing 1 ton ABS and 1 ton BioABS. When producing BioABS, soy hull is 10% by weight, and ABS : PLA is 30:70(34).

Table 3. 5 Comparison between ABS and BioABS input data

	Unit	ABS	BioABS
Input			
Styrene	[t]	0.564	0.152
Propylene	[t]	0.279	0.075
C ₄	[t]	0.205	0.055
Ammonia	[t]	0.113	0.031
Electricity	[GJe]	2.0	0.54
Fuel oil	[GJ]	0.5	0.135
Natural gas	[GJ]	0.4	0.108
Steam	[GJ]	1.2	0.324
PLA	[t]	0	0.63
Soy Hull	[t]	0	0.1

Source: MATTER Datasheet

3.3 Model: Technical Cost Model

The current trend for cost modelling approached for polymer composites is technical cost modelling (TCM), which is based on an activity based costing (ABC) approach, but use engineering, technical and economic characteristics associated with each manufacturing activity to evaluate its cost. TCM is a combined parametric and process flow simulation method used widely throughout the manufacturing industries where historical data is neither available nor exist(16). A production process is first identified. Then the process is divided into the contributing process steps. Costs of each operation are then combined to give a total cost for the production process(18). Therefore, the complex problem of cost analysis is reduced to a series of simpler estimating problems. The costs of these elements are derived from inputs including process parameters and production factors, such as labour and capital requirements, production volumes, energy use and so on. These elements are calculated based on engineering principles, economic relationships, and manufacturing variables.

As the composite is new material, there is a lack of information about financial assessment of it. This study will use technical cost model(18) to estimate the costs of the new material. The equations (1)(2)(3) below are used in the study.

$$Profit = Revenue - Cost \quad (1)$$

$$\pi_j = P_j Q_j - Cost_j \quad (2)$$

$$Cost_j = \sum_{i=1}^n X_{ij} \times P_i \quad (3)$$

$$j = A (ABS) \text{ or } B (BioABS)$$

X_{ij} = amount of input i needed to make 1t of j

P_i = market price of input i

Assume: $P_A = P_B$, $Q_j = 1t$

Equation (1) and (2) are both used to get ABS and BioABS profit. Equation (3) is used to get ABS and BioABS production cost. We assumed BioABS market price is the same with ABS market price. When calculating, we took 1 ton ABS and 1 ton BioABS in consideration. To assess the financial feasibility, there are two questions need to be considered. One is whether BioABS profit is positive; the other is whether BioABS profit is higher than ABS, in other words, whether BioABS costs less than ABS. Table 1.2 shows how to calculate ABS and BioABS cost.

Table 3. 6 Comparison between ABS and BioABS total cost

	ABS	BioABS
Input 1 (X_1)	Amount used $X_{1A} \times P_1$	Amount used $X_{1B} \times P_1$
Input 2 (X_2)	Amount used $X_{2A} \times P_2$	Amount used $X_{2B} \times P_2$
.....		
Input n (X_n)	Amount used $X_{nA} \times P_n$	Amount used $X_{nB} \times P_n$
Total Cost	$\sum_{i=1}^n X_{iA} \times P_i$	$\sum_{i=1}^n X_{iB} \times P_i$

3.4 Input Prices

Input prices are needed before using technical cost model. The prices of the inputs and their source of the price information are listed in Table 3.6.

Table 3. 7 Prices of variable inputs required to produce one ton of ABS and BioABS

Input	Average Price (P_i)	Source
Styrene	\$1529.3/t	http://www.dewittworld.com/portal/Default.aspx?ProductID=2
Propylene	\$1390.74/t	http://www.dewittworld.com/portal/Default.aspx?ProductID=102
C ₄	\$2050/t	http://www.dewittworld.com/portal/Commentaries/MarketCommentary.aspx?ProductID=103
Ammonia	\$754/t	http://farmdocdaily.illinois.edu/2014/04/monthly-fertilizer-prices-spring2014-with-comparisons.html
Electricity	\$21.83/GJe	Key Canadian Electricity Statistics
Fuel oil	\$15.73/GJ	Natural Resources Canada
Natural gas	\$3.15/GJ	Natural Resources Canada
Steam	\$7.45/GJ	https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/team15_benchmark.pdf
PLA	\$2200/t	Davies, 2011
Soy Hull	\$210/t	http://agebb.missouri.edu/dairy/byprod/bplist.asp

Styrene, Propylene and C₄ price data is all from DeWitt & Company(46-48). Styrene spot price is \$1227.5-1752/t in Korea from 2012 to 2013, Propylene spot price in North America is \$1021-2094.4/t from 2011 to 2013, and C₄ chemical (butadiene) is \$1984-2116/t in US in 2012.

According to the Agricultural Marketing Service, an agency of the U.S. Department of

Agriculture, the monthly prices for Ammonia (anhydrous) averaged \$899 per ton in 2009, \$485 in 2010, \$747 in 2011, \$848 in 2012, \$872 in 2013, and \$673 per ton in 2014(49). Key Canadian Electricity Statistics (release in 2013) reported the average industrial electricity price in 2012 is 7.86 ¢/kWh(50). Based on U.S. Department of Energy, Steam price is \$9.39/1000 lb(51). PLA price under NatureWorks' Ingeo brand name is \$0.9-1/1b and highest price is chosen(52). University of Missouri Extension provides Soy Hull price from different companies from \$175/t to \$245/t(53). In Table 3.6, all price data is average price and has been done unit conversion.

Figure 3. 4 Par crude postings at Edmonton, monthly, 2010-2013

Source: Natural Resources Canada

Figure 3.4 shows the crude oil price trend from 2010 to 2013. According to Table 3.7, the average price of crude oil is 600.65 CAN \$/m³ from January to September in 2013.

Table 3. 8 Par crude postings at Edmonton monthly – 2013

Date	IMPERIAL OIL	SHELL	SUNCOR	AVERAGE	
	Cdn \$/m3 @ 15 °C, 825/0.3% S)			Cdn \$/m3	Cdn \$/bbl
2013-01	553.41	552.87	552.16	552.81	87.83
2013-02	558.37	555.64	555.54	556.52	88.44
2013-03	564	563.26	563	563.42	89.53
2013-04	573.18	574.23	574.47	573.96	91.21
2013-05	601.36	600.58	602.77	601.57	95.6
2013-06	576.8	576.06	565.94	572.93	91.04
2013-07	667.27	665.68	667.55	666.83	105.97
2013-08	668.14	668.16	667.61	667.97	106.15
2013-09	650.2	649.33	649.93	649.82	103.26
Average	601.42	600.65	599.89	600.65	95.45

Source: Natural Resources Canada

Figure 3.5 indicates the natural gas price change between 2010 and 2013 in Canada. The average price of natural gas is \$3.15 /GJ in 2013 (Table 3.8).

Figure 3. 5 Canadian Natural Gas price, monthly, 2010-2013

Source: Natural Resources Canada

Table 3. 9 Canadian Natural Gas: monthly--2013

Date	Price, CAN\$/GJ
2013-01	3.00
2013-02	2.90
2013-03	2.87
2013-04	3.27
2013-05	3.50
2013-06	3.41
2013-07	3.11
Average	3.15

Source: Natural Resources Canada

.Through technical cost model, we can get to know the cost of ABS and BioABS. Then compare them to see whether BioABS is financially feasible.

3.5 Summary

This chapter highlights physical production process of two approaches and outlines the model used to determine the costs of producing composites in the two methods. The next chapter outlines the results of cost and sensitivity analysis, and followed by comparison discussion to assess the financial feasibility of BioABS for automotive applications relative to the petroleum-based ABS composite.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter begins by presenting the results of breakeven price for each composite. Then it is followed by sensitivity analysis. The sensitivity analysis evaluates effects of input price on breakeven price of ABS and BioABS. The cost comparison will be subject to a sensitivity analysis to see how price changes could influence the results. Finally, @RISK is used to do advanced analysis. Input price distributions will replace average input prices. The cost comparison will indicate to the auto industry whether BioABS is financially feasible alternative and, if not, what improvements are required to make it attractive to the current composite.

4.2 Results and discussion

4.2.1 Cost results

In summary, Table 4.1 gives the combination cost data of ABS and BioABS. Given the input use requirements (Table 3.5) and input prices (Table 3.6), ABS production cost is \$1817.72/t and BioABS is \$1896.55/t. BioABS production cost is approximately 4% higher than ABS.

The price of raw materials has a significant influence on the production cost. For ABS total cost, Styrene accounts the largest part, almost a half (47.45%). The average price of Propylene, C₄, and Ammonia is \$1529.3/t, \$1390.74/t, and \$2050/t. The input cost of these three materials represents 21.35%, 23.12%, and 4.69%, respectively. The proportion of the four raw materials cost is about 97% of total cost. Besides, to produce 1 ton ABS, it also costs \$43.66 electricity,

\$7.87 fuel oil, \$1.26 natural gas, and \$8.94 steam. They occupy 2.40%, 0.43%, 0.07%, and 0.49% of total cost.

Table 4. 1 Input costs and total costs of producing one ton of ABS and BioABS

Input	ABS	BioABS
Styrene	862.53(47.45)	232.45(12.26)
Propylene	388.02 (21.35)	104.31(5.50)
C ₄	420.25(23.12)	112.75(5.95)
Ammonia	85.20(4.69)	23.37(1.23)
Electricity	43.66(2.40)	11.79(0.62)
Fuel oil	7.87(0.43)	2.12(0.11)
Natural gas	1.26(0.07)	0.34(0.02)
Steam	8.94(0.49)	2.41(0.13)
PLA	n.a.	1386(73.08)
Soy Hull	n.a.	21(1.11)
Total	\$1817.72 (100)	\$1896.55 (100)

For BioABS, PLA plays the most important role in the total cost and it accounts for 73.08%. On the contrary, soy hull only takes up 1.11%, a small part of whole cost. Other input percentage is all less than that of ABS. To produce 1 ton BioABS, it costs \$232.45 Styrene, \$104.31 Propylene, \$112.75 C₄, and \$23.37 Ammonia. These four raw materials occupy 12.26%, 5.50%, 5.95%, and 1.23%, respectively. Electricity, fuel oil, natural gas, and steam are all less than 1%.

Figure 4. 1 ABS price from March 2012 to February 2014 in EU

Source: http://plasticker.de/preise/preise_monat_single_en.php

From Figure 4.1, we can find that: ABS average market price over last two years is \$1976.6/t; It is higher than breakeven price of ABS and BioABS; Both ABS and its bio-based alternative can cover the variable cost of production. Even though the cost of BioABS is higher than ABS, it is lower than ABS average market price. When the market price of BioABS is between its breakeven price and ABS market price, BioABS is financially feasible alternative.

4.2.2 Sensitivity Analysis

The effect of a one percent change in input price on the variable cost of production is listed in Table 4.2. And the input price at which the variable cost of production is equal for ABS and BioABS is given in the last column.

PLA and soy hull prices have no effect on ABS cost. When PLA price increases 1%, BioABS cost increase 0.7308%. When soy hull price increases 1%, BioABS cost increases 0.0111%.

When PLA price is reduced by 5.69% (\$2074.87/t), the cost of BioABS and ABS are the same.

When PLA price is below \$2074.87/t, BioABS breakeven price is lower than ABS. In terms of soy hull only, no matter how its price changes, BioABS breakeven price is always higher than ABS.

Table 4. 2 Sensitivity analysis of production costs of ABS and BioABS to changes in input prices

Input	Effect of a 1% Change in Input Price on Variable Cost of		Input Price where Production Cost of ABS=BioABS
	ABS	BioABS	
Styrene	0.4745%	0.1226%	1720.63(12.51%)
Propylene	0.2135%	0.055%	1777.16(27.78%)
C ₄	0.2312%	0.0595%	2575.53(25.64%)
Ammonia	0.0469%	0.0123%	1715.37(127.5%)
Electricity	0.024%	0.0062%	75.82(347.33%)
Fuel oil	0.0043%	0.0011%	231.71(1373.06%)
Natural gas	0.0007%	0.0002%	273.12(8570.36%)
Steam	0.0049%	0.0013%	97.44(1207.96%)
PLA	n.a.	0.7308%	2074.87(-5.69%)
Soy Hull	n.a.	0.0111%	n.a.

Figure 4. 2 Changes in production cost price as Styrene price changes

Figure 4.2 shows the changes in cost of production as Styrene price changes while keeping all other variables' value. With the increase of Styrene price, ABS cost increased faster than BioABS. For every cent increase in Styrene price, the cost increases by 0.4745% for ABS and 0.1226% for BioABS. When Styrene price increases by 12.51%, ABS cost is equal to BioABS cost. When Styrene price is lower than \$1720.63/t, the production cost of BioABS is higher than ABS. When Styrene price is higher than \$1720.63/t, the situation is opposite.

Figure 4.3 shows the changes in production cost for ABS and BioABS as Propylene price changes while keeping all other variables' value constant. For every cent increase in Propylene price, the cost increases by 0.2135% for ABS and 0.055% for BioABS. When Propylene price rises by 27.78% and reaches \$1777.16/t, BioABS production cost is equal to ABS. If Propylene price continues to grow, BioABS cost will be lower than ABS.

Figure 4. 3 Changes in production cost as Propylene price changes

Figure 4. 4 Changes in production cost as C₄ price changes

Figure 4.4 shows the changes in production cost for ABS and BioABS as C₄ price changes while keeping all other variables the same. The changes in C₄ price influence on ABS more than BioABS. When C₄ price grows 1%, ABS and BioABS breakeven price grows 0.2312% and

0.0595% respectively. The cost of production of BioABS is lower than ABS only when C_4 price is higher than \$2575.53/t. It is at least 25.64% more than the current price.

Figure 4. 5 Change in production cost as Ammonia price changes

Figure 4.5 shows the changes in production cost for ABS and BioABS as Ammonia price changes while all other variables not changing. ABS and BioABS production cost both increase with Ammonia price rising. For every cent increase in Ammonia price, the cost grows by 0.0469% for ABS and 0.0123% for BioABS. With the increase of Ammonia price, the difference between ABS and BioABS cost is smaller. Until Ammonia price rises to \$1715.37/t, about two times as the current price, ABS and BioABS cost is the same. Then if Ammonia price continues to grow, ABS cost will higher and higher than BioABS.

For electricity, fuel oil, natural gas and steam, their increase all makes ABS and BioABS production cost grow, but not significantly. ABS will rise by 0.024%, 0.0043%, 0.0007% and 0.0049%, respectively. The effect is less on BioABS. BioABS will rise by 0.0062%, 0.0011%, 0.0002% and 0.0013% %, respectively. In terms of only one input, if ABS cost equals to BioABS,

electricity price needs to increase by 347.33%, fuel oil price needs to rise by 1373.06%, natural gas price needs to go up by 8570.36%, and steam price needs to rises by 1207.96%.

4.2.3 Advanced Analysis

In this part, @RISK is used to do advanced analysis. @RISK is an add-in to Microsoft Excel for analyzing risk and uncertainty. It mathematically and objectively computes and tracks many different possible future scenarios, then shows the probabilities and risks associated with each different one(54).

4.2.3.1 Input Analysis

@RISK's distribution fitting tool can be used to suggest good fits to the data. Figure 4.6-4.15 represent best-fitting distributions to these input prices.

For Styrene price (Figure 4.6), the actual minimum, maximum, mean, standard deviation is 1227.5, 1752, 1529.32 and 146.27, respectively. Uniform distribution with parameters 1217.01 (minimum value) and 1762.49 (maximum value) is the best-fitting. Its mean value is 1489.75 and standard deviation is 157.47.

Figure 4. 6 Fit comparison for Styrene price

Figure 4.7 shows Propylene actual price minimum, maximum, mean, standard deviation being 1021.02, 2094.39, 1390.74 and 247.77 respectively. The best-fitting distribution is Pert distribution with parameters 1014.3 (minimum), 1200.1, and 2487.8(maximum). Its mean value is 1383.75 and standard deviation is 241.39.

Figure 4. 7 Fit comparison for Propylene price

Figure 4.8 indicates C₄ actual price minimum, maximum, mean, standard deviation being 1619, 2673, 2029.87 and 278.48 respectively. Figure 4.9 shows Ammonia actual price minimum, maximum, mean, standard deviation being 485, 899, 754, and 156.69 respectively. ExtValue distribution fits best for C₄ and ExtValueMin distribution fits best for Ammonia. The former parameters are 1905.34 and 216.24, respectively, and the latter are 818.57 and 101.87 each. The former mean and standard deviation is 2030.16 and 277.34; the latter is 759.77 and 130.65.

Figure 4. 8 Fit comparison for C₄ price

Figure 4. 9 Fit comparison for Ammonia price

When considering the energy, electricity price (Figure 4.10) implies minimum, maximum, mean, standard deviation being 12.61, 36.97, 22.89 and 6.79, respectively. The best-fitting distribution is ExtValue distribution with parameters 19.78 and 5.65. Its mean value is 23.04 and standard deviation is 7.24.

Figure 4. 10 Fit comparison for Electricity price

Source: Comparison of Electricity Prices in Major North American Cities, 2014(55)

For fuel oil price (Figure 4.11), the actual price minimum, maximum, mean, standard deviation is 13.47, 17.49, 15.35 and 1.37, respectively. Uniform distribution with parameters 13.10 (minimum value) and 17.86 (maximum value) fits best. Its mean value is 15.48 and standard deviation is 1.37.

Figure 4. 11 Fit comparison for Fuel Oil price

Figure 4.12 provides natural gas actual price minimum, maximum, mean, standard deviation being 1.57, 5.24, 3.24 and 0.81 respectively. The best-fitting distribution is Logistic distribution with parameters 3.25 (mean value) and 0.43. Its standard deviation is 0.78.

Figure 4. 12 Fit comparison for Natural Gas price

Figure 4.13 represents steam price distribution. It is assumed that steam price will be within a min-max range, and that Uniform distribution is applicable to describe the possible price of steam. As mentioned above, the mean price is \$7.45/GJ(51). The minimum is assumed 10% lower (6.71) and the maximum is assumed 10% upper (8.20). Its mean standard deviation is 0.43.

Figure 4.14 shows PLA price distribution. PLA most likely price is \$2200/t(56). It minimum price is \$1980/t(52) and its maximum price is \$2640/t(57). It is assumed that Pert distribution is applicable to describe the possible PLA price. Its mean value is 2236.67 and standard deviation is 121.61.

Figure 4. 13 Uniform distribution for Steam price

Figure 4. 14 Pert distribution for PLA price

For soy hull price (Figure 4.15), the actual price minimum, maximum, mean, standard deviation is 85.43, 238.43, 129.61 and 36.05. Pert distribution with parameters 85.43 (minimum value), 85.43 and 342.56 (maximum value) fits best. Its mean value is 128.28 and standard deviation is 36.22

Figure 4. 15 Fit comparison for Soy Hull price

Source: U.S. Census Bureau, Oilseed Crushings and USDA, Agricultural Marketing Service, National Monthly Feedstuff Prices, 2012(58)

Table 4. 3 Summary of input price distribution

Input	Mean Value (P_i)	Price Distribution
Styrene	1489.75	Uniform
Propylene	1383.75	Pert
C ₄	2030.16	ExtValue
Ammonia	759.77	ExtValueMin
Electricity	23.04	ExtValue
Fuel oil	15.48	Uniform
Natural gas	3.26	Logistic
Steam	7.45	Uniform (assumed)
PLA	2236.67	Pert (assumed)
Soy Hull	128.28	Pert

Table 4.3 shows the summary of input price distribution. The mean value of every price is different from actual average price (Table 3.6)

4.2.3.2 Output Analysis

Table 4.4 indicates input costs and total costs of ABS and BioABS by using @RISK. The input prices are mean values of every distribution mentioned above. The BioABS total cost is 6% higher than ABS cost.

Table 4. 4 Input costs and total costs for producing one ton of ABS and BioABS@RISK

Input	ABS Input Cost(\$)	BioABS Input Cost(\$)
Styrene	840.22	226.44
Propylene	386.07	103.78
C ₄	416.18	111.66
Ammonia	85.85	23.55
Electricity	46.08	12.44
Fuel oil	7.74	2.09
Natural gas	1.30	0.35
Steam	8.94	2.41
PLA	n.a.	1409.10
Soy Hull	n.a.	12.83
Total Cost (\$)	1792.38	1904.66

Table 4. 5 Summary statistics for ABS total cost

Statistics		Percentile	
Minimum	1383.74	5%	1591.17
Maximum	2605.65	10%	1628.26
Mean	1792.38	15%	1655.88
Std Dev	126.79	20%	1679.40
Variance	16076.831	25%	1700.38
Skewness	0.2168104	30%	1719.85
Kurtosis	2.8215487	35%	1738.24
Median	1789.34	40%	1755.70
Mode	1780.99	45%	1772.69
Left X	1591.17	50%	1789.34
Left P	5%	55%	1806.05
Right X	2006.90	60%	1823.02
Right P	95%	65%	1840.33
Diff X	415.73	70%	1858.62
Diff P	90%	75%	1878.25
#Errors	0	80%	1900.02
Filter Min	Off	85%	1925.68
Filter	Off	90%	1958.09
Max			
#Filtered	0	95%	2006.90

Figure 4. 16 Fit comparison for ABS total cost

According to Table 4.5 and Figure 4.16, ABS total cost actual minimum, maximum, mean, standard deviation is 1383.74, 2605.65, 1792.38 and 126.79 respectively. The best-fitting distribution is BetaGeneral distribution with parameters 7.52, 13.98, 1350.90 (minimum), and 2613.10(maximum). Its mean value is 1792.34 while standard deviation is 126.90. There is 90% for ABS total cost being between \$1591/t and \$2007/t.

Table 4. 6 Change in output statistic for ABS total cost

Rank	Name	Lower	Upper
1	Styrene	1654.40	1930.98
2	Propylene	1704.00	1928.89
3	C4(butadiene)	1715.38	1912.36
4	Ammonia	1761.10	1812.85
5	Electricity	1772.42	1822.83
6	Fuel Oil	1790.90	1793.48
7	Steam	1791.56	1793.11
8	Natural Gas	1791.86	1792.68

Figure 4. 17 Inputs ranked by effect on ABS total cost mean value

Table 4.6 and Figure 4.17 show that how input prices change ABS total cost mean value and the range of changes. Styrene price has the most effect on ABS mean cost, and it can cause ABS mean cost changes from 1654.40 to 1930.98. Second rank is Propylene price, which makes range between 1704 and 1928.89. The following is C₄, Ammonia, and Electricity with range being 1715.38-1912.36, 1761.10-1812.85, and 1772.42-1822.83. The prices of fuel oil, steam and natural gas have slightly impact on ABS mean cost. According to Table 4.2, when ABS cost is

the same with BioABS cost because of one input price changing, the cost is \$1926/t. The range of cost changes caused by Styrene or Propylene covers the value (\$1926/t), so through Styrene or Propylene price fluctuating, the production cost of ABS can reach the same value. For C₄ or Ammonia, it is impossible to lead ABS cost and BioABS cost the same.

Table 4.7 and Figure 4.18 indicate the summary of BioABS total cost distribution. The actual cost minimum, maximum, mean, standard deviation is 1658.03, 2258.28, 1904.66 and 84 respectively. The best-fitting distribution is BetaGeneral distribution with parameters 4.92, 7.76, 1657.88 (minimum), and 2293.76(maximum). Its mean value is 1904.71 and standard deviation is 83.77. There is 90% for BioABS total cost being between \$1775/t and \$2050/t.

Table 4. 7 Summary statistics for BioABS total cost

Statistics		Percentile	
Minimum	1658.03	5%	1774.78
Maximum	2258.28	10%	1797.74
Mean	1904.66	15%	1814.84
Std Dev	84.00	20%	1829.34
Variance	7055.3295	25%	1842.31
Skewness	0.2441186	30%	1854.47
Kurtosis	2.6173481	35%	1866.11
Median	1900.02	40%	1877.52
Mode	1885.46	45%	1888.80
Left X	1774.78	50%	1900.02
Left P	5%	55%	1911.44
Right X	2050.13	60%	1923.23
Right P	95%	65%	1935.58
Diff X	275.35	70%	1948.71
Diff P	90%	75%	1962.83
#Errors	0	80%	1978.54
Filter Min	Off	85%	1996.41
Filter	Off	90%	2018.55
Max			
#Filtered	0	95%	2050.13

Figure 4. 18 Fit comparison for BioABS total cost

From Table 4.8 and Figure 4.19, PLA price places the most important role on BioABS total cost mean value. BioABS mean cost change range is from 1658.03 to 2258.28. The second and third rank is Styrene and Propylene, which could cause scope between 1867.24 and 1942.19, between 1880.51 and 1941.35, respectively. The following is C₄, Ammonia, electricity and soy hull with range being 1883.83-1937.02, 1895.95-1910.18, 1899.52-1912.51, and 1901.00-1912.94. The last three ranks are fuel oil, natural gas and steam price. They almost have no effect on BioABS mean cost.

Table 4. 8 Change in output statistic for BioABS total cost

Rank	Name	Lower	Upper
1	PLA	1785.99	2045.69
2	Styrene	1867.24	1942.19
3	Propylene	1880.51	1941.35
4	C ₄ (butadiene)	1883.83	1937.02
5	Ammonia	1895.95	1910.18
6	Electricity	1899.52	1912.51
7	Soy Hull	1901.00	1912.94
8	Fuel Oil	1904.02	1905.13
9	Natural Gas	1904.09	1905.10
10	Steam	1904.39	1905.07

Figure 4. 19 Inputs ranked by effect on BioABS total cost mean value

Figure 4. 20 Fit comparison for ABS market price

ABS market price distribution can be seen from Figure 4.20. The actual minimum, maximum, mean, standard deviation is 1647, 2187, 1976.63, and 119.22. Logistic distribution with parameters 1978.30 (mean value) and 63.12 fits best. Its standard deviation is 114.49. There is 90% for ABS market price being between \$1823/t and \$2187/t. In terms of Table 4.2, when PLA falls to \$2074.87/t, ABS and BioABS production costs are the same (\$1817.72/t). It can be seen from Table 4.2 that it is possible for ABS and BioABS reach the same cost by dropping PLA price. It is also possible for Styrene and Propylene to make BioABS having the same cost with ABS. C₄ can cause BioABS cost \$1926/t; however, it cannot cause ABS cost to reach that value, so there is no opportunity for the two composites to have the same cost by C₄.

Compared with Table 4.4, ABS market mean price (\$1976.63/t) is higher than both ABS mean cost (\$1792.38/t) and BioABS mean cost (\$1904.66/t). BioABS can be commercially feasible and compete with ABS if there is a small market premium for this green bio-product.

Figure 4.21 indicates the comparison between BioABS cost and ABS cost. The red one represents ABS total cost distribution and the blue one shows BioABS total cost distribution.

BioABS standard deviation is smaller than ABS, so BioABS cost distribution is more centralized than ABS cost distribution.

Figure 4. 21 Comparison between BioABS cost and ABS cost

Figure 4. 22 Difference between BioABS cost and ABS cost

Figure 4.22 provides the difference between BioABS cost and ABS cost ($Cost_B - Cost_A$). The minimum, maximum, mean, standard deviation is -478.90, 578.08, 112.45 and 120.45, respectively. The positive value means that BioABS cost is higher than ABS cost, accounting 82.1%. On the contrary, the negative value represents BioABS costs less than ABS. There is 90% for the difference in the range from -86 to 311.

Figure 4. 23 Influence of percentage change in input prices on the difference in variable costs between BioABS and ABS

In Figure 4.23, the steeper the curve is, the more important role the input has. PLA has the biggest effect on the cost difference, followed by Styrene, Propylene, C₄ and Ammonia. Other inputs (electricity, soy hull, fuel oil, steam and natural gas) have very small impact. The slope of PLA is positive, which means BioABS cost rises faster than ABS when PLA price goes up, so cost difference between traditional and bio-based method will rise. For Styrene, Propylene, C₄ and Ammonia, the difference will decrease if the input price declines, as the slope of curves is negative. When PLA price drops about 6% (Table 4.2), cost of ABS and BioABS is the same and the difference is zero. When PLA price goes down by more than 6%, BioABS costs less than ABS, and people will switch over to the bio-based materials.

Chapter 5: Conclusions

5.1 Introduction

The purpose of this study was to assess the financial feasibility of composites made from engineered soy hull and BioABS for automotive applications, relative to the petroleum-based composites. It was completed through the use of technical cost model and sensitivity analysis. Results were presented in Chapter 4. This chapter brings all aspects together to provide a conclusion to this study.

5.2 Summary

The global annual production of plastics has a continuous growth from 1.7 million tons in 1950 to 288 million tons in 2012(59). Traditional plastic is derived of petroleum. It is widely used for consumer goods production, mainly for its good wide range of properties, easy and cheap to produce. However, on the environmental point, petroleum-based plastics pose some problems. Climate change, a consequence of greenhouse gas emission mainly from fossil fuel combustion, has become seriously environmental issue. Landfill is the other concern. The total amount of plastics sending to landfill in Canada and the US every year equates to about 1.6 million tons(60). Since petroleum is non-renewable resource, there are concerns about the sustainability of its use. With the resource becoming scarcer, the fossil fuel price will increase and it will raise petroleum-based plastics price as well. As a result, for the aforementioned environmental and financial reasons, there is an increasing interest in seeking lower cost, green materials to replace these existing products.

Acrylonitrile butadiene styrene (ABS) is a petroleum-based plastic and widely used in automotive sector. It can be produced out using a liquid phase, suspension or emulsion process. In this paper, emulsion polymerisation is chosen as production process and the share of acrylonitrile, butadiene, styrene is 25%, 20%, 55%, respectively(32). In order to get finished applications, such as instrument panels, wheel covers, and leaf springs, ABS then needs four steps in the processing: drying, extrusion, drying and injection molding.

The world's automobile plastics demand is predicted to increase at an estimated CAGR (Compound Annual Growth Rate) of 8.5% from 6.7 million tons in 2011 to 10.2 million tons in 2016. Among all the automotive plastics, polypropylene accounts 36%, followed by polyurethanes (17%), ABS (12%), composites (11%), HDPE (10%), polycarbonates (7%), and PMMA (7%)(61).

The global consumption for ABS has been steadily growing over the last 10 years. In 2000, global ABS demand hit 4560559 tons, and went up to 6381746 tons in 2010. Growth is focused on Asia Pacific region, where production capacity has expanded significantly according to strong demand. China is estimated to keep the largest ABS regional market and is expected to make up approximately 61% of the global demand by 2018. To enjoy the advantage of low labor and operating costs, many multinational manufacturing companies shift their manufacturing units to China. China also is the largest automotive manufacturing nation and demands huge volumes of plastics, of which ABS is an essential part. Household appliances (38%), electrical and electronics (24%), and the automotive sectors (14%) were the leading segments for world's ABS consumption in 2010. Global ABS demand is predicted to increase 10909987 tons in 2020 at an estimated CAGR of 5.5%(62).

BioABS is a bio-based replacement for ABS. It is made by blending ABS with PLA and soybean hulls. Polylactide or polylactic acid (PLA) is a biodegradable plastic derived from 100% renewable resources like corn, sugar beets or rice. BioABS processing is similar with ABS. The machines they use are the same. When producing BioABS, soy hull is 10% by weight, and ABS : PLA is 30:70(34).

Technical cost modelling is chosen in this paper to estimate ABS and BioABS production cost. It is based on an activity based costing (ABC) approach, but use engineering, technical and economic characteristics associated with each manufacturing activity to evaluate its cost.

After calculation, ABS production cost is \$1817.72/t and BioABS is \$1896.55/t. BioABS production cost is roughly 4% higher than ABS. ABS average market price in last two years is \$1976.6/t (Figure 4.1), higher than BioABS cost. BioABS can be commercially feasible and compete with ABS if there is a small market premium for this green bio-product.

Raw materials account large part of the total cost, more than 96%. The prices of raw materials have significant influence on the production cost. For ABS, styrene has the biggest impact on production cost. For BioABS, PLA has the biggest influence. When PLA price is reduced by 5.69% (\$2074.87/t), the cost of BioABS and ABS is the same.

With the increase of styrene, propylene, C₄, and ammonia price, ABS cost increased faster than BioABS. On the other hand, electricity, fuel oil, natural gas and steam prices change have not significant influence on ABS and BioABS cost.

When using @RISK to analysis, the input prices are the mean values of every input distribution. They are different from actual average prices. The BetaGeneral distribution fits best for both

ABS total cost and BioABS total cost. The mean value of ABS total cost and BioABS total cost is 1792.38 and 1904.66. BioABS mean cost is slightly higher than ABS (about 6%). ABS market price best-fitting distribution is Logistic distribution. Its mean value is 1978.30, which is higher than both ABS mean cost and BioABS mean cost. As a result, BioABS can be commercially feasible and compete with ABS if there is a small market premium for this green bio-product. When considering input price distributions, Styrene has the biggest impact on ABS production cost, and PLA has the biggest influence on BioABS. It is the same as the situation with considering actual average input prices.

Comparing BioABS and ABS cost with uncertainty, it is 82% possibility that BioABS costs more than ABS. When PLA price increases, cost difference will become bigger. However, when Styrene, Propylene, C₄ and Ammonia price rises, cost difference will drop, on the contrary.

BioABS profit is above zero, but less than ABS profit. When PLA price falls more than 6% or Styrene price increases by 12.5% (Table 4.2), BioABS cost will be less than ABS cost, and the bio-based plastic profit will be higher than the petroleum-based plastic. In that case, people will switch over from traditional method to bio-based method.

The US produces the greatest amount of soybeans in the world, about one third soybean global production. Other large producers include Brazil, Argentina, China, India, Paraguay, and Canada. Within North America, soybean production is centered around the Great Lakes region, which also has major automakers and auto parts suppliers(10). When soybean hull can be used to produce polymers for auto components, value addition to the agricultural processing residue will provide economic sustainability to the agricultural commodity group as well as the industries.

5.3 Limitations and Suggestions for Further Research

Geographic sector is not considered in this study. Prices of input could be different a lot in different regions. Steam and PLA price distributions are assumed. The assumed distributions may be not applicable to actual situations. Transportation fee would have an impact on ABS and BioABS input cost. Additionally, labor and capital cost was not included when calculating due to lack of information. With technical development, ABS and BioABS production methods will change, which would affect production cost significantly. This thesis was conducted based on ABS and BioABS data from literature, the same study should be done when updated data becomes available.

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