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A COMPARATIVE LIFE CYCLE ASSESSMENT:
POLYETHYLENE AND STARCH FOAMS

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CHISA KANDYDA BROOKES

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Ramani Narayan.

Major Professor's Signature

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A COMPARATIVE LIFE CYCLE ASSESSMENT: POLYETHYLENE AND STARCH FOAMS

By

CHISA KANDYDA BROOKES

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ABSTRACT

A COMPARATIVE LIFE CYCLE ASSESSMENT: POLYETHYLENE AND STARCH FOAMS

By

Chisa Kandyda Brookes

Recent federal initiatives to support biomass R&D suggest the importance of having viable alternatives to foreign oil be economically and environmentally attractive. This thesis explores the environmental value of the bio-based starch foam and the petrochemical-based PE foam via a comparative LCA while constructively commenting on the methodological approach. This study follows the methodology outlined in the ISO 14040 standards. Data and models are gathered directly from or from collaborations between Argonne, Cargill Dow, US EPA, NIST, and more. Eight impact categories are covered, each normalized to the associated U.S. normalization value. The total energy required for producing 17,000 ft^3 of PE and starch foam are 1.1E6 MJ and 1.02E5 MJ respectively. This makes PE foam production an energy intensive process and, with high energy prices, starch foams may be economically attractive. The impact assessment results reveal PE foam to have the greatest domination with the ozone and global warming potentials by being almost five times greater than the associated starch value and being the only contributor, respectively. Starch foam dominates one of the seven impact categories—the eutrophication potential—and only by 19%. From the results, areas of improvement have been identified. Unfortunately, data is a limiting factor and should be taken into consideration when reviewing the results. This study not only provides a numerical record of a bio-based and petrochemical-based product, but it discloses LCA as a viable benchmarking tool and as a guide for improving processes, while providing constructive recommendations for future life cycle assessments.

To God and to my parents, my sisters, brother and, my island—St. Croix USVI

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Chapter 1: Introduction

Finding alternatives to non-renewable natural resources has been an ongoing effort to better the world's environmental position. The Kyoto Protocol [1], a world attempt to address concerns about the environment, has committed countries into decreasing greenhouse gases that contribute to climate change. The burning of fuel and coal, and the production of electricity, all contribute significantly to the production of some greenhouse gases. To reduce the greenhouses gases from these non-renewable resources, renewable resources are being sought, and products, processes and technologies are being developed to incorporate these renewable resources. In particular, the United States is keenly aware of its undeniable reliance on foreign oil. Thus, there are federal initiatives to support biomass research and development. In a recent paper published by the *Journal of Industrial Ecology*, Duncan mentions the enactment of Title III of the Agricultural Risk Protection Act (Public Law 106-224), the Biomass Research and Development Act of 2000 [2]. This act is in place to increase coordination across departments in the federal government in relation to biomass research and development [2]. This effort is encouraging the effort to convert biomass into bio-based products.

Bio-based materials are made from annually renewable biomass such as corn, wheat and potatoes, and have been made as an alternative to some petrochemical-based materials. Plastics are one area in which bio-based materials are now being used as an alternative. Specifically, for polyethylene (PE) foams, which are used in sporting products, building products and in packaging, there is now an alternative. Starch foams made from corn can be used in building products and in packaging and have also been the material used to make innovative toy products [3]. Although starch foams seem to be more environmentally friendly, as an alternative it is still necessary to evaluate the environmental footprint of each product. Evaluating the environmental footprint entails the investigation of the impact left on the environment as a result of that product.

A tool used to quantify the environmental impact of a product is Life Cycle Assessment (LCA). LCA takes into account the inputs and outputs of a product, then classifies and converts harmful emissions into impacts such as global warming, ozone depletion and acidification. While it is important to explore the economical, social and environmental aspects of a product to determine the holistic contribution of that product, LCA focuses mainly on the environmental impact of the product.

This research intends to quantify and compare the environmental impacts of both bio-based and petrochemical-based foams via life cycle assessment. Foam is chosen as a result of great progress made to utilize foam made from both biomass and fossil fuels in the same capacity. Most importantly, this work intends to increase the understanding of, and critique the use of life cycle assessment as a tool to quantify product environmental impacts. This research allows for the creating of a numerical-based record of continuous progress towards a cleaner environment, and it highlightss areas of improvement for both foam production processes.

Chapter 2: Background and Literature Review

The use of more renewable resources to create products (corn to produce foam) is supported by sustainable carbon cycling, which is explained in a Global Carbon Cycling diagram from Narayan [4]. The diagram depicts the CO_2 cycle as it relates to fossil fuel dependant plastics and as it relates to biomass dependant plastics. On an annual basis, for both the fossil fuel and biomass dependant plastics, CO_2 is consumed by biomass and bio-organics. After many years, (on the order of 10^6) fossil resources are generated below the earth's surface. Fossil fuel is then extracted, refined and sold as fuel or feedstock to distributors or chemical and polymer plants. For biomass dependant products, the biomass is used directly in the bio-chemical industry to be used in the production of fuels, chemicals and polymers, without the long time period of 10^6 years. Over about one to 10 years, the CO_2 from both fossil fuel and biomass products is released into the atmosphere.

As discussed by Narayan, the rate at which the CO_2 is being dispensed from the processed products is not balanced with the rate of CO_2 consumption for fossil fuel formation [4]. Narayan also explains that the rate at which CO_2 is dispensed can be balanced by the rate at which CO_2 is consumed by ensuring that more biomass is planted to use the released CO_2 [4]. The fossil fuel route is limited in that the resource is not being generated as fast as it is being consumed.

Although a fossil fuel route is limited in that it will eventually be consumed faster than it is generated, fossil fuel is still the main source for making many products including polyethylene foams. Jimenez-Gonzalez mentions that life cycle inventory from the refinery, is ubiquitously included in "virtually all life cycle studies" [5]. While many products utilizing renewable resources are still in the development stage, starch foams have moved towards commercialization [3]. However, starch foams still depend on fossil fuels indirectly through transportation needs among others and sometimes even directly by using fossil based products as fillers or additives. Thus, some life cycle inventory non-renewable inputs, such as diesel oil, must be taken into consideration for starch foams.

Both old and new products (e.i. polyethylene foam and starch foams) are being studied to understand each product's environmental impact. Bousted produced much of the preliminary work of LCA's by completing life cycle inventories or eco-profiles of almost 50 plastics, polymers and chemicals combined [6-7]. Much of his work is used as a reference, if not embedded, in preliminary portions of many LCA's. For example, the Cargill Dow study on polylactide production uses the methodology, software and core databases of the Bousted Consulting organization [8] to show a life cycle assessment of a relatively new bio-based product.

Cargill Dow focuses on a triple bottom line, which amounts to making economically, socially and environmentally beneficial products [8]. The company is lead by this triple bottom line—incorporating economic, environmental and social sustainability. In attempting to meet all of these criteria, the company also strives to make a product that is comparable if not superior to its petrochemical counterparts. A study of polylactide (PLA) using life cycle assessment was used to benchmark PLA, the new bio-based product, to the existing petrochemical polymers [8].

The relation between fossil energy use and global climate change for the new bio-based product is of key interest in the Cargill Dow study compared to the results from petrochemical polymers. Comparing engineering estimates of PLA production fossil energy requirements to that of several other petroleum-based polymers, PLA production uses 25-55% less fossil energy than that of the petroleum-based products [8]. More specifically, the estimated fossil energy use of PLA production is 25% less than that of the fossil energy use for LDPE [8]. In future studies, Cargill Dow intends to move from a corn-based feedstock production run to a corn residue-based feedstock production run that utilizes wind power to replace electricity inputs. The impact in relation to energy use is a reduction of 90% when compared to petroleum-based polymers [8].

The life cycle assessment study of PLA by Cargill Dow also considered the global warming impact of both PLA and other petrochemical polymers. The study revealed that with the engineering estimates using corn as a feedstock there is a "substantial advantage over most polymers" and that the bio-based product is "comparable to several others" [8]. In terms of the PLA relation to LDPE, although there was slightly more methane production from PLA, the overall global warming effect was still greater for LDPE than for PLA. For the case where corn residue is used as the feedstock and wind power replaces electricity inputs, there are actually "greenhouse benefits" [8]. The greenhouse gases are negative (due to CO_2 absorption by plants) when looking at the cradle-to-gate life cycle.

The Cargill Dow study is one of the few, but not the only comparative study on bio-based and petrochemical-based products. The LCA of biofibers versus glassfibers for plastic reinforcements was another comparative study completed by Gfeller B. Laban and others [9]. This study was more comprehensive than the Cargill Dow study considering the clearly outlined format of the report according to ISO 14040 standards, the number of impacts covered, the cradle-to-grave life cycle with incineration as the end-point conducted, and the alternative disposal methods examined.

The results in regards to energy use for the china reed fibers (biofibers) versus the glass fibers showed that china reed fiber uses significantly less energy than does the glass fibers. For both fibers, polypropylene (PP) production is where the most energy is required. The china reed uses less energy for PP production because there is more china reed and less PP used in the china reed pallets [9]. This reduction in PP also accounts for the reduction in weight of the pallet and thus a slightly lower fuel use requirement [9]. Also, the study shows that the production for china reed fibers uses far less energy than the production of glass fibers. All these factors account for the lower energy use found with china reed versus glass fiber pallets.

There are eight impacts associated with the cradle-to-grave study concerning china reed and glass fiber reinforced pallets. For the reference study, of the eight impacts, eutrophication was the only one in which the glass fibers outperformed the china reed fibers. The greenhouse and ozone gases were higher for the glass fibers along with the other six impact categories. For the study considering bioactive discharge instead of incineration, the bioactive discharge pollutants far outweigh the incineration pollutants, making incineration the better alternative of the two.

Martin Patel offers significant conclusions in his review of twenty life cycle assessments, seven of which were in regards to starch polymer pellets and some starch products such as films and loose fills [10]. For starch polymer pellets, the scores are all better when compared to polyethylene pellets except in the case of eutrophication. Patel mentioned that energy requirements for starch polymer pellets were 25 – 75% less than the energy requirements for polyethylene polymer pellets and that the emissions related to green house gases were 20 – 80% less as well. The ranges were as a result of differing starch and copolymer blends [10].

Similar to the aforementioned LCA's, starch and polyethylene foams will be assessed to understand their individual environmental impact and to understand how they compare to one another. This LCA will allow for a segmental understanding of each production process, identifying areas that need improvement or need to be studied further in order to model other segments.

Chapter 3: Methodology

The methodology used to complete this study came from the framework developed by the International Organization for Standardization 14040 series [11 – 14]. Under this framework, a goal and a scope is formulated, an inventory of the inputs and outputs for the process or product being studied is compiled, the outputs of the inventory phase are related to impact categories and the interpretation phase discusses the results and conclusions along with providing recommendations. The phases are shown in Figure 1 and a more detailed overview of the LCA process can be found in Appendix A along with a developed environmental decision model, which incorporates the LCA methodology.

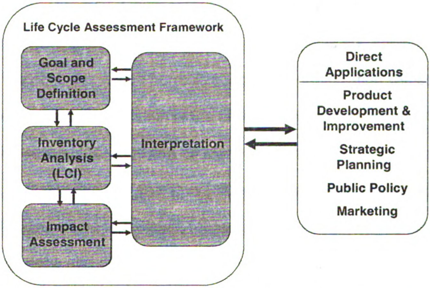


Figure 1. Phases of a Life Cycle Assessment as demonstrated in ISO 14040

The impact assessment phase calculations are governed by the equation below.

$$\sum_i m_i \times XP_i = XPindex$$

In the equation above, i represents each emission in a specific impact, m is the mass of emission i, XP is the impact potential characterization factor that relates the emission, i to the impact X, XPindex is the total impact potential index. The characterization factors XPi are numbers that give the emission's potential value regarding a certain impact. These factors are compiled in the technical manual and user guide for Building for Environmental and Economic Sustainability (BEES) [15]. Once the impact potential index is calculated, it is normalized by values supplied by *The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts* (TRACI) developed by U.S. Environmental Protection Agency [16]. One important factor is that BEES was developed with support from the U.S. EPA Office of Pollution Prevention and Toxics. Thus, the impact assessment results will be specific to U.S. impacts and impact factors. Also, each impact index will be normalized to U.S. normalization values. A simple example for the calculation of the Global Warming Impact and its normalization to the U.S. value can be found in Appendix B.

The format of this document will follow the framework developed by ISO. A goal and scope will be formulated, followed by inventory then impact assessment review and discussion. Finally a conclusion will be made along with recommendations under interpretation. The references and appendices will follow and conclude the document.

Chapter 4: Goal Formulation and Scope of Study

There are many products and processes whose environmental impact can be studied to help improve the product or process' impact on earth; one such product is foam. Foam is a product commonly produced from a petrochemical based feedstock. Thus, some of the emissions associated with extracting and processing crude will be included in the environmental impact of petrochemical-based foams. Similarly with corn-based foams, included in its environmental assessment would be the emissions associated with corn cultivation and processing. Comparing the environmental footprints of these two types of foam will lead to an understanding of how we can improve the impact of foam on the environment and it will provide numerical evidence for the ongoing discussion regarding environmental contributions of petroleum-based products versus other products.

4.1 Goal

The goal of this research is to improve our understanding of the environmental impact of foam produced from two different feedstock sources via conducting a comparative assessment. The objectives for study includes the following:

(1) To perform a comparative life cycle assessment

(2) To compare a petrochemical-based foam to an agricultural-based foam

(3) To examine the methodology of the ISO standards on performing an LCA

This LCA is intended to support the petrochemical and bio-based product producers to further examine various improvement opportunities. This study is also intended for LCA practitioners.

4.2 Scope

The scope of this study entails the consideration of several components as mentioned in the ISO 14040 series [11]. Figure 2 shows the progression towards completing the scope of the study and it also shows the relationship of the scope components to three phases of life cycle assessment.

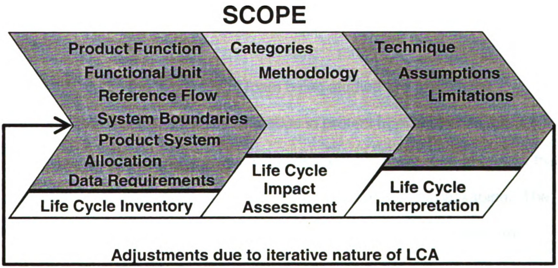


Figure 2. Scope components related to other phases in the LCA methodology

The intent of the scope section is to envision the how the LCA will be performed. The scope adds structure to the overall process and is subject to revision during the actual process of the LCA. In Figure 2 many components are listed for each phase (other than the Goal & Scope phase) in an LCA. This comparative LCA will attempt to cover the scope thoroughly, providing insight to future work on polyethylene and starch foams.

4.2.1 Product Characterization

Foam has many uses in various areas. Some areas where foams are used include agriculture for padding animals to prevent bruising, athletics for equipment such as wall padding in wrestling, construction for insulation or sound absorption purposes and packaging for protection of goods. Low-density polyethylene foam used for packaging goods is used primarily for surface protection among other things. Starch foam is successfully used in the toy and packaging industry.

In this study, the two types of foam being studied are used in the packaging of electronics, specifically laptops to protect from scratches and for light cushioning. This study only takes into account the foam used to protect the surface of the laptop, and does not take into account any other packaging. The Dell Inspiron 8600 is used as the model laptop with the following weight and dimensions given in Table 1. With the dimensions in Table 1, the amount of foam (ft^3) needed to cover a number of laptops and the weight of the foam covering (kg) can be calculated. Thus a functional unit can be developed. An approximate value of the dimensions is given to account for some give within the sleeve used to cover the laptop.

Weight	Travel Module & Battery	6.9 lbs	**Approximate dimensions**
	Cd Drive & Battery	7.2 lbs	
Dimensions	Height	1.52 in.	3 in. = 0.25 ft
	Width	14.22 in.	16 in. = 1.33 ft
	Depth	10.87 in	12 in. = 1 ft.

Table 1. Specifications for model laptop used in study

4.2.2 Functional unit development

The functional unit for this study of petrochemical and bio-based foams is to supply the foam packaging needed to pack 50,000 laptops with the specific laptop dimensions given earlier. The amount of material needed to cover the 50,000 laptops is shown in Table 2 for an optimal density of 0.85 kg/ft^3 [17].

Foam (ft^3)	~ 17000
Polyethylene and Starch (kg)	~ 14450

Table 2. Material and Foam requirements

The amounts shown in Table 2 show the functional flows of the system. The seventeen thousand ft^3 of foam is the main reference flow.

A summary of the development of the functional unit and reference is shown in Figure 3 as performed in ISO 14049 [14]. The product being studied is identified along with examples of the various functions that are associated with that product. The function of surface protection is chosen. The actual function identified is to protect the surface of laptops in packaging. To quantify the

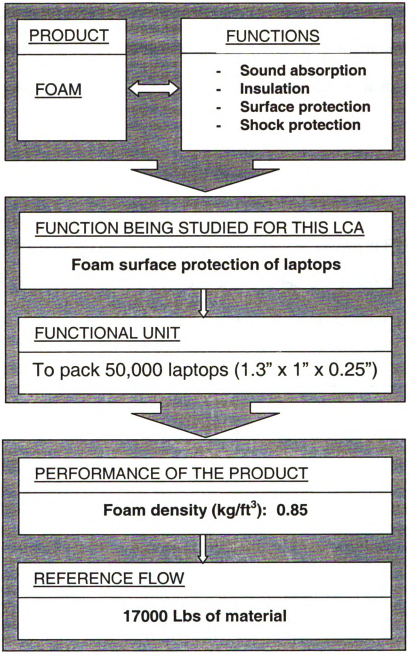


Figure 3. ISO format for functional unit and reference flow development

function, the functional unit is developed. The functional unit is to supply the foam needed to package 50,000 laptops with the dimensions given (1.3' x 1' x 0.25'). With the functional unit developed a standard measurement or performance is given to determine the reference flow. Thus, with a foam density of 0.85 kg/ft^3, the reference flow would be 17,000 ft^3 of foam, which is approximately how much foam is needed to cover 50,000 laptops.

4.2.3 Product Systems & Boundary Identifications

A. Polyethylene system

The whole life cycle of foam is delineated as shown in Figure 4. Figure 4 includes the production, use and disposal phase encompassing an entire life cycle. The actual portion of the cycle being studied will be shown later.

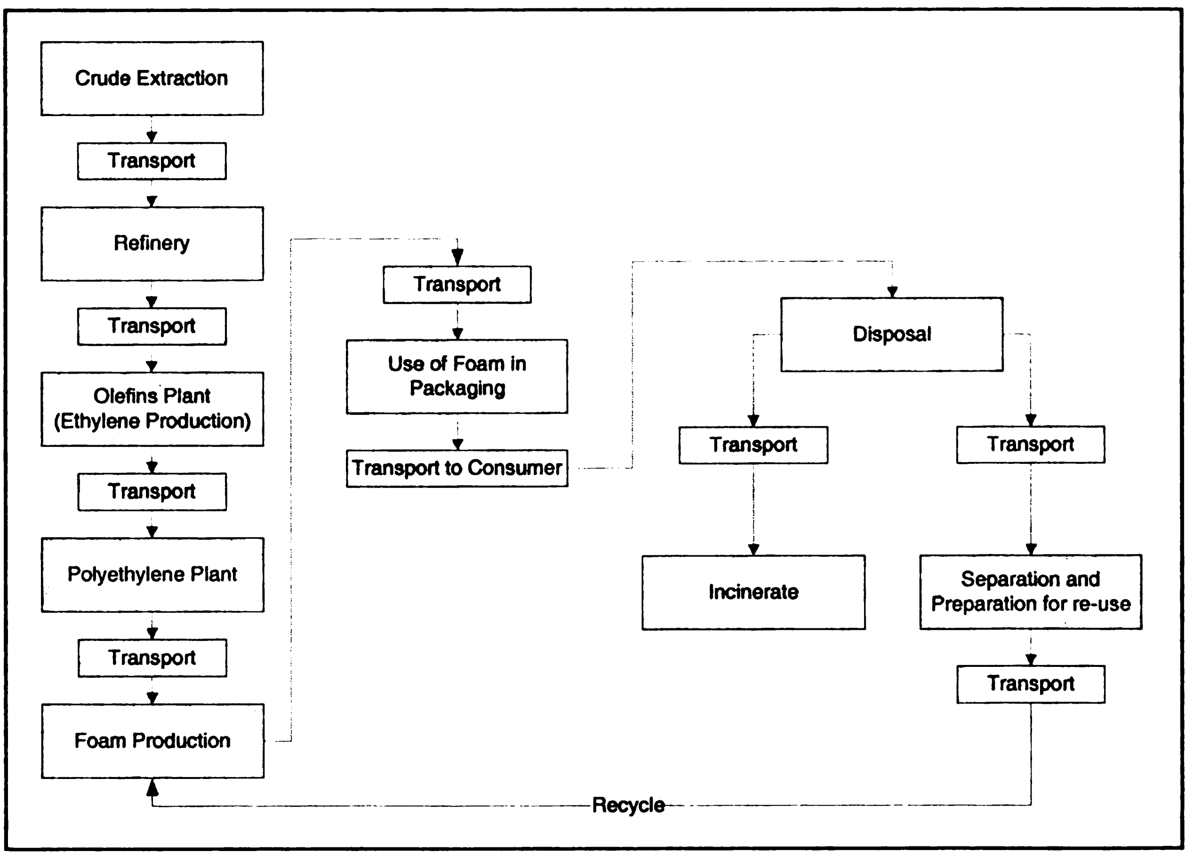


Figure 4. Process flow diagram for polyethylene foam

Crude is extracted and goes through refining, processing and polymerization via a refinery, olefins plant and polyethylene plant respectively. All transportation associated with these processes is included. The polyethylene is then transported to a foam production plant where the polyethylene undergoes extrusion. In this study, the foam product is then transported to the company where it is assumed that the cutting and shaping of the foam is performed. The company then uses the foam in the packaging developed and sends the laptop to the consumer. The consumer disposes of the packaging and from there the polyethylene packaging can be sent to a landfill or an incinerator. In the case of recycling, the polyethylene would be transported to a separation plant where the PE foam is gathered and transported back to the foam manufacturer for reuse.

B. Starch Foam

Similar to the polyethylene foam system, the whole life cycle of foam was

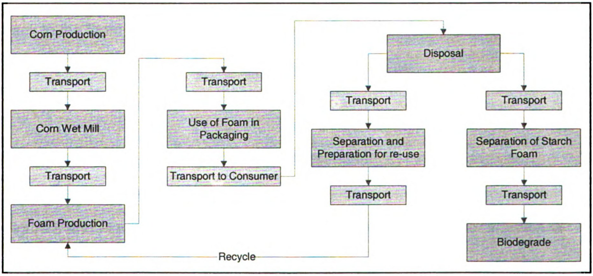


Figure 5. Process flow diagram for starch foam

delineated as shown in Figure 5. Figure 5 includes the production, use and disposal phase encompassing an entire life cycle. Again, the actual portion of the cycle being studied will be shown later.

In the case of starch foam the process begins with corn production where corn seeds are planted and the products are harvested. The corn grain is transported to a corn wet-mill, also referred to as a corn refinery. In this refinery is where the corn is steeped and milled, and starch is separated. This process produces four other products, which include germ, corn gluten meal, corn gluten feed, and heavy steep water. After separation, the starch is transported to the foam production plant and extruded. Similar to polyethylene foam production, in this study the foam produced is transported to the company where it is assumed that the cutting and shaping of the foam is performed. The company then uses the foam in the packaging developed, and sends the laptop to the consumer. The consumer disposes of the packaging and the starch foam is transported to a site to be separated and recovered. The recovered starch foam is either sent back to the foam manufacturer to be re-used (like polyethylene) or, unlike polyethylene, sent to a composting site for biodegradation.

C. Starch and Polyethylene Systems studied

The starch and polyethylene system assessed in this life cycle is shown in Figure 6 and Figure 7. These systems can be studied and compared because they are equivalent. They use the same functional unit, the same performance

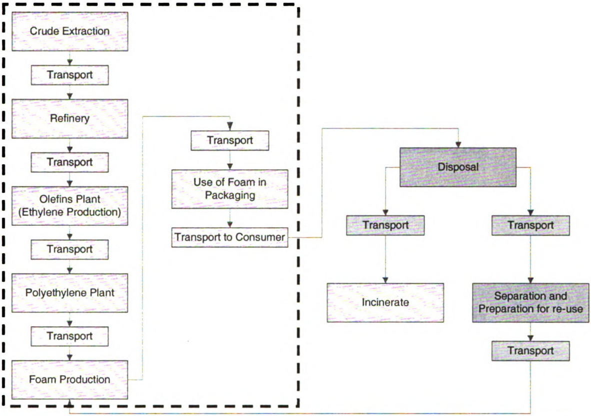


Figure 6. Process flow diagram for PE foam showing system boundaries

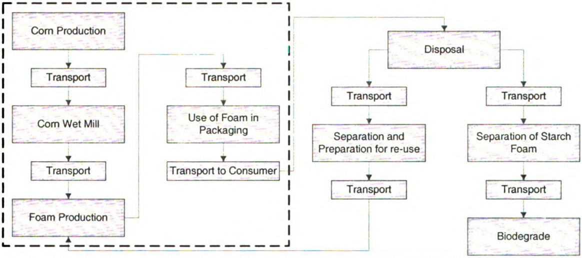


Figure 7. Process flow diagram for starch foam showing system boundaries

characteristics, the same methodologies follow and they use the same system boundaries. Because of the similarities of units within the product system, they units are cancelled in both systems under the assumption that the unit would contribute the same inputs and outputs to each system. Figure 8 show both polyethylene and starch foam systems after units are cancelled out.

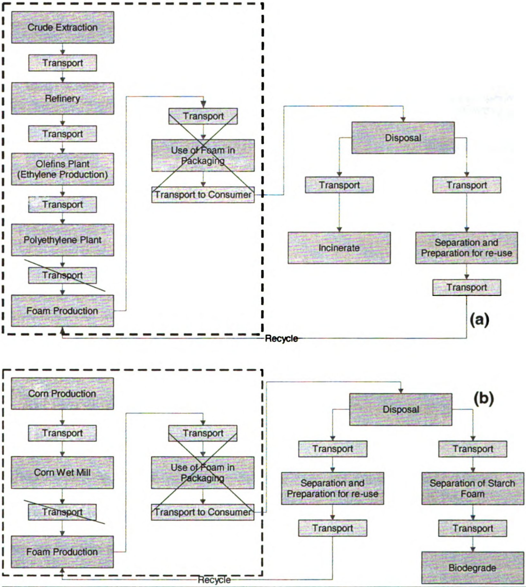


Figure 8. Cancellations for both (a) PE foam and (b) starch foam systems

4.2.4 Data Assessment

The data gathered for this study are for the following units shown in Figure 9. The dashed line indicates the various data groups that constitute the overall

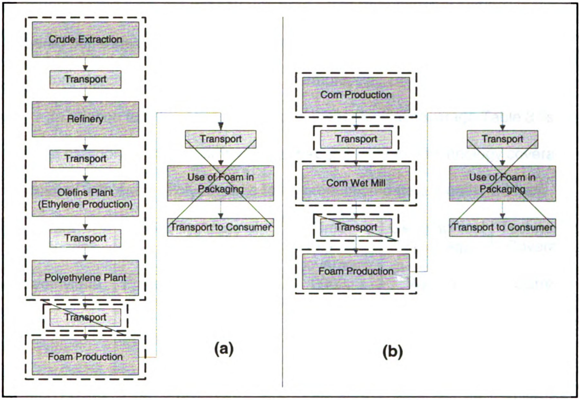


Figure 9. System data groups for both (a) PE foam (b) starch foam

LCA. For polyethylene foam (a), data have been gathered for crude extraction up until the polyethylene plant including all transportation. The foam production data have been estimated based on foam extrusion procedures and from literature. The transport portion is cancelled out under the polyethylene foam system as for the starch foam (b), under the assumption that the transportation inputs and outputs from the polyethylene plant and the corn wet-mill to the foam production plant are equal. For starch foam the corn production data are gathered also incorporating all transportation except for the transport of the grain to a corn wet-mill. A transportation module called the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model [18], accounts for the transportation inputs and outputs associated with transporting corn grain to the corn wet-mill. Starch production from the corn wet-mill is gathered separately. Similarly to polyethylene foam, data for the extrusion of foam from starch are estimated or from literature.

In relation to time, geographical and technological coverage Table 3 lists the data categories and the time-related, geographical and technology coverage associated with each. Polyethylene foam production data are gathered from

Data Categories	Specific Areas of Data Use	Time-related coverage	Geographical Coverage	Technology Coverage
Polyethylene Foam	Polyethylene production	2003, Bousted	Western Europe, North Sea	Current
	Foam production	Literature based estimations	U.S.	Current
Starch Foam	Corn growing	200x, Cargill Dow	U.S., Midwest	Current
	Transport to CWM	2004, GREET for Cargill Dow	U.S.	Current
	Corn Wet Mill (CWM)	2004, Cargill Dow	U.S., Midwest	Current
	Foam production	Literature based estimations	U.S.	Current
Normalization	Normalization Values	2003, BEES from US EPA	U.S. based	-------
Impact Ass.	Impact factors	2003, BEES	U.S. based	-------

Table 3. Time, technological and geographical coverage related to data

reports completed by Bousted [7] for the Association of Plastic Manufacturers (Plastics Europe), also known as APME. In both cases (polyethylene and starch) the foam production data have been estimated using literature and research information. For the case of starch foams, corn growing and corn wet milling data have been gathered from Cargill Dow [19-21] along with the transportation data for corn grain to the corn wet-mill. The transportation data from Cargill Dow came as a result of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. The GREET model was developed by Center for Transportation Research at Argonne National Laboratory and was sponsored by the U.S. Department of Energy [18].

All the data used in this study are less than five years. The technology used, related to the machinery and techniques, to supply this data corresponds to current practices in the field today. In terms of geographical coverage, while it would be ideal to have all the data from the U.S. or to have world data, this is not yet practical. These data are only as good as the collection source. Thus, all the uncertainties of the original data are present in this data. However, the sources for data in this paper are accepted in the respective regions by credible associations, companies and departments. Thus, the data provide a solid basis for going forth with the assessment.

4.2.5 Allocation Procedures

Allocating inputs and outputs to multiple products is a common procedure in many LCA's because many have processes that produce multiple products (see more in Appendix A). Allocation is necessary in order to assign the appropriate amount of inputs and emissions to the appropriate product. The data gathered and used in this study, incorporates allocation procedures and attempts to avoid allocation whenever possible by creating sub-processes.

The processes in which allocation is considered include polyethylene production and corn wet milling. These processes produce products other than polyethylene and starch and thus allocation is necessary. In the case of the polyethylene production data, the inputs and outputs for units such as crackers (responsible for multiple products) from various polyethylene plants in Western Europe are averaged and allocated on a simple mass basis [7]. In the corn wet-milling process allocation is based on the dry mass of the intermediate and/or final product because the system is divided into sub-systems allowing for a better understanding of how to allocate the resources and burdens to the appropriate product [19]. Other allocation methods exist. However, the allocation methods discussed above mainly pertain to the allocation procedures related to this study.

4.2.6 Impacts and Impact Methodology

Eight impact categories are considered in this study. All eleven impact categories, some related emissions, and category indicators, are shown in the Table 4. The first nine are considered, with human health as one impact. The impact categories chosen are as a result of reviewing the TRACI and BEES documentation [15-16]. Both are products of the United States and thus they both take into consideration the impacts that are global as well as those that are

U.S. specific and even those that are locally focused within the U.S. The TRACI document considers eleven, but mentions twelve impact categories. Water use

IMPACT CATEGORY	RELATED EMISSIONS	CATEGORY INDICATOR	INFO. SOURCE
ozone depletion	CFCs, Halons, HFCs release Cl^-, Br^-,	CFC-11	TRACI -BEES
global warming	CO_2, CH_4, N_2O, CFCs, HFCs	CO_2,	TRACI -BEES
acidification[1]	SO_2, NO_x to SO_4^{2-}, NO_3^-, HCL, HF, NH3	H^+,	TRACI -BEES
eutrophication[1,2]	NO_x and P to NO_3^-, PO_4^{3-},	P or N	TRACI -BEES
photochemical smog[1]	NO_x, VOCs, CO, CH_4	NO_x,	TRACI -BEES
human health cancer	HTP of all toxic emissions	HTP to Benzene	TRACI -BEES
human health noncancer	HTP of all toxic emissions	HTP to Toluene	TRACI -BEES
human health criteria	PM_{10}, $PM_{2.5}$ and SO_2, No_x to SO_4^{2-}, NO_3^-,	Disability Adjusted Life Years (DALY)	TRACI -BEES
ecotoxicity	HTP of all toxic emissions	2-4-Dichlorophenoxy AceticA	TRACI -BEES
fossil fuel use	Indentify type of fuel being studied	Energy input/consumption of fuel/unit of product	TRACI -BEES
land use[1]	Land being studied	T&E density	TRACI -BEES
water use	significant use of H_2O with low availability	direct inventory (volume)	TRACI -BEES

[1]Characterization factors are available for nine different groups of U.S. states based on regions. These impact categories are location sensitive. For the case of land use, there is county specific data. Using state or national data greatly reduces the value of the TRACI Threatened & Endangered densities
[2]P or N will be the category indicator depending on which substance is the limiting nutrient in the surface waters.
[3]Human Toxicity Potential found for all emissions then compared to baseline values for Benzene (carcinogenic) or Toluene (non carcinogenic); chemical emissions compared by toxicological eqivalencies.

Table 4. Impact categories and related information and sources

is the only impact category that isn't characterized by TRACI. Water use is assessed by the use of inventory data [16]. Also, in TRACI, the human health impact category is divided into human health: cancer and human health: non-cancer impact categories, which is not the case in BEES.

In terms of the categories, the BEES document contains much of the same impact categories, as does the TRACI document, seeing as the impact assessment methodology in BEES is taken from TRACI with few exceptions. The impact category of indoor air quality is specific to buildings and is assessed in the BEES [15]. Also the impact categories of human health: cancer and human health: non-cancer are grouped under human health. Although there are many impact assessment methods, BEES follows the methods derived in TRACI. The collaboration of the two documents is the source of the eleven impact categories discussed in this study and shown in Table 4.

In summary, the emissions from the life cycle inventory are classified into impact categories like global warming or acidification as shown in Figure 10. The emissions are then related to the category indicator by a characterization factor (or the potential of that emission to perform as the category indicator) developed by the impact assessment methodology used. The summation of all the emissions characterized in a particular impact category yields the impact potential index, such as the global warming potential or acidification potential. Figure 10 shows the relation of changing emission values to an impact index.

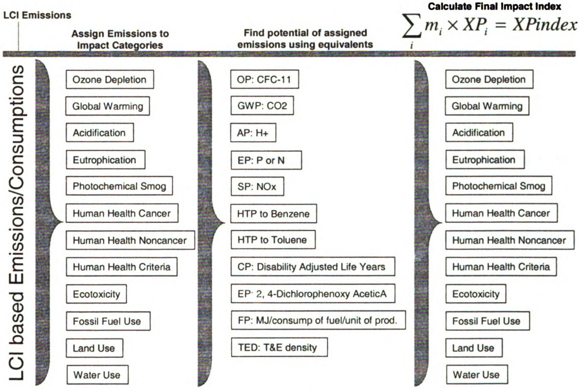


Figure 10. Impact assessment calculation procedural flow

4.2.7 Interpretation

With the impacts assessed, each category is expressed in specific units. The numbers from one assessment are helpful in comparison to another assessment, but only if each assessment is comparable. The numbers themselves, however, do not give much information in relation to a larger picture. The results of an impact assessment mean nothing on their own; they are just numbers. Thus, normalization data developed by TRACI and used in BEES allow for a relation between the results gathered in this study and the current U.S. environmental position for each impact category. By dividing the study results by the normalization values, the results are measured against U.S. positions, thereby creating an avenue for comparison to the overall U.S. picture. For more on normalization please refer to the Life Cycle Assessment Summary (Appendix A).

4.2.8 Assumptions and Limitations

The following points indicate various assumptions and/or limitations to this life cycle assessment.

- Only the direct production of the polyethylene foam and starch foam along with diesel, gasoline, natural gas, and liquid petroleum gas production were included in this LCA. The production and/or resources due to infrastructure, machinery and the like were not included due to the assumption that infrastructure and machinery and even people and office supplies are all common in production arenas and thus can be left out.

Justification from the PriceWaterhouseCoopers [22] study shows that these segments do not need to be included.

- The production of and any production related to the laptops referred to in this study was not accounted for. Similar to the TV production in the PricewaterhouseCoopers study on expanded polystyrene, the production of laptops is not specifically related to the production of polyethylene and starch foams.

Chapter 5: Life Cycle Inventory

This phase of the LCA incorporates all the data to produce the aggregate emissions for each unit based on the functional unit of packaging 50,000 laptops. The section discusses (1) the systems studied using more detail, (2) the data layout in the LCI phase, and (3) the data collection and calculation procedures specific to polyethylene foam and starch foam respectively. The starch foam portions of this segment discuss the topics of corn growing and corn wet milling separately.

5.1 System and unit descriptions

5.1.1 Polyethylene System

Going from fossil fuels to polyethylene pellets to polyethylene foam requires a combination of various processes. The process for producing polyethylene foam begins with crude extraction as shown in Figure 11. Fossil fuels must first be located and extracted from the ground and this stage is often referred to as the exploration and production stage. The crude is extracted and transported by barge or pipeline to a refinery. At the refinery the crude is distilled and cracked to produce various products based on the volatility of the products in the crude.

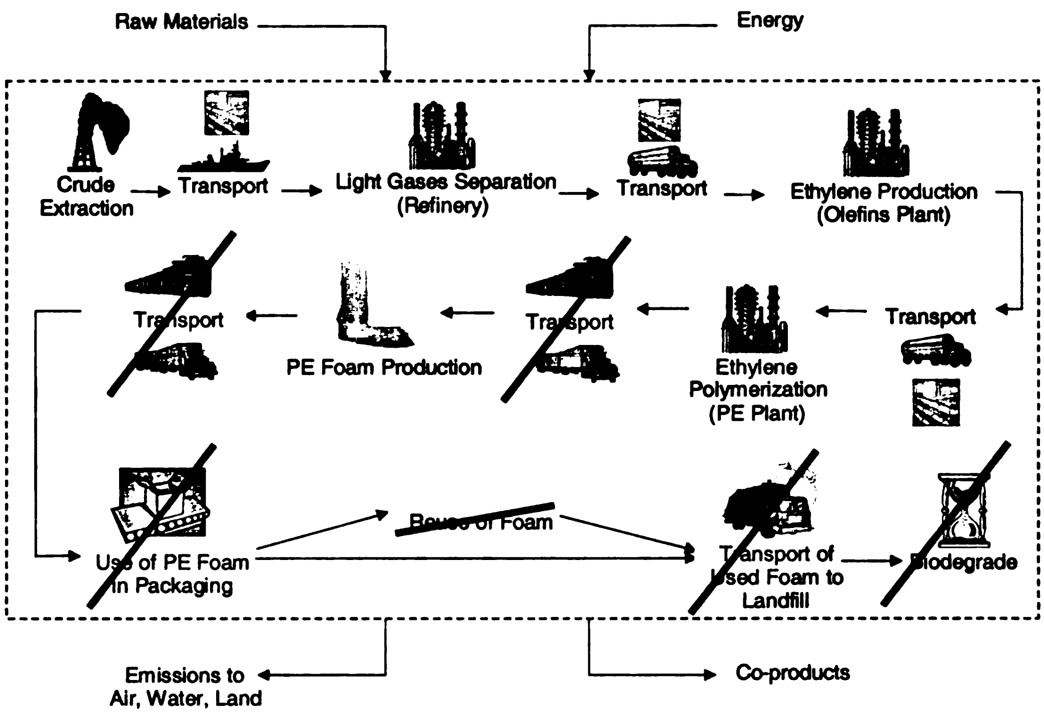


Figure 11. Pictorial process flow for polyethylene foam

As shown in Figure 12 (a), the light gases come off the top of the distillation tower and it contains gases from methane to butane. For this study, the key product produced in distilling and cracking, which is separated out with the light gases is ethane. The light gases are transported by pipeline to a nearby ethylene production plant or an olefins plant as feed. Through a series of

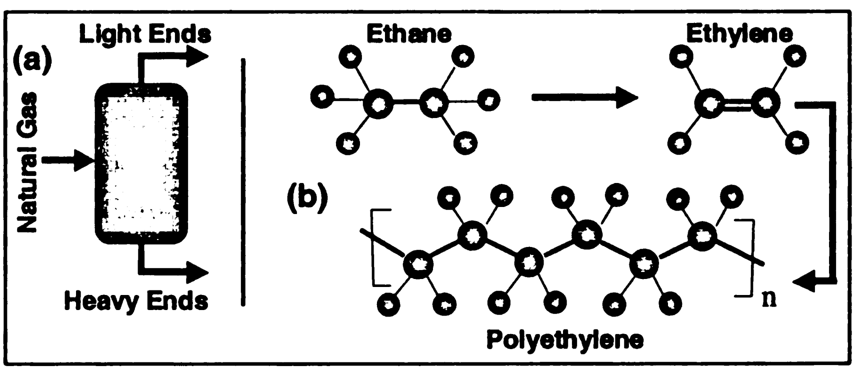


Figure 12. (a) Simple separation tower (b) Reaction of ethane to PE

distillation towers, ethane is separated out from other light gases. Once ethane is separated, it is then cracked to form ethylene as shown in Figure 12 (b). The ethylene is then transported by truck to a polyethylene plant. Polymerization of ethylene at the plant produces polyethylene resin or pellets as shown in Figure 12 (b). They are then transported by rail or truck to foam manufacturers. Foam manufactures mix the polyethylene resin with various additives amounting to about 2% of the feed [17] and extrude the polyethylene resin, injecting a blowing agent as the feed is heated and mixed traveling down the length of the barrel. The mixture is forced through a die at the end of the extruder and the foam process begins as the blowing agent expands the polyethylene due to the drop in pressure. Most of the blowing agent escapes as the foam leaves the die, expanding the polyethylene and thus producing foam. The rest of the blowing agent leaves the foam material over time as air fills the pockets that were initially filled by the blowing agent.

5.1.2 Starch-based system

Similar to polyethylene foam production, starch foam production comes as a result of a combination of processes—growing the corn, corn wet milling and starch extrusion. Figure 13 shows the picturesque process flow of starch foam production with the incorporated unit cancellations. To get starch pellets from corn, corn must be grown and Figure 14 shows more details in regards to the corn growing and corn wet milling process.

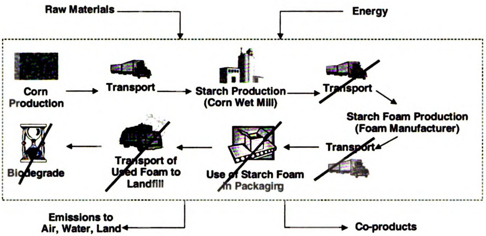


Figure 13. Pictorial process flow for starch foam

A. Corn Growing Process

To grow corn, the land is tilled using machinery in order to level the ground, loosen the soil and tear up unwanted weeds. Once the ground is ready, machinery is used again to plant the seed at an optimal distance, maximizing the

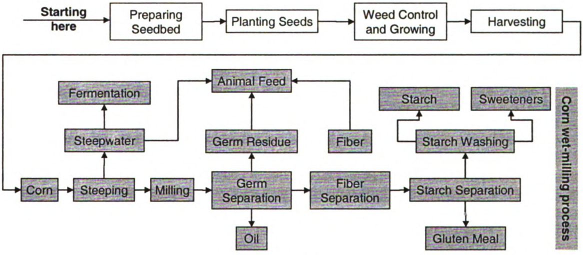


Figure 14. Corn Production and the corn wet-milling process

growth and yield of the crop. As the corn is growing, machinery is used to control weed growth, loosen the soil for oxygen to get to the roots, and to add water and chemicals to the soil. Finally, the corn is harvested and the kernels are removed from the corn and transported by truck to a nearby corn wet-milling facility.

B. Corn Wet-Milling Process

To begin the process of corn wet-milling the corn received from farmers is first cleaned of all extraneous material mixed in with the corn. The kernels of the corn is then steeped in dilute sulfuric acid bath for about 20 to 36 hours (Cargill Dow Paper) and prepared for the next step—milling. The remaining steep water is used in other areas such as fermentation or in animal feed. In milling, the corn is simply grinded. Then the germ is separated from the mixture, and washed and dried to be sold. The germ is the inner part of the kernel. The germ of the corn is used to produce corn oil and the residue from this process is also used for animal feed. After the germ is separated the fiber, starch and gluten meal of the kernel remains. They are separated (fiber and starch) and the fiber is used as animal feed while the starch and gluten meal mixture go through another separation. Once the starch and gluten meal is separated, starch is washed and prepared to be sold.

Similar to polyethylene, the starch is transported to a foam manufacturer to produce foam starch, and is subjected to the same process steps as polyethylene. Additives are mixed with the starch. The mixture continues to be mixed and begins to melt, being heated down the length of the extruder. Water, the blowing agent in this case, is injected into the mixture traveling through the extruder barrel. The mixture is then released from the extruder via a die. Once the product hits the ambient air, liquid water undergoes a phase transition to steam and the rapid expansion swells the product, producing foam. Figure 15 shows an example of such an extruder—specifically a single-screw extruder. A

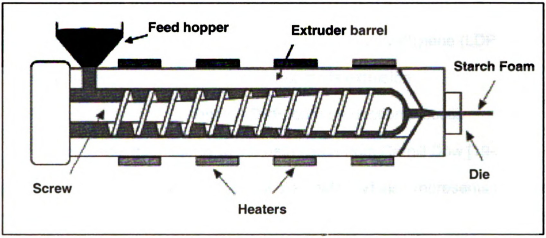


Figure 15. Common single-screw extruder

more common extruder used is the twin-screw extruder, which goes through the same process as a single-screw extruder except with two screws rotating in opposite directions of each other to enhance mixing.

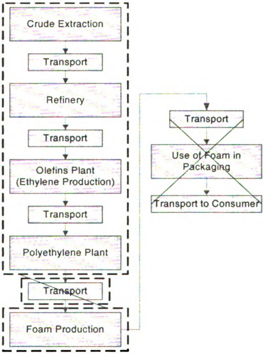


Figure 16. PE system data groups

5.2 Data Layout Description

For polyethylene foams, majority of the data were gathered from Bousted [7]. Figure 16 shows the grouping of the collected data. The actual data within the life cycle inventory phase that will be included are as follows:

1. Energy data (by segments, by energy type, by fuel type and in total) for both the polyethylene and foam extrusion data
2. Input data for both the polyethylene and foam extrusion data
3. Emissions for the production of low density polyethylene (LDPE)
4. Emissions for the production of foam via extrusion
5. Emissions from the entire LDPE foam production process

For starch foams the majority of the data came from Cargill Dow [19-21]. Figure 17 shows the grouping of the collected data and also represents how the data will be presented. The actual data within the life cycle inventory phases that will be included follows:

1. Energy data (by various categories) for both starch production and foam extrusion
2. Input data for both starch production and foam extrusion
3. Corn growing emissions

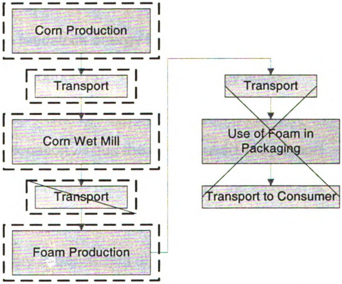


Figure 17. Starch system data groups

4. Emissions for the production of starch from the corn wet-mill
5. Emissions from the production of foam via extrusion
6. Emissions from the entire process

5.3 Polyethylene Foam LCI Data

5.3.1 Energy Data

To produce polyethylene foams energy from various sources (ex. Coal, lignite, sulfur) were necessary. While various types of fuel were used in the production of polyethylene foams, the data presented in Bousted's LCI divide the data into the following categories:

- Feedstock Energy
- Transport Energy
- Fuel Energy
- Fuel Production and Delivery Energy

Feedstock energy incorporates all the energy stored in materials used for the feed. To describe the feedstock energy Bousted explains, "whereas true fuels, once burned, are gone for good, the feedstock energy for materials is simply 'borrowed' and is rolled up within the product" [6]. Transport energy largely depends on the type of transport used. The type of transport used to move materials and products depends on location. Thus the energy used in transport is location dependant and, for the polyethylene data in this study, the location is West and Northern Europe. Another location-dependant energy category is fuel production and delivery. This category is dependant on the type of fuels used, the age of the plant, and the method of distribution of energy [6]. While some countries rely on oil for electricity production and distribution, others depend on coal or on gas and others rely on a proportion of various fuel types. Thus, some variation will be present when calculating energy contributions, for example, in Venezuela versus Western Europe. Fuel energy is the energy actually utilized by the process industries. Bousted refers to this category as the technology-dependant portion of the process [6]. The amount of fuel energy used will depend on the overall efficiency of the process industries.

These energy categories (feedstock, transport, fuel, and fuel production) were then further divided into fuel type. The fuel types used are listed below:

- Electricity
- Oil Fuels
- Other Fuels

Electricity is in its own category due to the high production energy caused by low efficiency in the industry [6]. The oil fuels category includes all fuel derivatives of crude oil. Finally, the other fuels category contains all other forms of fuel providers such as coal, wood, lignite, sulfur and more. However the main make-up of the 'other fuels' group is attributed to natural gas [6].

The energy data for each type of foam (starch and polyethylene) will be presented separately. It is important to keep in mind the variation in energy production techniques and the dependency of other energy data on certain technology or varying geography.

5.3.2 All Other Data

The data, outside of the energy data, used for polyethylene production incorporate all material inputs and all outputs. The outputs are separated into air, water and solid emissions and all inputs and outputs are given in mg/kg of LDPE.

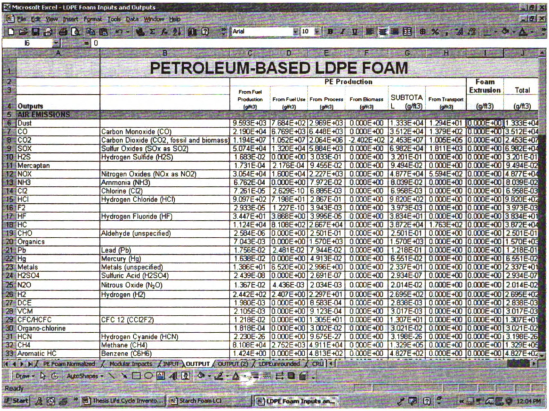
The emissions, whether air, water or solid, are divided into the five sub categories listed below:

- Fuel production
- Fuel use
- Transport
- Process
- Biomass

Emissions related to each of these categories are listed and finally summed for the total emissions released for low-density polyethylene. While the first three subcategories have been touched on before the process and biomass categories have not been discussed. Process refers to the outputs associated with the actual production that leads to polyethylene. Biomass refers to the outputs associated with the use of biological materials. Biomass is included in the study to account for any CO_2 credits that amount from accounting for biomass inputs and outputs.

5.4 Data Calculation Procedures for Polyethylene LCI

The data for polyethylene were taken from Bousted and placed in the format shown in Figure 18. The format shown is specifically for the output data. The input data have the same format in terms of segments (polyethylene and foam extrusion), but there is no separation into subcategories (transport, process, biomass etc…).



	Outputs		From Fuel Production (g/ft3)	From Fuel Use (g/ft3)	From Process (g/ft3)	From Biomass (g/ft3)	SUBTOTAL (g/ft3)	From Transport (g/ft3)	Foam Extrusion (g/ft3)	Total (g/ft3)
1		PETROLEUM-BASED LDPE FOAM								
2–3			PE Production						Foam Extrusion	Total
5	AIR EMISSIONS									
6	Dust		9.593E+03	7.684E+02	2.969E+03	0.000E+00	1.333E+04	1.294E+01	0.000E+00	1.333E+04
7	CO	Carbon Monoxide (CO)	2.190E+04	6.769E+03	6.448E+03	0.000E+00	3.512E+04	1.379E+02	0.000E+00	3.512E+04
8	CO2	Carbon Dioxide (CO2, fossil and biomass)	1.194E+07	1.052E+07	2.064E+06	-2.402E+02	2.453E+07	1.005E+05	0.000E+00	2.453E+07
9	SOX	Sulfur Oxides (SOx as SO2)	5.074E+04	1.320E+04	5.884E+03	0.000E+00	6.982E+04	1.811E+03	0.000E+00	6.982E+04
10	H2S	Hydrogen Sulfide (H2S)	1.683E-02	0.000E+00	3.033E-01	0.000E+00	3.201E-01	0.000E+00	0.000E+00	3.201E-01
11	Mercaptan		1.731E-04	2.176E-04	9.455E-02	0.000E+00	9.494E-02	0.000E+00	0.000E+00	9.494E-02
12	NOX	Nitrogen Oxides (NOx as NO2)	3.054E+04	1.600E+04	2.227E+03	0.000E+00	4.877E+04	5.594E+02	0.000E+00	4.877E+04
13	NH3	Ammonia (NH3)	6.762E-04	0.000E+00	7.972E-02	0.000E+00	8.039E-02	0.000E+00	0.000E+00	8.039E-02
14	Cl2	Chlorine (Cl2)	7.261E-05	2.629E-10	6.885E-03	0.000E+00	6.958E-03	0.000E+00	0.000E+00	6.958E-03
15	HCl	Hydrogen Chloride (HCl)	9.097E+02	7.198E+01	2.867E-01	0.000E+00	9.820E+02	0.000E+00	0.000E+00	9.820E+02
16	F2		2.933E-05	1.227E-10	3.943E-03	0.000E+00	3.973E-03	0.000E+00	0.000E+00	3.973E-03
17	HF	Hydrogen Fluoride (HF)	3.447E+01	3.868E+00	3.995E-05	0.000E+00	3.834E+01	0.000E+00	0.000E+00	3.834E+01
18	HC		1.124E+04	8.108E+02	2.667E+04	0.000E+00	3.872E+04	1.763E+02	0.000E+00	3.872E+04
19	CHO	Aldehyde (unspecified)	2.584E-06	0.000E+00	2.501E-01	0.000E+00	2.501E-01	0.000E+00	0.000E+00	2.501E-01
20	Organics		7.043E-03	0.000E+00	1.570E+03	0.000E+00	1.570E+03	0.000E+00	0.000E+00	1.570E+03
21	Pb	Lead (Pb)	1.756E-02	2.481E-02	7.944E-02	0.000E+00	1.218E-01	0.000E+00	0.000E+00	1.218E-01
22	Hg	Mercury (Hg)	1.638E-02	0.000E+00	4.913E-02	0.000E+00	6.551E-02	0.000E+00	0.000E+00	6.551E-02
23	Metals	Metals (unspecified)	1.386E+01	6.520E+00	2.996E+00	0.000E+00	2.337E+01	0.000E+00	0.000E+00	2.337E+01
24	H2SO4	Sulfuric Acid (H2SO4)	2.439E-08	0.000E+00	2.691E-07	0.000E+00	2.934E-07	0.000E+00	0.000E+00	2.934E-07
25	N2O	Nitrous Oxide (N_2O)	1.367E-02	4.436E-03	2.034E-03	0.000E+00	2.014E-02	0.000E+00	0.000E+00	2.014E-02
26	H2	Hydrogen (H2)	2.442E+02	2.407E+00	2.297E+01	0.000E+00	2.695E+02	0.000E+00	0.000E+00	2.695E+02
27	DCE		1.980E-03	0.000E+00	8.583E-04	0.000E+00	2.838E-03	0.000E+00	0.000E+00	2.838E-03
28	VCM		2.105E-03	0.000E+00	9.123E-04	0.000E+00	3.017E-03	0.000E+00	0.000E+00	3.017E-03
29	CFC/HCFC	CFC 12 (CCl2F2)	1.218E-02	0.000E+00	1.305E+01	0.000E+00	1.307E+01	0.000E+00	0.000E+00	1.307E+01
30	Organo-chlorine		1.818E-04	0.000E+00	3.002E-02	0.000E+00	3.021E-02	0.000E+00	0.000E+00	3.021E-02
31	HCN	Hydrogen Cyanide (HCN)	2.230E-26	0.000E+00	9.675E-27	0.000E+00	3.198E-26	0.000E+00	0.000E+00	3.198E-26
32	CH4	Methane (CH4)	8.108E+04	2.752E+03	4.911E+04	0.000E+00	1.329E+05	0.000E+00	0.000E+00	1.329E+05
33	Aromatic HC	Benzene (C6H6)	1.424E+00	0.000E+00	4.813E+02	0.000E+00	4.827E+02	0.000E+00	0.000E+00	4.827E+02

Figure 18. General layout of data collection spreadsheet (output shown)

The first column contains the actual emission name given by Bousted. The second column creates a cross-reference relating the emissions automatically to the emissions used in the LCIA phase. Poylethylene production data are in a segment of its own, and the inputs to each subcategory (transport, process, biomass etc…) are still separated. The following column is the foam extrusion outputs. The last column is a total of all outputs. This format also keeps the emissions separated by air, water and solid.

The process to prepare the polyethylene data involves the three major steps listed below.

1. Unit conversions

2. Functional Unit relation

    i. Foam density determination

3. Scale-up Calculations

These steps are applied to the energy, input and output data. All the polyethylene output data are converted to g/kg LDPE and the input data are converted to kg/kg LDPE. In addition to having all the data converted to the respective units, the data are also related to the functional unit of the study, which is to provide material to cover 50,000 laptops. The relation is found via the foam density, which incorporates the reference flow of 17000 ft^3. With a density of 0.85 kg LDPE/ft3, the data are scaled to the functional unit of 17000 ft^3.

To accommodate the iterative process of life cycle assessment, a small program made in Microsoft Visual Basic is developed to automate the scale-up calculations for polyethylene. By clicking on the scale button located in the LDPE input spreadsheet, the energy, input and output data are scaled by the desired factor leaving all energy, input and output data on a per 17000 ft^3 basis. The data are presented in this manner (in relation to the reference flow that is based on the functional unit of this study).

5.5 Starch Foam LCI Data

Starch foam data collection varied immensely from polyethylene data collection. The data provided by Cargill Dow include spans over sixteen spreadsheets. The main inputs such as corn seeds, fertilizers, pesticides, electricity and fuel are accounted for several Midwest states. The study also accounts for the carbon dioxide credit gained from photosynthesis.

The data collected from Cargill Dow [19-21] are from two different data groups. One data group is for corn growing and, the other, for corn wet milling. The corn growing data list the total inputs (including land, corn seeds, the CO_2 credit, nitrogen emission from the field, and the yield among other things) associated with each Midwest state in the study within one worksheet. The information associated with the production of the main inputs to corn growing such as, fertilizers, pesticides, electricity, fuel (diesel, propane, gasoline and natural gas) are in a separate worksheet detailing all the inputs, outputs and energy associated with its production. In addition to this, the fuels also had a separate worksheet detailing the inputs, outputs and energy associated with the burning or use of the fuel.

In corn wet milling the inputs and outputs for each segment are recorded, and only those segments that are related to starch are included in the inputs and outputs for starch. In corn wet milling four other products are made. Thus, for the segments or processes used to contribute to the four other products, the inputs and outputs are allocated. Starch drying data were estimated based on drying data of other products from corn wet milling.

5.5.1 Energy Data

From corn growing, energy contributions to starch foams came from the production of the fertilizers, pesticides, electricity and fuel. Most inputs produced had the associated energies below.

- Feedstock
- Fuel
- Non-renewable
- Renewable
- Total energy

The feedstock energy pertains to the energy within the raw materials used in that particular production process. Fuel energy pertains to the energy of the actual fuel (coal, gas, wood etc...) used in the production process. Non-renewable energy is the energy that comes from resources that are being depleted faster than they can be restored. Renewable energy pertains to the energy that comes from a source that has the ability to be restored at the same rate that it is being depleted. The total primary energy is the sum of the feedstock and fuel energy or the sum of the non-renewable and renewable energy [23].

The worksheets containing inputs and outputs related to the use of fuels provides a fuel and feedstock energy for the use of that fuel. These energies cancel out in the use phase. The fuel energy is converted to feedstock energy, which, in turn, is combusted.

For energy associated with corn wet milling, data were gathered directly from the segments. Energy related to the corn wet milling was dominated by electricity use and natural gas consumption. Most of the natural gas consumption comes from steam production and drying of products. There is energy recovered and re-used in this process. Thus, the energy is cancelled out and not reported in the energy data presentation.

5.5.2 All Other Data

The remaining data (outside of the energy data) from starch production are collected in a manner similar to that of the energy data collection. For fertilizers and pesticides and under corn growing, the inputs and outputs correspond to 1 kg of the particular fertilizer or pesticide. Similarly for the production of diesel, gasoline, natural gas and propane, the inputs and outputs are gathered for 1 kg of the respective fuel. More input and output data are available for the aforementioned fuels, but this time corresponding to a specific amount of energy. For example to produce roughly 8 MJ of energy from diesel would take 0.197 kg of diesel and there is a set amount of each emission associated with the combustion of diesel fuel. Only for electricity is the input and output data corresponding to the production of 1 MJ (versus 8 MJ) of electricity given.

For input and output of materials from the corn wet milling process, the data are gathered in much the same way as the energy data are gathered. Data are gathered directly from the segments. Material inputs and outputs related to the corn wet milling are collected for each segment.

5.6 Data Calculation Procedures for Starch Foam LCI

The data for starch foam are gathered in four spreadsheets, two for corn growing and two for corn wet-milling respectively. The data are formatted similar to Figure 18 shown earlier. In addition to these two spreadsheets, another spreadsheet with the totals from the Midwest states (which included the main inputs, some outputs and a CO_2 credit) is used for the base analysis for starch foam production. A cross-reference sheet is made separate from the main data collection sheets. To calculate emissions the following steps were followed:

- Consolidate data in input and output spreadsheet
  - CG: Utilize functions and formulas to extract data from over sixteen spreadsheets from Cargill Dow
  - CWM: Perform data entry of all data from Cargill Dow technical paper
- Functional unit relation (same as before–using a 0.85 kg/ft^3 density)
- Primary unit conversions
  - CG: All inputs were in kg and all outputs in grams. No initial conversions required due to program development, which incorporates automatic changing of the kg inputs to gram inputs.
  - CWM: Data retrieved as kg input/day or kg output/day. Thus a conversion is necessary to change inputs and outputs to grams/day. Also, electricity is converted from kWh to MJ.
- Data Analysis – See Appendix C for example of calculations

- Corn Growing (CG)
  - Calculate weighted averages of main inputs, nitrogen emissions and CO_2 credits from the various states
  - Perform secondary unit conversions
    - (kg(input) or g(output))/(kg or MJ X) to (kg(input) or g(output))/ft^3 where X could be a fertilizer, a pesticide, or a fuel
    - Change inputs in analysis sheet from (kg input/ha) to (factor/ft^3)
  - For the fuels the weighted average of fuels (MJ) is used to scale-up the input and output data from the fuel use spreadsheet and data from that sheet will be used to scale up data from the fuel production sheet
  - Develop transportation data using model developed by GREET
- Corn Wet Milling (CWM)
  - Perform allocation on inputs and outputs based on mass
- Develop two separate programs to automate the scale-up process for corn growing and corn wet milling

The data are consolidated into two worksheets (input and output) for corn growing and into two worksheets (input and output) for corn wet-milling. For corn growing data, formulas are written in the corn growing input and output worksheets to pull data from the sixteen spreadsheets from Cargill Dow. For the corn wet-milling process, data from a Cargill Dow technical paper [19] are entered manually, in segments. The next step relates the starch data to the functional unit of the study incorporating the foam density basing the data on the same functional unit as polyethylene foam. All units for corn growing and for corn-wet milling input and output data are converted via the automation program developed for scaling up or are incorporated within the sheet.

The next step was data analysis. For the corn growing data various steps were taken as shown below in more detail.

1. Calculate the weighted average of land use, yield, inputs (seeds, fertilizers, pesticides, fuels), nitrogen emissions and CO_2 credits.
2. Perform secondary unit conversions
    a. Convert all the data to reflect kg input/ft^3 foam or g output/ft^3 foam by doing the following:
        i. Convert weighted averages in the analysis spreadsheet from kg/ha or MJ/ha to per kg/ft^3 or MJ/ft^3
        ii. Use the above conversion of kg/ha to kg/ft^3 to change all fertilizer and pesticide inputs and outputs to kg input/ft^3 or g output/ft^3
        iii. Use the above conversion of MJ/ha to MJ/ft^3 to change all fuel use inputs and outputs to kg input/ft^3 or g output/ft^3

iv. Use the kg input/ft^3 from the fuel use spreadsheet in the fuel production spreadsheet to convert the inputs and outputs to kg input/ft^3 or g output/ft^3

For the corn wet-mill inputs and outputs, the data analysis performed includes allocation by a mass basis, of the input and output contributions from starch production.

Finally, to accommodate the iterative process of life cycle assessment, a small program made in Microsoft Visual Basic is developed to automate the scale-up calculations for corn growing and corn wet-milling. For corn growing a more sophisticated program is developed to scale-up the factors to be used throughout the respective spreadsheets instead of directly scaling-up the actual values in the spreadsheet. The scale-up program developed for the corn-wet milling process was similar to the polyethylene scale up process in that the scale-up is performed directly on the values in the spreadsheet. Regardless, by clicking on the scale button located in the corn growing input spreadsheet and in the corn wet-milling input spreadsheet, the energy, input and output data are scaled by the desired factor. This leaves all energy, input and output data on a per 17000 ft^3 basis. The data will be presented in this manner—in relation to the reference flow that is based on the functional unit of this study.

Chapter 6: Life Cycle Impact Assessment

All energy data and impact results presented in this section are based on the functional unit of providing the foam necessary to cover 50,000 laptops for packaging. This corresponds to producing about 17000 ft^3 of foam, which is the reference flow. While each production segment isn't separated due to how the data is received, portions of the production process that could be shown in segments are presented accordingly. To recap the origins of the data sets or systems involved in this study, review Table 3 or Figure 8 respectively. The results presented in this section are from the specific data sets mentioned and covers the particular system being investigated.

6.1 Energy Data Results

6.1.1 Polyethylene Foam

Table 5 represents the energy associated with producing polyethylene foam based on the functional unit of this study. The reference flow is located in

For production of 17000 ft^3 foam	Electricity	Oil fuels	Other fuels	Final Total by energy type
Feedstock Energy	0.00E+00	4.13E+05	3.32E+05	7.45E+05
Transport Energy	7.87E+03	1.21E+03	2.80E+02	9.36E+03
Fuel Energy	5.79E+04	9.19E+04	8.71E+04	2.37E+05
Fuel Prod. & Delivery Energy	1.27E+05	2.26E+03	4.50E+03	1.33E+05
LDPE Production Total	**1.92E+05**	**5.08E+05**	**4.24E+05**	**1.12E+06**
Foam Extrusion	2.61E+03	0.00E+00	0.00E+00	2.61E+03
Final Total by fuel type	1.95E+05	5.08E+05	4.24E+05	**1.13E+06**

Table 5. Summary of energy (MJ) related to PE foam production

the upper left corner. The lower right corner represents the total energy from the entire system. The totals associated with LDPE production are bolded in the lower half of the table. Totals by fuel type (electricity, oil fuels and other fuels) are shown in the last row and totals by the type of energy are shown in the last column.

From the results, it is clear that polyethylene production dominates the energy consumption in the overall process. Foam extrusion is only 0.2% of the total energy consumed in the process. Comparison by fuel types lead to fuels derived from crude contributing the most to energy consumption. The oil fuels group is followed by the other fuels group (mostly natural gas, but also coal, wood, sulfur etc...) and electricity turns out to be the lowest contributor to energy consumption according to the data. Comparison by types of energy points to the feedstock energy as the highest contributor to energy consumption followed by fuel energy, fuel production and delivery energy and transport energy in that order. Figure 19 depicts the latter comparison and relates the types of energy to fuel types. While oil fuels are the greatest contributor to energy consumption in general, oil fuels only dominate in the feedstock energy and fuel energy categories. On the other hand with electricity being the least contributor to energy consumption, it dominates in the fuel production and delivery energy and the transport energy. Figure 20 shows the percent distribution of the types of energy by fuel types that supports the previous statement. The fuel energy category utilizes from about 18 to about 30 percent of each fuel type category. For foam extrusion all energy is consumed via electricity.

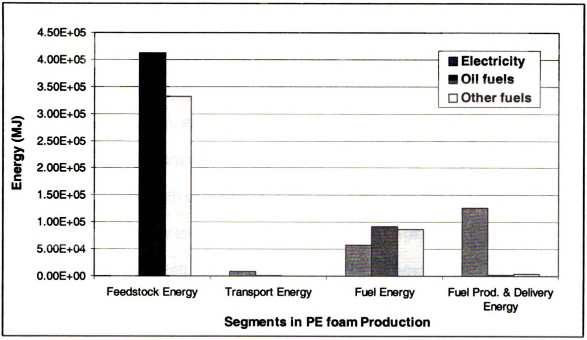


Figure 19. PE foam production energy consumption by type of energy

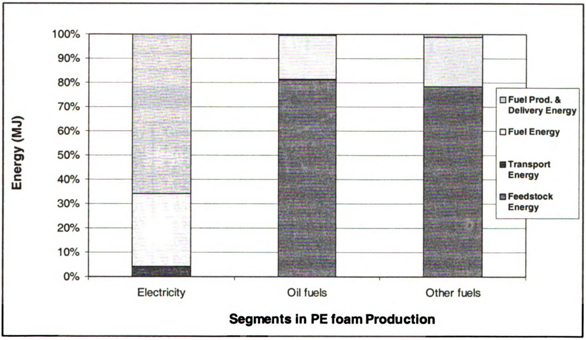


Figure 20. Distribution of PE foam production energy consumption

6.1.2 Starch Foam

The energy data shown in Table 6 is for starch foam. The energy is based on the functional unit of this study. The data in Table 6 represents the energy associated with corn growth, corn wet-milling and foam extrusion. Table 6 incorporates energy from various fertilizers, pesticides and fuel types. To accommodate the length of the table, it has been split into the two pieces. The second half of the table is shown right below the first. Again, the reference flow is located in the upper left corner, and the lower right corner of the lower table represents the total energy from the entire starch production system. The totals

For production of 17000 ft^3 foam	N	P	K	Herbicide	Insecticide	Lime
E Feedstock Energy	9.32E+03	9.77E+03	7.21E+00	1.01E+03	4.04E+01	3.86E+01
E Fuel Energy	1.16E+04	1.92E+03	1.29E+03	2.80E+03	1.41E+02	3.46E+02
E Non Renewable Energy	2.08E+04	1.17E+04	1.28E+03	3.75E+03	1.78E+02	3.83E+02
E Renewable Energy	8.97E+01	7.39E+00	1.90E+01	5.47E+01	3.00E+00	1.41E+00
Corn Growing Totals	**2.09E+04**	**1.17E+04**	**1.30E+03**	**3.80E+03**	**1.81E+02**	**3.85E+02**
Corn Wet Milling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Foam Extrusion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Starch Final Total	2.09E+04	1.17E+04	1.30E+03	3.80E+03	1.81E+02	3.85E+02

	Diesel	Electricity	Gasoline	Natural Gas	LPG	Totals
E Feedstock Energy	9.29E+03	1.13E+00	1.29E+03	5.75E+02	2.77E+03	3.41E+04
E Fuel Energy	1.56E+03	1.33E+03	3.35E+02	1.23E+02	3.65E+03	2.50E+04
E Non Renewable Energy	1.08E+04	1.30E+03	1.62E+03	6.98E+02	6.42E+03	5.89E+04
E Renewable Energy	1.03E+01	3.76E+01	1.85E+00	1.24E-01	3.27E+00	2.28E+02
Corn Growing Totals	**1.09E+04**	**1.33E+03**	**1.62E+03**	**6.98E+02**	**6.43E+03**	**5.92E+04**
Corn Wet Milling	0.00E+00	5.51E+03	0.00E+00	2.21E+04	0.00E+00	2.77E+04
Foam Extrusion	0.00E+00	1.56E+04	0.00E+00	0.00E+00	0.00E+00	1.56E+04
Starch Final Total	1.09E+04	2.25E+04	1.62E+03	2.28E+04	6.43E+03	**1.02E+05**

Table 6. Summary of energy (MJ) related to starch foam production

associated with corn growing are bolded in the lower half of the table. Totals by main inputs are shown in the last row of the entire table and are shaded gray. Totals by the type of energy are in the last column of the lower table.

The energy data for starch foam shows that corn growing dominates the energy consumption followed by corn wet-milling and foam extrusion in that order. Of all the fertilizer inputs, nitrogen production contributed the most with about 21K MJ of energy followed by phosphorous and potassium production. Comparing pesticides and/or additives, herbicide is the largest contributor to energy consumption followed by insecticide, then lime respectively. Lastly, comparing all the fuels, diesel by far is responsible for the largest energy consumption. Liquified petroleum gas (LPG) followed by electricity, gasoline then natural gas follow diesel in energy consumption.

Focusing on corn growing, the fertilizers and pesticides and the respective

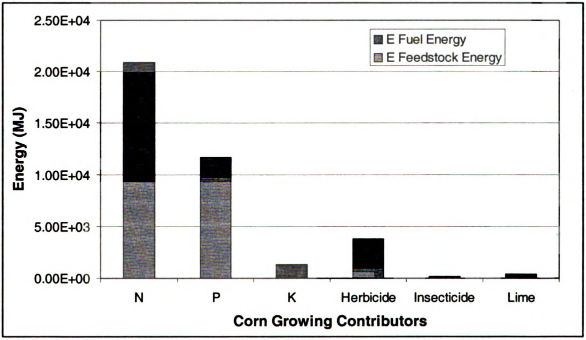


Figure 21. Starch foam corn growing phase energy (fertilizers and herbicides)

fuel and feedstock energy in Figure 21. The feedstock energy only has a significant presence in nitrogen, phosphorous and herbicide production, while fuel energy is present in significant portions in all of the fertilizers and in almost all of the pesticides. On the contrary, Figure 22 below shows that feedstock energy is present in all fuel types except electricity, while fuel energy is present in

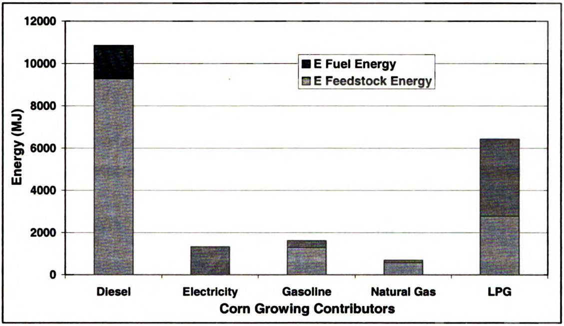


Figure 22. Starch foam corn growing phase energy (fuels)

all of the fuel types and dominates only in the electricity and the LPG categories.

With the focus still on corn growing, Figure 23 below shows the non-renewable energy for all major inputs (fertilizers, pesticides, fuels). The key non-renewable, energy consumption contributors are nitrogen, phosphorous, diesel and LPG. Of all the main inputs, nitrogen production consumes the most non-renewable energy, followed by phosphorous, then diesel, then LPG production. Taking notice of the energy scale in Figure 23 displaying the non-renewable

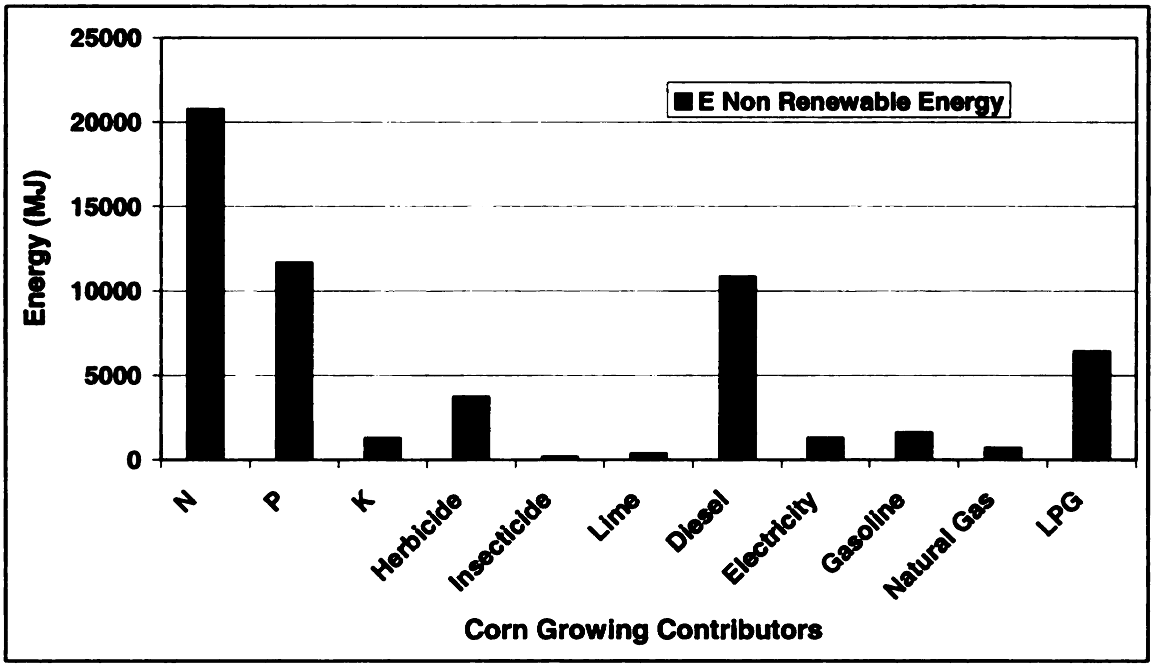


Figure 23. Non-renewable energy from starch foam corn growing phase

energy associated with each major input in corn growing, the renewable energy portion is only a small percentage. However, when the renewable energy for each major input is compared the results can be seen in Figure 24.

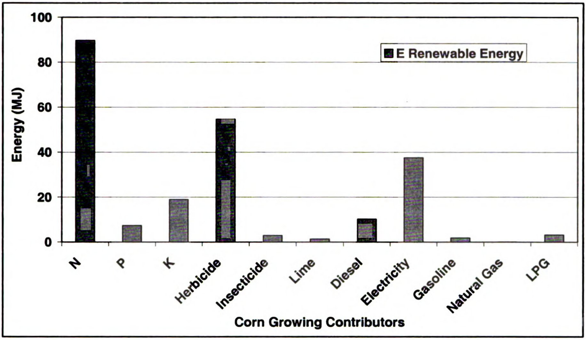


Figure 24. Renewable energy from starch foam corn growing phase

Interestingly, the key players in renewable energy are now nitrogen, herbicide, electricity and potassium in that order. Compared to each other, the production of these inputs contributes significantly to renewable energy. The only major input that did not contribute any renewable energy is the fuel, natural gas.

Table 6 (first table under starch foam) shows that the corn wet mill and foam extrusion processes are small contributors to energy consumption once compared with the corn growing process. However, taking a look at the distribution of fuels in corn growing, corn wet-milling and foam extrusion separately shows which fuels made major contributions to each segment.

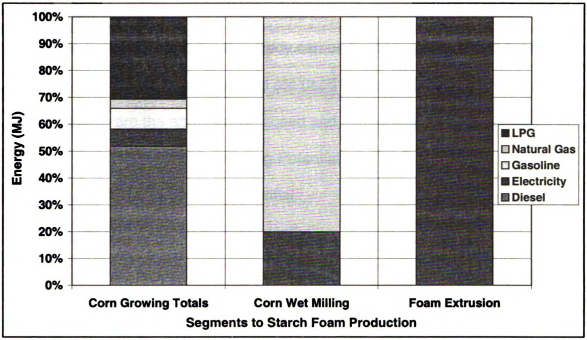


Figure 25. Energy from starch foam production by segments and fuel type

Figure 25 shows the only contributor to foam extrusion is electricity. For corn wet-milling the only two contributors are electricity and natural gas of which natural gas is responsible for the largest energy consumption in this segment. Corn growing contributions to energy have been discussed.

Overall, both foams contribute significantly to energy consumption based on the given functional unit. Table 7 shows the total energy consumed based on, not only the functional unit, but also on the system studied for both starch and polyethylene foams. The starch foam final energy total is over one order of magnitude less than that of the low-density polyethylene foam final energy.

For production of 17000 ft^3 foam	Total Energy
Starch Final Total	1.02E+05
LDPE Final Total	1.13E+06

Table 7. Total energy (MJ) for starch and PE foam production

6.2 Impact Assessment Results

The impacts covered in this study can be found in the goal and scope segment of the thesis. Abbreviations are used to simply the presentation of the graphs. Below are the abbreviations used and the corresponding potential.

- GWP: Global Warming Potential
- AP: Acidification Potential
- EP: Eutrophication Potential
- CP: Criteria Air Pollutant Potential
- HP: Human Health Potential
- SP: Smog Potential
- OP: Ozone Potential
- ECP: Ecological Toxicity Potential

The order in which the potentials are listed here are the same way they are listed in the graphs.

6.2.1 Polyethylene Foam

The overall results for the impact assessment, based on the functional unit

Production of 17000 ft^3 foam	GWP	AP	EP	CP	HP	SP	OP	ECP
Normalization Values	2.558E+07	7.800E+08	1.921E+04	1.920E+04	1.588E+08	1.515E+05	3.402E+02	8.165E+04
PE Foam (PF)	2.783E+07	5.660E+06	2.189E+03	1.102E+03	1.818E+08	6.116E+04	1.307E+01	8.009E+03
Normalized PF Values	1.088E+00	7.257E-03	1.139E-01	5.737E-02	1.145E+00	4.037E-01	3.841E-02	9.809E-02
PE Plant/Extrusion (PEP)	2.773E+07	5.546E+06	2.166E+03	1.075E+03	1.818E+08	6.047E+04	1.307E+01	8.009E+03
Normalized PEP Values	1.084E+00	7.110E-03	1.128E-01	5.599E-02	1.145E+00	3.991E-01	3.841E-02	9.809E-02
Transport (Trans)	1.005E+05	1.144E+05	2.238E+01	2.647E+01	0.000E+00	6.937E+02	0.000E+00	0.000E+00
Normalized Trans Values	3.927E-03	1.466E-04	1.165E-03	1.379E-03	0.000E+00	4.579E-03	0.000E+00	0.000E+00

Table 8. Summary of impact assessment for PE foam production

related to producing 17000 ft^3 of polyethylene foam, can be seen in table 8. The normalization values developed by EPA and NIST are in the second row. The polyethylene (PE) original values are divided by the normalization values and the resulting, normalized value is shown under each original value, respectively. In most cases, the normalization value was greater than the calculated PE foam values. However, in two cases the PE foam values were actually greater than the normalization values (GWP and HP).

The impact results from assessing the LCI for polyethylene foam lead to the normalized results in Table 8 and also Figure 26. Figure 26 gives a graphical view of the LCI data from PE foam production. The potentials that carry the most weight in regards to polyethylene production include global warming, human

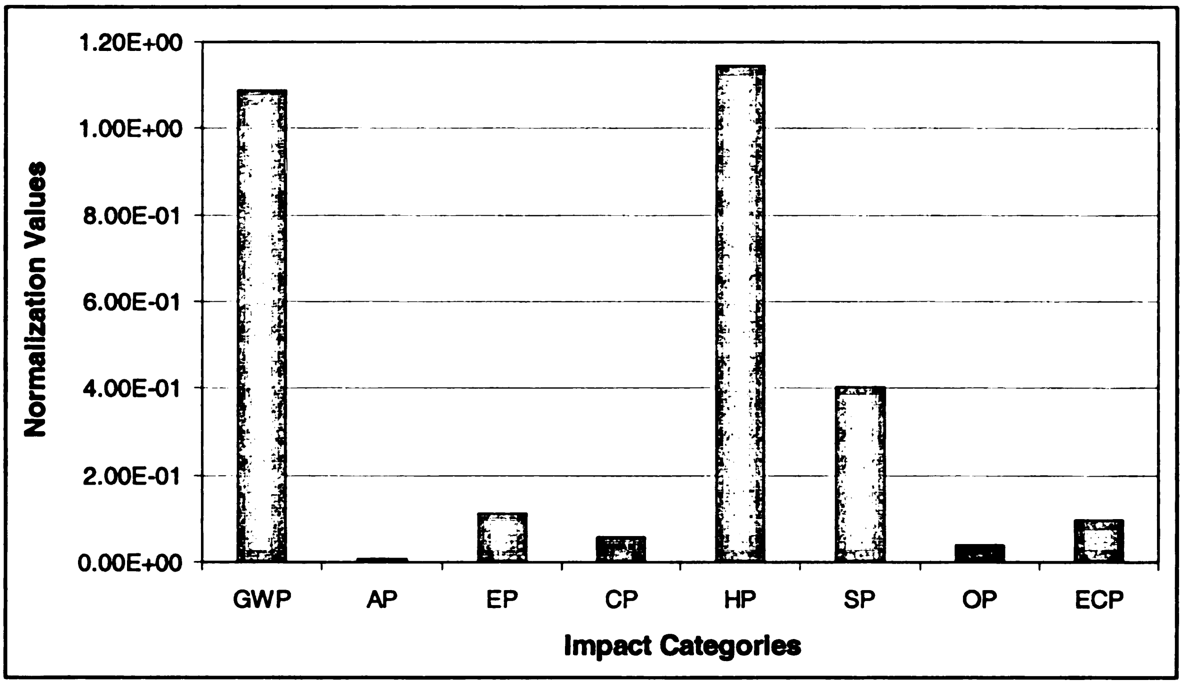


Figure 26. Normalized impact assessment results for PE foam production

health, and smog potential. The potential carrying the least weight is the acidification potential. The remaining potentials fall in between.

To gain a better understanding of how the impacts are distributed on a percent basis Figure 27 is shown below. Compared to all the impacts, the human health potential makes up 39% of the impact of PE foam on the environment, while the global warming potential from producing PE foam, with 37%, follows closely. The next major contributor responsible for 14% of the total impact from PE production is smog potential. The remaining potentials follow accordingly with the next being the eutrophication potential (4%), the ecological toxicity potential (3%), the criteria air pollutant (2%), the ozone potential (1%) and finally the acidification potential (almost 0%).

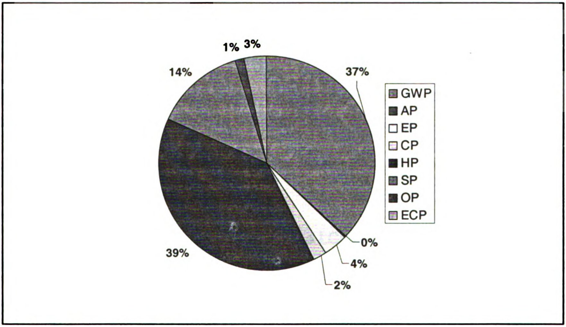


Figure 27. Percentage distribution of each impact category in PE production

6.2.2 Starch Foam

The overall results for the impact assessment, based on the functional unit related to producing 17000 ft^3 of starch foam, can be seen in table 9. The normalization values developed by EPA and NIST are, again, shown below in the

Production of 17000 ft^3 foam	GWP	AP	EP	CP	HP	SP	OP	ECP
Normalization Values	2.558E+07	7.800E+08	1.921E+04	1.920E+04	1.588E+08	1.515E+05	3.402E+02	8.165E+04
Starch Foam (SF)	6.060E+06	1.698E+06	2.709E+03	9.170E+02	1.285E+08	2.106E+04	1.702E-02	1.781E+03
Normalized SF	2 369E-01	2 177E-03	1.410E-01	4.776E-02	8 093E-01	1.390E-01	5.004E-05	2.181E-02
Corn Growing (CG)	4.534E+06	1.495E+06	2.464E+03	8.585E+02	1.284E+08	1.480E+04	1.702E-02	1.516E+03
Normalized CG Values	1.772E-01	1.917E-03	1.282E-01	4.471E-02	8.086E-01	9.766E-02	5.004E-05	1.857E-02
Corn Wet Mill/Extrusion (CWM)	1.185E+06	3.531E+04	7.386E+01	3.960E+01	0.000E+00	1.086E+03	0.000E+00	0.000E+00
Normalized CWM Values	4.631E-02	4.527E-05	3.844E-03	2.062E-03	0.000E+00	7.167E-03	0.000E+00	0.000E+00
Transport (Trans)	3.415E+05	1.671E+05	1.711E+02	1.891E+01	1.028E+05	5.176E+03	0.000E+00	2.651E+02
Normalized Trans Values	1.335E-02	2.143E-04	8.904E-03	9.848E-04	6.476E-04	3.416E-02	0.000E+00	3.247E-03

Table 9. Summary of impact assessment for starch foam production

second row. The starch foam original impact values are divided by the normalization values and the resulting, normalized value is shown under each original value respectively. In all cases the normalization value was greater than the calculated starch foam values. The human health potential value from producing starch foam is the closest to the respective U.S. normalization value being the lesser value by about 0.3 units.

The impact results from assessing the LCI for starch foam lead to the normalized results in Table 9 and also Figure 28. Figure 28 gives a graphical view of the LCI data from starch foam production. The ozone and acidification potentials from starch foam production are, for all practical cases, non-existent. All the other potentials are around or below the 0.2 mark in relation to the study guidelines and the U.S. normalization values. By far, the potential carrying the

most weight in regards to starch foam production is the human health potential. The normalization value for the human health potential is slightly over 0.8, which is still below the U.S. normalization values. Notice that the same scale used to show the normalization values for PE foam is used for starch foam.

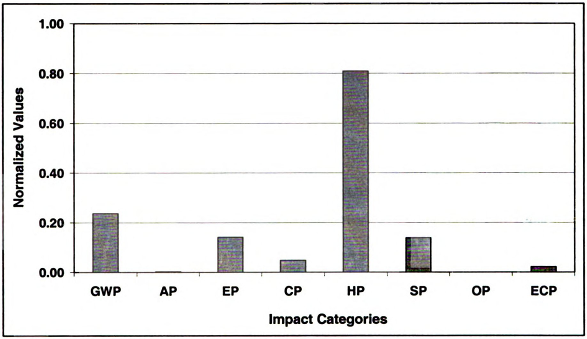


Figure 28. Normalized impact assessment results for starch foam production

To gain a better understanding of how the impacts are distributed on a percent basis Figure 29 is shown below. Compared to all the impacts, the human health potential makes up 58% of the impact of starch foam on the environment, while the global warming potential, with 17%, trails behind. The next contributors responsible for 10% each of the total impact from starch production are the eutrophication and smog potential. The criteria air pollutants and the ecological toxicity potentials follow with 3% and 2% respectively. The other potentials (ozone and acidification potentials) do not contribute significantly under this assessment. They make up virtually 0% of the total impact.

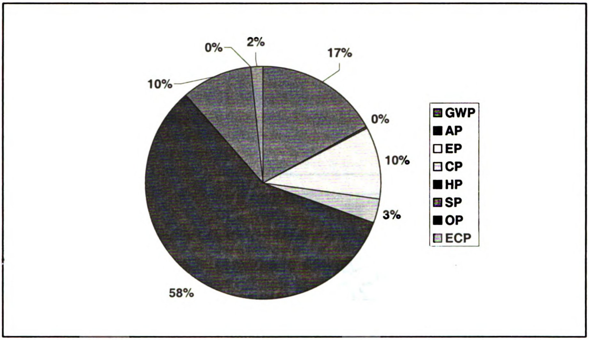


Figure 29. Starch production % distribution of each impact category

6.2.3 Polyethylene and Starch Foam

Considering the systems studied and based on the information gathered, polyethylene and starch foams both contribute to the environmental impacts studied, but in different magnitudes. The normalized values of both polyethylene and starch foam are shown below, side by side, in Figure 30. In PE foam production, the normalized values confirm that all the potentials studied impacted the environment. From greatest to least contributor is the global warming, human health, smog and eutrophication, ecological toxicity, criteria air pollutants, ozone and acidification potentials. In starch foam production, the normalized values confirm that all but one of the potentials studied contributes to the environment. From greatest to least contributor is the human health, global warming, eutrophication, smog, criteria air pollutant, ecological toxicity and acidification potentials. The ozone potential, in all practicality did not impact the environment from starch foam production. The impact from the acidification potential is also almost non-existent.

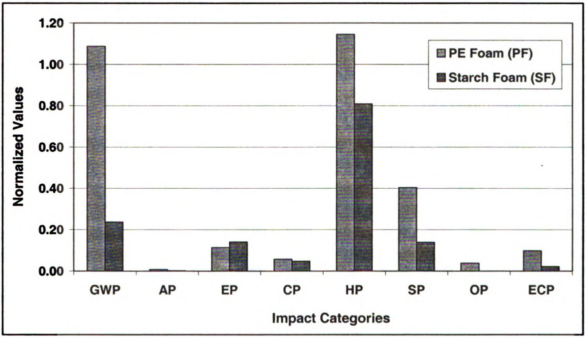


Figure 30. Normalized impact assessment results for PE and starch foams

Of the eight impact categories covered in this study, seven are dominated by PE foam production. The ozone potential is only existent because of polyethylene foam production. The global warming potential is almost 5 times greater than the global warming potential of starch foam. The human health potential follows by contributing about 30% more via PE foam production when compared to starch foams. The smog and ecological toxicity potentials for PE foam are roughly 67% and 78% larger, making them about three and over four times larger than the normalized values for starch foam production, respectively. In terms of the criteria air pollutant potential, PE foam production continues to dominate by being 20% larger than starch foam production normalized value. Taking a closer look at the relatively small acidification potential, PE foam manages to be 71% or over 3 times greater than the associated starch production value. The only potential that PE foam production does not dominate is the eutrophication potential, and while starch foam production dominates the potential, it is only by 19%.

Figure 31 displays percentages for each product impact contribution on a 100% basis when the total impact for a particular category is considered. The

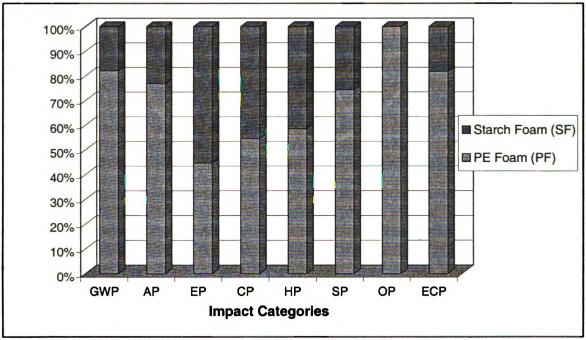


Figure 31. PE and starch foams % distribution of impact assessment

domination of starch foam production or polyethylene foam production in each impact category can be easily seen. Even when normalized to the total form each impact category for starch and polyethylene production, the starch foam production only dominates in one of the eight impact categories—the eutrophication potential.

Chapter 7: Life Cycle Interpretation

The life cycle interpretation phase of the LCA provides conclusions and recommendations based on the goal set forth in the beginning. To recap, the goal of the research is to gain insight on the environmental performance of polyethylene and starch foam by performing a comparative life cycle assessment. The completion of the assessment, allows for recommendations regarding the LCA methodology used. This segment covers discussions regarding energy and impact results, any corresponding limitations, and recommendations relating to the study and to the LCA methodology.

7.1 Life Cycle Impact Assessment Results and Limitations

The energy result of this study is particularly interesting. The results shows that to produce 17000 ft^3 of polyethylene foam with a 0.85 kg/ft^3 density to package 50,000 laptops, almost eighteen times the amount of energy required by starch, under the same conditions, would be required for PE foam. The feedstock energy used to produce the polyethylene foam is truly where most of the energy use came from, accounting for roughly 66% of the total energy for polyethylene foam production. Furthermore, the fuels derived from oil made up over 50% of the total feedstock energy. The results indicate that polyethylene foam production is a very energy-intensive process. Considering that starch foam production takes a significantly lower amount of energy to produce, it is a very financially attractive option in terms of energy, being that energy prices are at an all-time high.

Another area in which the price can be high is in environmental fines if key emissions are not kept at a desired level set by EPA. Equally important, although less visible, is the environmental impact left by the production of polyethylene and starch foam. In relation to United States standards (via normalization) starch foam production is lower in all categories, indicating the values are below 1. In relation to polyethylene foam production, starch foam only dominates in the eutrophication potential and not by much. In addition, the overall impact category potential is still significantly less than the U.S. associated normalization value. Emissions such as ammonia, nitrous oxides, and nitrogen oxides are the key emissions that caused starch foams to dominate in this category. There is a spike in nitrogen oxides because in the case of both polyethylene and starch foam, they are generated via diesel production and diesel use in transportation. However, starch foam production also generates nitrogen oxides from fertilizers and pesticides. This additional source of emissions is responsible for the eutrophication potential results. Besides the eutrophication impact category, all the other impact categories are dominated by polyethylene foam production.

Polyethylene foam production dominates the seven other impact categories. At the root of PE foam production is oil production. Most of the resulting emissions can be attributed to fuel related segments in the overall PE foam production. Polyethylene pellet production is tied to the major contribution of crude production to energy and impact results, along with the associated emissions. Any ability to decrease the amount of PE used to make the same product would greatly benefit the impact resulting from polyethylene foam production.

These results show that both polyethylene foam and starch foam have room for environmental improvement. The ability to identify exactly why impacts are a certain value is related to the ability to identify where emissions were generated. The modular format used by Cargill Dow [19-21] to record data is truly valuable in being able to identify areas of the process that need to be improved. The results show that while there are impact advantages to both polyethylene and starch foams, there are disadvantages to both as well. However, polyethylene foam dominates seven of the eight impact categories, being the only contributor to the ozone depletion impact category while starch foam only dominates one of the eight impact categories. Thus based on the study parameters, starch foam is by far a better product for the environment than polyethylene foam.

Notwithstanding, continuous improvement on the starch foam production process is key to truly moving towards making an environmentally friendly product. Finding alternative fertilizers and pesticides or improving upon the fertilizers and pesticides that are available are simple ways to continue to improve the starch foam production process. Paying attention to the data collected leads to improvement, but closer attention to the data itself, is required.

While there are many limitations to life cycle assessments, data is the main limitation in the study. The most significant limitation from this study is, not surprisingly, the lack of data. Although providing detailed and ample data is

great for completing an LCA, providing this data also increases the probability that impacts for processes providing ample data may be greater than impacts for other processes where much data was not available. In this case, it is unrealistic to conclude that one process or product is better than the other. Data limitations may also call for estimations based on research, or the technical knowledge of the practitioner. This can also add to the inability to make conclusions on the results. One other limitation related to data is not being able to extract information due to the way the data is collected and recorded.

7.2 Recommendations: Study and LCA methodology related

Recommendations as a result of the study range from nationwide initiatives to more research to methodology improvements. They are listed below.

1. Polyethylene foam production can benefit by finding environmentally and economically attractive fillers. By introducing fillers the amount of PE used could be reduced, thereby reducing the contribution from fuel production and fuel use, resulting in an overall decrease in various impacts.
2. Modifying and/or eliminating fertilizers and pesticides to assist in reducing nitrogen oxide emissions and energy consumption can improve starch foam production.
3. To improve eutrophication results of starch foam consider improving processes connected to corn growing:
    a. Reduce the ammonia contribution mainly in nitrogen production.

b. Reduce nitrogen oxide contribution by using alternative fuels such as bio-diesel.
c. Reduce nitrous oxides by limiting N_2O emissions coming directly from the field.

4. Continue research on the results, taking a closer look to identify other improvement opportunities that may not be as apparent.
5. Study results if different composition combinations of a starch-polyethylene foam is used.
6. Identify transportation contributions to each system.
7. Incorporate end-life stages into the study to account for a cradle-to-grave assessment because much of benefit of starch foam is in its ability to decompose via composting.
8. Incorporate recycling and/or re-use as an after-use segment and study the effects on the overall results.
9. Develop nationwide initiative to gather basic data from different industries anonymously to aid in the development of highly reliable LCA's.
10. Define key emissions that should be included separately in the data collection phase to reduce the grouping of emissions into larger categories such as hydrocarbons versus methane, ethane and butane.
11. Incorporate modular recording and reporting in LCA procedure to assist with identifying improvement opportunities.

APPENDICES

Appendix A

Life Cycle Assessment Overview Introduction

Research on using LCA to understand the environmental impact of a product is gaining acceptance. The first ISO standard on LCA was developed in 1997. These ISO standards inform the reader that the standards developed only serves as a guide to performing LCA's.

Life Cycle Assessment serves many purposes and it encompasses a lot of information. The main purpose of an LCA is to examine the environmental portfolio of a product and report findings in a fair, accurate and concise manner. Embodying a cradle-to-grave ideology—incorporating inputs and outputs ranging from raw material acquisition to transportation contributions to final disposal of the product—is an important aspect of examining a products impact on the environment. Thus, the inputs and outputs gathered along with other information must be managed appropriately. Another purpose of LCA is to assist in making decisions. It is not the basis for making a decision. The iterative nature of an LCA allows for continuous incorporation of new data as it becomes available, and shows the evolving nature of the assessment while encouraging the idea of having additional factors to make a decision. LCA is also useful to benchmark a product to another product or to accepted standards to gain an understanding of the relative position of the studied product. Furthermore, LCA is a tool to guide the environmental process improvements of a product.

There are many steps to complete before an LCA may be used to assist in decision-making. The diagram below highlights the various phases of an LCA as described in ISO 14040.

Appendix A

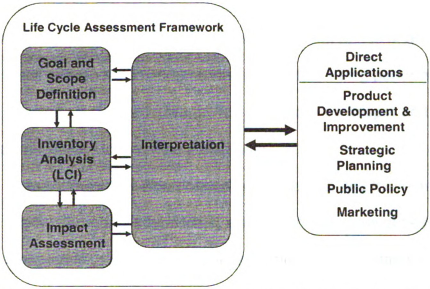


Figure 1: Phases of a Life Cycle Assessment as demonstrated in ISO 14040

As identified by the ISO 14040 standard, the framework of an LCA shown in Figure 1 includes the four main components listed below.

1. The definition of a goal and scope
2. Life cycle inventory analysis
3. Life cycle impact assessment
4. Life cycle interpretation

Each of these components is discussed in detail in the ISO 14040 series (1997 – 2000). For the purpose of this study, synopses of these components are discussed succinctly.

Appendix A

Goal & Scope

Defining the goal and scope of the study is the first phase of an LCA. The goal of the study is intended to address why the study is being performed along with whom the study is directed toward. The scope delves deeper and considers all the details necessary to meet the stated goal.

The scope of the study incorporates several areas, and these areas are mentioned briefly. A product's function(s) and functional unit must be identified and derived respectively. A functional unit, as defined by ISO Standard 14040, is the quantified performance of a product system for use of defining reference unit in an LCA study. The product system and system boundaries must also be drafted under the scope. The types of environmental impacts being considered in the study, as well as assumptions and limitations must be concisely included under the scope. These are the main areas of discussion included in the scope.

Life Cycle Inventory (LCI)

The LCI phase involves the gathering of data from sources and/or by calculations. Having the system boundaries defined, any significant inputs of resources such as land, material, energy, electricity, water, or fuel must be identified. Similarly, outputs such as product(s), or emissions to the air, water or land, must be identified. Allocating energy and/or materials to products that are not the focus of the study along with system expansions are both common activities to perform in this segment of the life cycle assessment.

Appendix A

Allocation and System Expansion:

When comparing two systems, the systems must be equal in terms of what is being produced. Allocation becomes necessary when there are multiple products in a process. The environmental burden associated with the system inputs must be allocated to all products that are formed as a result. The product being studied should not retain the entire burden of the system, but instead the outputs should be dispersed on a basis that fairly accounts for the contribution of one product relative to the others.

There are several bases for allocation. There can be an economic basis, which would then incorporate the fluctuating economic market prices and the associated economic values of products. One can allocate based on moles, volume, conductivity and more. Most commonly, however, allocation is done on a simple mass basis. For example, if product A makes up 60% by mass of all the products (B, C, and D) that came as a result of the production then 60% of all the inputs and outputs associated with the system would go to product A. One drawback to this method is that all the inputs and outputs may not have been related to product A.

To avoid allocation, system expansion is encouraged. System expansion is where the process in broken down into the most simple units and each unit input and output is allocated to the appropriate product. If the simplest unit still produces more than one product, then allocation is, again, considered and/or performed.

Appendix A

LCI importance to Life Cycle Impact Assessment (LCIA):

Once the data has been gathered, and allocations and/or system expansions are performed as necessary, the next component of life cycle assessment can be conducted. It is from the life cycle inventory data that the next phase is carried out. This data must be compiled in a concise manner making sure that all data sources are documented.

<u>Life Cycle Impact Assessment</u>

The data from the life cycle inventory is used along with the impact categories decided upon in the scope. This is where emission data is related to specific environmental phenomena such as global warming or acidification. Figure 2 shows some examples of emissions and the corresponding environmental impacts.

Possible Impact Categories	Related Emissions
Acidification	NO_x, SO_2
Ecotoxicity	NO_x
Enhanced Greenhouse Gas Effect	CO_2, CH4, N_2O,
Eutrophication	NO_x
Smog	NO_x, SO_2, CH4

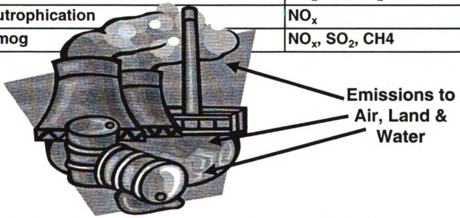


Figure 2: Example of Impact Categories and associated emissions

Appendix A

The methodology in this phase of the LCA as defined by ISO Standard 14042 follows the list shown below.

1. Selection of groups
    a. Impact categories – class representing environmental issues of concern
    b. Category indicators – quantifiable representation of an impact category; the category indicator may have units
    c. Characterization models – model applied to convert the assigned LCI results to the common unit of the category indicator
2. Assignment of LCI results to the impact categories (classification)
3. Calculation of category indicator factor to get impact category results

Once the potential impact category values are calculated, they are normalized to U.S. standards. The U.S. has compiled environmental values based on overall U.S. production for eleven impact categories. When the calculated value being studied is normalized to the U.S. value (by division), a value less than one indicate that the product environmental contribution has not exceeded the U.S. standards. Respectively, when the calculated value being studied is normalized to the U.S. value (by division), a value greater than one indicates that the product's environmental contribution has exceeded U.S. standards. After normalization, in a comparative study, products being studied are compared to one another

Appendix A

Sensitivity Analysis:

After the impact assessment results are calculated, performing sensitivity analyses is a common procedure. Sensitivity analyses entails studying the effect on the end results when key parameters are changed by some percentage. For example, if a certain input has a range of values, a sensitivity analysis can be performed to understand how sensitive the results are to that input by using the high and low values in a sensitivity analysis.

Life Cycle Interpretation (LCI)

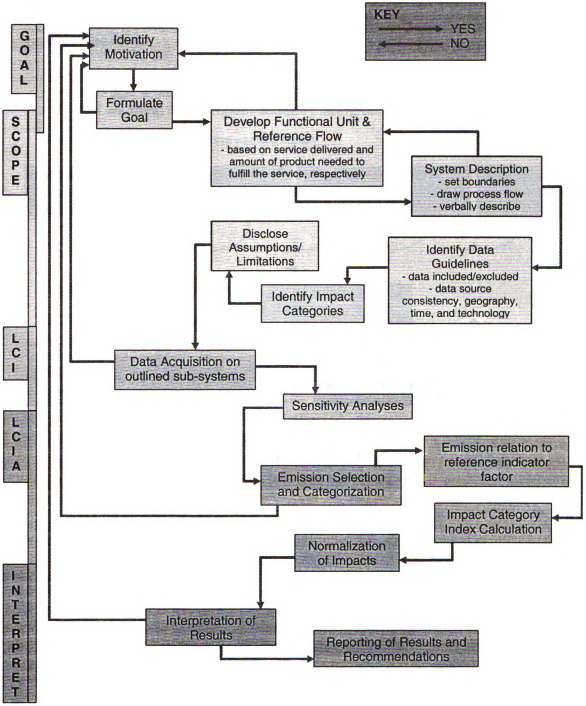
The life cycle interpretation component of the LCA framework involves (1) the analysis of results, (2) the formation of conclusions, incorporating limitations and (3) the making of recommendations based on findings of both the impact assessment and inventory analysis. It is important that this interpretation is consistent with the goal and scope defined initially and/or modified subsequently.

Concluding Life Cycle Assessment Overview:

LCA is a strong tool to environmentally evaluate old and new products. It is key to understanding a product's environmental contribution. More importantly, and less obvious is the ability of LCA to be used for benchmarking and process improvement.

LCA is an iterative approach to understanding a product's environmental impact. After completing a phase it may have to be modified and this affects all the other phases. While each component can be completed independently of the another, these components are very much intertwined. Overall, the defined approach set out by ISO Standards is only a guide and any opportunities to improve the assessment should be considered.

Appendix A


KEY
YES
NO
GOAL
SCOPE
LCI
LCIA
INTERPRET
Identify Motivation
Formulate Goal
Develop Functional Unit & Reference Flow
- based on service delivered and amount of product needed to fulfill the service, respectively
System Description
- set boundaries
- draw process flow
- verbally describe
Disclose Assumptions/ Limitations
Identify Data Guidelines
- data included/excluded
- data source consistency, geography, time, and technology
Identify Impact Categories
Data Acquisition on outlined sub-systems
Sensitivity Analyses
Emission relation to reference indicator factor
Emission Selection and Categorization
Impact Category Index Calculation
Normalization of Impacts
Interpretation of Results
Reporting of Results and Recommendations

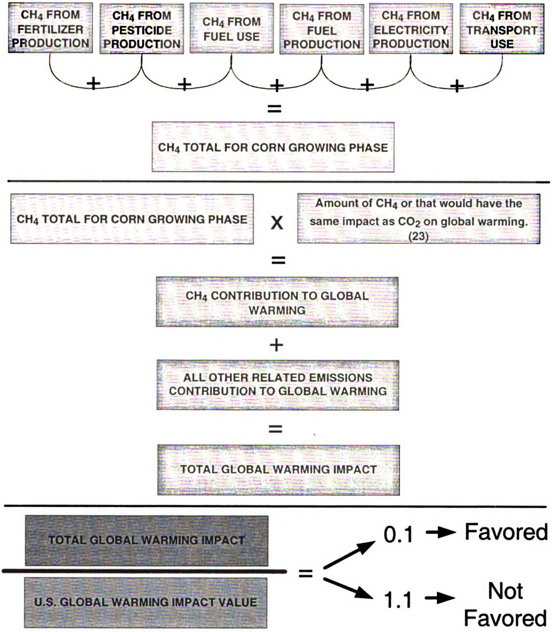
Appendix B

Sample calculation show emission to impact

Assumptions

- All emissions are already converted to CH_4 equivalents except methane
- Corn growing is the phase being considered
- An average amount of fertilizers, pesticides, fuel and electricity is known
- Global warming is the impact category being considered

Note: CH_4 is found only in the global warming impact



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