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An Evaluation of Environmental Impact Data Collection Methods Used in the Apparel Industry

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An Evaluation of Environmental Impact Data Collection Methods Used in the Apparel Industry

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Doctor of Environmental Science and Engineering

by

Elissa Faye Loughman

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ABSTRACT OF DISSERTATION

An Evaluation of Environmental Impact Data Collection Methods Used in the Apparel Industry

by

Elissa Faye Loughman

Doctor of Environmental Science and Engineering

University of California, Los Angeles, 2016

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The production and consumption of products and services is a major source of environmental impacts. With this in mind, the demand for environmental impact data on products and supply chains is increasing, and there is a need for companies to understand the best approaches to gathering reliable data for decision making. Life cycle assessment (LCA) is a commonly used measurement tool used to evaluate the environmental impacts of a product system. Businesses have an interest in understanding their environmental impacts but often don’t have the time or resources to commit to the academic approach of LCA to thoroughly assess all of their products and services.

The purpose of this research is to provide examples of how the corporate sector can optimize their resources to use LCA to measure the key environmental impacts in a product's life cycle. The environmental performance of products can improve by identifying critical issues present in the life cycle of products and taking constructive response actions. The apparel industry is the area of focus throughout this LCA research.

This dissertation a) uses a systematic review to examine the existing LCA research and data that is focused on the apparel industry, b) provides a case study of a collaborative approach to LCA using primary data from a supply chain vendor and a brand to develop a comprehensive product LCA, and c) examines the impacts of product packaging using LCA and an evaluation of product logistics to provide an example of how LCA and logistics systems can be used together to minimize environmental impacts.

LCA is a growing area of research and there is a substantial amount of data that has already been collected and shared via peer-reviewed publications, databases, and industry research. Industry professionals and academics can utilize existing data as a starting point for understanding the environmental impacts of their own products and processes. If there is a need for more specific product data, a collaborative LCA approach that engages supply chain partners to gather LCA data specific to the processes that they control proves to be an effective way to model a product system. In order to minimize data discrepancies it is essential for the participating companies to start with a consistent LCA methodology and commit to transparent data sharing.

Once the life cycle environmental impact data has been gathered, companies have an opportunity to evaluate the results and take action to reduce impacts. Packaging was used as an example of an opportunity to minimize the environmental impacts of a product system. The findings of the research highlight that if the company does not have control over the manufacturing and processing in a product system, opportunities to minimize impacts can be found within logistics and operational systems.

The dissertation of Elissa Faye Loughman is approved.

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2016

DEDICATION

I dedicate this dissertation to my parents, Ed and Susan Loughman.

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Chapter 1: The Case for Supply Chain Environmental Assessments in the Apparel Industry

Introduction

Climate change and the environmental damage that is being done to the Earth has become a growing concern in recent decades. The production and consumption of products and services is a major source of environmental impacts in our society (Tukker et al. 2006). In order to effectively make strides toward reducing environmental impacts, environmental considerations have to be integrated into a number of different types of decisions made by businesses, individuals, and policymakers (Nilsson and Eckerberg 2007). Various stakeholders such as governments, nongovernmental organizations (NGOs), and consumers play a role in addressing environmental impacts through regulations, advocacy, and consumption behavior. Though various stakeholders can play a role in driving changes that reduce society's impact on the environment, corporations stand out as one of the most important actors, as they have a great influence on society through their products and services, which support societal needs on a daily basis (Manda 2014). Companies are the primary organizers and drivers of resource flows and emissions from developed economies through their production of products and services (Berkhout 1997).

The necessity for a more sustainable approach to the production of consumer goods has been widely highlighted by international resolutions and directives as a key component to a more sustainable future. More and more, society is holding companies responsible for the social and environmental problems across the globe. It is important that companies consider the various corporate impacts they have on society and the environment and find ways that they can improve their contribution to society (Manda 2014). In order for businesses to be successful in a world with increasing consumer awareness, government legislation, scarcity of resources, and NGO activism, companies need to add environmental considerations into their business practices (Laszlo and Zhexembayeva 2011). In addition, the case has been made that companies have a tremendous amount to gain if they can proactively improve organizational sustainability performance by effectively integrating and addressing external pressures through their own practices. Sustainability efforts can be a source of opportunity, innovation, and competitive advantage (Porter and Kramer 2006).

In addition, NGO activity has been growing fast worldwide with the pursuit of environmental justice and to influence decision-making of corporations (O'Rourke 2005). Many international NGOs have dedicated campaigning programs to influence global production and consumption (O'Rourke 2005). The Institute of Public and Environmental Affairs (IPE), a Chinese NGO, focuses on identifying companies that are polluting or violating government regulations. Recently, IPE has collaborated with 20 NGOs and devised the Green Choice Alliance (GCA) program for responsible supply chain management. It intends to promote green supply chains by pushing large corporations such as brands and retailers to consider environmental performance of suppliers in procurement decisions (IPE 2014). As a collective group, the NGO community is broadening the awareness of consumers and making it known that programs and actions are needed to increase environmental considerations and improve transparency throughout value chains (Manda 2014).

Businesses have an opportunity to benefit from identifying the environmental impacts in their supply chains. Process improvements could lower energy and water usage and save operational costs (Worrell et al. 2003). Similarly, improving raw material utilization can save raw material costs and can reduce costs for handling and disposal of waste, driving the environmental footprint lower. Increased scarcity of raw materials such as water can lead to disruption of operations, or lost production activity, which will impact the revenue earning capacity. Such risks can be avoided by sustainability performance improvements in the supply chain (Koplin et al. 2007).

As pressure increases on brands to improve their environmental performance, it is important for them to communicate accurate information about the environmental practices in their operations. In order to do this, the primary and support functions of an organization need a reliable mechanism for evaluating environmental performance and implementing environmental reduction efforts. “You can’t manage what you can’t measure” is often stated in reference to the desire to manage environmental impacts. In order for a company to begin to work to reduce their environmental impacts, it is important for them to first measure their environmental impacts to determine where the high impact areas are in their business operations. Once environmental impacts have been measured, the knowledge gained should be used to inform how to reduce impacts going forward and can be used as the foundation of an environmental impact reduction strategy.

If businesses are going to be able to accurately address the key environmental issues caused by industry, environmental assessments need to go beyond a piecemeal approach and instead be based on an understanding of the interdependence of the various industrial systems involved in business operations. Approaching the integration of environmental impacts throughout business operations requires a holistic approach that includes learning about where raw materials come from, how they're made, and where they go when they are no longer being used. In order accomplish this, information on the environmental aspects of different systems is thus needed, as well as tools for assessing and benchmarking environmental impacts of different systems in a product life cycle (Finnveden and Moberg 2005).

Europe is leading the way regarding potential legislation requiring that brands measure the impacts of product using a life cycle approach. The European Commission has been working to formalize environmental regulations on products. In April 2013, the European Commission released the Product Environmental Footprint (PEF) Guide, along with the Organizational Environmental Footprint (OEF) Guide, under the premise of the "Single Market for Green Products Initiative" (EU PEF 2013). The Commission's actions are part of a larger recommendation toward sustainable consumption and production by the United Nations as well as the Commission itself.

The objective of the PEF Guide is to create a standard way for businesses to evaluate and communicate the environmental impacts of their products in order to enhance transparency and fair competition. The ultimate aim is to provide incentives to report and reduce environmental impacts. The PEF Guide is built on existing Life Cycle Assessment (LCA)-based product claim standards, such as ISO 14025, PAS 2050, BP X30-323, GHG Protocol, etc., and LCA standards and guides, such as ISO 14040, ISO 14044, and ILCD Handbook (EU PEF 2013). The PEF guide has emerged at a time when companies and other stakeholders have expressed a need for a well-established and broadly accepted product assessment methodology.

Brands that sell products in Europe, such as Patagonia, will be responsible for providing environmental impact information at the product level once this legislation is passed. It is important for brands to start establishing a system for gathering environmental impact data and conducting LCAs at the product level in order to prepare for the European Commission's legislation.

The life cycle approach to quantifying environmental impacts of products and systems, however, still has many limitations. Recent research that has focused on understanding these limitations found that there are two main needs in the scientific field of LCA: to increase the practicability of LCA and to increase consistency in methodologies (Zamagni et al. 2012). Practicability is the basic requirement to support real-world decisions in business and public policy making. Data quality and availability at reduced costs, simplified tools tailored to users' requirements, and approaches to uncertainty analysis, to mention a few, are nowadays still the object of further development (Zamagni et al. 2012).

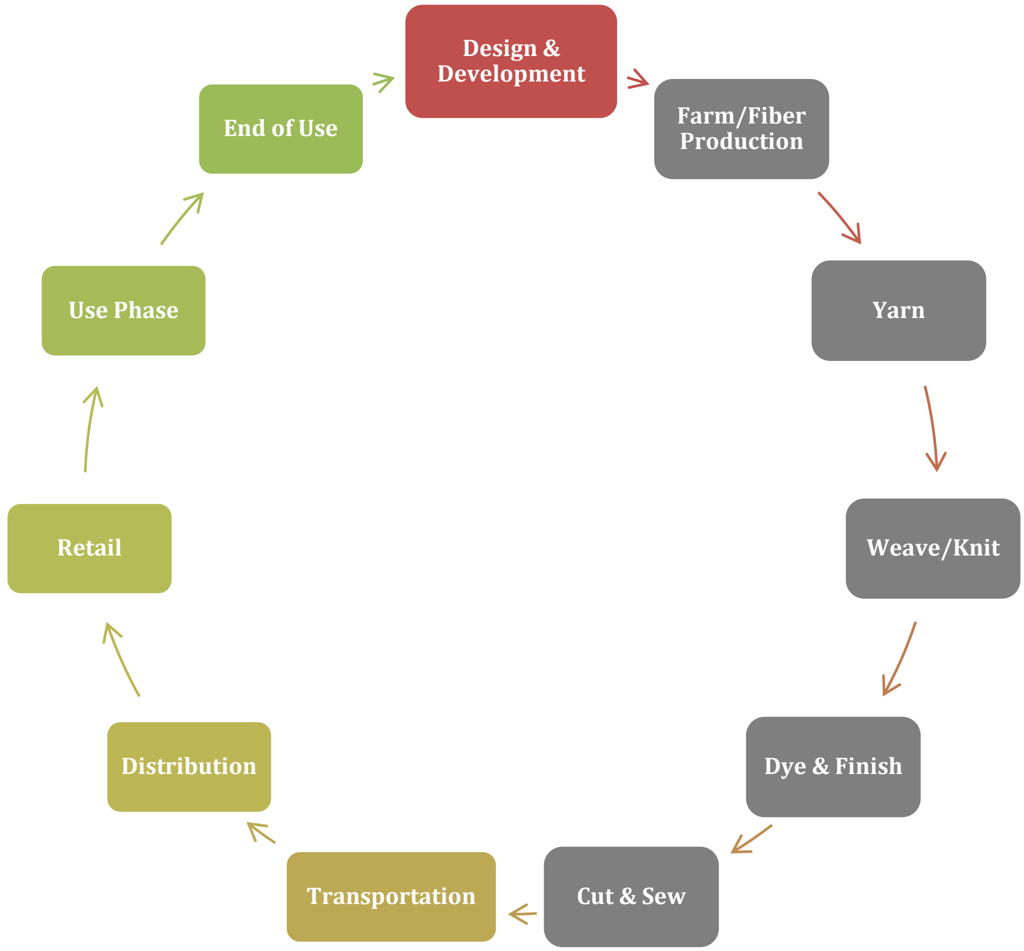
This research is focused on the initial measurement portion of the process businesses follow to reduce environmental impacts. This research bridges the gap between the academic approach and the corporate approach to environmental impact assessments by providing examples of how to use available resources to accurately measure the key environmental impacts in a product's life cycle.

Background and Significance

Fashion feeds a growing industry and ranks textile and clothing as the world's second-biggest economic activity for intensity of trade (Challa 2010). The global apparel industry is expected to generate $3,180 billion dollars in 2015 (Bodimeade 2013). With its growth comes an increase in environmental impacts. European Commission's Joint Research Centre (JRC) completed the *Environmental Impact of Products* (EIPRO) study in 2006. The study was conducted from a life cycle perspective and identified food and drink, transport, and private housing as the highest areas of environmental impact. Together they account for 70–80% of the environmental impact of consumption. Of the remaining areas, clothing dominated across all impact categories with a contribution of 2–10%.

Each of the five main industrial stages (shown in the grey boxes in Figure 1.1) typically required to make a garment have impacts on the environment. Within each of the five main industrial stages, there could potentially be several additional processes that occur, depending on fiber type and garment type. In addition to the manufacturing steps in the life cycle of a garment, the distribution, retail, consumer use, and end of use phases also result in environmental impacts. In order for brands to reduce those impacts, they must have an understanding of the processes that occur at each stage of the apparel life cycle.

Figure 1.1 Life cycle of an apparel product



Patagonia, Inc., based in Ventura, California, is a designer and retailer of alpine, fly-fishing, snow, surf, and sport-related apparel, equipment, footwear, and accessories. The brand is known primarily as a producer of durable outdoor apparel with an environmental ethic. Since the start of the company, Patagonia has incorporated environmental responsibility into product development and its business practices. Patagonia utilized a life cycle approach to measuring environmental impacts in the early 1990s, conducting an assessment on four materials used in the product line to determine those that had the greatest impacts and where in the supply chain the impacts occurred. The results of the study were then used to inform materials sourcing decisions for the various products in Patagonia's product line. Patagonia has numerous needs for current environmental assessment data but does not have a designated position to focus on gathering this information in a comprehensive way. This is not uncommon for many apparel brands. Patagonia, like many brands, is searching for an efficient and accurate method for evaluating environmental risks and impacts from their products.

There are currently numerous tools and approaches developed for measuring and rating environmental impacts of facilities, operations, and products. This research will focus on evaluating the application of Life Cycle Assessment (LCA) to the apparel sector. Sections one and two of the research in this dissertation will focus on evaluating the application of LCA. The last of the three sections will use LCA in conjunction with an evaluation of Patagonia's logistics systems to evaluate the opportunities within Patagonia's operations to minimize environmental impacts.

Statement of the Problem and Objectives

Regardless of the life cycle stage, all products and services have an impact on the environment. Identifying critical issues present in the life cycle of products and taking constructive response actions can improve the environmental performance of products. The environmental impacts from a company depend on the type of product systems, location of global supply chains, and related social and environmental problems from specific industries (Manda 2014). As businesses grow and expand their global operations, the ability to evaluate the environmental impacts of business operations becomes difficult and inherently complex. The demand for environmental impact data on products and supply chains is increasing, and there is a need for companies to understand the best approaches to gathering reliable data for decision making.

Brands within the apparel industry that have an interest in understanding their environmental impacts don’t often have the time or the resources to commit to the academic approach of LCA to thoroughly assess all of their products and services. Therefore, it is essential that businesses have alternative approaches to gathering environmental impact data that can be conducted by nontechnical employees, is usable and understandable by nontechnical audiences, and that provides an accurate assessment of impacts.

The main objective of this thesis is to provide apparel brands with valuable insights into how to best assess the environmental impacts of their operations and products. The hope is that the information produced through this research will lead to effective environmental impact data collection and corresponding impact reductions. In addition, it will provide insights to both academia and industry on how to streamline data collection efforts, evaluate environmental impacts, and identify environmental risk in a meaningful way.

The research is divided into three main objectives.

Objective 1: Apparel and Textile LCA Systematic Review

Objective 1 of this research consists of a systematic review of the resource use (energy and water use) data that has already been gathered in apparel and textile LCA research. The systematic review included an examination of existing literature and research focused on apparel and textile LCAs. The findings from the literature review were then synthesized to include only high-quality research. The goal of this research was to determine if existing data could be used by the industry to assess and compare the environmental impacts that result from the various processes required to manufacture apparel and textile products. The hope is that this research will enable brands to use the existing LCA data that has been identified through this research to determine the hot spots in apparel supply chains. In addition, by providing brands with the specific environmental impacts of a typical process, they can then compare their own supply chain environmental impact data to the baseline to determine if they are operating efficiently or inefficiently.

Objective 2: Evaluation of a Collaborative LCA Approach: Patagonia Product Case Study

Pending European legislation may require brands that sell products in Europe, such as Patagonia, to provide environmental impact information for individual products. The expectation is that LCA will be the foundation for the product-level environmental impact data that will be required to be reported. It is imperative that apparel brands start establishing a system for gathering environmental impact data and conducting LCAs at the product level in order to prepare for the European Commission's legislation.

One approach to conducting an LCA is to request that supply chain partners gather primary environmental impact data on the processes in the apparel product supply chain that they execute. This data can then be pieced together to create a complete product LCA. There are numerous reasons for brands and supply chain partners to be interested in collaborating on LCA efforts. From the brand perspective, it is difficult and time consuming to gather primary data from all steps in the supply chain. It is especially difficult in the apparel industry because brands don't typically own the manufacturing processes or facilities and manufacturing is typically contracted out.

By breaking down the life cycle into a series of sequential phases such as raw material extraction, processing, use phase, and end of life, and working with supply chain partners, brands can attempt to gather primary data at all steps in a product's life cycle. From the supply chain perspective, providing environmental information about their operations is an opportunity for manufacturers to build strong partnerships with the brands that they work with. In addition, this allows the supply chain partners to provide data that specifically reflects their processes. If they have implemented any impact reduction efforts in their processes or facilities, the data will show lower impacts, whereas generic LCA data may not reflect the specific technologies a supply chain partner is utilizing. The challenge with this approach, however, is that there are numerous types of LCA software systems, data inputs, and impact characterization factors that can be used by companies to conduct an LCA and that combining data from various systems may affect the results.

This research evaluated a LCA approach that combined primary data gathered from the various steps in the product life cycle using different LCA software in order to determine if it could be a sound approach to evaluating the life cycle impacts of a product. A case study was conducted that focuses on completing two LCAs on the same product using data from two different companies and using two different software systems. Patagonia, as well as one of its supply chain partners that manufactures technical jackets, jointly agreed upon the goal and scope for this case study.

The approach taken in this case study provided an example of how to utilize LCA in the corporate sector. With this in mind, the goal of this section of the research is to provide a recommendation on whether or not this approach to LCA is one that could be reliably used in the apparel industry. The approach to gathering data and completing a LCA and the comparisons of the findings of the two LCAs will indicate if such an approach is an effective and accurate way of gathering and organizing environmental impact data.

Objective 3: An Analysis of Environmental Impacts from Manufacturing and Transporting Product Packaging

Companies may excel at reporting, governance, and the utilization of environmental performance systems, yet they may still emit substantial amounts of pollution (Delmas et al. 2013). Or, more cynically, they may put in place processes for symbolic purposes, but not meaningfully pursue substantial outcomes (Delmas et al. 2013). As consumers and legislation are increasingly pushing firms' operations and products to reduce waste, it is essential to evaluate the materials used in packaging. The focus of Objective 3 will be to use LCA to determine and compare the environmental impacts of the two main product packaging options commonly used in the apparel industry. In addition, an operational evaluation was also conducted to determine the potential to reduce impacts by tailoring packaging strategies based on sales demands in different global regions and sales channels. This research provides an example of how of LCA and logistics systems can be used together to minimize environmental impacts.

As other brands work to address their own use of packing and plastic, the data generated in this research will help to guide informed decision-making across industries that rely on packaging to protect and market their products. The impacts that result from Patagonia's current logistics system, including transporting the packaged products from the packaging manufacturing facility to the apparel cut/sew facility, from the apparel cut/sew facility to Patagonia's distribution center, and from the distribution center to customers and retail locations, were examined. Environmental impacts were determined based on the weight of the packaging, the number of units packaged and shipped, the number of shipping cartons needed (based on the density of each carton), the distance of each shipment, and mode of transportation. This research provides insight on how LCA data and adjustments to logistics systems can be used to balance the need for packaging and the goal to minimize resource use.

The research and findings for each of the three objectives is explained in more detail in the following chapters.

Chapter 2: Objective 1 - Apparel and Textile LCA Systematic Review

Chapter 3: Objective 2 - Evaluation of a Collaborative LCA Approach: Patagonia Product Case Study

Chapter 4: Objective 3 - An Analysis of Environmental Impacts from Manufacturing and Transporting Product Packaging

Chapter 5: Conclusions

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Chapter 2: Apparel and Textile LCA Systematic Review

Introduction

There are several concepts and frameworks designed to assess the impact of human activities on the environment. Life Cycle Assessment is one of the tools that can be used to provide insight into the environmental impacts that result from manufacturing, distributing, and using products. LCAs typically evaluate the environmental impacts and resources used in all steps of a product's life cycle, from raw material acquisition, via production and use phases, to waste management (ISO 2006a). Traditional LCAs tend to include environmentally relevant physical flows to and from a life cycle and its subsystems and describe the environmental impact associated with these flows (Hojer 2008). Such flows can extend beyond greenhouse gas (GHG) emissions inventories to also include measurements of energy use, water use, chemical use, waste generation, etc.

LCA has become increasingly utilized as a decision-making tool to define what is and isn't a sustainable approach to production, use, and disposal of products. LCA can also be used to identify more sustainable solutions within the whole supply chain, including the choice of raw materials, transport between life cycle stages, and recycling or waste processing. In addition, approaching the knowledge-gathering process from a life cycle perspective can help to avoid making changes that ultimately increase environmental impacts (Rajagopal 2014).

Despite the advancement of LCA and its application for formulating policies in the European Union (EU), a great majority of companies do not use LCA to evaluate and improve the performance of their products and services on a daily basis (Manda 2014). Reasons for this vary. Global value chains are complex and thus collection of data from different activities of supply chain partners is both cumbersome and resource intensive, and sharing of data can involve confidentiality issues (O'Rourke 2014). An additional challenge with relying on LCA as the starting place for driving environmental impact reduction is that conducting a thorough and accurate LCA demands a certain level of expertise, it can be expensive and time consuming, and often the resulting data can be difficult to interpret.

Patagonia is considered a small to medium sized company, with sales at approximately 650 million dollars in 2015. Despite the annual sales of the company, the budget available for environmental and social responsibility programs is limited. Conducting LCAs is one of the many responsibilities of Patagonia's Social and Environmental teams. Estimates from the SAC indicate that hiring a consultant to complete one product LCA could cost $20,000–$40,000, with $20K being an estimated cost for a higher-level hot spot assessment and $40K being the cost of a full LCA. The price goes up from there if the company wants more specificity and requests the models afterward (2013 C. Childs, personal communication; unreferenced). Another estimate provided by Roos et al. (2015) expands upon this estimate. LCAs typically cost between USD 10,000 and 250,000—the price depends on the complexity, but routine work is usually toward the lower end of this scale (Roos et al. 2015). For brands like Patagonia that develop nearly 1,000 different products in a single season, the time and monetary cost to conduct LCAs on even a very small portion of their total products can add up quickly.

Another option to gathering LCA data is to have an internal employee conduct the assessments using purchased LCA software instead of hiring a consulting firm to complete the assessment. Initial research on the cost to conduct complete full product LCAs internally at Patagonia using LCA software indicates that this too can be a potentially expensive approach to gathering LCA data (see Table 2.1).

Table 2.1 Expected costs for product LCAs using Patagonia staff, LCA software, database licenses

List of Expenses	**One-time Costs ($)**	**Annual Cost ($)**
Patagonia LCA employee salary		$75,000
EcoInvent data (one license)	$3,500	$695
LCA software	$14,625	$5,850
LCA data set – Renewable raw materials	$3,250	$1,300
LCA data set – Textile finishing	$4,875	$1,300
LCA training	$3,200	
Total (one-time and annual fees)	**$29,450**	**$82,845**

Brands in the apparel industry, such as Patagonia, would like to begin using LCA data to inform decisions aimed at reducing environmental impacts resulting from business operations. There are three key uses for environmental LCA data in the apparel industry. First, the resulting initial inventory of environmental impacts that is gathered using an LCA approach can be used to identify the manufacturing processes that result in high environmental impacts. Such information can be used to determine what type of impact reduction programs are needed and which will have the greatest positive impact. Second, this information can be used to substantiate claims that are publically communicated regarding the environmental impacts of products. This enhances transparency and fair competition. Third, it is expected that Patagonia as well as all other brands selling products in Europe will need to comply with the European commission’s product labeling legislation.

The European Commission has been working to formalize environmental regulations on products. The objective of the regulation is to incentivize brands to report and reduce environmental impacts. This research has the opportunity to provide environmental impact data that the apparel and textile industries can use to meet product-labeling requirements.

Instead of spending the time and the resources to gather new LCA data, the apparel industry could first utilize the LCAs that have been conducted on the apparel and textile industries. Numerous LCAs have been completed on apparel products and the textiles used to make apparel. The LCAs that have been completed thus far, however, are difficult to find online, have been completed in silos, and the findings from one LCA are not often easily compared to the results another.

Chapman (2010) conducted a review of the LCA studies focused on apparel conducted to date. They were able to gather energy use data for the 11 most comprehensive LCAs they found. They data they gathered, however, was reported in units of clothing. The unit of measure was not consistent in that they showed energy use for one T-shirt compared to a shirt, briefs, trousers, blouse, jogging suit, and work jacket, which are not equal units of measure. In addition, the research focused solely on energy use and did not break out the energy inputs by life cycle stage. The results of this particular LCA review did not provide environmental impact data that can be used by other brands to evaluate their own products. In addition, since this assessment was completed, several more apparel and textile LCAs have been published.

Van der Velden et al. (2014) published a journal article titled: LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. This research focused on collecting publically available data with the goal of developing improved insight into the environmental burden of the life cycle of textiles. The impacts reported in the LCA Benchmarking study are primarily based on European manufacturing data and don't provide a representation of the impacts from the majority of the textiles currently being made in Asia. Material processing practices that occur in India and China were not included due to lack of available data. At this point in time, nearly 40% of apparel products sold in the US are imported from China. China's textile production accounts for nearly 54% of the world's total production. Indian textile industry is second largest after China and has share of 23% of the world's spindle capacity (30 Shocking…2015). In addition, the study did not include any information on water use in the fiber production and processing phases, and there are several materials important to the apparel industry that the research didn't address, including hemp, organic cotton, and recycled polyester.

Chemical Use in the Textile and Apparel Industry

Impacts from chemical use are an area of concern in the apparel industry. The environmental issues associated with textile products that have commanded the most attention by analysts are energy use, water depletion, and chemicals (Allwood et al. 2006). The chemicals of concern for textiles are located along the whole supply chain, from pesticide and fertilizer use in cotton cultivation to toxic emissions from wet treatment and toxic chemicals in the after-treatment (European Commission 2003). The choice among dyestuffs for textiles is crucial for the local environment at wet treatment sites in exporting countries, as dyestuffs can be carcinogenic, toxic, and/or persistent. Textile consumer products and wastewater from washing have been found to contain undesirable degradation products such as arylamines from azo dyes, as well as residues of process chemicals such as alkylphenol ethoxylates (Shams-Nateri et al. 2014).

The two main ways LCA has incorporated chemical use is by accounting for chemical inputs and reporting on toxicological impacts that are the direct results of the inputs reported in the LCA model. The chemical inputs often look like a list of resources required to complete the process being assessed. The toxicological impacts are communicated via a characterization factor. The method used to calculate equivalency factors for toxicity and ecotoxicity is based on the substance's inherent properties and includes the fate of the chemical substance in the environment as well as its impacts on living organisms. The central properties considered for a substance are:

- Toxicity – the ability to cause harmful impacts
- Persistence – the ability to remain in the environment for a long time
- Bioaccumulation potential – the ability to accumulate in living organisms and to be transmitted from one link in a food chain to the next (biomagnification). This also includes the substance's ability to accumulate in food for humans (Laursen et al. 2007).

Even with access to chemical use inputs and toxicity characterization factors, accounting for chemicals remains a weak point in LCA methodology and practice (Roos et al. 2015). In the study conducted by Roos et al. (2015), two research questions were investigated in a case study of hospital garments: 1) whether LCA adds value to assessments of the chemical performance of textile products, and 2) whether inclusion of toxicity issues in LCA affects environmental performance rankings for textile products. They concluded that the quantitative and holistic tool LCA is useful for environmental decision makers in the textile industry, and becomes more effective when chemical impacts are included. In addition to these findings, some LCA approaches and methodologies encourage the inclusion of chemicals in LCAs. The SAC is one example; they encourage LCA-based environmental product declarations (EPD) of textile chemicals and are in the process of developing guidance material that includes that requirement (Schenck 2013).

The objective of this research is to provide a systematic review of the LCAs that have been completed to date on apparel and textile products to establish a working body of data that can be used by the industry to assess the environmental impacts of materials and processing used in apparel and textiles. According to Lifset (2012), systematic quantitative review of LCAs are not very common. This systematic review builds upon the findings from the 2014 LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane and adds in additional regional textile processing data. In addition the impacts from the chemicals used in textiles will be a focus in the data gathering process.

Since the review of textile LCAs in Chapman (2010), many more LCAs have been made available to the industry. The systematic review of the life cycle assessments that have been conducted on the apparel industry thus far will provide an up to date review of the data currently available and address the use of chemicals in the textile industry. The data and the learnings gathered in this research will make high quality and current environmental data available for the apparel and textile industries to use to evaluate their own products. This portion of the dissertation provides a comprehensive review of LCA studies on textile and apparel products.

Methods

The research includes a review of completed LCAs and focuses on organizing the data outputs of the selected LCAs in a way that can be easily understood and used by the apparel and textile industry.

Systematic Review

LCA studies were gathered using complementary search strategies to identify relevant studies for the analysis. A 2003 study suggested that extending searches beyond major databases and including grey literature would increase the effectiveness of reviews (Savoie et al. 2003). Grey literature is generally defined as academic literature that is not formally published. Grey literature can be an important source of information for researchers because it tends to be original and recent (Debachere 1995). Examples of grey literature include technical reports from government agencies or scientific research groups, working papers from research groups or committees, and white papers. Grey literature was included in all three search strategies.

The literature search for the systematic review included Internet-based searches to find published LCA research on textiles and apparel. Peer reviewed scientific journals such as *The International Journal of Life Cycle Assessment* and *Journal of Industrial Ecology* were a specific focus. The Google and journal searches were guided by keyword searches. The keywords/phrases used in the search include: life cycle assessment, life cycle inventory, environmental impact, textiles, materials, fabrics, apparel, and supply chain. The citations in the papers found were then reviewed to determine if there are any additional relevant journal articles on LCAs conducted in the apparel or textiles industries.

The scope of the search included studies done on all life cycle stages from origin of fiber through end of use for select apparel products. In addition, the focus of the literature review was on apparel and textile products made using the following materials: cotton, organic cotton, polyester (PET), recycled polyester (recycled PET), nylon, hemp, organic hemp, lyocell, modal and wool. Lastly, the environmental impact metrics searched for in this research included energy use, water use, and chemical use. These impact metrics are the focus of this study due to the fact that they are the typical inputs used in creating a life cycle inventory. To gain an understanding of what is causing the environmental impacts in a product's life cycle stages, it is essential to understand the inputs. When this information is known, it is then possible to make informed decisions on how best to minimize those impacts.

In order for the LCA data in this study to gain broad validity and long-term industry use, the outputs of this review must satisfy the needs of the apparel industry and government policymakers as well as expectations of the broader LCA community. With this in mind, the studies found in the search were reviewed for data quality and applicability to the scope of this research to determine which ones to use in the outputs of the review. The studies that were found within the scope of this research were included on the basis of four criteria: type of review, transparency of the data, if the study was within the scope of this research, and if the data was current. The studies found in the literature review that did not meet the criteria were not included in this analysis.

LCA Data Collection: Scope, system boundaries, and functional unit

The scope of this study is cradle-to-gate processes of the production chain, including raw material extraction, spinning, manufacturing fabric (knitting and weaving), and dyeing and finishing. Data on the transport, use phase (washing by the user) and the end-of-life phase are not included in the scope of this research. Data was collected for cotton, organic cotton, PET, recycled PET, nylon, hemp, organic hemp, lyocell, modal and wool. Each of these materials are used widely in both the apparel industry in general as well as the outdoor apparel industry. Organic cotton and recycled polyester are emerging trends in the apparel industry. Organic production of cotton constitutes less than 1 per cent of total cotton production, but organic production is increasing and is expected to increase further due to increased demand (Laursen et al. 2007). Further, a number of brands and retailers are buying organic cotton. These include H&M, C&A, Nike, Zara, Anvil Knitwear, prAna, Puma, Williams-Sonoma, Target, and Otto Group (Babu and Selvadass 2013). In addition, brands like The North Face have publically committed to using 100% recycled polyester in their polyester garments by 2016 indicating a growth in the availability and application of recycled polyester.

The data outputs of this research are based on a functional unit of 1 kilogram of fiber for each appropriate step in the supply chain. The unit of measure is 1kg of fiber for the fiber/extraction phase and spinning and 1kg of fabric for knitting, weaving and the fabric processing phases of dyeing and finishing. This unit of measure was chosen because it can be universally applied to various weights and sizes of textile and apparel products through an easy conversion based on the specification of the product being evaluated.

The approach required to convert the environmental impact data from a function unit of 1kg to a functional unit of one product simply requires information on the amount of fiber needed to make the garment being evaluated. Supply chain vendors will be able to provide this information. For example, if 1kg of cotton fiber yields 30 t-shirts, then the environmental impacts of 1kg of fiber can be divided by 30 to reveal the impacts of one t-shirt. A jacket will likely require a heavier weight fabric than a t-shirt and will also require more yards of fabric that a t-shirt. Such conversions will be specific to garment type, fiber type, and fabric construction.

For each of the fiber types and processes, energy use, water use, and chemical use data was gathered. For each of the data points, the location where the data was collected was also gathered, when possible. The paragraphs immediately following this one describe the approach taken to gathering the energy use and water use data. Because the process of gathering and assessing chemical use in LCA is less well defined, the approach taken to collect chemical use data was separate from the energy use and water use data collection. Details on the approach taken for gathering chemical use data will be explained in more detail in the Chemical Use Data Collection section.

These impact metrics are the focus of this study due to the fact that they are the typical inputs used in creating a life cycle inventory. LCA methods used in impact assessments have a variety of characterization factors that relate the inflows and outflows from the inventory to potential environmental impacts. ISO 14044 states that the characterization factors “are applied to convert the assigned LCI results to the common unit of the category indicator”. The approach taken in this research was to gather direct inputs instead of impact characterization factors; the midpoint impacts reported in the results of the various LCAs were not the focus of this assessment. This approach reduces additional variability between studies by avoiding the need to reconcile different characterization factors and varying units of measure used by the various LCA software systems.

Some LCAs report environmental impacts results as a single indicator. A single indicator in Life Cycle Inventory Analysis (LCIA) is one single score to express the result of the cumulative inventory list in one indicator, either at the midpoint or endpoint level. Because the goal of the study is to provide brands and the larger apparel and textile industries with an understanding of the environmental impacts of their materials, LCAs that used the single score approached were not taken into account.

In addition, by providing input data, other brands can use the data as inputs into an LCA that can be customized to specific products. For example, many apparel products are made using a blend of fabrics, such as cotton/poly blends. By providing input data such as energy use and water use for cotton and polyester, a brand can use the input data to build the impacts for the specific cotton/poly blend that they manufacture. Brands and industry can then use the LCA impact characterization models that best apply to their region and environmental priorities.

The data points gathered from the LCAs collected in the systematic review were organized by process and fiber type. The data was kept in the form of resource inputs and converted to a common unit of measurement to allow for easier comparisons. In the case of energy, the energy inputs are reported in MJ. Water use is reported in liters. In some cases, there were several studies that identified inputs for the same fiber and process. All of the data points found for each fabric and process were kept in the data report in order to show the variety of data available for each fiber type and the difference in impacts between regional processes.

Chemical Use Data Collection

There are a few approaches to reporting chemical impact in LCA. Most are reliant upon the use of toxicological impact characterization factors and are reported using several measures such as human toxicity, persistent toxicity, ecotoxicity and aquatic toxicity. Rarely is the actual type of chemical and amount used reported in LCA studies.

The method development for LCA of chemicals has taken several important steps forward in recent years (Hauschild et al. 2011) but still suffers from weaknesses, which have led to the exclusion of impact from chemicals from most recent textile LCAs (Roos et al. 2015). Of the available approaches to measuring toxicity impacts, the European Commission recommends the USEtox method (Rosenbaum et al. 2008). That method however is not complete for textile chemicals (Terinte et al. 2014). Other researchers have used a range of methods for simplified incorporation of toxicity in LCIA in order to fill in the data gaps. One of the simplified approaches has been to merge the life-cycle perspective with chemical risk information to replace missing characterization factors (Finnveden et al. 2009).

Despite these efforts, several researchers have concluded that the assessment of chemicals is still a weak point in a recent overview of best practices for LCIA in LCA (Sala et al. 2012). According to Roos et al. (2015), chemical issues are generally assessed on a qualitative basis in the textile production chain, which means that their comparative significance is not always comprehended. Some LCA practitioners have taken the approach of declaring the presence or absence of regulated substances in the textile production chain (Schenck 2013).

Based on the challenges presented in previous research, the primary goal for the chemical use and chemical impact data collection was to gather all quantitative chemical use input data available in the studies found in the systematic review. In addition, the scope was broadened from the approach used to gather energy use and water use LCA data and included gathering toxicological impact midpoint data when available.

Results

Systematic Review Results

50 studies were found that met the scope of the project. Please refer to Appendix A for a comprehensive list of the fifty studies that were identified. After reviewing all 50 studies it became clear that although an LCA looked to be of high quality and focused on the apparel industry, not all fit into the scope of this study. Of the fifty studies that were found, nineteen studies met the criteria established in the methodology for this research. Those that were not included were removed for four main reasons: the studies were not peer reviewed, data transparency was low, the assessment was out of the scope of this research, or the data was out of the date range established for this research. Numbers 1-4 below provide more detail on why certain studies were ultimately excluded from this systematic review.

1. **Non-peer reviewed study.** Some of the research found was industry or brand commissioned and did not go through any peer review. The approach taken in this research was to focus on using data from peer-reviewed journal LCAs. There were a

few exceptions to this. The last column in Table 2.2 indicates if the LCA was from a peer-reviewed journal.

2. **Low data transparency.** Several LCA studies did not include specific energy use, water use or chemical input data. Others did include such data but did not report the data in a unit that could be converted to 1 kg of fiber, yarn, or fabric. For example, the functional unit used in the classic study “Life cycle analysis of a polyester garment” by Smith et al. (1995) was 1 million wearings of a garment. In another study by Steinburger et al. (2009), data was reported per 100 days of garment use for a cotton T-shirt and polyester jacket. In other cases, the data provided was not broken out by process. In all of these examples, there was no accurate way of converting the information provided to a standard unit of process input data.

3. **Out of scope**. The scope for this research included specific fiber types and the life cycle stages of fiber production through dyeing and finishing. Some studies found addressed fiber types not included in this research or focused on use phase and end of life impacts. Several peer-reviewed journal articles that initially seemed applicable were ultimately excluded because they were out of scope.

4. **Out of date range**. All studies conducted or published prior to 2000 were excluded from the results of this study. Based on the initial studies gathered in the systematic review, there all well over 50 LCAs focused on apparel and textiles. Due to the abundance of information collected since 2000, it did not seem too limiting to exclude studies over 15 years old.

Table 2.2 List of nineteen LCAs included in the data results

	Title	Authors	Journal/ Organization	Year	Peer Reviewed Journal
1	Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling	L. Shen, E. Worrell, M. Patel	Resources, Conservation and Recycling	2010	Yes
2	Apparel Industry Life Cycle Carbon Mapping		BSR	2009	
3	Life Cycle Assessment for Cultivation of Conventional and Organic Seed Cotton fibres	K. Babu Babu, M. Selvadass	International Journal of Research in Environmental Science and Technology	2013	Yes
4	Life Cycle Assessment of Cotton Fiber and Fabric		Cotton Incorporated	2012	
5	Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester	N. Cherrett, J. Barrett, A. Clemett, M. Chadwick and MJ Chadwick	BioRegional Development Group and WWF Cymru, SEI (Stockholm Environment Institute)	2005	
6	Life cycle energy and GHG emissions of PET recycling: change-oriented effects	L. Shen, E. Nieuwiaar, E. Worrell, M. K Patel	International Journal of Life Cycle Assessment	2011	Yes
7	Quantification of environmental impact and ecological sustainability for textile fibres	S. Muthu, Y. Li, JY Hu, PY Mok	Ecological Indicators	2011	Yes
8	Environmental assessment of textiles	S. Laursen, J. Hansen, H. Knudsen, H. Wenzel, H. Larsen, F. Kristensen	EPIDEX	2007	
9	Life cycle Assessment of raw materials for non-wood pulp mill: Hemp and Flax	S. Gonzalez-Garcia, A Hospido, G. Feijoo, M.T. Moreira	Resources, Conservation and Recycling	2010	Yes
10	LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastine	N. Van Der Velden, M. Patel, J. Vogtlander	International Journal of Life Cycle Assessment	2012	

11	Environmental impact assessment of man-made cellulose fibres	L. Shen, E. Worrell, M. Patel	Resources, Conservation and Recycling	2010	Yes
12	Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics	N.Terinte, BMK Manda, J. Taylor, K.C. Schuster, M.K. Patel	Journal of Cleaner Production	2014	Yes
13	The environmental impacts of the production of hemp and flax textile yarn	H. Van der Werf, L.Turunen	Industrial crops and products	2007	Yes
14	Life Cycle Assessment (LCA) of Organic Cotton		PE International & Textile Exchange	2014	
15	Eco-profiles of the European Plastics Industry Polyamide 6 (Nylon 6)	I. Boustead	Plastics Europe	2005	
16	Eco-profiles of the European Plastics Industry Polyamide 66 (Nylon 66)	I. Boustead	Plastics Europe	2005	
17	Understanding the environmental impacts of wool: A review of Life Cycle Assessment Studies	B. Henry	Australian Wool Innovation & International Wool Textile Organization	2012	
18	Energy-Efficiency Improvement Opportunities for the Textile Industry	A. Hasanbeigi	China Energy Group, Energy Analysis Department, Environmental Energy Technologies Division	2010	
19	Moving down the cause-effect chain of water and land use impacts: An LCA case study of textile fibres	G. Sandin, G. Peters, M. Svanstrom	Resources, Conservation and Recycling	2012	Yes

Table 2.2 Reasons for exclusion from the data results and number of studies excluded for each reason

	Reasons for Exclusion	Number of Studies Excluded

1	Non-peer reviewed study	9
2	Low data transparency	10
3	Out of scope	8
4	Out of date range	2

LCA Data Collection Results

Data was found for each of the fiber types and processes included in the scope of this research. The scope of the study included 10 fiber types: cotton, organic cotton, PET, recycled PET, nylon, hemp, organic hemp, lyocell, modal, and wool. For each of the processes and fiber types, the hope was to gather energy use, water use, and chemical use data. The goal was achieved, but the review of existing research also revealed numerous data gaps. Not all of these inputs were found for each of the fiber types and processes. Energy use data was consistently found. Water use data was available for the fiber processing stage, but far less available for the yarn spinning, knitting and dyeing, and finishing stages. Data units were modified from the original studies to make the units consistent across studies. The energy use measurement is in MJ and includes electricity use, steam, fuel, renewable energy, etc. Water use is measured in liters.

Some chemical inputs and toxicity assessments were found in the studies. The data found was primarily attributed to the chemical use at the fiber production and the dyeing and finishing life cycle stages. However, the data was not consistently reported and therefore difficult to include in the standard format used in tables 2.5-2.13 below. Instead of including actual data points for chemical use in tables 2.5-2.13, it is simply noted if there is a reference to chemical inputs or impacts in the study. The chemical input and impact data findings will be addressed in detail in the next section under Chemical Use Data Collection Results.

A specific focus of the data gathering process for this research was to identify the location where the data was originally gathered. Most of the LCA studies included in this research reported the region where the data was collected. Of the nineteen studies reviewed, three did not report a location of where the data was collected. Most often a country was referenced; it was rare to find more specific locations identified. In two of the LCAs, the introduction mentioned that data was gathered from several countries but the data points referenced throughout the research were not always clearly linked to specific locations and may have even been averaged.

The fiber production data came from a broader variety of regions while the majority of the studies with fabric processing data classified the origin of their data as coming from Europe. Refer to Table 2.4 below for an overview of the data type and region where it was collected. Tables 5-10 are organized by fiber type and show fiber processing energy and water use inputs.

Table 2.3 Geographic regions reported in the nineteen LCAs reviewed in this research

	Western Europe	Central Europe	Turkey	Russia	Borneo	China	India	USA	Taiwan	New Zealand	Tanzania
Cotton and organic cotton fiber						X	X	X			
Cotton and organic cotton fabric			X			X	X	X			X

processing											
PET and recycled PET fiber	X							X	X		
PET fabric processing	X										
Nylon 6 and Nylon 6,6 fiber	X										
Nylon fabric processing	X										
Hemp and organic hemp fiber	X	X									
Hemp fabric processing	X										
Lyocell and modal fiber	X	X		X	X						
Modal fabric processing	X	X									
Wool fiber										X	
Wool fabric processing											

Fiber growing and/or processing data were found for all ten fiber types. Please refer to tables 2.5-2.9 for fiber processing specific data.

Table 2.4 Conventional and organic cotton fiber production data and sources

Process	Location	Functional unit (1 kg of fiber)	Energy Use (MJ)	Water Use (Liters)	Chemical Use Data	Source
Conventional cotton cultivation	Punjab, India	1 kg	12	9,958	No	Cherrett et al. 2005
Conventional cotton cultivation	USA	1 kg	23	9,958	No	Cherrett et al. 2005
Conventional cotton cultivation	China, India, US	1 kg	15	2,100	No	Cotton Inc. 2012
Conventional cotton cultivation	Not referenced	1 kg	60	22,000	Included scale of human health impacts	Muthu et al. 2011
Conventional cotton cultivation	North Western China	1 kg	96	4710	No	Sandin et al. 2013
Conventional cotton cultivation	US and China	1 kg	58	57,000	Toxicity assessments included	Shen et al.2010
Organic cotton cultivation	Punjab, India	1 kg	8	9,958	No	Cherrett et al. 2005
Organic cotton cultivation	USA	1 kg	10	9,958	No	Cherrett et al. 2005
Organic cotton cultivation	Not Referenced	1 kg	22.45	2,000	Toxicity assessment included	Laursen et al. 2007
Organic cotton cultivation	Not Referenced	1 kg	54	24,000	Included scale of human health impacts	Muthu et al. 2011
Organic cotton cultivation	India, Turkey, China,	1 kg	15	15,000	No	Textile Exchange 2014

	Tanzania, USA					

Table 2.5 PET and Recycled PET fiber production data and sources

Process	Process Details	Location	Functional Unit (1 kg fiber)	Energy Use (MJ)	Water Use (Liters)	Chemical Use Data	Source
PET - fiber production		Not Referenced	1 kg	125	62	Included scale of human health impacts	Muthu et al. 2011
PET - fiber production	Virgin PET amorphous grade	Europe	1 kg	66.64		No	Boustead 2005
PET - fiber production	Process water	Western Europe	1 kg		130	No	Terinte et al. 2014
PET - fiber production		Europe	1 kg	104		No	Cherrett et al. 2005
PET - fiber production		USA	1 kg	127		No	Cherrett et al. 2005
PET - fiber production		Western Europe	1 kg	95	125	Toxicity assessments included	Shen et al. 2010a
PET - fiber production	Virgin PET (staple and filament) (large scale production)	Western Europe	1 kg	95		Toxicity assessments included	Shen et al. 2010b
PET - fiber production		Europe	1 kg	78.4		No	van der Velden et al. 2014
Recycled bottle processing	Bottle sorting, compacting, baling	Western Europe	1 kg	Negligible		No	Shen et al. 2011
Recycled PET - fiber production	PET bottle to flake production	Western Europe	1 kg	3.5		No	Shen et al. 2011

Recycled PET - fiber production	PET Flake to Pellet production	Western Europe	1 kg	1.85		No	Shen et al. 2011
Recycled PET - fiber production	Mechanical Recycling (Staple fiber)	Western Europe	1 kg	13		Toxicity impacts included	Shen et al. 2010b
Recycled PET - fiber production	Semi-Mechanical (filament)	Taiwan	1 kg	23		Toxicity impacts included	Shen et al. 2010b
Recycled PET - fiber production	Chemical, to BHET recycling (filament) (small scale production)	Taiwan	1 kg	39		Toxicity impacts included	Shen et al. 2010b
Recycled PET - fiber production	Chemical, to DMT recycling (filament) (small scale production)	Western Europe	1 kg	51		Toxicity impacts included	Shen et al. 2010b

Table 2.6 Nylon 6 and Nylon 6,6 fiber production data and sources

Process	**Location**	**Functional Unit (1 kg Fiber)**	**Energy Use (MJ)**	**Water Use (Liters)**	**Chemical Use Data**	**Source**
Nylon 6 - fiber production	Europe	1 kg	120.47	185	Inputs and air emissions/waste outputs included	Boustead 2005 (Muthu et al. 2011 referenced Boustead 2005 data)
Nylon 66 - fiber production	Europe	1 kg	138.62	663	Inputs and air emissions/waste outputs included	Boustead 2005 (Muthu et al. 2011 referenced Boustead 2005 data)

Table 2.7 Hemp and organic hemp fiber production data and sources

Process	**Process Details**	**Location**	**Functional Unit (1 kg of fiber)**	**Energy Use (MJ)**	**Water Use (Liters)**	**Chemical Use Data**	**Source**

Fiber cultivation - Hemp	Electricity for scutching	Spain	1 kg	4.37	No supplemental irrigation reported	Reported inventory of pesticides	Gonzalez - Garcia et al. 2010
Fiber cultivation - Hemp	Hemp processing - kg of useful fiber	Hungary	1 kg	39	No supplemental irrigation reported	Reported inventory of pesticides	Van der Werf et al. 2007
Fiber cultivation - Conventional Hemp - Traditional process	Dew retted and processed through an aligned scutch mill system as used by the linen industry	UK	1 kg	8	2,041	No	Cherrett et al. 2005
Fiber cultivation - Organic Hemp - Traditional process	Dew retted and processed through an aligned scutch mill system as used by the linen industry	UK	1 kg	2	2,041	No	Cherrett et al. 2005

Table 2.8 Lyocell and modal fiber production data and sources

Process	Location	Functional unit (1 kg of fiber)	Energy Use (MJ)	Water Use (Liters)	Chemical Use Data	Source
Lyocell Fiber production	Europe	1 kg	42	263	Toxicity assessments included	Shen et al. 2010a
Lyocell Fiber production	Southern Sweden	1 kg	0	135	No	Sandin et al. 2013
Lyocell Fiber production	Eastern Russia	1 kg	1.8	516	No	Sandin et al. 2013
Lyocell Fiber production	Borneo	1 kg	0.537	948	No	Sandin et al. 2013
Modal Fiber production	Austria	1 kg	25	472	Toxicity assessments included	Shen et al. 2010a

Table 2.9 Wool fiber production data and sources

Process	Location	Functional Unit (1 kg fiber)	Energy Use (MJ)	Water Use (Liters)	Chemical use data	Source
Wool fiber production	New Zealand	I kg	63	125	Included a scale of impacts to human health	Muthu et al. 2011(Referencing Barber and Pellow 2006)
Wool fiber production	Not Referenced	1 kg	42		No	BSR 2009
Wool fiber - production	New Zealand	1 kg	46		No	Henry 2012 (Referencing Barber and Pellow 2006)

The data for this research was gathered in order to provide a library of information for brands to use to start to understand the impacts of their products. The intention of this research is not to compare each of the fiber types to one another based on inputs for numerous reasons. The LCAs that are available in the apparel and textile industry have been completed by different organizations, using different methods and boundary conditions, different LCA software systems and different environmental impact characterization factors. Another important reason for not comparing the data found in this research is that natural (cotton, organic cotton, hemp, organic hemp, lyocell, modal and wool) and synthetic (polyester, recycled polyester, nylon 6 and nylon 6,6) fibers cannot really be compared as they are not typically interchangeable materials, due to their differing technical, physical, and chemical properties.

That caveat aside, there were some clear observations made in the data gathered. The findings from the fiber process data points collected show variations in fiber process energy and water demands across the fiber types. The data indicates that there is a considerably larger energy requirement for production of synthetic (virgin polyester and nylon) fiber in comparison to cotton, organic cotton, hemp, lyocell and modal. That was shown across the data points gathered. However, the recycled polyester fiber data indicated that the energy input requirements for recycled polyester were from 15-104 MJ less than that of virgin polyester, resulting in a 12-82% reduction in energy use. In terms of water use, a comparison shows that the water use in polyester production consistently less than that required in cotton, hemp, lyocell, modal and nylon fiber production. The water use difference between polyester and nylon may be due to differing boundary conditions for gathering the data in the studies.

In addition, data was found for processing both organic and conventional cotton and organic and conventional hemp fiber. Only one data point was found for organic hemp fiber processing but that data point indicated that organic hemp fiber processing required ¼ the energy inputs than conventional. More data points were found for conventional and organic cotton fiber production. The findings for cotton fiber processing varied and did not consistently indicate that the energy use requirements are less for organic cotton fiber production.

When comparing the energy use and water use across data that was found for all fibers it is clear that virgin nylon and polyester have the greatest energy use. It is also clear that cotton and organic cotton have the greatest water use. Please refer to figure 2.1 and figure 2.2 below.

Figure 2.1 Comparison of energy use across fiber types. Standard deviation of the available data is shown using error bars.

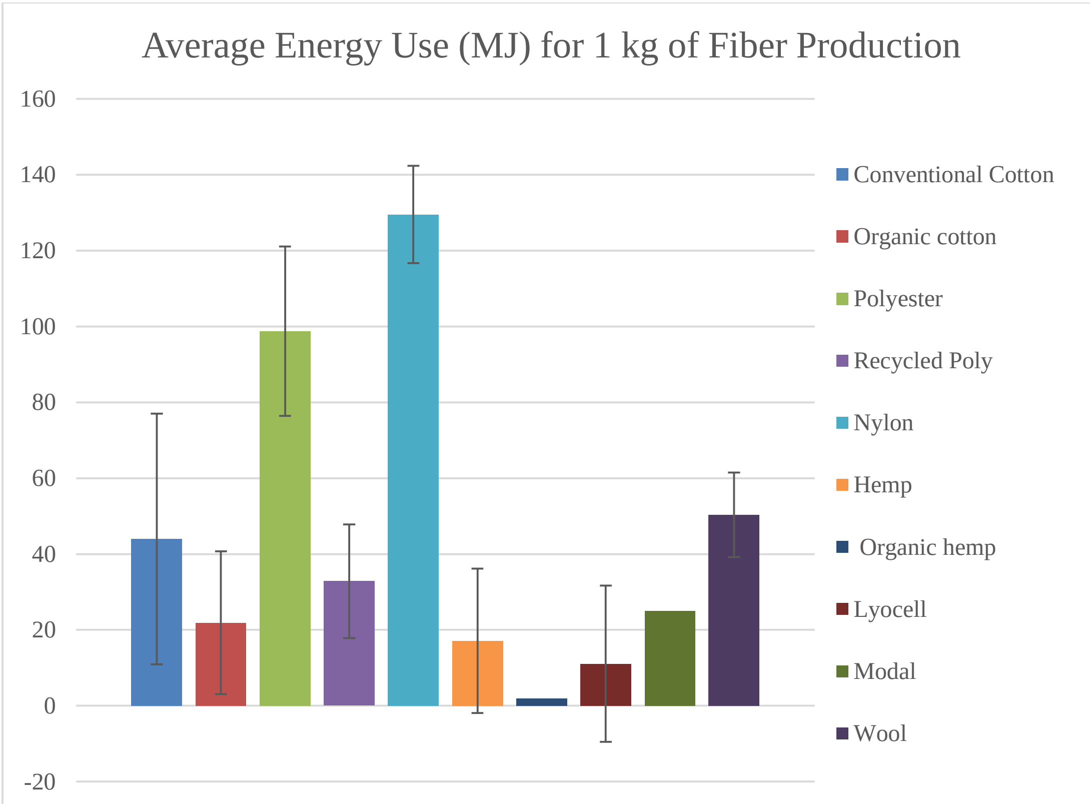
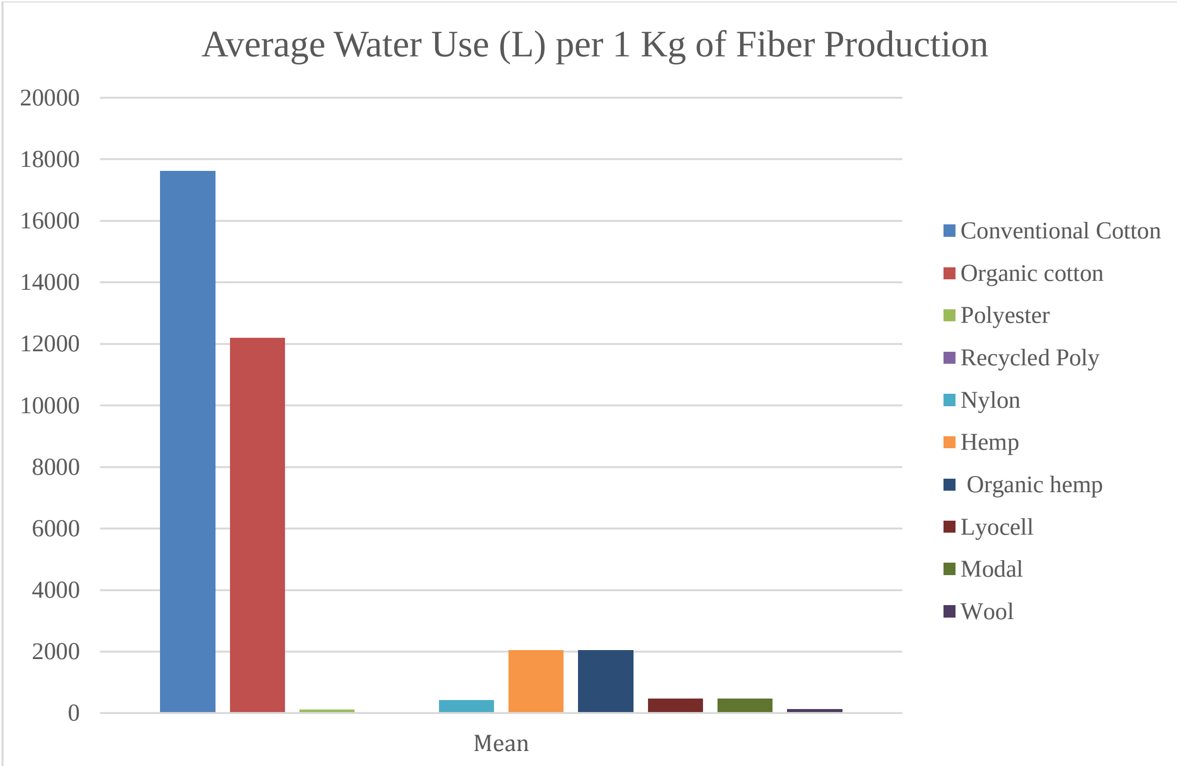


Figure 2.2 Comparison of water use across fiber types. Standard deviation is not shown in this chart due to the limited availability of water use data for each of the fibers.



Data was found for cradle-to-gate processes in the production chain including spinning, manufacturing fabric (knitting and weaving), and dyeing and finishing. The data available was not as specific to fiber type as it was for the fiber-processing step in the supply chain. The goal was to collect energy use, water use, and chemical use inputs for each of these supply chain steps. The chemical use data will be discussed in the following section. The spinning, knitting, weaving, and dyeing and finishing processes had far less water use information available. Wool processing was not found in the literature. In addition, no data was found for processing lyocell. Modal processing data, however, was included and could be used as proxy data to represent processing of lyocell. Polyester and nylon data points were often lumped together and considered "synthetic". Tables 2.11-2.13 break out the data by processing stage. Table 2.11 includes fiber spinning and yarn production processes. Table 2.12 includes weaving and knitting. Table 2.13 includes the dyeing and finishing processes.

Table 2.10 Yarn processing data and source for Cotton, Polyester, Nylon, Hemp, Modal and Wool

Process	Process Details	Location	Functional Unit (1 kg of yarn)	Energy Use (MJ)	Water Consumption (Liters)	Chemical Impacts	Source
Cotton - yarn production		Punjab, India	1 kg	3		No	Cherrett et al. 2005
Cotton - yarn production		USA	1 kg	2.5		No	Cherrett et al. 2005
Cotton - yarn production		Unknown	1 kg	27.55		Toxicity assessment included	Laursen et al. 2007
Cotton - yarn production	Opening, Cleaning, Mixing	China, India, US	1 kg	0.3		No	Cotton Inc. 2012
Cotton - yarn production	Carding	China, India, US	1 kg	0.384		No	Cotton Inc. 2012
Cotton - yarn production	Combing	China, India, US	1 kg	0.195		No	Cotton Inc. 2012
Cotton - yarn production	Drawing	China, India, US	1 kg	0.21		No	Cotton Inc. 2012
Cotton - yarn production	Roving (ring spinning only)	China, India, US	1 kg	0.637	20	No	Cotton Inc. 2012
Cotton - yarn production	Ring Spinning	China, India, US	1 kg	7.28	20	No	Cotton Inc. 2012
Cotton - yarn production	Rotator Spinning	China, India, US	1 kg	5.29	20	No	Cotton Inc. 2012
Cotton - Spinning	45 decitex (Where decitex represents yarn thickness of 1g/10km)	Not Referenced	1 kg	243.2		No	van der Velden et al. 2014

Cotton - Spinning	70 decitex (Where decitex represents yarn thickness of 1g/10km)	Not Referenced	1 kg	156.4		No	van der Velden et al. 2014
Cotton - Spinning	150 decitex (Where decitex represents yarn thickness of 1g/10km)	Not Referenced	1 kg	72.9		No	van der Velden et al. 2014
Cotton - Spinning	300 decitex (Where decitex represents yarn thickness of 1g/10km)	Not Referenced	1 kg	36.5		No	van der Velden et al. 2014
PET - Spinning	Spinning extruder polymer filaments 80-500 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg	19.2		No	van der Velden et al. 2014
PET - texturizing	Texturizing of polymers	Europe	1 kg	10.8		No	van der Velden et al. 2014
Nylon-Spinning	Spinning extruder polymer filaments 80-500 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg	19.2		No	van der Velden et al. 2014
Nylon - texturizing	Texturizing of polymers	Europe	1 kg	10.8		No	van der Velden et al. 2014
Hemp - yarn production	Scouring	UK	1 kg	15	82	No	Cherrett et al. 2006
Hemp - yarn production	Yarn spinning	Central-European (Hungary)	1 kg	75		Reported inventory of pesticides used	van der Werf et al. 2007
Hemp - yarn production	Yarn drying	Central-European (Hungary)	1 kg	40		Reported inventory of	van der Werf et al. 2008

						pesticides used	
Hemp - yarn production	Yarn - winding	Central-European (Hungary)	1 kg	70		Reported inventory of pesticides used	van der Werf et al. 2009
Hemp - yarn production	Yarn production - other	Central-European (Hungary)	1 kg	45		Reported inventory of pesticides used	van der Werf et al. 2010
Modal scouring	Scouring	Austria	1 kg black knitted modal fabric	13.2		No	Terinte et al. 2014
Modal spinning	Spinning	Austria	2 kg black knitted modal fabric	19.4		No	Terinte et al. 2014

Table 2.11 Knitting and Weaving data and sources for cotton, polyester, nylon, and modal

Process	Process Details	Location	Functional Unit (1 kg fabric)	Energy Use (MJ)	Water Consumption (Liters)	Chemical Impacts	Source
Cotton - fabric production	Knitting	China, India, US	1 kg	0.31	2	No	Cotton Inc. 2012
Cotton - fabric production	Compaction	China, India, US	1 kg	4.7	2	No	Cotton Inc. 2012
Cotton - fabric finishing	Finishing for yarn and batched dyed fabrics	China, India, US	1 kg	8	2.5	No	Cotton Inc. 2012
Modal knitting	1 kg black knitted modal fabric	Austria	1 kg dyed fabric	2.5		No	Terinte et al. 2014
Weaving - Cotton, polyester and nylon	45 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	356.4		No	van der Velden et al. 2014

Weaving - Cotton, polyester and nylon	70 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	229.1		No	van der Velden et al. 2014
Weaving - Cotton, polyester and nylon	150 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	106.9		No	van der Velden et al. 2014
Weaving - Cotton, polyester and nylon	300 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	53.4		No	van der Velden et al. 2014
Knitting - Cotton, polyester and nylon	83 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	5.5		No	van der Velden et al. 2014
Knitting - Cotton, polyester and nylon	200 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	2.3		No	van der Velden et al. 2014
Knitting - Cotton, polyester and nylon	300 decitex (Where decitex represents yarn thickness of 1g/10km)	Europe	1 kg undyed fabric	1.5		No	van der Velden et al. 2014

Table 2.12 Dyeing and Finishing data and sources for cotton, polyester, nylon, and modal

Process	Process Details	Location	Functional Unit (1 kg dyed fabric)	Energy Use (MJ)	Water Consumption (Liters)	Chemical Use Data	Source
Cotton - Fabric Pretreatment	Wet operation steps (including singeing, desizing, scouring, mercerizing and bleaching)	Not Referenced	1 kg	27.1		No	Van der Velden et al. 2014

Cotton - fabric production	Prep and Batch Dyeing	China, India, US	1 kg	10.718	23	No	Cotton Inc. 2012
Cotton - yarn dyeing	Prep and Yarn Dyeing	China, India, US	1 kg	93.623	26	No	Cotton Inc. 2012
Polyester (non woven) Drying	Mangle only	Europe	1 kg	28.15		Chemical inputs for dyeing	Hasanbeigi 2010
Polyester (non woven) Drying	Suction slot	Europe	1 kg	14.02		Chemical inputs for dyeing	Hasanbeigi 2010
Nylon (woven) drying	Mangle only	Europe	1 kg	11.79		Chemical inputs for dyeing	Hasanbeigi 2010
Nylon (non woven) drying	Mangle only	Europe	1 kg	28.15		Chemical inputs for dyeing	Hasanbeigi 2010
Nylon (woven) drying	Suction slot	Europe	1 kg	5.57		Chemical inputs for dyeing	Hasanbeigi 2010
Nylon (non woven) drying	Suction slot	Europe	1 kg	14.02		Chemical inputs for dyeing	Hasanbeigi 2010
Modal - conventional dyeing	Conventional fabric dyeing	Austria	1 kg	72		No	Terinte et al. 2014
Modal spin - dyeing	Mass dyeing, softening, drying	Austria	1 kg	8.4		No	Terinte et al. 2014

The research completed by van der Velden et al. (2014) showed that the smaller diameter cotton yarns required more energy to spin, whereas the energy required for spinning all diameters of synthetic yarns remained the same due to the nature of the spinning process for synthetic yarns. Cotton yarns are considered to be spun yarns and are made of staple fibers twisted around each other in the spinning process. The quality of the yarn depends amongst others on the length of the fibers. Longer fibers are stronger than shorter ones. A smaller diameter cotton yarn will need fewer fibers that are highly twisted. Fabrics that are made of high twisted yarns are flatter, smoother, or shinier than fabrics of low twisted yarns. Ring spinning is often the method used to make such higher quality cotton yarns and likely uses more energy than open-ended spinning, which produces low twisted yarns.

Yarn dyeing required more energy than batch dyeing for cotton fabrics while spin dyeing required less energy than conventional dyeing for modal. No data was found that addressed dying hemp or wool fabrics.

Chemical Use Data Collection Results

The findings from this research indicate a shortcoming in the existing textile and apparel LCAs that have been completed thus far. Seven of the nineteen studies included in this research addressed chemical use in some way. There is a clear distinction between chemical use input data and the toxicity characterization factors. Finding either proved to be very challenging.

Twelve of the nineteen studies, however, did not include chemicals inputs or toxicity impact data. Even the studies that did address chemical use or chemical impacts in some way had limitations to the way chemical use was evaluated. In addition to being infrequently reported in the LCAs reviewed, both types of data rarely reported chemical inputs or toxicity impacts in the same way and several of the studies reported that toxicity characterization factors have been shown to be inaccurate. Table 2.14 below shows the nineteen studies that were reviewed in this research and the column to the far right indicates if they reported on chemical inputs or toxicity impacts.

Table 2.13 LCAs that addressed chemical use or impacts

	Title	Author	Journal/ Organization	Year	Addressed Chemical use
1	Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling	L. Shen, E. Worrell, M. Patel	Resources, Conservation and Recycling	2010	Yes
2	Apparel Industry Life Cycle Carbon Mapping		BSR	2009	No
3	Life Cycle Assessment for Cultivation of Conventional and Organic Seed Cotton fibres	K Babu Babu, M Selvadass	International Journal of Research in Environmental Science and Technology	2013	Yes
4	Life Cycle Assessment of Cotton Fiber and Fabric		Cotton Incorporated	2012	No
5	Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester	N. Cherrett, J. Barrett, A. Clemett, M. Chadwick and MJ Chadwick	BioRegional Development Group and WWF Cymru, SEI (Stockholm Environment Institute)	2005	No
6	Life cycle energy and GHG emissions of PET recycling: change-oriented effects	L. Shen, E. Nieuwiaar, E. Worrell, M. K Patel	International Journal of Life Cycle Assessment	2011	No
7	Quantification of environmental impact and ecological sustainability for textile fibres	S. Muthu, Y. Li, JY Hu, PY Mok	Ecological Indicators	2011	Yes
8	Environmental assessment of textiles	S. Laursen, J. Hansen, H. Knudsen, H. Wenzel, H. Larsen, F. Kristensen	EPIDEX	2007	Yes
9	Life cycle Assessment of raw materials for non-wood pulp mill: Hemp and Flax	S. Gonzalez-Garcia, A Hospido, G. Feijoo, M.T. Moreira	Resources, Conservation and Recycling	2010	Yes
10	LCA benchmarking study on textiles made of cotton, polyester,	N. van der Velden, M. Patel, J. Vogtlander	International Journal of Life Cycle Assessment	2012	No

	nylon, acryl, or elastane				
11	Environmental impact assessment of man-made cellulose fibres	L. Shen, E. Worrell, M. Patel	Resources, Conservation and Recycling	2010	Yes
12	Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics	N.Terinte, BMK Manda, J. Taylor, K.C. Schuster, M.K. Patel	Journal of Cleaner Production	2014	No
13	The environmental impacts of the production of hemp and flax textile yarn	H. van der Werf, L.Turunen	Industrial crops and products	2007	Yes
14	Life Cycle Assessment (LCA) of Organic Cotton		PE International & Textile Exchange	2014	No
15	Eco-profiles of the European Plastics Industry Polyamide 6 (Nylon 6)	I. Boustead	Plastics Europe	2005	No
16	Eco-profiles of the European Plastics Industry Polyamide 66 (Nylon 66)	I. Boustead	Plastics Europe	2005	No
17	Understanding the environmental impacts of wool: A review of Life Cycle Assessment Studies	B. Henry	Australian Wool Innovation & International Wool Textile Organization	2012	No
18	Energy-Efficiency Improvement Opportunities for the Textile Industry	A. Hasanbeigi	China Energy Group, Energy Analysis Department, Environmental Energy Technologies Division	2010	No
19	Moving down the cause-effect chain of water and land use impacts: An LCA case study of textile fibres	G. Sandin, G. Peters, M. Svanstrom	Resources, Conservation and Recycling	2012	No

Chemical input data

Six papers did include chemicals input information. One study by Babu and Selvadass (2013) reported chemical inputs at the fiber growing stage of the lifecycle. These inputs were reported in kg of chemical per kg of seed cotton produced. A study by Gonzalez-Garcia et al. (2010) reported chemical inputs at the fiber growing stage for hemp in kg input per kg fiber produced. Refer to Table 2.15 below for a list of the chemical inputs at the cotton and hemp fiber growing stage of the lifecycle. van der Werf et al. (2007) also reported chemical inputs for growing hemp, but reported them using units of kg per hectare. The units in this form are not comparable. What can be seen is that the pesticides used are consistent with those reported in Babu and Selvadass (2013) and Gonzalez-Garcia et al. (2010). Boustead (2005) reported the inputs in mg to produce 1 kg of Nylon 6 and 1 kg of Nylon 6,6 (refer to Table 2.16).

Table 2.14 Summary of inventory data for cultivation of 1 kg of conventional cotton, organic cotton and hemp.

Inputs	Functional Unit	Cotton – Conventional (Source: Babu and Selvadass 2013)	Cotton – Organic (Source: Babu and Selvadass 2013)	Hemp (Source: Gonzalez-Garcia et al. 2010)	Hemp (Source: van der Werf et al. 2007
Nitrogen fertilizer	1 kg	0.085116 kg/kg cotton seed fibers		0.085 kg/kg hemp fiber	68 kg/hectare
Single superphosphate	1 kg	0.058264 kg/kg cotton seed fibers		0.065 kg/kg hemp fiber	30 kg/hectare
Phosphate rock (P_2O_5)	1 kg	-	0.018767 kg/kg cotton seed fibers		

Potassium chloride (K2O)	1 kg	0.044273 kg/kg cotton seed fibers	0.04154 kg/kg cotton seed fibers	0.125 kg/kg of hemp fiber	144 kg/hectare
Pyretroid-compounds	1 kg	0.0003 kg/kg cotton seed fibers			
Organophosphorous compounds	1 kg	0.005639 kg/kg cotton seed fibers			
[thio]carbamate-compounds	1 kg	0.000016 kg/kg cotton seed fibers			
Insecticides	1 kg	0.000306 kg/kg cotton seed fibers			
Herbicides	1 kg	0.000112 kg/kg cotton seed fibers			
Calcium Oxide (CaO)	1 kg				333 kg/hectare

Table 2.15 Gross raw materials required to produce 1 kg of Nylon 6 and Nylon 6,6

Raw material	Nylon 6 Input in mg	Nylon 6,6 Input in mg
Air	1400000	1700000
Animal matter	<1	<1
B	240	1
Barytes	3	3500
Bauxite	92	60
Bentonite	94	39000
Biomass (including water)	14000	6
Calcium sulphate (CaSO4)	9	<1
Chalk (CaCO3)	<1	<1
Clay	<1	<1
Cr	<1	1
Cu	2	7
Dolomite	21	610

Fe	1700	<1
Feldspar	<1	1
Ferromanganese	1	1
Fluorspar	1	<1
Granite	<1	2
Gravel	6	<1
Hg	<1	3200
Limestone (CaCO3)	2600	<1
Mg	1	170000
N2	350000	<1
Ni	<1	350
O2	270000	6
Olivine	16	3
Pb	11	<1
Phosphate as P2O5	400	1
Potassium chloride (KCl)	<1	<1
Quartz (SiO2)	<1	850
Rutile	<1	<1
S (bonded)	<1	14000
S (elemental)	340000	190
Sand (SiO2)	850	17
Shale	26	29000
Sodium chloride (NaCl)	57000	<1
Sodium nitrate (NaNO3)	<1	<1
Talc	<1	<1
Unspecified	<1	25
Zn	33	

Source: Boustead 2005

Input data at the dyeing and finishing stages looked quite different than that at the fiber production life cycle stage. The information found addressed the chemicals that were used to dye and finish but didn't provide exact amounts of inputs. For example, Terinte et al. (2014) included a list of chemicals and auxiliaries that are typically applied in the dyeing process, which include:

- Sodium sulphate (Na2SO4)
- Soda ash (Na2CO3)

- Caustic soda (NaOH)
- C. I. Reactive Black 5 (contain a vinylsulphone group as a reactive radical)

Terinte et al. (2014) explained that the pigments used for spun-dyed modal fabric are mostly carbon black or organic pigments, and that most organic pigments are prepared from azo, anthraquinone, triarylmethane, and phthalocyanines. In addition, they explained that reactive dyes consist of the same ingredients but the formulation for pigments and reactive dyes is different. Neither of these papers provided specific amounts of chemical inputs. The amounts needed are key to understanding the overall environmental impacts of each input. A paper by Hasanbeigi (2010) did however provide some specific information on how much auxiliaries and dyestuffs were required for different dye machines, though it did not list the specific auxiliaries and dyestuffs that are used.

Table 2.16 Specific input data for cotton dyeing with reactive dyestuffs in conventional jet machine, a new generation jet machine and single-rope jet machines

Input	Unit	Conventional jet machine	New Generation jet machine	Single-rope jet machine
Auxiliaries	g/kg	15-75	8-40	5-25
Dyestuffs	g/kg	10-80	10-80	10-80

Source: Hasanbeigi 2010 (originally from European Commission 2003)

Not all the dye is fixed to the fiber during the dyeing process. Table 2.18 shows the percentage of unfixed dyes for various textiles. The reactive dyes and sulphur dyes used for cotton and viscose have the poorest fixation rate. Poor fixation rates result in wastewater effluent problems.

Table 2.17 Percentage of unfixed dye that may be discharged in the effluent for different dye types and applications

Fiber	Dye type	EPA	OECD	ATV	Bayer	IPPC
Wool	Acid dyes					5%-15%

Wool	Reactive dyes					3%-10%
Nylon	Acid dyes	20%				
Cotton and viscose	Azoic dyes	25%	5%-10%	5%-10%		10%-25%
Cotton and viscose	Reactive dyes	50%-60%	20%-50%	5%-50%	5%-50%	20-45%
Cotton and viscose	Direct dyes	30%	5%-20%	5%-30%	10%	5-35%
Cotton and viscose	Pigment		1%	1%		
Cotton and viscose	Vat dyes	25%				5%-35%
Cotton and viscose	Sulphur dyes	25%	30%-40%	30%-40%		10%-40%
Polyester	Disperse	15%	8%-20%	8%-20%	5%	1%-15%

Source: Terinte et al. 2014 (adapted from Lacasse et al. 2004)

<u>Toxicity impacts</u>

Of the 19 papers reviewed in this research, five of the papers addressed toxicity impacts. CML 2001 toxicity characterization factors were the most commonly used. CML 2001 was developed by the Institute of Environmental Sciences, Leiden University, The Netherlands. It includes a set of impact categories and characterization methods that provide the quantitative measurements for the impact assessment step of LCA. Muthu et al. (2011) included a scale of impacts to human health, but it wasn't reported in a commonly used measurement and was therefore not comparable. Those that used the CML 2001 toxicity indicators are included in Table 2.19 below. All included human toxicity, fresh water aquatic ecotoxicity, and terrestrial ecotoxicity. Babu and Selvadass (2013) also included freshwater sediment ecotoxicity. Studies that focused on wool and hemp fiber did not have toxicity assessments and they are therefore not included in the toxicity comparison table below. These studies included the disclaimer that the quality of toxicity calculations in LCA tools is currently still doubtful and research is underway to improve the methodologies and to make the databases more complete.

Table 2.18 Cradle to factory gate toxicity impacts comparison from 1 kg of organic cotton, conventional cotton, PET, Modal and Lyocell fiber

Impact Category and Unit	Organic Cotton	Conventional Cotton	PET	Recycled PET (mechanical)	Recycled PET (semi-mechanical)	Recycled PET (Chemical, BHET)	Modal	Lyocell	Source
Human Toxicity (kg 1.4DB eq./kg)		2	4				0.765	0.470	Shen et al. 2010a
Fresh water aquatic ecotoxicity (kg 1.4DB eq./kg)		17	0.058				0.093	0.085	Shen et al. 2010a
Terrestrial ecotoxicity (kg 1.4DB eq./kg)		2	0.012				0.016	0.005	Shen et al. 2010a
Human Toxicity (kg 1.4DB eq./kg)	0.933	1.118							Babu and Selvadass 2013
Fresh water aquatic ecotoxicity (kg 1.4DB eq./kg)	0.385	0.480							Babu and Selvadass 2013
Terrestrial ecotoxicity (kg 1.4DB eq./kg)	0.009	0.010							Babu and Selvadass 2013
Freshwater sediment ecotoxicity (kg 1.4DB eq./kg)	0.825	1.025							Babu and Selvadass 2013
Human Toxicity (kg 1.4DB eq./kg)			4.303	0.362	0.415	0.745			Shen et al. 2010b
Fresh water aquatic ecotoxicity			0.058	0.296	0.25	0.303			Shen et al. 2010b

(kg 1.4DB eq./kg)									
Terrestrial ecotoxicity (kg 1.4DB eq./kg)			0.012	0.007	0.007	0.017			Shen, Worrell, Patel 2010

However preliminary these toxicity assessments are, they do provide a starting point for comparing the toxicity impacts of various fibers used in the apparel and textile industry. According to these three studies that evaluate organic cotton, conventional cotton, PET, modal, and lyocell fiber, PET fiber has the highest human toxicity impact. More than 90% of the impact is caused by air emission of PAH (polycyclic aromatic hydrocarbon) in amorphous PET production (Boustead 2005a). Cotton has the highest fresh water ecotoxicity and terrestrial ecotoxicity, mainly due to pesticides use (Shen et al. 2010a).

Laursen et al. (2007) reported toxicity results for human toxicity, ecotoxicity and persistent toxicity, but didn’t report specific values for the various fiber types. They instead reported toxicity impacts by percent of impact at each stage in the life cycle. The LCA of a cotton T-shirt included in Laursen et al. (2007) covered all life cycle stages, from origin of fiber through end of the life of the product. Unfortunately, Laursen et al (2007) did not include a weight conversion that indicated the amount of cotton needed to make a T-shirt. Without this information, it is challenging to accurately use the environmental impact data for one shirt to calculate the environmental impacts of 1 kg of fiber (the unit of measurement used in this research). Because they included the entire life cycle of a product as the scope of the assessment, it is very challenging to determine how the findings in compare with the ecotoxicity results in the three LCAs included in Table 2.19.

There were several papers that included some toxicity impacts, but noted that some chemical impacts were missing from the assessment and explained the reason why the information was excluded. Three papers made this note: Cotton Incorporated (2012), Shen et al. (2010a), and Terinte et al. (2014). Each provided the same explanation for the exclusion of certain toxicological assessments. Their reasoning was that they had concerns about the quality of toxicity calculations in LCA tools, caused by the lack of reliable toxicity assessment models and the limited data availability.

Cotton Incorporated (2012) presented their toxicity assessment in a qualitative way. They explained that the UNEP- SETAC USEtox® characterization model was used for determining Ecotoxicity Potential (ETP) and Human Toxicity Potential (HTP). Results showed that over the entire cradle-to-grave life cycle of cotton, nearly all of ETP is associated with pesticide application during the agricultural production phase. They noted that the precision of the current USEtox® characterization factors is less robust than for all other impact categories that were evaluated, such as GWP. In addition, emission profiles for some of the substances are incomplete, resulting in a high level of uncertainty in the toxicity assessment. For this reason, they used USEtox® characterization factors in their research as a means to identify the key contributors within a product life cycle, which significantly influences the product's toxicity potential. Materials were noted as 'substances of high concern', but comparative assertions across products or across impact categories were not made.

Shen et al. (2010a) explained past research revealed a dominant effect from marine aquatic ecotoxicity over all other environmental impacts due to the high uncertainties of the environmental impact from non-ferro metals in the CML method. None of the studies included in this research reported specific marine aquatic ecotoxicity impacts.

In general, the theme across the LCAs included in this research is that toxicity impact assessments were generally unreliable and explained that many textile chemicals lack toxicity impact characterization factors and therefore could not be included in LCA calculations. They explained that toxicity impacts were not included quantitatively due to lack of data and characterization factors for dyes and detergents.

Conclusions

This study represents comprehensive effort to find reliable data and report it in a consistent way. Energy use, water use, and chemical inputs were the focus of this study due to the fact that they are the typical inputs used in creating a life cycle inventory. By approaching the data collection process in this way, a library of data points has been created that can be used by individual companies and the larger apparel industry. The data provided in this research can be used as inputs into future LCAs that are conducted on specific products or processes or can be used as points of reference when new LCAs are completed to show impact reductions. The variety of data provided can allow a LCA practitioner to select data based on a specific process or specific region. This LCA data can also be customized to reflect the impacts of materials that are made using a blend of fabrics such as cotton/poly blends. By providing input data such as energy use and water use for cotton and polyester, a brand can use the input data to build the impacts for a cotton/poly blend. The goal of this research was not to compare the fibers to one another, but rather to provide usable data for brands to make informed decisions on what materials to use based on the corresponding environmental impacts of manufacturing those materials.

Systematic Review Discussion

There are numerous LCAs that evaluate apparel and textile available. The body of available research grows each year. However, the data that is available is of variable quality and new and existing LCAs are inconsistent in their reporting. For example, functional units chosen for studies can vary. Most use a single item of clothing; however, others use impact per wash, packs of clothing, or a set weight of clothing. In some studies, only the environmental impacts are reported and resource inputs are not shared. In addition, often one or two environmental indicators are the focus of the study, while other significant impact areas are ignored. These inconsistencies can make interpreting the results from different LCA studies problematic.

For this research, the functional unit used was 1kg of fiber for the fiber/extraction phase and spinning and 1kg of fabric for knitting, weaving, and the fabric processing phases of dyeing and finishing. This unit of measure was chosen because it will enable future use of the LCA data by industry, academia, and LCA practitioners. The functional unit of 1kg of fiber identifies impacts specific to the fiber growing and spinning life cycle stages while the functional unit of 1kg of fabric reveals the impacts that result from the knitting, weaving, dyeing, and finishing stages.

Often, the ultimate goal of a LCA is to evaluate the total impacts of a specific product, like an apparel garment. Reporting the environmental impacts of a garment without showing the input data in a standard way makes the information less useful for others wanting to apply the knowledge to their own specific product or process. There are two main benefits to reporting the data using a functional unit of 1kg. First, it identifies process impacts. If a brand wants to start reducing the impacts of its products, it needs to know what processes are causing the primary impacts and develop strategies for minimizing those impacts at the process level. This research has shown that numerous LCA studies have been completed on apparel products, indicating that the apparel industry has been able to quantify the environmental impacts of products. Now the industry needs to work to identify the life cycle stages that have the greatest impacts. By reporting data in a process-by-process way and in a standard unit of measure, the LCA can help to identify hot spots in the supply chain. Once those are identified, brands will know where to focus environmental improvement efforts. Second, this approach enables users of the data to select the specific process data that best applies to their own processes in order to best evaluate their own products. This also allows them to avoid using data that does not apply to their product. There are inherent assumptions made in a single product LCA. For example, some include impacts of washing in the consumer use phase of the LCA and impacts from disposal. Both of these life cycle stages are largely based on assumptions, and a future practitioner may not want to use those same assumptions.

The 1kg unit of measure can be universally used to calculate the specific impacts of various different textile and apparel products through an easy conversion based on the specification of the product being evaluated. The approach required to convert the environmental impact data from a functional unit of 1kg to a functional unit of one product simply requires information on the amount of fiber or fabric needed to make the garment being evaluated. Supply chain vendors will be able to provide this information. For example, if 1kg of cotton fiber yields 30 t-shirts, then the environmental impacts of 1 kg of fiber can be divided by 30 to reveal the impacts at the fiber level of the supply chain for one t-shirt. A jacket will likely require a heavier weight fabric than a t-shirt and will also require more yards of fabric that a t-shirt. Such conversions will be specific to garment type, fiber type, and fabric construction. In addition, conversions can and should be made at each life cycle stage.

A typical LCA is a sum of the impacts of all life cycle stages. The impacts at each life cycle stage are calculated independently and then summed to create a complete product LCA. For example, a certain weight of fiber will be needed to make one cotton t-shirt. The impacts of 1kg of cotton fiber can then be multiplied by the weight of fiber needed to make a t-shirt to determine the environmental impacts of one t-shirt at the fiber growing stage. That may or may not be the same amount of weight needed at the fabric dyeing and finishing stage. A t-shirt often requires more fabric than is actually used in the garment to accommodate for cutting scraps in the garment manufacturing stage. The weight of the total fabric needed, including the parts that will end up being scrap, should be multiplied by the impacts of 1 kg of fabric to accurately measure the impacts from the fabric manufacturing and dyeing and finishing life cycle stages. This approach can be applied to all life cycle stages for a product LCA.

In addition to the nuances in the functional units used, comparing and using reported results from LCA studies is also complex due to the number of methodological differences between studies. Differences in methodologies are often unidentifiable because it is challenging to capture all the boundary conditions and assumptions that were made in the text of the LCA report. Sandin et al. (2013) quantified impacts using both a consequential LCA and attributional LCA approach. The two approaches resulted in different inventory data and provide an example of how different boundary conditions can cause varying results. Knowing this, again, makes it difficult to have confidence that the data can be compared between studies.

Another finding was that although there are numerous LCA studies available for textiles and apparel, many of them are focused on evaluating the same handful of fibers. There are a large variety of textiles used to make clothing; however, LCAs are mainly confined to garments fabricated from cotton, polyester, and viscose. Little quantitative data are available for other textiles such as hemp and wool. There is also little data on fiber blends.

Aside from these limitations, the systematic review performed in this research resulted in finding 19 resources that provided specific process input data. Due to the quantity of high quality LCA studies found, it was possible to find data on the key fabric manufacturing processes for the 10 fibers that were the focus of the study.

In addition to the 19 studies that provided the data points for this research, two studies were identified that provided insight into process efficiency and environmental impact reduction and can be used as resources in the apparel industry. The papers, Energy efficiency guidebook for textile industry by Hasanbeigi (2010) and Environmental Improvement Potential of Textiles (IMPRO-Textiles) by Beton et al., are excellent resources for brands and manufacturers in the apparel industry to reference for process-specific efficiency guidance.

Comments on the data

The specific scope of this study helped to minimize data uncertainty. Because the data gathering process was focused on inputs only (energy use, water use, and chemical inputs), the variation that could have resulted from trying to compare various environmental impact characterization factors was eliminated. Also, the studies that include consumer use and end of life impacts rely upon making specific assumptions, particularly for consumer habits during the use phase and disposal phase. Such assumptions don't always accurately reflect real actions and can cause a high degree of uncertainty in the results. Because those life cycle stages were not included in this research, some uncertainty was avoided.

In addition, by not focusing on collecting CO_2 emissions data, another opportunity for inaccuracy may have been avoided. An example good example of this can be seen in the BSR Study (2009) that highlighted the methane emissions from sheep during the wool production process. The results of their research showed that the energy use to produce the wool fiber was shown to be less than cotton, but emissions were much greater due to GHG emissions from sheep. They acknowledged that methane emissions from sheep are a large but highly uncertain source of GHGs and explained that estimates of methane emissions varied per sheep vary from 5kg/head/year to 19kg/head/year. In addition, some of the GHG emissions from raising sheep can be attributed to other sheep products, such as meat. By changing assumptions, GHG emissions can increase or decrease. The focus on including energy use inputs and region where the processing is occurring can allow a brand or industry LCA practitioner to calculate the CO_2 emissions that best represent the specific process they are trying to measure.

Some papers did not include the raw data and only provided the environmental impact results by impact category, which does not provide an indication of what the energy and water inputs were. This makes it difficult to make comparisons between technologies and to use the data to make meaningful change in the processing and supply chain that reduces environmental impacts.

The goal of this data gathering process was to collect water use inputs for each of these supply chain steps. The assessment of water use in LCAs has historically been limited to an inventory level and reported as the volume of water used. The spinning, knitting, weaving, and dyeing and finishing processes had far less water use information available. This was both disappointing and surprising, as it is well documented that dyeing and finishing is known to be both a large water user and polluter. Attempts to quantify the impact of water use all along a product supply chain can be challenging, as there is uncertainty in determining what volume of water to quantify and how to interpret this volume in terms of environmental impact (Sandin et al. 2013). This difficulty may help to explain why there was so little water data provided in the existing LCA studies.

The region where the study was conducted was consistently referenced in the LCAs reviewed in this research. The location of the process data is particularly important detail when assessing potential for environmental or toxicological impacts. Air emissions are highly dependent of fuel source. Different countries and regions use different types of energy resulting in different air emissions. For example, CO_2 emissions associated with cotton range widely from 2.35 to 5.89 kg of CO_2 per kg of fiber. In this case, however, organic cotton grown in the USA has the lowest value, despite less energy being used in the organic cotton system employed in Punjab. This discrepancy reflects the different fuel mix used by the two countries, implying that the proportion and type of fuel used to generate energy in India produces greater CO_2 emissions per unit of fuel than that used in the USA, which in turn produces greater CO_2 emissions than that used in the UK (Cherrett et al. 2005). Location information will be specifically helpful to brands that want to calculate CO_2 emissions based location of production.

In addition, different countries have different environmental regulations. In developing countries, environmental legislation is often lax and/or not implemented properly, resulting in the potential for greater impacts. For example, in Shen et al. (2010a), human toxicity, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity addressed the impacts from US cotton but not the impacts from Chinese cotton. The reason is that Chinese cotton uses different pesticides and fertilizers and many of them cannot be assessed with the CML methods, which would cause underestimation of impacts. The practitioners therefore decided to use the toxicity impacts of US cotton as a proxy for the toxicity impacts of cotton. However, this approach most likely still underestimates the toxicity impacts of Chinese cotton, because US cotton farming has to comply with stricter legal requirements on fertilizer and pesticide use than many other conventional cotton cultivations in the rest of the world. The complexity of considering differences in location, energy use, and corresponding pollution can result in a much richer and more accurate understanding of global environmental impacts and the opportunities to minimize those impacts.

Addressing Chemical Impacts

The general lack of data available on chemical use was consistent with previous research. Roos et al. (2015) commented that typically research does not report on quantity of chemicals used, whether or not the substances are used in closed systems or otherwise, whether emissions and waste are properly treated, and which substances are used instead of the regulated ones. The absence of such important environmental aspects makes LCA findings much less informative as tools for environmental decision-making.

The chemical data that was found in the LCAs reviewed consistently revealed that the main chemical inputs and risk for toxicity in the life cycle stages of textile production are in the fiber production stage and the dyeing and finishing stage. Increased chemical inputs are inherently linked to an increase in chemical outputs, which leads to increases in human and ecotoxicity impacts.

The major chemical inputs in a typical textile lifecycle are at the fiber growing life cycle stage and the dyeing and finishing stage. Chemical inputs at the fiber growing stage include fertilizers, pesticides, herbicides and fungicides for natural fibers. In addition, synthetic fibers require chemical inputs as shown in Table 16, which includes the inputs required to produce nylon 6 and nylon 6,6. Through this research, chemical inputs for cotton, organic cotton, hemp, organic hemp, and nylon were identified. The insight into such specific input data can be used by brands and the larger apparel industry to start to understand the chemicals used in the textile manufacturing process.

The chemicals and auxiliaries that are used in the dying and finishing phase are the main area for chemical concern in the fabric processing life cycle step. Through this research several pieces of information, including types of chemicals and auxiliaries used, amount used, and amount that adheres to the fabric, were found.

Toxicity

It was clear from reviewing the existing LCA studies that much confusion and uncertainty still remains regarding assessing the toxicity of a substance or process. The significance of chemicals in terms of environmental and health impact in a life-cycle perspective is a complex equation in which exposure must be considered in addition to chemical effects such as toxicity, acidification, eutrophication, and even greenhouse emissions from the degradation products (van Zelm et al. 2010). Due to this complexity, emission profiles for many substances used in the apparel industry are incomplete. The number of "elementary flows" (substances) related to toxicity can range from 1,000 to 10,000, and the variation in toxic impact of those substances can vary by orders of magnitude (Cotton Incorporated 2012).

Even if there were toxicity characterization factor for all the chemicals used in textile processing, there are numerous variables that affect the toxicity of a process. One area where there is a high degree of uncertainty is the emission factors to estimate the fate of a chemical, particularly pesticides, at the time of application. There are numerous factors that impact a compound's final resting place at the time of application, such as humidity, wind speed, percent plant and weed cover, and type of application equipment used. In addition, there is further uncertainty in the factors used to predict the fate and transport of the compound once it does come to rest (Cotton Incorporated 2012).

Another example where process specifics can affect the toxicity assessment is in the dye and finishing processing. Dyeing techniques are highly diverse, both in terms of the chemical choices (vat dyes, direct dyes, and reactive dyes are some possibilities) and the equipment (Roos et al. 2015). In addition, varying exposures can affect toxicity impacts. For example, there are a variety of occupational risks in the dyeing mill. The workers are frequently exposed to dye dust, a variety of acids, synthetic detergents, dye carriers, fixatives and solvents during activities such as weighing of dyes, preparing dye baths in open dyeing machines, and handling of the dyed fabric. The risk of developing cancer, such as bladder cancer, esophageal cancer, and stomach cancer, as well as dermatological problems, is high among textile dyeing and printing workers (Terinte et al. 2014). Each variation in process and chemical used can result in differing potential for toxicity impacts. Current LCA methodologies do not yet cover these process intricacies and the toxicological impacts that result.

Future use of LCA Data

Filling in Data Gaps

There are numerous data gaps that became apparent after reviewing the nineteen LCAs included in this research. It was clear through this research that there is a need for more information on chemical inputs as well as toxicological characterization factors to assess the human and environmental impacts of the chemicals. The current predominantly qualitative assessments of chemicals in the textile product supply chain may prevent the significance of chemical impacts from being fully comprehended. The disregard of chemical issues in sustainability assessments can lead to erroneous conclusions and guide sustainable development in the wrong direction (Roos et al). In order to address this potential, there is a need for more information and an agreed upon approach to incorporating chemical use in LCA.

It is easy to be overwhelmed with the complexities of accounting for chemical impacts in an LCA. As mentioned throughout this paper, the first step is to know the chemicals are being used in a process and the known discharges. Volumes used should be included as far as possible, and it should be noted whether it is a discharge or a substance used in production. Without access to the chemical inputs into a process, it is impossible to measure the resulting impacts. According to Laurent et al. (2012), the key elements to assessing chemicals include the following: (a) identifying the most significant chemicals in terms of environmental and health impact in the life cycle of textile products, (b) developing the LCIA methods to cover characterization factors for these chemicals, and (c) including the chemicals both in the life-cycle inventories made by LCA practitioners and in commercial LCA databases.

According to Laursen et al. (2007), there are at least 20,000 different chemical substances are being used in Denmark, and they are all different as to their harmful properties for the environment and health. The point in mentioning this is to convey that it is a daunting task to understand the toxicity impacts of each of the 20,000 different chemical substances. It does not make sense to enter all chemicals that occur during the lifecycle of the studied product in the lifecycle assessment model. Such a list would not contribute to the assessment, as many substances are relatively harmless, and secondly, it would quickly become unwieldy to assess. It is therefore recommended to complete a preliminary assessment of whether the substances have special harmful impacts on the environment or health (Laursen et al. 2007). This assessment can be based on whether or not the chemicals are included on lists of substances that are harmful to health and the environment and if the products/auxiliary substances are labeled with specific risk indications. Substances classified as hazardous to health and/or the environment should then be included in the lifecycle assessment matrix. The three elements proposed by Laurent et al. (2012) and the prioritization concepts suggested by Laursen et al. (2007) can be used as guidance in the efforts to advance the incorporation of chemical impacts into LCA in a more reliable way.

In addition to the need for more chemical information, there is a need for more specific process water use data. The data gathered through this process revealed that water use data is limited in its availability. Water stress and vulnerability are key global concerns and many of the processes involved in making textiles are water intense. For example, in most of the regions where cotton is grown, rainfall is insufficient to provide the necessary moisture for the growth of the crop to give commercially viable yields. Rainfall provides only about 30 per cent of the water demand of the cotton crop in many cotton growing areas of the USA, leaving the rest to be supplied by irrigation (Cherrett et al. 2005). The amount of water supplied through various methods of irrigation represents a huge demand on what can be very limited total water resources. Thus, the situation arises where the irrigation demand is met to the detriment of other competing demands such as domestic, municipal, and industrial supplies, although the quality of water for competing uses is not identical. It is important to have an accurate understanding of regional water demands for certain processes in order to ensure that textile processing is occurring in locations where water resources are available to meet the needs without being a detriment to the various other water demands in a region.

Impact reduction

The ultimate goal of gathering LCA data is to inform process improvements that reduce demand for resources and negative impacts on the environment. By focusing on gathering more data on the resource and chemical inputs into a process, there will be more information that can be used to make decisions that minimize environmental impacts in the future. There are two main areas that have the potential to result in environmental impact reductions: minimizing the use of harmful chemicals and improving the efficiencies of the processes used in textile manufacturing. Chemical use can be reduced through agricultural practices such as organic and biodynamic farming. Chemical substitution is also an approach that aims to minimize the harmful effects of chemicals by replacing process chemicals that have a high pollutant strength or toxic properties with others that have less impact on effluent quality (Entec UK Ltd 1997). Replacing chemicals with enzymes could also provide opportunities for impact reduction (Beton, Environmental improvement potential of textiles).

Process improvements can also provide an opportunity to reduce environmental impacts. Research has already been conducted that has identified processes that reduce impacts. One example from Terinte et al. (2014) explained that spun-dyed fabrics do not contribute to salinization due to the absence of salts in spin-dyeing. This is because a very low amount of pigments are required and entrapment of the pigment in the fiber structure is high. The spun-dyed fabric can be expected to cause substantially lower human and eco-toxicity impacts compared to conventionally dyed fabric (Terinte et al. 2014). In addition, the spin dying process, when applied to modal fabric, has one-tenth the energy demand as the conventional dyeing process. This process improvement is one that provides an example of minimizing both demand on energy resources and toxicity impacts.

Making comparisons

The ability to make comparisons across LCA studies would make LCA an even more useful tool. There are currently limitations to comparing studies due to inconsistent methodologies, scopes, assumptions, units of measurement, and boundary conditions. Comparative assertions are strongly discouraged unless methodologies are consistent (Henry 2012). The hope, however, is that as LCA becomes more streamlined and established methods and approaches become more widely used, there will be more opportunities to compare studies and use the data gathered to make informed product and process decisions to minimize environmental impacts. When comparisons can be made across processes, fiber, chemicals, regions, etc. in an accurate way, changes to existing practices will be more likely to actually reduce environmental impacts. As an example, comparisons can allow brands and the larger industry to evaluate fibers to determine if they can be replaced with a less impacting fiber, to compare an alternative knitting technique that reduces water use in the dye process to a conventional process, or could provide an opportunity to evaluate alternative agricultural practices that may reduce agrochemical use.

The design of this data gathering process allowed for some comparison across fibers and processes. If all the data collected in LCAs could be accurately compared, we would gain a much greater understanding of the various factors that drive environmental impacts.

Closing remarks

The quantitative and holistic approach offered by LCA is one reason why it is commonly applied as a tool to identify the improvement potential in the environmental performance of products. With the inclusion of chemical impacts, LCA will become a more relevant tool for textile assessment by providing holistic guidance to environmental decision makers. There is still the need for more transparency in terms of reporting resource use and chemical use inputs. The goal is to reach a point where all inputs and quantities of those inputs are readily available and can be used to incorporate into the environmental impact evaluation process.

Even with that caveat, I hope the work presented here will inspire further efforts to make use of the burgeoning LCA literature. This research will be helpful to those brands and industry partners that need an understanding of environmental data but have limited resources and time to gather the data on their own. It will give them the ability to immediately start understanding the environmental impacts of the materials used in apparel products. The hope is that this data will eventually be used to help guide materials selections based on environmental impacts in the future.

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Chapter 3: Evaluation of a Collaborative LCA Approach: Patagonia Product Case Study

Introduction

The product system is becoming the focus of environmental policy because products are the key linking elements in the economic-environmental system (Berkhout 1997). LCA is a systems tool that can assess and help improve the environmental performance of products by providing insights into the environmental impacts of the whole value chain (ISO 2006a; ISO 2006b). The LCA environmental assessment approach captures the complexity of a product system. The European Commission has been working to formalize environmental regulations on products and is using LCA as the foundation for the regulation.

In April 2013, the European Commission released the Product Environmental Footprint (PEF) guide along with the Organization Environmental Footprint (OEF) guide, under the premise of the "Single Market for Green Products Initiative" (EU PEF 2013). The Commission's actions are part of a larger recommendation toward sustainable consumption and production by the United Nations and the Commission itself. The objective of the PEF guide is to create a standard way for businesses to evaluate and communicate the environmental impacts of their products in order to enhance transparency and fair competition. The ultimate aim is to provide incentives to businesses to report and reduce environmental impacts. The PEF guide is built on existing LCA-based product claim standards, such as ISO 14025, PAS 2050, BP X30-323, GHG Protocol, etc., and LCA standards and guides, such as ISO 14040, ISO 14044, and ILCD Handbook (EU PEF 2013). The PEF guide has emerged at a time when companies and other stakeholders have expressed the need for a well-established and broadly accepted product assessment methodology.

Europe is one step ahead of other countries by going beyond corporate reporting and aiming to require product environmental footprints (LCAs) for consumer products. Brands that sell products in Europe, such as Patagonia, will be responsible for providing environmental impact information at the product level once this legislation is passed. The European Commission’s efforts to formalize environmental regulations on products have been taken seriously by the apparel industry and in an effort to prepare for future environmental labeling requirements on products sold in Europe, Patagonia and other brands have been investigating ways to adhere to such requirements. In order to accurately report environmental impacts of products, apparel brands need access to accurate product manufacturing and supply chain data. It is imperative that Patagonia starts establishing a system for gathering environmental impact data and conducting LCAs at the product level in order to prepare for the European Commission’s legislation.

The SAC is a trade organization comprised of brands, retailers, manufacturers, governmental and nongovernmental organizations, and academic experts affiliated with the global apparel and footwear market. The SAC has created a forum for these organizations to work in a collaborative way toward measuring and reducing the environmental and social impacts of apparel and footwear products around the world. One of the work products that have resulted from SAC’s efforts is the creation of Product Category Rules (PCRs) for a technical shell.

PCRs are a set of specific rules, requirements, and guidelines for developing Environmental Product Declarations (EPDs) for one or more product categories. PCRs address the product category definition and scope of the LCA study conducted. They include guidance on what should and shouldn't be included in the inventory analysis (data collection and allocation), impact category selection and calculation rules, and other additional environmental information. PCRs provide a globally accepted way to standardize quantitative, LCA-based measurements of product life cycle impacts. The benefits of an industry-wide standard approach for apparel is that data collection can be made more efficient for suppliers by minimizing redundancies and inconsistencies through common data collection formats and requests. In addition, impact assessment results of products are comparable on a life cycle basis, and information is transparent to allow understanding of limitations and comparability (Schenck 2013).

According to ISO 14040 and 14044 standards, there are four main phases of an LCA. The first is to develop a goal and scope for the assessment. The second phase is the Life Cycle Inventory (LCI) analysis, which includes the identification and quantification of the material and resource inputs as well as emissions and product outputs from the product over its life cycle in relation to the functional unit. The third phase is Life Cycle Impact Analysis (LCIA), which aims to provide an understanding of the magnitude and significance of the environmental impacts caused by the studied systems emissions, land use, and resource extractions that were identified during inventory analysis (Seppala 2002). The last phase is the interpretation phase, which includes summarizing the results from the LCI and LCIA and providing conclusions and recommendations.

In order for LCA to be used as an effective mechanism for educated decision-making within industry, the approach to gathering LCA data and conducting the analysis needs to work within the structure of corporate operations. The apparel industry has expressed interest in enlisting a collaborative data approach to gathering LCA information for apparel products. In the context of this paper, a collaborative data gathering approach refers to the concept of industry partners that each play a role in producing a single product gathering data specific to the processes that they control, own, or operate, and sharing that data with the other businesses involved in manufacturing the specific product.

For example, in the supply chain for an apparel product, there are many steps involved in the manufacturing process, which may not be carried out by the same company and are most often not owned by the brand that ultimately sells the product. The fabric manufacturer, garment assembler, and the Brand that ultimately markets and sells the product all manage certain steps in the life cycle of the apparel product. In a collaborative LCA approach, each of these supply chain partners would gather LCA data specific to the processes that they control and use them together to create a complete product LCA. A key component of this approach is that vendors and brands openly share the data they collect.

The goal and hope is that by sharing data and ultimately making LCA data publicly available, more brands and supply chain partners will have access to environmental impact data, thus stimulating an open discussion between companies, consultants, suppliers, and academics about how best to manage environmental impacts. Combining inventory data from different sources, prepared by different individuals, has the potential to be a very effective way to conduct an LCA study. By breaking down the life cycle into a series of sequential phases such as raw material extraction, processing, use phase, and end of life, brands can attempt to gather accurate data at all steps in a product's life cycle. Once specific process data is available, brands can gather process data that best applies to their products in order to build a complete LCA.

Interesting examples of the involvement of business' stakeholders in the context of LCA have been reviewed but, so far, community-wide participation in LCA is not structured (Sala et al. 2012). Sala et al. (2012) noted that at this point in time, stakeholder involvement in LCA is a less explored field and approaches to stakeholders' involvement should be further developed (Sala et al. 2012).

A supply chain collaboration model completed by Nakano and Hirao (2011) began to explore this idea, but there were many details in the process that were not examined. They did however find that collaborative activities with business partners have potential to improve environmental performance of product and life cycle assessment (LCA). They noted in their research that collection of LCA data from supply chain is a major issue for LCA practitioners. In order to address this challenge, they proposed a Supply Chain Collaboration Model (SCCM), which is a framework for collecting producer-specific LCA data from business partners and for promoting improvement activity of product environmental performance. They completed three case studies that provided examples of two or three partner companies collaborating to complete an environmental improvement project for a product and completing process analysis techniques such as LCA.

This research takes the findings from Nakano and Hirao (2011) and focuses on the specific details required to complete a collaborative LCA. This research provides a case study to determine if data collected using the same methodology, but analyzed using two different LCA software systems and by two different LCA practitioners, results in a sound and reliable LCA approach. According to Rajagopal (2013), different studies employing different system boundaries, different sources of data, and different modeling approaches seem to provide widely varying estimates of the [environmental] benefits of a technology. In this case study, the same methodology was used as guidance for all steps in the life cycle. Despite this, there is still the potential that results can differ when using a collaborative approach to LCA.

The challenge is that each organization will likely build their process LCA using different LCA software that provides access to different data sets and impact characterization models. There are numerous LCA software systems available to businesses that can be used to complete LCAs. LCA software systems are computerized tools used to model the environmental impacts of a product system. Commonly used systems in the US and in Europe include GaBi, SimaPro, and Open LCA. Certain countries also have specific LCA software systems commonly used within that country. Each of these LCA software systems contains data sets that are used to model the resource inputs and outputs of a product system. In addition to data sets, these software systems also include various different impact characterization models that can be used to quantify the environmental impacts of the product system.

When using different LCA software systems, there may be variations in the regionally specified inventory data. Quantifying inputs and outputs is the key component of the LCI step of a LCA and involves creating an inventory of flows from and to nature for a product system. Inventory flows often include inputs of water, energy, and raw materials, and outputs of releases to air, land, and water. To develop the inventory, a flow model of the technical system is constructed using data on inputs and outputs. The input and output data sets are not necessarily the same across LCA software systems. The effect of an inexact flow match (when the different systems don't have the same input or output data) could potentially change the environmental impact outputs.

In addition, differing software systems may employ different environmental indicators used to measure a specific impact. The limitations and opportunities of this process will be highlighted in the Conclusions and Discussion section as well as the guidance on whether or not this approach to LCA should be used within industry and/or academia.

Speck et al. (2015) completed a systematic comparison of the evaluation of several life cycle packaging software systems including COMPASS, SimaPro, GaBi, and Package Modeling. The research supported the concerns mentioned in the previous paragraphs and found significant discrepancies in LCA results from different software systems. The results from the LCA software systems being studied were not in alignment and, in some cases, results were more than an order of magnitude different between software. In addition, varying availability of common impact categories among the software limited comparisons to four categories: greenhouse gas emissions, fossil fuel/non-renewable energy, eutrophication, and water depletion (Speck et al. 2015).

The research completed by Speck et al. confirms that there is a high potential for varying results when utilizing different software systems. The fact, however, is that the investment in a LCA software system is large, regarding both monetary costs for the system itself, corresponding data sets, and the time and resources required to train employees on how to use the software system. Once a company has invested in a LCA software system, it is not practical for them to move away from that investment and change the software system they are using. In addition, it is challenging for supply chain vendors that have partnered with several different brands to ensure that the software systems they are using match with the various software systems used by the brands they are working with. With this in mind, it is important for companies to be able to both utilize the software systems that have invested and collaborate with other companies using different software systems.

This research attempts to address the complexities that result from using more than one LCA software system by evaluating the practical application of a collaborative data approach to completing an apparel product LCA. This research includes a case study that evaluates how using two LCA software systems to complete different life cycle stage assessments can be reconciled in one product LCA. The approach taken in this research is designed to determine if it is possible to use different software systems and still get reliable and consistent LCA results.

Methods

In order to understand how a collaborative approach to LCA could work, a case study was conducted focusing on completing two LCAs on the same product, using data from two different companies and two different software systems. Both companies used the

Sustainable Apparel Coalition's Product Category Rules (PCRs) for a Technical Shell as the LCA methodology.

Past research completed by Sala et al. (2012) noted that theoretically, in the goal and scope phase of the methodology, the interested parties should be involved in order to better define the decision context and the purpose of the study, but in practice an LCA is carried out for one actor only. With this in mind, Patagonia, with one of its supply chain partners that manufactures technical jackets, jointly agreed upon the goal and scope for this case study. Patagonia's supply chain partner is considered a vertical supply chain vendor due to the fact that they control and execute all the processes involved in manufacturing garments. These processes include manufacturing the fiber and the fabric, dyeing and finishing the fabric, and assembling the garment.

The opportunity to complete this case study was unique for Patagonia. Gathering process-specific data for each step in a product supply chain is very challenging. Many supply chain vendors are hesitant to share such specific data, as it can often be a reflection of proprietary processes. In addition, many vendors don't have the resources or expertise to conduct LCAs. Patagonia has a handful of supply chain partners that have completed material-specific and product-specific LCAs, but they are not willing to share the more detailed inputs and outputs at each stage in the product life cycle. They often also don't share the methodology or boundary conditions used to complete the LCA, making it difficult to understand which aspects of the product system are or aren't included in the LCA. Hence, having the opportunity to see process-specific data from one of Patagonia's specific supply chain partners and have it presented in a format that can be used in an LCA is extremely rare.

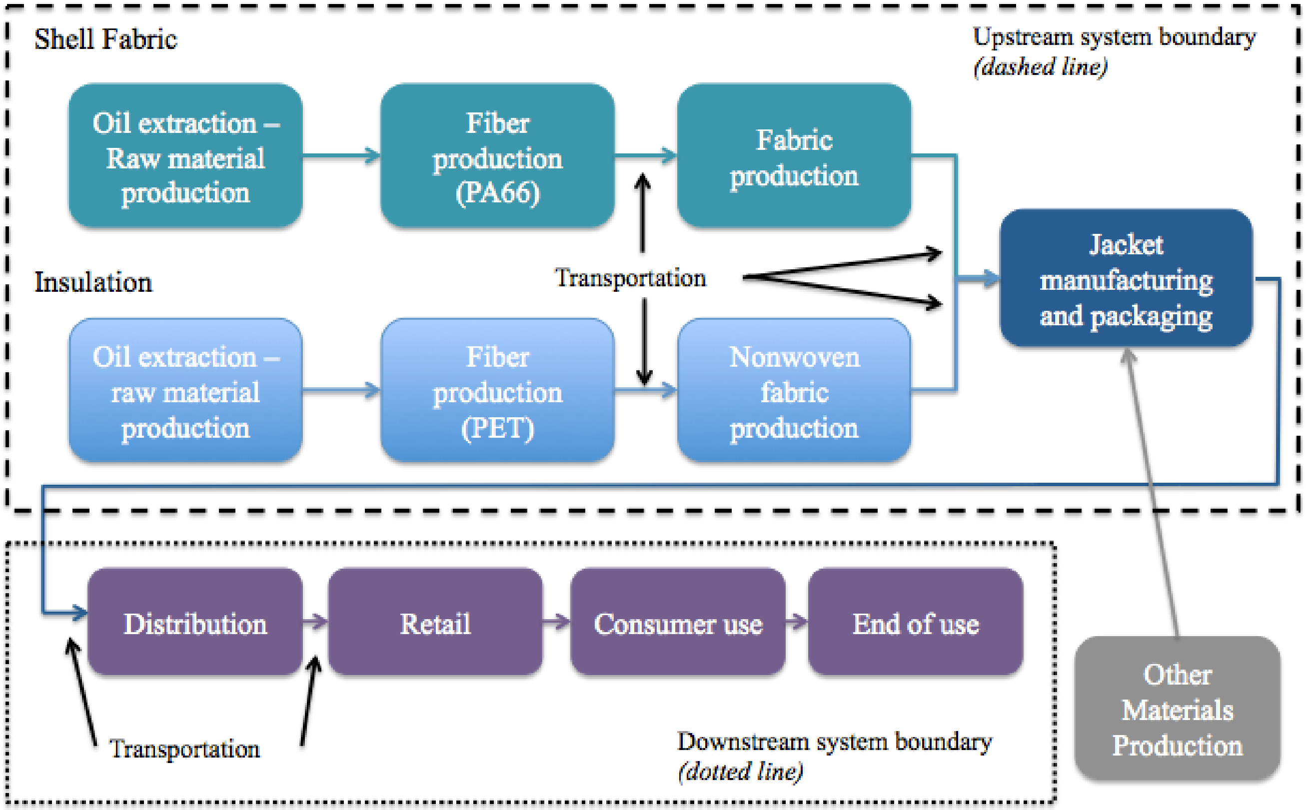
Patagonia was fortunate enough to have one synthetic fabric manufacturer that was willing to participate in this case study and provide product-specific data. This gave Patagonia the unique opportunity to create a comprehensive product LCA that includes primary data.

The vertical supply chain vendor completed the LCI for the upstream manufacturing steps of the product life cycle while Patagonia completed the LCI for the downstream life cycle phases, including distribution, retail, use, and end of use phase of the product life cycle (Table 3.1). A flow chart of both upstream and downstream processes is included in Figure 3.1.

Table 3.1 Upstream and downstream life cycle stages

Upstream life cycle stages (vertical supplier processes)	Downstream life cycle stages (Patagonia processes)
Fiber manufacturing	Distribution (storage in warehouse)
Fabric manufacturing	Retail (point of sale)
Fabric dyeing and finishing	Use of product (consumer use)
Product assembly (cut and sew)	End of product use (disposal)
Transportation between all upstream life cycle stages	Transportation between all downstream life cycle stages

Figure 3.1 Life cycle stages of the technical jacket



Shell Fabric
Upstream system boundary
(dashed line)
Oil extraction – Raw material production
Fiber production (PA66)
Fabric production
Insulation
Transportation
Jacket manufacturing and packaging
Oil extraction – raw material production
Fiber production (PET)
Nonwoven fabric production
Distribution
Retail
Consumer use
End of use
Other Materials Production
Transportation
Downstream system boundary
(dotted line)

Two different LCA modeling software systems were used to compile the data needed for all processes included in the life cycle of the technical jacket. The upstream life cycle stages, including transportation between each stage, were modeled using a Japanese LCA software system called MiLCA. GaBi was used to model the downstream lifecycle stages including the distribution, transportation, product use, and end of life stages of the garment’s life cycle. Once this process was completed, the upstream data from the vertical supply chain partner was given to Patagonia and a LCA was completed using GaBi. Concurrently, Patagonia’s downstream data was shared with the vertical supply chain partner and a full product LCA was completed using MiLCA. Refer to Table 2 to see a matrix of the different practitioners and software systems used to complete the two LCAs. This process allowed for a comparison to determine if a collaborative approach to LCA produces similar results.

LCA software and characterization model details

When choosing an LCA software system to use, a company or LCA practitioner is also by default choosing the impact characterization models it has access to. Most LCA software systems include more than one impact characterization model available to use in the system. Examples of impact characterization models include: ReCiPe LCIA methodology developed by RIVM, CML, PRe Consultants, Radboud Universiteit Nijmegen, and CE Delft; LCIA CML 2001, which is developed by the Institute of Environmental Sciences, Leiden University, The Netherlands; TRACI - The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, developed by the US EPA; and ILCD, which is the European Platform on Life Cycle Assessment provided by the European Commission, Joint Research Centre (JRC).

Once the software system is chosen, the LCA practitioner then has the opportunity to choose from the impact characterization models provided in their LCA software. Each of the impact characterization models can calculate various environmental impacts. Characterization factors are derived from the characterization model, which is used to convert an assigned life cycle inventory analysis result to the common unit of the category indicator. Typical impacts addressed by impact characterization models include global warming potential (GWP), eutrophication potential, ozone depletion, ozone creation, acidification, toxicity impacts to humans and to the environment, and resource depletion. Some of the impact characterization models overlap in their units of measurement and others do not. The reasons for choosing a characterization model can vary from LCA to LCA and will depend on a variety of factors including purpose of the study, the region where the LCA is being completed, how current the models are, etc. The paragraphs below explain the two LCA software systems used to complete this case study and the characterization models available within each one.

MiLCA's software provides impact characterization models that address global warming potential (GWP), eutrophication potential, ozone depletion, ozone creation, acidification, impacts to human health, and resource depletion. The main impact assessment model is LIME 2 (Life-cycle Impact assessment Method based on Endpoint modeling), which is the Japanese life-cycle impact assessment method. MiLCA also contains some of the ReCiPe characterization methods. For the purposes of this report, the characterization factors included in MiLCA that best match those required by Earthsure (2013) were used.

Refer to table 3 for details on the characterization factors used to model each area of impact reported in the case study.

The GaBi software also provides assessment of environmental impacts such as global warming potential (GWP), eutrophication potential, ozone depletion, ozone creation, acidification, impacts to human health, and resource depletion. GaBi has four different data sources/methodologies that it utilizes to provide life cycle impact analysis. These four include: ReCiPe, LCIA CML 2001, TRACI, and ILCD. For the purposes of this report, the GaBi model will use the TRACI characterization factors. The main areas of impact that will be assessed are GWP, eutrophication potential, and resource depletion. Energy use and water use inputs will also be reported.

Table 3.2 below shows the LCA software system used for each LCA and the LCA practitioner for each LCA. Table 3.3 includes the specific impact categories that were selected for this case study to quantify the impacts in each life cycle stage of the technical jacket.

Table 3.2 LCA data, software and practitioner matrix

	Supplier's LCA		Patagonia's LCA	
	Software	**LCA Practitioner**	**Software**	**LCA Practitioner**
Upstream Processes	MiLCA	Vertical Supplier	MiLCA	Vertical Supplier
Downstream Processes	GaBi	Patagonia	GaBi	Patagonia
Complete LCA	MiLCA	Vertical Supplier	GaBi	Patagonia

Table 3.3 Impact categories and units of measurement selected to be evaluated in this LCA case study

Life Cycle Impact	Units
Global Warming	Kg CO_2 equivalents
Eutrophication	Grams P- equivalents
Energy Use	MJ
Water Scarcity	Liters of water equivalents
Abiotic Resource Depletion	Antimony (Sb) equiv.
Toxicity	Kg 1,4 DB equivalents
Smog Air production	Kg O_3 equivalents
Waste Percent	% or weight

The impact characterization models and units of measurement that were used in in the MiLCA assessment and the Gabi assessment are included in Table 3.4.

Table 3.0.4 Characterization models and units of measurement used in the MiLCA and GaBi assessments

Life Cycle Indicator	Vendor LCA – using MiLCA software		Patagonia LCA – using GaBi software	
	Units	Models	Units	Models
Eutrophication	Kg P - Equiv.	EP (Heijungs, 1992, 2000)	Kg N - Equiv.	TRACI 2.1
GWP (Global Warming)	Kg CO_2 equivalents	100-year GWP IPCC, 2007	Kg CO_2 equivalents	TRACI 2.1 (IPCC)
Energy Use	MJ	MiLCA regional energy data	MJ	GaBi regional energy data
Water Scarcity	Kg	Fresh water use	Kg	Fresh water use

Abiotic Resource Depletion	Kg Sb equivalents	CML 2002	MJ surplus energy	TRACI 2.1
Acidification	-	-	Kg SO_2 equivalents	TRACI 2.1
Human Health Particulate Air	-	-	Kg PM 2,5 equivalents	TRACI 2.1
Smog Air Production	-	-	Kg O_3 equivalents	TRACI 2.1
Waste Percent	%	Upstream primary inventory data collected	-	-

Functional Unit

The functional unit for the LCA in this research is one technical jacket. For the purposes of the research, the scope is even further defined to include the primary materials, based on weight, used in the garment. The focus of this case study will be on the outer fabric, the liner fabric, and the nonwoven insulation (components a. and b. below). Zippers and other materials will be excluded from this study. According ISO 14044 (2006), mass of the product is one cut-off criteria that can be used in LCA to decide which inputs are to be studied. When using mass as the criterion, all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled are required to be induced in the study. In the case of this study, we focused on assessing the contents of the garment that made up 90% of the total weight of the garment. Zippers and other trim components make up less than 10% of the weight of the garment and are therefore not included in the assessment.

<u>Jacket components included in the research:</u>

a.) Outer fabric and lining fabric made of Polyamide 66 (PA66), also known as nylon b.) Nonwoven insulation by polyethylene terephthalate (PET)

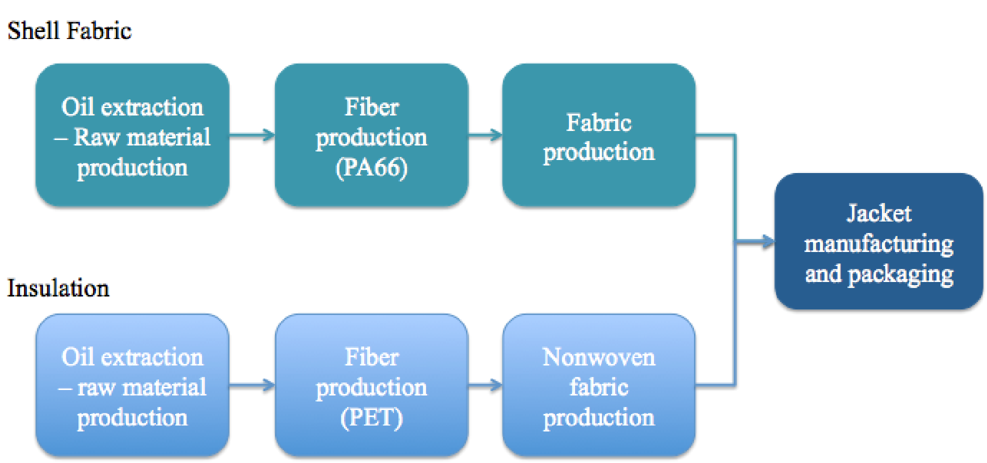
Patagonia makes four types of this specific jacket; men's and women's hooded and men's and women's non-hooded. For the purposes of this study Patagonia and its vertical supplier chose to focus on the men's non-hooded jacket, as it is the most representative product of the larger technical jacket category made using synthetic insulation.

Upstream and Downstream Data Collection Method and Approach

Upstream System Boundaries

Patagonia's vertical supplier is responsible for the polymerization through jacket production phases of the life cycle. The system boundary for data provided by the vertical supplier mirrors its operational responsibilities and includes raw material extraction (a process not carried out by the vertical supplier) through jacket production.

Figure 3.2 Upstream processes included in the scope of the men's non-hooded jacket



Upstream Data Collection

Data provided by the vertical supplier was collected in Japan and Vietnam at the facilities where each unit process occurs. Primary data from producing and processing at each site was used. Secondary data was used when primary data could not be obtained. In the case of the research, secondary data was used to represent bought materials and utilities. Secondary data was gathered through the IDEA version 1.1.0 developed by National Institute of Advanced Industrial Science and Technology (AIST) and Japan Environmental Management Association for Industry (JEMAI). IDEA is the inventory database loaded on the LCA software MiLCA provided by JEMAI.

Upstream Calculation Details and Assumptions

Energy Use:

Electricity use and other fuel data were gathered at the various manufacturing facilities. Power grid mixes were determined using MiLCA background data. The renewable energy rate was calculated by determining the amount of renewable energy in the electricity grid for the various upstream stages.

Transportation:

Transportation impacts are included in the upstream system boundaries. Transportation calculations were completed using the MiLCA software. The following assumptions were made for the upstream transportation calculations:

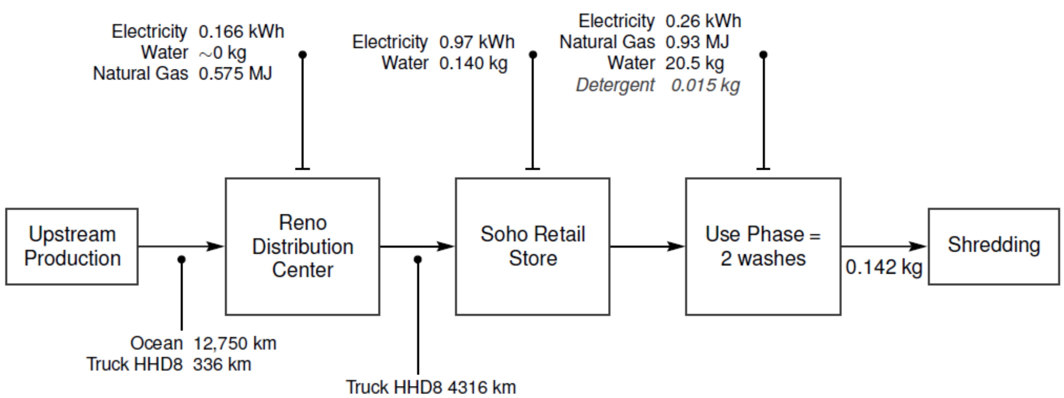
- Distances between sites were estimated using Google Maps for land transportation and Ports.com for ocean transportation.
- The assumption was made that 10-ton delivery trucks were used for land transportation. This assumption was made because the 10-ton delivery trucks are most common in the transportation industry in Japan (JAMA 2013).
- Load rate of trucks are assumed to be 62%, which is the default value of 10-ton delivery trucks in MiLCA.

- The assumption was made that container ships are used for sea transportation. The average size container ships operated by main Japanese shipping companies are greater than 4000 TEU (Japanese Shipowner's Association 2013).

Downstream System Boundaries

Patagonia was responsible for providing the life cycle data that represents the distribution, retail, use, end of use, and transport phases of the life cycle. The system boundary for data provided by Patagonia mirrors its operational responsibilities and includes the use and end of use stages in the life cycle. Downstream processes were modeled based on the Patagonia operational model shown in Figure 3.3.

Figure 3.3 Downstream processes in Patagonia's operational model



Downstream Data Collection

Distribution:

Patagonia owns and operates a distribution center located in Reno, Nevada. Utility consumption was estimated from the total annual facility electricity consumption, natural gas, and water over the 2013 calendar year. Inventory requirements were allocated on a unit product basis, assuming annual through-flow of 10 million items. Solid waste management was omitted from the model as the majority of waste produced by the facility was recycled in 2013, and in consequential LCA it is customary to treat recycling flows as cut-offs (Ekvall and Weidema 2004) when they are not integral to the product system being modeled. The non-recycled solid waste flows were very small compared to the functional unit and were excluded.

Retail:

Utility consumption impacts at the retail level are based on data gathered from Patagonia's SoHo store. The SoHo store was used as representative of retail operations for Patagonia. Patagonia has 30 stores located in the United States. Patagonia's SoHo store is one of the busiest stores in terms of sales, so if anything it is an overestimation of typical retail location energy use. The data used in the assessment included total consumption of electricity and water over the 2013 calendar year at the SoHo retail store. Inventory requirements were allocated on a unit product basis, assuming 2013 annual through-flow of 71,462 items. No gas usage was reported for the SoHo retail location and therefore natural gas use was not included in total energy use in the retail stage.

Product Use:

Use phase was modeled based on the wash parameters of the Performance Jacket PCR shown in Table 5 below. Earthsure developed the parameters for the SAC's PCR guidance for a technical jacket. Inventory requirements included 21g detergent, 0.73 kWh energy, and 29 L water per kg wash per load. Guidance from the PCR is based on numerous assumptions resulting in low data quality. In particular, no specification is made regarding the type or composition of laundry detergent.

There are no current, comprehensive, and reliable statistics available on how the public cleans their clothing. What data exists indicates that the public makes generic decisions about how to group clothes for cleaning, and that there are significant cultural differences in washing habits. For example, in Europe, apparel is more likely to be ironed than in the US. In Japan and China, the water used in washing machines is typically derived from used bath water. Since about 90% of the energy consumption of washing machines comes from heating water, this leads to very different impacts of washing in different parts of the world (Earthsure 2013).

Although studies have shown that the use phase of apparel is a major environmental hotspot, the data available to estimate environmental impacts of the use phase are of very mixed quality. In order to bring comparability to the EPDs, the Earthsure PCR guidance document followed as the methodology for this LCA identifies a fixed use phase model. That model instructs that, the use phase cleaning shall be modeled according to the manufacturer's instructions, e.g. machine wash, line dry. One cleaning cycle per year shall be calculated. The EPD shall report use phase cleaning impacts for a weighted average of all markets.

With the SACs PCR guidelines in mind and the variability in consumer use practices and washing machine impacts, the assumption was made that the garment was washed two times over its lifetime and line-dried in accordance with garment care specifications. The Earthsure PCR guidance document instructs that, the use phase cleaning shall be modeled according to the manufacturer's instructions, e.g. machine wash, line dry and that one cleaning cycle per year shall be calculated. The baseline assumption was that this technical jacket will be washed twice over its lifetime was made based on several further assumptions. First, the jacket is an outerwear piece, is not worn next to skin, and therefore not dirtied as quickly as garments that are worn next to skin. It is therefore less likely to need to be washed regularly. Second, the jacket is a cold weather piece and would be worn in the winter months only. It is therefore seasonally used. Third, it was estimated that the jacket would be used for four years and washed every other year.

The energy use during the wash cycle was split evenly between electricity and natural gas. In addition the detergent used in the downstream life cycle stage of consumer washing, was assumed to contain 25% by weight sodium triphosphate builder, corresponding to a mass fraction of phosphorus of 6.3%.

Table 3.5 Wash Parameters (Earthsure 2013 data used in the SAC's PCRs)

Parameter	Units	EU	North America	Japan	China
Use of Washer	Percent	100	100	100	100
Energy for washer	kWh/kg clothing	0.29	0.73	0.03	0.03
Water for washer	L/kg clothing	11	29	32	30

Detergent Use	Grams/kg	41	21	10	10
Hand Wash	Percent	0	0	0	50
Water for hand wash	L/kg clothing	N/A	N/A	N/A	N/A
Use of Tumble Dryer	Percent	25	85	10	5
Electricity for Dryer	kWh/kg clothing	0.73	0.83	0.83	0.83
Use of Iron	Percent	100	0	90	50
Electricity for Iron	kWh/kg clothing	0.67	0.58	0.58	0.58

End of Use (Disposal):

The end of use life cycle stage was modeled as a recycling process. Patagonia currently collects all used Patagonia products for recycling. Nylon garments, such as the technical jacket, are eligible to be shredded and may displace an equivalent mass of primary thermal insulation. Recycling impacts were modeled as a maximum potential displacement and do not include reverse logistics or reprocessing. The model assumes that 40% of the technical jackets will be recycled at the end of their useful life. This assumption is made due to the fact that Patagonia communicates to customers that they collect and recycle all used Patagonia gear but that not all garments will likely be returned to Patagonia.

The LCA model assumes that the recycled garment will be used as insulation and incorporates the benefits of displacing the need to manufacture virgin insulation. The displaced product was modeled as an equal mix of polyisocyanurate using the PE process "EU-27: Polyisocyanurate (PIR high-density foam)" and the Plastics Europe process "RER: Polyurethane flexible foam (PU)".

Downstream Calculation Details and Assumptions

Except where noted, all background processes were modeled using cradle-to-gate processes drawn from the GaBi Professional Database, version 6.106 (Service Pack 24).

Energy use:

Electricity production was modeled as a mix of cradle-to-gate processes representing US conditions. Power grid mixes were determined from the US EPA eGrid 9th edition, representing 2010 conditions. Grid mixes were based on NERC regions, not on subregions or states. Power for the Reno Distribution Center (DC) was modeled using the WECC grid mix; power for the retail store and the use phase were modeled using the RFC grid mix.

- Natural gas thermal energy was modeled with the PE cradle-to-gate “US: Thermal energy from natural gas” process.
- Fuel production for diesel fuel and heavy fuel oil were drawn from PE cradle-to-gate processes representing US conditions.
- Tap water production impacts were not modeled. Water consumption was modeled as a direct resource extraction of surface water.
- Wastewater treatment impacts were not modeled. There were not any ready-made data sets describing US wastewater treatment, and the scope of this project did not include analysis of wastewater treatment.

Transportation:

Transportation impacts from the shipment of products between downstream life cycle stages were included in the downstream system boundaries. Transportation calculations were done using the GaBi software. Two legs of transportation were included in the downstream processes.

1. Transportation from garment assembly facility to Patagonia's Reno DC. This required ocean freight from Asia to Oakland and truck transport from Oakland to the Reno DC.
2. Transportation from the Reno DC to a retail store location. The transportation model assumed truck transport from the Reno DC to Patagonia's SoHo store based in New York City.

The following assumptions were made for the transportation calculations:

- Truck transportation was modeled using emission factors derived from the EMFAC model (California Air Resources Board 2011). Fuel economy of trucks was estimated to be 6.5 miles per gallon of diesel fuel from based on a payload of 11.5 short tons, corresponding to a utilization factor of 0.42 (Committee to Assess Fuel Economy 2010).
- Ocean transportation was modeled using the PE unit process "GLO: Bulk Commodity Carrier" having a utilization factor of 0.48, using heavy fuel oil.

Results

The environmental impacts of Patagonia's technical jacket were assessed using LCA thinking for this research case study. All life cycle stages from origin of raw material through disposal at the end of its useful life were included in the LCA. In addition, a collaborative approach to LCA was used, where the supply chain vendor provided primary data for the upstream life cycle stages while Patagonia provided primary data for the downstream life cycle stages. Both companies shared their primary data with one another and each completed a full product LCA on the technical jacket using their preferred LCA software. This resulted in two complete product LCAs on the same product. The results of the two LCAs will be included in the next section titled *Comparison of LCA Results*. The section following the *Comparison of LCA Results,* titled *Review of Collaborative LCA Approach,* addresses the approach taken to this LCA, the inconsistencies in the results, and provides explanations on why those inconsistencies occurred.

Comparison of LCA results

This section includes the results of the LCAs organized by impact category. The three areas where the data was consistent enough to compare through the life cycle of the product in both the MiLCA and GaBi results were GWP, energy use, and water use. Eutrophication and Resource Depletion were also measured through the entire life cycle of the technical jacket; however, the results were modeled using different characterization factors and units of measurement.

Data was shared between the two companies down to the life cycle stage, making it possible to include and compare impacts at each stage in the life cycle for both upstream and downstream processes. The results section of this research includes both the results of the two LCAs completed as well as a comparison of the results. The comparison of the results will be included in the section titled *Review of Collaborative LCA Approach* below.

A table showing comparisons between the vertical supplier's reported LCIA results and GaBi results is included below in Table 3.6. The results in Table 6 include total life-cycle impacts, integrating upstream and downstream process impacts, using MiLCA and GaBi respectively. The results show that the two LCA models are in close alignment in the three impacts categories that were comparable, energy use, water use and Global Warming Potential (GWP). The Patagonia LCA using the GaBi software showed higher impacts in energy use and GWP, where as the Vertical Supplier's LCA using the MiLCA software resulted in the highest water use. The eutrophication potential and resource use impacts could not be compared as they were calculated using different characterization models and different units of measurement.

Table 3.6 Total life cycle impact results per garment from MiLCA and GaBi models for 5 impact categories.

Impact Category	**MiLCA**	Unit	Characterization Model	**GaBi**	Unit	Characterization model
Global Warming	10.52	Kg CO_2 equiv	100 year (IPCC 2007)	11.31	Kg CO_2 equiv	TRACI 2.1
Eutrophication Potential	0.0015	Kg P equiv	EP (Heijungs, 1992, 2000)	0.0054	Kg N equiv	TRACI 2.1
Energy Consumption	169.55	MJ	Energy use	183.62	MJ	Energy use
Water Consumption	530.09	Kg	Fresh water use	522.32	Kg	Fresh water use
Resource Consumption	0.05	Kg Sb equiv	CML 2002	16.21	MJ surplus energy	TRACI 2.1 Resources, Fossil Fuels

Upstream results

Both the MiLCA and GaBi LCA show that upstream impacts drive the life cycle results. This was true for the energy use, water use, and global warming potential impact categories. The one exception is that the use phase in the downstream portion of the life cycle dominates the eutrophication impacts.

Regarding the upstream processes, the MiLCA and GaBi results lined up on all accounts. Both models show that the PA66 Fabric Production process in the upstream life cycle stages has the greatest global warming potential (GWP), eutrophication potential, and energy use. Water use, however, is shown to be highest in the Oil Extraction - Raw Material Production for PA66 phase. The Raw Material Production for the non-woven PET fabric has the second greatest water use in both models. The upstream impacts shown in the GaBi and MiLCA models are included in Table 3.7.

Table 3.7 Upstream impacts shown in the GaBi and MiLCA models. The different rows represent the different life cycle stage and the columns represent environmental impact categories.

Upstream Impacts								
	Oil Extraction - Raw Material Production (PA66)	Yarn Production (PA66)	Fabric Production (PA66)	Raw Material Production: non woven fabric	Fiber Production (PET)	Non woven Fabric Production	Sewing and Packaging	Transport
GaBi: CML2001, Eutrophication Potential (EP) [kg N-Equiv.]	1.393E-04	1.145E-04	2.738E-04	3.706E-05	1.718E-05	7.074E-05	8.459E-05	7.600E-05
MiLCA: EP (Heijungs, 1992, 2000) [kg Phosphate-Equiv]	3.220E-05	1.809E-05	6.329E-05	8.544E-06	3.989E-06	1.740E-05	1.955E-05	1.754E-05
GaBi: IPCC global warming, [kg CO_2-Equiv.]	2.184	1.908	4.228	0.641	0.266	1.016	0.384	0.045
MiLCA: IPCC global warming, [kg CO_2-Equiv.]	2.184	1.320	4.227	0.641	0.266	1.033	0.384	0.045
GaBi: Fresh water use [kg]	226.944	2.203	101.014	101.309	28.378	34.211	7.610	0.012
MiLCA: Fresh water use [kg]	226.988	7.957	101.018	101.274	28.383	34.208	7.610	0.012
GaBi: Energy resources [MJ]	36.744	28.420	68.730	16.911	3.668	14.486	7.504	0.634
MiLCA: Energy Use [MJ]	38.136	18.123	65.660	16.794	3.842	14.737	7.457	0.627

Downstream Results

As mentioned earlier, the use phase eutrophication impacts were the greatest in the entire life cycle of the technical jacket. In regards to the downstream impacts specifically, both models show that the retail phase has the greatest energy use and GWP for Patagonia's operations. Retail electricity use drives retail emissions. Regarding downstream impacts, water use was greatest in the use phase. In addition, more water was used in the use phase than in the upstream processes of PA66 yarn production, sewing and packaging, and transport. Downstream results are shown in Table 3.8.

Table 3.8 Downstream impacts by process provided in the GaBi and MiLCA models. The different rows represent the different life cycle stage and the columns represent environmental impact categories.

Downstream Impacts				
	Reno Distribution Centre	**Soho Store**	**Use phase**	**End of Life (displaced impacts from recycling)**
GaBi: CML2001, Eutrophication Potential (EP) [kg Nitrogen-Equiv.]	0.000039	0.000187	0.006850	-0.001940
MiLCA: EP (Heijungs, 1992, 2000) [kg Phosphate-Equiv]	0.000009	0.000045	0.001850	-0.000582
	0.000039	0.000187	0.006850	-0.001940
GaBi: IPCC global warming, [kg CO_2-Equiv.]	0.16658	0.88126	0.21141	-0.61918
MiLCA: IPCC global warming, [kg CO_2-Equiv.]	0.22295	0.69100	0.18900	-0.68700
GaBi: Fresh water use [kg]	0.00000	0.14000	20.90000	-0.00190
MiLCA: Fresh water use [kg]	0.00000	0.14000	22.50000	-0.00196
GaBi: Energy resources [MJ]	2.92	13.72	3.88	-14.00
MiLCA: Energy Use [MJ]	3.28	10.67	2.92	-12.70

Using the GaBi model, the downstream results were analyzed with respect to their sensitivity to several inventory parameters. The following sensitivities were measured: number of washes in the product lifetime, phosphorus content of laundry detergent, and the recycling rate determined by the portion of jackets that are recycled at the end of life. The parameters of the sensitivity analysis using the GaBi software are included in Table 3.9.

Doubling the number of washes was seen to have a negligible effect, except, again, on the matter of eutrophication. With that in mind, the sensitivity of different percentages of phosphorus content in detergent was analyzed. The results showed that phosphorous content in detergent are very significant to the eutrophication results. If detergents used phosphorus alternatives, which are not eutrophying, or if wastewater treatment effectively processes eutrophying wastes, the impacts from the use phase may be much smaller.

Both models showed that avoided impacts from recycling are small compared to primary production, suggesting that the PA66 / PET material of the jacket is more ecologically intensive to produce than the foam material it would likely displace when it is recycled. The recycling rate was seen to have a moderate impact global warming potential. This reiterates that the displaced products do not seem to be very energy intensive.

Table 3.9 Sensitivity analyses conducted on the results with respect to their sensitivity to three inventory parameters, number of washes, % phosphorous content in the laundry detergent, and % of garments recycled at the end of life.

Sensitivity Indicator	Default	Low	High
Number of washes	2	-	4
Use phase laundry detergent phosphorous content	6.3%	1.26%	12.6%
Recycling rate	40%	0%	80%

The results of the sensitivity analysis are included in Tables 3.10 and 3.11 below. The row headings indicate the parameters that were altered.

Table 3.10 Results of sensitivity analysis showing changes in the Global Warming Potential impact category.

Kg CO_2 - Equiv.	Baseline	Washes - Hi	Phosphorus % - Hi	Phosphorus % - Lo	Recycling Rate - Hi	Recycling Rate - Lo
Upstream Production	10.672	10.672	10.672	10.672	10.672	10.672
Distribution Ctr	0.167	0.167	0.167	0.167	0.167	0.167
Retail	0.881	0.881	0.881	0.881	0.881	0.881
Consumer Use	0.211	0.423	0.211	0.211	0.211	0.211
End of Life	-0.619	-0.619	-0.619	-0.619	-1.238	0.000
Net Total	11.312	11.524	11.312	11.312	10.693	11.931

Table 3.11 Results of sensitivity analysis showing changes in the Eutrophication potential impact category.

Kg N-Equiv.	Baseline	Washes - Hi	Phosphorus % - Hi	Phosphorus % - Lo	Recycling Rate - Hi	Recycling Rate - Lo
Upstream Production	0.00028	0.00028	0.00028	0.00028	0.00028	0.00028
Distribution Ctr	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004
Retail	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019

Consumer Use	0.00685	0.01371	0.01368	0.00139	0.00685	0.00685
End of Life	-0.00194	-0.00194	-0.00194	-0.00194	-0.00387	0.00000
Net Total	0.00542	0.01228	0.01225	-0.00004	0.00349	0.00736

Review of Collaborative LCA Approach

There were two main discrepancies between the MiLCA results and the GaBi results. The first and most easily identified difference was in the impact characterization models used. The second was due to discrepancies in inventory input and output data. The following paragraphs will first examine the differences between the impact characterization models and then review the how the differences in the inventory flows were identified and the possible explanation for such differences.

Impact Characterization Models

A primary difference between the two LCAs was the impact characterization models used and the units used to represent the impact categories. The environmental impact characterization models and units of measurement that were to be evaluated in this case study were included in the methodology (Earthsure 2013). Despite this, there were discrepancies that arose when evaluating the results of the LCAs. Refer to Table 3.12 to see a snapshot of the differences.

Table 3.12 Variations in characterization models and units of measurement used in the MiLCA and GaBi assessments

Life Cycle Indicator	MiLCA		GaBi	
	Units	Models	Units	Models
Eutrophication	Kg P - Equiv.	EP (Heijungs, 1992, 2000)	Kg N - Equiv.	TRACI 2.1
GWP (Global Warming)	Kg CO_2 equivalents	100-year GWP IPCC, 2007	Kg CO_2 equivalents	TRACI 2.1 (IPCC)

Energy Use	MJ	Higher heating value (all)	MJ	GaBi regional energy grid mix
Water Scarcity	Kg	Fresh water use	Kg	Manual entry in GaBi
Abiotic Resource Depletion	Kg Sb equivalents	CML 2002	MJ surplus energy	TRACI 2.1
Acidification	-	-	Kg SO_2 equivalents	TRACI 2.1
Human Health Particulate Air	-	-	kg PM 2,5 equivalents	TRACI 2.1
Smog Air Production	-	-	Kg O_3 equivalents	TRACI 2.1
Waste Percent	%	Upstream primary inventory data collected	-	-

As the chart above shows, the three impact categories that matched and could be compared through the life cycle of the product in both the MiLCA and GaBi results were GWP, energy use, and water use. In the case of GWP, the IPCC impact characterization model was in both LCAs. For energy use and water use, the input data was shared, which ensured consistency throughout the lifecycle of the product.

Eutrophication results and resource depletion were measured in both LCAs across all life cycle stages. These impact categories, however, were measured using different characterization factors and different units of measurement. Acidification, human health particulate air (particulate production), smog air (ozone production), and waste percent were three impact areas that were not consistently measured across all life cycle stages in the two LCAs. The GaBi results included a measurement of acidification, human health particulate air, and smog air production. The MiLCA software did not include these impact characterization models, and therefore these impact categories were excluded from the MiLCA LCA. The MiLCA results included a measurement of waste percent for the upstream life cycle stages. Waste percentage data was not included in the downstream data collection procures and was therefore not included in the final results.

A further description of the impact categories that were modeled across the lifecycle of the product in both the MiLCA and GaBi LCAs are included below.

Global Warming Potential: Both the MiLCA software and the GaBi software utilize the IPCC Global Warming characterization model. The result of using the same model is that there is near-100% agreement across all life cycle stages.

Total Energy Use: Energy use is an inventory indicator taken directly from the inventory data. There was generally good agreement between the two LCA software systems because the energy input data used across all life cycle stages was the same for both LCAs. This was made possible because both the upstream and downstream data included a high level of transparency. Any discrepancies in energy use were due to differing regional energy data sets in the two different LCA software systems.

Total Water Use: Fresh water use is an inventory indicator taken directly from the inventory data. There was strong agreement between the two software systems. Similar to the energy use data, the water use recorded across all life cycle stages was the same for both LCAs. This was the case because the same upstream and downstream data were used in both

LCAs. Any discrepancies in water use were due to slight variations in the data sets in the two different LCA software systems.

Eutrophication: The MiLCA model measured eutrophication in kg of Phosphorous equivalents while the GaBi model used kg of Nitrogen equivalents. The specific conversion factors used to normalize the outputs into units of phosphorous and nitrogen could not be identified and therefore could not make a direct comparison.

Resource use: Both MiLCA and GaBi contain characterization factors that represent the impacts to resources. The LCA models, however, did not consistently report resource use and the unit of measurement used in the two software systems differed. The MiLCA software used abiotic resource depletion (measured in kg antimony (Sb) equivalents) as its measure of resource use. No resemblance could be found between the MiLCA abiotic resource depletion indicator and any of several versions of the same indicator in GaBi. The TRACI 2.1 characterization factor used in GaBi measures resource use in terms of mega joules (MJ) of surplus energy. The background conversion factors were not available, making it impossible to accurately convert from MJ of surplus energy (GaBi units) to Sb-equivalent (MiLCA units). These inconsistencies made it challenging to compare the resource use impacts and thus this characterization factor was excluded from the tables comparing the upstream and downstream impacts in the GaBi and MiLCA models.

Inventory Flows

Inventory flows in LCA include flows from and to nature for a product system. Inventory flows include inputs of water, energy, and raw materials, and outputs include releases to air, land, and water. Input and output data are collected for all activities within the product life cycle. In the case study used in this research, there was generally good agreement of inventory flows in the two LCAs due to data sharing. Because both companies were willing to share their primary data, the same input data was available to use in both LCAs, across all life cycle stages. Specifically, the upstream process data provided by the vertical supplier showed specific input and output flows for each process in the upstream supply chain stages. For the most part, discrepancies in the results were primarily due to differing available data sets in the two different LCA software systems.

The following paragraphs will include review consistencies and inconsistencies in inventory flow data sets provided by the MiLCA and GaBi software systems and the impacts that those differences likely had on the results of the two LCAs. In addition, a mathematical comparison of the results at each life cycle stage is included to show which life cycle stages had the most consistent results and those that had the greatest discrepancies.

The MiLCA model of the upstream processes was input into GaBi by identifying a mapping between elementary flows included in the vertical supplier upstream data and existing flows in GaBi. After the flows were mapped, the upstream processes were entered directly into GaBi and computed as unit outputs. The MiLCA model included 53 elementary inputs (resource draws) and 75 elementary outflows (emissions). This process revealed that most, but not all, of the MiLCA flows were characterized for environmental impact. Several of the upstream flows from MiLCA did not have exact analogs in GaBi and had to be approximated. Flows without exact matches fell into four categories: fossil fuel flows, urban air emissions, disposal flows, and resources. Examples of the differences between how these flows were modeled in MiLCA and GaBi are included in Table 3.13 below.

In the GaBi model, fossil fuel flows were modeled with slightly different heating values than those specified in the MiLCA model. Flows were selected that approximated the values provided by the vertical vendor. The effect of the inexact fossil fuel flows was to change the apparent resource consumption impact category score. Because the heating values of fossil fuels vary not only by geography, but also by shipment, any interpretation of these values must factor in this variation. The GaBi flow database showed higher heating values for crude oil varying mainly around 42-47 MJ/kg, with most close to the middle of this range. The vertical supplier assumed 44.7 MJ/kg (higher heating value) for crude oil. The flow used in the GaBi model was regionally non-specific and 45.8 MJ/kg. Using this value the GaBi model resulted in slightly higher material resource consumption figures. The range of uncertainty (approximately 10%) is nominal and is typical of the range of geographic variations in the fossil fuel market.

For air emissions from transportation, the difference between impact scores for urban and generic emissions will vary by geography. The MiLCA had output flows specific to urban air close to ground impacts, indicating emissions from urban freight transport. The GaBi LCIA methods did not contain regionally-specific characterization factors, nor different characterization factors for urban vs. generic emissions. In the GaBi model, such emissions were modeled identically to generic emissions. Thus the substitution of flows had no effect on the results under the chosen LCIA methods.

The disposal and resource flows were not characterized in the MiLCA or GaBi LCIA methods reported. Disposal flows including *earth/sand* and *metal wastes* disposed to landfill were created as empty flows with no impacts. Resources including *brine, marble, natural* *latex*, *serpentine*, and *silica stone* were created as empty flows with no impacts. Thus, the omission of both of these had no impacts.

Table 3.13 Examples of inexact flow matches between MiLCA and GaBi

Category of inexact flow match	Direction	MiLCA elementary flow name	GaBi elementary flow name	unit
Resources	Input	Brine	Not included in GaBi flow database	kg
Resources	Input	Marble	Not included in GaBi flow database	
Resources	Input	Silica stone	Not included in GaBi flow database	kg
Fossil fuel flows	Input	Crude oil, 44.7 MJ/kg	Crude oil, 45.8 MJ/kg	kg
Fossil fuel flows	Input	Not included in MiLCA flows	Hard coal, 27.4 MJ/kg gross	kg
Fossil fuel flows	Input	Metallurgical coal, 29.0 MJ/kg	Metallurgical coal, 31.7 MJ/kg	MJ/kg
Fossil fuel flows	Input	Natural gas, 54.6 MJ/kg	Natural gas, 54.6MJ/kg	MJ/kg
[redacted]				
Urban air emissions	Output	Carbon dioxide (biogenic)	Carbon dioxide (biogenic)	kg
Urban air emissions	Output	Carbon dioxide (fossil)	Carbon dioxide (fossil)	kg
Urban air emissions	Output	Carbon dioxide (fossil – urban air, close to ground)	Close to ground classification not specified in GaBi flow database	kg
Urban air emissions	Output	Nitrogen dioxide (urban air, close to ground)	Close to ground classification not specified in GaBi flow database	kg
Urban air emissions	Output	Sulfur dioxide	Sulfur dioxide	kg
Urban air emissions	Output	Sulfur dioxide (urban air, close to ground)	Close to ground classification not specified in GaBi flow database	kg
Disposal flows	Output	Earth and sand (landfill) – created as an empty flow indicating it has to impact on the results	Earth and sand (landfill) – created as an empty flow indicating it has to impact on the results	kg

Disposal flows	Output	Metal wastes (landfill) – created as an empty flow indicating it has to impact on the results	Metal wastes (landfill) – created as an empty flow indicating it has to impact on the results	kg

The differences between the input and output flow analogs in the MiLCA and GaBi systems were evaluated to assess if differences affected the final data outputs. There were two ways the input and output flow analogs varied between the two LCA software systems. Either the data analogs did not match up identically in the input or output, or an analog was missing in one of the LCA software systems. In general, a missing flow resulted in lower impact scores in categories where the flow has an impact. In the case where there was an inexact flow match and the two flows had different characterization factors, the impact scores were affected. The evaluation of the input and output analogs revealed that although MiLCA and GaBi did not have all of the exact same analogs, such differences did not have a substantial effect on the final results.

The results of the GaBi LCA and the MiLCA LCA were compared at each upstream and downstream life cycle stage for all impact categories. The MiLCA totals were divided by the GaBi totals to determine the consistency of the results at each life cycle stage. Table 3.14 shows a comparison of the GaBi and MiLCA results for the upstream impacts.

Table 3.14 Comparison of the consistency of the upstream impacts results for the GaBi and MiLCA models. Columns represent life cycle stage and row represent impact categories.

Upstream Impacts									
	Total	Oil Extraction - Raw Material Production (PA66)	Yarn Production (PA66)	Fabric Production (PA66)	Raw Material Production: non woven fabric	Fiber Production (PET)	Non woven Fabric Production	Sewing and Packaging	Transport
GaBi: Eutrophication Potential (EP) [kg N-Equiv.]	8.133E-04	1.393E-04	1.145E-04	2.738E-04	3.706E-05	1.718E-05	7.074E-05	8.459E-05	7.600E-05

MiLCA: EP (Heijungs, 1992, 2000) [kg P-Equiv]	1.807E-04	3.220E-05	1.809E-05	6.329E-05	8.544E-06	3.989E-06	1.740E-05	1.955E-05	1.754E-05
COMPARE (MiLCA / GaBi) x 100%	22.2%	23.1%	**15.8%**	23.1%	23.1%	23.2%	24.6%	23.1%	23.1%
GaBi :IPCC global warming, [kg CO_2-Equiv.]	10.67	2.184	1.908	4.228	0.641	0.266	1.016	0.384	0.045
MiLCA: IPCC global warming, [kg CO_2-Equiv.]	10.10	2.184	1.320	4.227	0.641	0.266	1.033	0.384	0.045
COMPARE (MiLCA / GaBi) x 100%	106.9%	100.0%	**69.2%**	100.0%	100.0%	100.0%	101.7%	100.0%	100.0%
GaBi: Fresh water use [kg]	501.68	226.944	2.203	101.014	101.309	28.378	34.211	7.610	0.012
MiLCA: Fresh water use [kg]	507.45	226.988	7.957	101.018	101.274	28.383	34.208	7.610	0.012
COMPARE (MiLCA / GaBi) x 100%	101.2%	100.0%	**361.2%**	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
GaBi: Energy resources [MJ]	177.10	36.744	28.420	68.730	16.911	3.668	14.486	7.504	0.634
MiLCA: Energy Use [MJ]	165.38	38.136	18.123	65.660	16.794	3.842	14.737	7.457	0.627
COMPARE (MiLCA / GaBi) x 100%	103.0%	103.8%	**63.8%**	95.5%	99.3%	104.8%	101.7%	99.4%	98.9%

When looking at the COMPARE rows shaded in grey in Table 3.14, a notation of 100% indicates that the two results are the same. For the two impact category scores, GWP and the two inventory inputs (energy use and water use), the COMPARE rows are in very close agreement, close to 100% across the board). Pairs of estimates that are identical between GaBi and MiLCA indicate that the inputs, outputs, and impact characterization model used for that impact category were the same.

Table 3.14 shows that GWP has close to 100% across the board, indicating that the data between the two LCAs are in good agreement across the upstream life cycle stages. Cumulative energy demand is good agreement. There is some fluctuation around 100%, which is explicable based on differences in regional energy data sets and differences in heating values between MiLCA and GaBi. Water use is in very close agreement, having 100% across the majority of the life cycle stages. The identical results for water use and nearly identical results for energy use are a reflection of the fact that input data used in both models was the same. Eutrophication is consistently low indicating that the MiLCA results are always about 23% of the GaBi results. This is due to using different impact characterization methods in MiLCA and GaBi.

The yarn production PA66 process is the only life cycle stage that shows a consistent and substantial difference between the MiLCA results and GaBi results. The yarn production for PA66 is consistently lower than the processes around it, by about the same amount (30%) in three categories and substantially higher in one impact category. The GWP, energy use, and water use results in MiLCA for PA66 yarn production are about 70% that of the GaBi model. Water use for PA66 yarn production is three times higher. As mentioned earlier, eutrophication results across the upstream life cycle stages showed that MiLCA results are always about 23% of the GaBi results except in the case of PA66 yarn production, which was 15.8% lower than the GaBi results. If the PA66 yarn impacts were increased by a factor of 30%, they would show very good agreement with the other impact stages. These findings suggest that there is a discrepancy between the inventory input into the MiLCA model and the impact assessment results.

The likeliest explanation for this discrepancy is that there is a scaling difference between the vertical supplier's reported inventory results and impact results. It is possible that either the inventory results are reported 30% too high, or the impact results are reported 30% too low. This could easily be the result of operator error when extracting data; for example, it may have resulted from changing the quantity of PA66 in the garment. A deeper analysis of the of the unit inventory and/or impact scores for the PA66 yarn production would be needed to determine the exact reason for this discrepancy. The nature and specificity of the data needed to determine this discrepancy with certainty is beyond the scope of what is possible in this assessment.

The downstream impact comparison calculation mirrored that of the upstream impact comparison. Table 3.15 shows the results of the downstream data comparison for each impact category.

Table 3.15 Comparison of the consistency of the downstream impacts results for the GaBi and MiLCA models. Columns represent life cycle stage and row represent impact categories.

Downstream Impacts				
	Reno Distribution Centre	**Soho Store**	**Use phase**	**End of Life (displaced impacts from recycling)**
GaBi: CML2001, Eutrophication Potential (EP) [kg Nitrogen-Equiv.]	0.000039	0.000187	0.006850	-0.001940
MiLCA: EP (Heijungs, 1992, 2000) [kg Phosphate-Equiv]	0.000009	0.000045	0.001650	-0.000582
COMPARE (MiLCA / GaBi) x 100%	23.0%	24.0%	24.0%	30.0%

GaBi: IPCC global warming, [kg CO_2-Equiv.]	0.16658	0.88126	0.21141	-0.61918
MiLCA: IPCC global warming, [kg CO_2-Equiv.]	0.22295	0.69100	0.18900	-0.68700
COMPARE (MiLCA / GaBi) x 100%	133.8%	78.4%	89.4%	111.0%
GaBi: Fresh water use [kg]	0.00000	0.14000	20.90000	-0.00160
MiLCA: Fresh water use [kg]	0.00000	0.14000	22.50000	-0.00196
COMPARE (MiLCA / GaBi) x 100%	NA	100%	107.6%	163.3%
GaBi: Energy resources [MJ]	2.92	13.72	3.88	-14.00
MiLCA: Energy Use [MJ]	3.28	10.67	2.92	-12.70
COMPARE (MiLCA / GaBi) x 100%	112%	77%	75%	90%

Downstream inventory results had more variability across the downstream life cycle stages. This is due to variability in inventory flows used in the two models that can be explained by a missing step in the data sharing process. The process used to share and map the MiLCA flows to the GaBi flows in the upstream life cycle stages was not replicated for the downstream life cycle stages. For the upstream life cycle assessment, the upstream processes was input into GaBi by identifying a mapping each individual elementary flow included in the vertical supplier upstream data. After the flows were mapped, the upstream processes were entered directly into GaBi and computed as unit outputs. For the downstream life cycle stages, the energy use and water use inputs were simply shared with the vertical supplier. The inventory flows used in the GaBi model for the downstream life cycle stages were not specifically identified when sharing the data with the vertical supplier.

The ranges in the consistency in GWP and cumulative energy demand in the down stream processes at the distribution center and retail location can be explained by differences in regional grid mixes and heating values used in the two LCA models. The use stage and end of life inconsistencies will be addressed in the following paragraphs.

Water use is in good agreement for the DC and retail life cycle stages. It varies by about 7% in the use life cycle stage. This is most likely due to differing laundering assumptions made in the Technical Jacket PCRs (Earthsure 2013). Please refer back to Table 3.5 for the wash parameters specified in the Technical Jacket PCRs. The wash parameters identified energy use and water use differences between countries. The wash parameters table shows water use per wash is higher in Japan than in the US and energy use per wash is lower in Japan than in the US. These parameters were used as guidance for both LCAs completed in this case study. As a reminder, the MiLCA software is a specific system created and primarily used in Japan, whereas the GaBi system is a US based system that is more reflective of US data. Table 3.15 shows that the results of the LCA comparison are consistent with the wash parameters provided in the Technical Jacket PCRs in that energy use was lower in the MiLCA assessment and water use was lower in the GaBi assessment.

Energy use and water use again differs in end of life stage. End of life accounting is complex and can be approached in a variety of ways. Of all the downstream processes, the end of life cycle stage showed the greatest discrepancies across all impact categories. This is due to the general complexity of end of life accounting in LCA as well as differing inventory data used to model end of life in the two software systems.

Eutrophication is again consistently low due to the different impact characterization models used in MiLCA and GaBi. However, it remains consistently low, indicating that there is consistency across the results, though they are measured in different units.

Conclusions and Recommendations

There is a limited amount of past research completed on the viability of having various supply chain partners, using differing software systems, share data to complete a product LCA. In addition, the research that has been completed has shown that using different software systems causes discrepancies in the results (Speck et al 2015).

Although there were variations in the final assessments, the approach taken in this case study revealed that the effect of using two different LCA software systems on the overall impact assessment was minimal. The collaborative approach used in the case is shown to be sound primarily because there was visibility to all aspects of the methodology and because the both the upstream and downstream data providers shared specific process and inventory results. The data provided by both Patagonia and the vertical supplier included the energy and water used in each step of the product's life cycle, which ensured that the data used to create both LCA models were based on the same inputs.

There is an inherent level of uncertainty in the field of LCA, which has characterized it as being a tool that is most useful for detecting order of magnitude effects, such as the importance of a specific life cycle stage in overall energy resource demand in a product system. Smaller effects and differences in the models are generally indicative but not conclusive. With this in mind, the evaluation of a collaborative LCA approach did indicate that there were variations in results, but the variations were generally not substantial. When the variations in the results of the two LCAs are viewed from an order of magnitude perspective, the results are constant.

The opportunity to compete this case study was very unique. Prior to the completion of this case study, Patagonia was concerned that using several LCA software systems and practitioners to complete a LCA would result in inconsistent results. With that in mind, this case study was designed to produce identical LCA results in order to show if it is possible to get consistent results when using two different LCA software systems to complete a product LCA. The hope in designing the study in this way was to assess if a collaborative approach to LCA could produce a reliable analysis of the environmental impacts of a product system.

The results showed negligible variations between the two LCAs, which indicates that by utilizing the same methodology and approach and sharing data at each step in the supply chain, it is possible to piece together various primary process data to create a complete product LCA. The success of this case study was by design, but there were key learnings that will help ensure that future collaborative approaches to LCA also produce reliable results.

After reviewing all aspects of the LCA approach, it was possible to identify the limitations to the open LCA approach and which aspects of this approach affected the consistency of the data. It was determined that the main discrepancies in the results of the two LCAs in this case study were due to differing data sets and the use of different characterization models. The data sets and characterization factors are specific to the LCA software systems, and differences between them are the result of using different LCA software systems. Both assessments utilized regionally specified inventory data, which is acceptable and encouraged in LCA. This is a standard outcome that results from using two different software systems with different regional data; this difference in data sets can't be avoided. However, agreeing to use the same LCA software systems and specifying the data sets that should be used in the LCA could eliminate discrepancies in the results due to differing data sets.

By using same impact characterization models, the discrepancies that result from the different impact characterization factors would be avoided. It may be possible to eliminate the discrepancies that result from differing impact characterization models without requiring that all practitioners use the same LCA software systems. Most LCA software systems include several different impact characterization models, and it is up to the user to select the one that will be used in the analysis. In addition, there are only a handful of impact characterization models available to use, so many LCA software systems include the same impact characterization models. By discussing the impact characterization models available in each software system in the beginning of a project, it is theoretically possible that the software systems would offer the same impact characterization models for each of the impacts categories that will be evaluated.

Using this case study as an example, it is possible that the discrepancies that resulted from using differing impact characterization models could have been minimized if we had initially communicated about the impact characterization models that both parties had access to. If overlap in the models available are found, both parties can continue using their preferred LCA software system and use of the same LCA software system would not be necessary.

With this in mind, it is important to address that there are established uncertainties and ambiguities within the field of LCA that sharply limit its utility as a scientific tool. These shortcomings apply to the field of LCA as a whole, not to any specific method or study. For instance, the MiLCA background database itself has not been critically reviewed. The GaBi background database has also not been critically reviewed. Moreover, the field has not developed a thorough mechanism for critical review and quality validation. As data quality validation gets better, the results will come with more confidence.

In addition to noting the limitations of LCA, it is also prudent to acknowledge that not all individuals tasked with completing a LCA or managing a LCA project will be well versed in the field of LCA. The findings from this research can help to inform a typical, non-expert LCA project manager how to complete a successful collaborative LCA. There are four key factors that, if used, can help to ensure successful execution of the collaborative approach to LCA. Failing to think through and agree upon any of these four factors would result in a product system LCA that is far less consistent across life cycle process steps. The application of each of these four factors to the findings from this case study will be explained in more detail in the following paragraphs.

1. All parties involved should agree upon the methodology that will be used to gather data and conduct the analysis. Functional unit and boundary conditions should be agreed upon before starting a project.

2. Data sharing should happen at the inventory level and should include a relatively complete documentation of background processes.
3. The impact characterization models that will be used in the LCA should be agreed upon from the start of the project. All parties should decide ahead of time which impact characterization models will be used and use those consistently across all life cycle stages. It is recommended to use the most current versions and most widely accepted impact models to ensure the best results.
4. Utilize the same LCA practitioner to complete all parts of the LCA if possible. This factor can be a bit more challenging to achieve, but will result in a more consistent and accurate end product.

It should be acknowledged that gaining agreement on four factors listed above is challenging to accomplish. Patagonia would prefer to gather primary data specific to their products and supply chain processes as often as they possibly can. However, very few vendors are willing to share their process specific data. In addition, very few vendors have the resources or expertise to complete LCAs on their operations. In this case study, Patagonia had the unique opportunity to partner with a supply chain vendor to create a comprehensive product LCA that includes some primary data for one product. A tremendous amount of work went into completing the LCAs, and replicating this for multiple products is both challenging and time consuming.

Having an agreed-upon methodology is the first factor listed above because it is the key component to any LCA. The starting point for this LCA case study was to agree to use the same methodology. The hope was that by approaching the project this way from the start, all parts of the product system would be evaluated in a consistent way. The methodology used in this case study was created by the SAC (the Technical Jacket PCRs) and is reputable and is consistent with broader LCA practices. This methodology was used as guidance for both the MiLCA and GaBi LCA.

It was possible to validate the consistency of the data because both the upstream and downstream data included a high level of transparency. Specifically, the upstream process data provided by the vertical supplier showed specific input and output flows for each process in the upstream supply chain stages. The transparency provided by both the vertical supplier and Patagonia made it possible to compare the results with the MiLCA and GaBi background database as a validation check. Although there were differences in the data sets used in two LCA software systems, this analysis revealed that because data inputs were the same, the differences between software system data sets resulted in minimal variations in the results.

It was clear from this case study that using the same impact models for all parts of the LCA is a key aspect to ensuring the success of a collaborative approach to conducting a LCA. The research conducted by Speck et al. (2015) that evaluated several life cycle packaging software systems found that varying availability of common impact categories among the software systems limited comparisons to four categories: greenhouse gas emissions, fossil fuel/non-renewable energy, eutrophication, and water depletion. The findings from this case study are in alignment with Speck et al. (2015) with regards to the limitations of finding overlap in the impact categories offered in different LCA software systems.

Different environmental characterization models based on different units of measurement were used in the two LCA software systems, making it difficult to compare impacts across life cycle stages. In this case study, impact comparisons were limited to five categories: energy use, water use, greenhouse gas emissions, eutrophication, and resource use. Comparisons between the results of the two software systems could only be made for three of the five categories that were consistently measured across all life cycle stages. The units of measure were not consistent for eutrophication and resource use. For example, the MiLCA software measured resource depletion using kg of Antimony (Sb) equivalents, while the GaBi software provided the TRACI 2.1 metric of MJ of surplus energy. These two results were then impossible to reconcile.

This case study clearly showed the importance of agreeing on the impact characterization models that will be used in all life cycle stages prior to starting a collaborative LCA. This will allow for the impacts calculated for each life cycle stage to be added together to build a complete product LCA. In addition, this will ensure that the important impact areas are measured and addressed at each life cycle stage.

It is important to understand the specific skills needed and role required of the practitioners gathering the LCA data and completing the assessment prior to starting a LCA. The approach taken in this case is a good representation of how two businesses that have partnered to manufacture a commodity, could approach a full product LCA. Requiring that the same practitioner to complete both the MiLCA assessment and the GaBi assessment may have minimized the variations that were found in this case study. That, however, is not a common scenario in the business world. If two different companies are completing LCA assessments on their own processes, it is not likely that the same person will collect the data and complete the assessment for both companies.

In order to ensure that all components of the LCA are completed in the same way, it is important to consider the value of having the same practitioner complete all parts of the LCA when using collaborative approach to LCA. By ensuring that the same person completes all parts of the assessment, variation due to user abilities and preferences would be minimized. This would also create the opportunity for the same software system and impact characterization models to be used across lifecycle stages.

Concluding thoughts

The success of this case study is more a reflection of the approach and method taken, rather than the specific data gathered from the product outputs. The goal of this section of this research was to provide a recommendation on whether or not engaging supply chain stakeholders in a collaborative approach to LCA is one that could be reliably used in the apparel industry. The study shows that it is possible to piece together environmental impact data from individual lifecycle processes into a full product assessment.

This conclusion is based on a single product analysis, but the findings from this product analysis can be used as guidance for using a collaborative approach to product LCAs in the future. Patagonia has gained a tremendous amount of value from the process used in this case study and hopes to have the opportunity to participate in data collection and assessment similar to this again in the future.

If future collaborative LCA studies follow the guidance, approach, and learnings from this case study, errors in the process can be avoided. Most importantly, this approach provides a viable method for engaging supply chain partners in the data collection process. A stakeholder-based approach was proposed by Thabrew et al. (2009), suggesting that the fundamental concept of life cycle thinking can be effectively used to incorporate stakeholders in the research and decision-making process, which can lead to more comprehensive, yet achievable, life cycle assessments. A collaborative approach to LCA could help to support the theory proposed by Thabrew et al. (2009). The hope is that this research can bring credibility to the collaborative LCA approach both within industry and academia.

This case study provides a model for industry to show that sharing process-level environmental impact data can lead to additional insights into a complete product system. If the broader industrial sector is able to participate in a collaborative data collection approach with an agreed-upon LCA methodology, there will be an increasing amount of current data that can be used to inform decisions to minimize in environmental impacts in supply chain operations.

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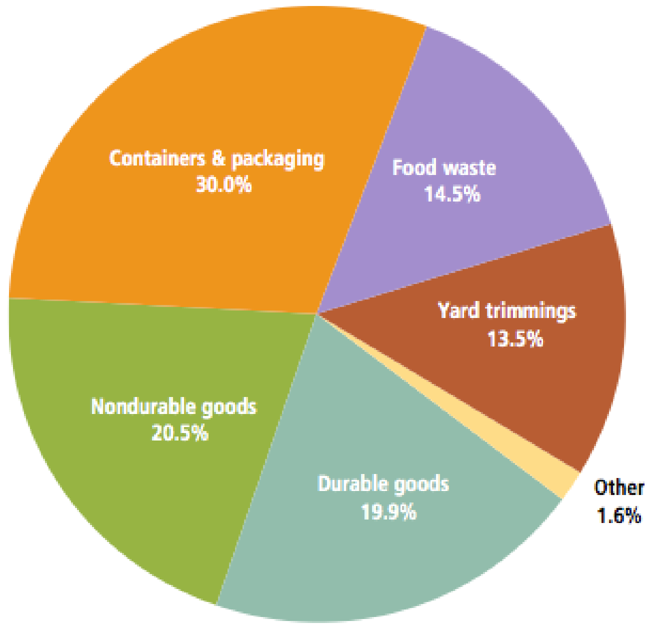
Chapter 4: An Analysis of Environmental Impacts from Manufacturing and Transporting Product Packaging

Introduction

As the world's population has grown and become more urban and affluent, waste production has risen. Rubbish is being generated faster than other environmental pollutants, including greenhouse gases (Hoornweg 2013). Packaged goods have become a part of present day society, and in many ways, packaging has improved efficiencies and made it possible for consumer goods to get to individuals unharmed. Unfortunately, the volume of the packaging waste has increased dramatically in recent years and most often becomes trash. Packaging is particularly wasteful because, unlike other consumer goods, it is often only used once and then discarded. In 2012 the US Environmental Protection Agency (EPA) reported that Americans generated approximately 251 million tons of waste. The breakdown, by weight, of waste generated in 2012 by product category is shown in Figure 4.1. Containers and packaging made up the largest portion of MSW generated; about 30 percent, or 75 million tons.

Figure 4.1 Total US Municipal Waste Generation by Category 2012 (251 million tons)



Waste generation affects the environment and human health and it is a reflection of an inefficient use of natural resources by the society. Although the problem of today's waste generation has been recognized, brands continue to use packaging in order to sell products. In addition to the contribution to waste generation, packaging has additional environmental impacts that result from the various stages in the life cycle of the packaging product. Like any other product system, the resources required, the manufacturing stages to create the packaging, and the transport of packaging all have environmental impacts.

Packaging is a part of the overall product offering and has both a physical and psychological function (Roper and Parker 2006). The physical aspect of packaging allows the product to be protected, preserved, and stored until used. In addition, it helps to inform customers of essential product attributes, including the calorific content of food items, and it satisfies legal obligations of the manufacturer, such as providing sell by or use by dates.

Lastly, packaging is a key element in conveying important brand messages to consumers (Blyth 2001). Product packaging is one of the most significant in-store communication tools (Couste 2012). Packaging design must attract consumers in an increasingly competitive and quickly changing market while fulfilling the essential physical functions required for the extended supply chain (Scortar 2013).

The notion that packaging may act as a marketing piece that serves to sell the product and is not just a container or protector of the product has been well documented in past research. Packaging is viewed as a brand communication vehicle (Nilsson and Ostrom 2005), and an attractive appearance can be a purchasing stimulus (Ghoshal 2010). As consumer choice has widened, marketers are increasingly interested in the use of packaging as a branding mechanism, and in the case of fast-moving consumer goods, the marketing communications aspect of packaging is now often an important differentiator (Fill 2002). Jeweler Tiffany & Co.'s blue box is a perfect example of how a package can create worldwide brand identification.

The packaging is expected to provide the consumer with a visual sales pitch that leads to purchasing and using the product (Roper and Parker 2006). Brands must design packaging that will both convince the retailer to stock the product and convince the consumer to purchase the product. The physical aspects of the packaging have to work with the brand messaging to create consumer demand and thereby sell the product. Packaging can often increase initial costs (Minami et al. 2010). However, if a firm is able to differentiate its product with new packaging, they have the potential to increase sales (Atagan and Yukcu 2013).

Background: Patagonia’s Performance Baselayer Packaging

Patagonia has begun using a new packaging design for its performance baselayer product line (PBL). PBL is a category of products made and sold by Patagonia that provides insulation and is worn under layers, similar to long underwear. This category of product has been a cornerstone of the Patagonia brand and its connection to the consumers since its inception 40 years ago. Pricing for the PBL products ranges from $50 to $120, depending on specific style of the product. Prior to the new packaging design, Patagonia rolled the garment and packaged it in a plastic bag. This packaging method is referred to as the polybag packaging solution. The reason for the shift in packaging is that rolled garments did not merchandise in the retail setting very well, which may have caused a barrier between customers trying on and purchasing PBL products.

Similar products, sold by competitors, are packaged in boxes. This packaging solution protects the garment and looks well organized when displayed. The feedback that Patagonia has received regarding rolling the product and displaying it without any protective packaging (the polybag is removed from the product before it is placed on display in stores) is that it does not provide a good shopping experience for the customer because they have to unroll the garment to have a full view of it and try it on. In addition, because the fabric is exposed, many shoppers touch it. Customers typically cannot get it back in to the roll once they finish, leaving the display area unorganized. The goals of developing an alternative packaging and display solution for PBL is to make it easier for the customer to see, try on, and buy, and for the retailers to manage, merchandise, and maintain.

The new package that Patagonia is using for the PBL line is a box in the shape of a hexagon (hex box packaging solution) made of 100% recycled paperboard. The package will be used in all of Patagonia's global sales channels. The shift to a package with a cleaner and more modern design aesthetic is expected to attract greater interest in the product and make it easier for customers to try on and sales associates to keep organized. The change increases the volume of packaging material used to package PBL products and will likely increase the environmental impacts relative to the current packaging option.

Figure 4.2 Image of Patagonia's original approach to PBL packaging and store merchandising. The product is rolled, held together with a rubber band and the hangtag is displayed to provide information for the customer.

Figure 4.3 Image of Patagonia products in the polybag packaging. Polybags are removed prior to displaying products in the store.

Figure 4.4 Image of Patagonia's new PBL packaging, referred to as the hex box

Prior to introducing the hex box packaging solution, Patagonia had a standardized packaging approach and packaged all of its apparel products in a polybag. Patagonia's reason for packaging each product in a polybag is to protect the product as it travels from the finished good factory to the distribution center, as it travels through the distribution center, and ultimately in its transit to the final customer. In addition, the polybag packaging protects the product from getting dirty and dusty in back stock areas in retail locations.

The introduction of the hex box packaging solution for the PBL product line has shifted Patagonia away from a standardized packaging approach to a more customized approach. The hex box packaging was designed as a sales mechanism as well as a protective container. Patagonia's sales channels include direct sales and wholesale sales. Approximately 60% of Patagonia sales are through wholesale, which means Patagonia sells products through other retailers such as REI, MEC in Canada, and other various specialty outdoor stores. The main need for the hex box packaging is in wholesale environments where Patagonia products are merchandized next to competing brands. In addition, there are regional preferences to packaging PBL boxes. The purchasing habits in both Japan and Europe indicate that customers prefer to purchase baselayer products when they are in a package. The package ensures that numerous customers do not touch the products.

Background: environmental impacts from manufacturing and transporting packaging

Packaging, although manufactured and used to protect another product, is a product of its own. Packaging materials are made of resources and require energy and water to process and manufacture. Just like any other product, by examining the product system from a life cycle perspective, it is possible to find ways to make improvements to the packaging that reduce its overall environmental impacts.

Improvement measures in sourcing and manufacturing can significantly reduce the overall impact of packaging products. There are several life cycle assessment studies of packaging materials and processes, most of them analyzing the impact of resource extraction and manufacturing. In addition to evaluating environmental improvements that can be made via material selection and manufacturing improvements, logistics systems can also be considered as an opportunity to minimize environmental impacts. Logistics systems include transportation, product handling, packaging, and warehousing. Oftentimes companies have direct control or strong influence over the details of their logistics systems. The control or strong influence over logistics systems makes for an opportunity for improvements in efficiency and corresponding environmental impact reductions.

A handful of studies have taken both the complexity of real logistics systems and LCA into consideration when evaluating environmental impacts. There is, however, a lack of studies using real world data to assess logistics systems (Zhang 2013). The paragraphs below provide an overview of past research that has been done in this area and also reveals that the intersection of LCA and corporate logistics systems is not widely documented.

In 2013, a group of students from UCSB's Bren School of Environmental Science and Management did a research project focused on reducing the greenhouse gas emissions from transportation of Patagonia products to US-based customers. The project was initially motivated by an interest to integrate alternative fuels in Patagonia's distribution network. The findings of the project revealed that the avoidance of high GHG emitting fuels is particularly challenging, but there are non-fuel switching options available that more effectively reduce GHG emissions. The group considered emissions as a function of package density, since the package density parameter is observed to be one that Patagonia can control. They found that increasing package density and trailer volume inputs resulted in a significant reduction in greenhouse gas emissions. By reducing the package density by 20%, emissions increase by 19.25%. Similarly, by increasing the package density by 20%, emissions decrease by 12.83% (Choe et al. 2013). Their findings revealed that changes in technology mix, driving cycle, or even fuel choice are all unable to reduce emissions as much as package density.

This research has important implications for Patagonia. Patagonia, not operating its own fleet, has more control over the density of their packages than the types of vehicles moving packages and type of fuel used in each vehicle. This study revealed to Patagonia that it has the capability of either increasing or reducing environmental impacts from transportation through its own operational approach to packing and transporting products.

In addition to opportunities to improve efficiencies through packaging shipments more densely, the amount and size of packaging were included in a research project focused on the impacts manufacturing and shipping food. The study by Davis and Sonesson (2008) found that energy efficiency in industry and households, less consumer transport, and minimizing packaging all proved to be key factors to minimizing environmental impacts in their supply chain.

A study on the environmental impacts from shipping books to customers in China conducted by Zhang and Zhang (2013) found that logistics accounts for a significant portion of the total energy use and CO_2 emissions in business-to-customer retailing. This study, however, did not factor in packaging or the opportunity to investigate if there is an opportunity to minimize the overall impacts of the logistics system by making changes to the packaging system.

Williams and Tagami (2003) conducted a comparative case study of the energy used to sell online versus conventional book retailing in the Japanese book sector. Several aspects to selling were factored into their assessment, including energy consumption from the customers' trip to and from the store, book packaging, and sales point. Their results of this study indicate that important factors influencing the energy efficiency of business to consumer e-commerce include packaging, loading factors of courier trucks, number of trips per delivery, and residential energy consumption. Each book traded through e-commerce consumed more energy because of the additional packaging used (5.6 MJ/book) compared with conventional retail (5.2 MJ/book).

The limited amount of research found on the environmental impacts of logistics systems and the intersection between LCA and logistic systems indicate that this is area that has not been widely studied. This research will work to fill that gap by examining how LCA and a detailed evaluation of logistics systems can intersect to maximize opportunities to reduce the environmental impacts of packaging.

As consumers and legislation are increasingly pushing firms' operations and products to reduce waste, it is essential to evaluate the necessity of packaging. Ultimately, Patagonia prefers to use minimal packaging on its products. This research will use LCA to determine and compare the environmental impacts of the hex box and polybag packaging solutions. In addition, it will evaluate the opportunities within Patagonia's logistical system to use the hex box to maximize sales of specific products in specific regions and sales channels and minimize use of the box on products and in regions and sales channels where the boxes are less necessary. The aim of the study is to gain knowledge of the environmental impact of packaging through the product supply chain and to explore the effect of various improvement measures in the post-manufacturing logistics systems.

The result of this research will be used to provide insight to Patagonia on how to balance both customer needs and minimize resource use. In addition, these results can be used to inform the decisions of other apparel brands. As other brands work to address their own use of packaging and plastic, the data generated in this research will help to guide informed decision-making across any industry that relies on packaging to protect and market their products.

Methods

The packaging evaluation will consist of two main parts:

Part 1: Comparison of packaging life cycle impacts: This part of the research will focus on comparing the environmental impacts that result from all steps in the life cycle of the packaging products. This will include product processing and manufacturing, customer use, and end of use for both the hex box packaging solution and the polybag packaging solution.

Part 2: Operational evaluation to determine the potential to reduce impacts by tailoring packaging strategies based on product type and demands in global regions and sales channels.

Table 4.1 below shows the life cycle stages for the hex box and polybag packaging options and the corresponding section of the research that will address their environmental impacts.

Table 4.1 Project scope for both packaging options

Life Cycle Stages for both packaging options	Research Components
Resource extraction for product packaging and transport packaging components	Part 1
Processing	Part 1
Product assembly	Part 1

Transportation of product and transport packaging material from manufacturing to the apparel manufacturing facility	Part 1
Transportation of product and transport packaging from apparel manufacturing facility to distribution center	Part 2
Transportation of product and transport packaging from distribution center to wholesale and retail locations	Part 2
Distribution (storage in warehouse)	Not included
Retail (point of sale)	Not included
Use of product (consumer use)	Not included
End of product use (disposal)	Part 1

Scope of Packaging Evaluation (Part 1 and Part 2):

The scope of this research will include all packaging components used in the product and transport packaging. Product packaging is defined as the packaging used for individual products. Transport packaging includes the additional materials used when shipping products from manufacturing to the distribution center and from the distribution center to customers and retail locations.

The hex box packaging includes a 100% recycled content corrugated box and a paper wrap to protect the hex box during shipping. This packaging solution, which includes both a corrugated box and a sheet of paper, will be referred to as the hex box packaging solution for the remainder of this chapter. The polybag packaging includes a 100% virgin content polyethylene bag. This packaging solution will be referred to as the polybag packaging solution for the remainder of this chapter. Because the product will have a hangtag for all packaging solutions, the hangtag is not a differentiator and will not be included in the analysis. The transport packaging for the hex box includes an 18.5x24.5x16.5 corrugated carton and a large polybag to line the paperboard carton. The transport packaging used to ship products with the polybag packaging solution includes a 16x18x18 corrugated carton.

The hex box and polybag packaging solutions and the transport packaging for both solutions will be evaluated over the entire life cycle from origin of materials through end of its useful life. The specific logistics for the transportation of both packaging solutions and the transport packaging from apparel manufacturing facility to distribution center and from distribution center to retail and wholesale locations will be evaluated in more detail in Part 2 of the research.

Table 4.2 Product packaging components for both packaging solutions

Hex Box Packaging	Polybag Packaging
100% recycled content corrugated hex box	100% virgin polyethylene bag
100% recycled content and unbleached paper protective wrap	

Table 4.3 Transport packaging components for both packaging solutions

Hex Box Packaging	Polybag Packaging
18.5x24.5x16.5 60% recycled content corrugated carton	16x18x18 60% recycled content corrugated carton
100% virgin polyethylene bag to line the box	

Part 1: Comparative Packaging LCA

The hex box and the polybag are made of corrugated board and polyethylene, respectively. Both are materials commonly used in packaging. Due to this, a literature review revealed that there is current LCA data on the materials used in the hex box packaging solution and the polybag packaging solution. After reviewing all data sources, it was apparent that the existing studies were current and used best available data to assess the life cycle impacts of the corrugated board and polyethylene bags. Because both current and high quality data was available, it was decided to use LCA data gathered from the literature instead of completing a new LCA on corrugated board and polyethylene.

A more detailed description of the data source selection process and the scope for the LCAs found in the literature is included in the sections below, titled *Hex box packaging solution life cycle data collection and sources* and *Polybag packaging solution life cycle data collection and sources*.

Hex box packaging solution life cycle data collection and sources

Given multiple levels of uncertainty in LCA, and more specifically LCAs completed by other organizations, it is challenging to select one data source or study as being the best representative for a similar product system. Two primary sources were found that matched the needs of this research fairly closely. The hope was to find an LCA that addressed all life cycle stages and included CO_2 equivalents, energy use, water use, and waste generation impacts in the evaluation of the material. In addition, the product system being evaluated had to be fairly transparent in order to extrapolate out impacts by a specific functional unit that could be adjusted to meet the needs of this research.

The two sources found included an LCA completed by the Corrugated Packaging Alliance, completed 2014, and an online resource that calculates life cycle impacts of various paper-based products created by the Environmental Paper Network. The results in the Corrugated Packaging Alliance (2014) study were closely aligned with the results provided by the Environmental Paper Network's Paper Calculator. The paper calculator, however, would allow for a consistent calculation across all pulp based products being assessed, including 100% recycled content corrugated board, 60% recycled content corrugated board used as transport packaging, and 100% recycled content paper wrap to protect the hex box packaging. The Corrugated Packaging Alliance (2014) LCA included only the evaluation of a 100% virgin fiber content corrugated board and a 100% recycled content corrugated board. Other research would have been needed to account for the life cycle impacts of the paper wrap, and several assumptions would have been required to modify the data to represent the 60% recycled content corrugated board used in the transport packaging.

One additional and substantial drawback to the data presented in Corrugated Packaging Alliance (2014) was that they accounted for negative CO_2 emissions at the pulp and paper making operations and explained that this was due to the removal of biomass. They explained that removal of trees grown to produce containerboard offset a large proportion of all Greenhouse Gas emissions (GHGs) (biogenic CO_2 and other GHGs). The research stated that live trees absorb and capture carbon from the atmosphere. That carbon remains trapped in the harvested wood fiber and manufactured corrugated product through its entire life cycle, right up to end-of-life. The captured carbon, having been removed from the atmosphere, offsets that which is emitted at end-of-life. They did acknowledge that emissions of CO_2 do occur at pulp and paper mills, noting that a portion of the sequestered carbon is released through combustion of biomass fuels during processing. There are numerous assumptions made in this approach to accounting for carbon emissions at the paper processing life cycle stage. In addition, the published LCA didn't include an explanation of the CO_2 emissions calculations, making it impossible to modify such assumptions. Due to this factor, the Corrugated Packaging Alliance LCA study was not used in this research.

Instead, the LCA data provided in the Paper Calculator (2014), created by the Environmental Paper Network, was used to evaluate the paper-based products used in this assessment. The paper calculator data was chosen for use for three main reasons. First, the Paper Calculator (2014) is based on research done by the Paper Task Force, a peer-reviewed study of the lifecycle environmental impacts of paper production and disposal. Second, the underlying data is updated regularly. Third, it had the capability of addressing the three types of paper-based products included in this evaluation (100% recycled content corrugated hex box, the 100% recycled content unbleached paper, and the 60% recycled content corrugated shipping carton).

There are several details of the paper based packaging products that should be noted here. First, Patagonia uses four different size hex box packaging options. They are differentiated by size, and include 4”, 6”, 10” and 12” size hex boxes. All four sizes will be included in all aspects of this research. In addition to each of the boxes, there is a corresponding size paper that is wrapped around the box to protect it during shipping. The protection is used to ensure the box isn’t damaged, as it is used as part of the product display when merchandised in a retail location. Refer to Figure 4.5 to see the hex box display used in retail locations. Last, 60% recycled content corrugated cartons are used in transport for products packaged in the hex box packaging solution as well as in the polybag packaging solution. The corrugated cartons will also be included in this analysis.

Figure 4.5 Hex box PBL packaging merchandised in a store

Figure 4.6 Corrugated carton used to transport products from manufacturing to DC and from DC to sales locations

The calculator allows for customization of the products that are evaluated. In the case of this research, the specific attributes of the three paper based products were gathered from the vendors that provide Patagonia with packaging materials. This information was then input into the Paper Calculator (2014) to evaluate the lifecycle impacts of each of the three paper-based products.

The Paper Calculator (2014) provides measurements of CO_2 equivalents, energy use, water use, and waste generation. The calculator's measurement of GHG emissions includes carbon dioxide (CO_2) and methane, which it measures in CO_2 equivalents, and a net energy measurement, which includes the total energy used throughout the lifecycle of the product being evaluated. The Paper Calculator (2014) includes an energy credit for energy that is created by burning paper at the end of its life. The net energy takes the total amount of energy required to make the paper over its life cycle and subtracts this energy credit. If most of the energy used to make the paper is purchased, then the energy credit might make the Net Energy lower than the Purchased Energy. The water consumption measurement accounts for the amount of process and cooling water that is consumed or degraded throughout the life cycle of the paper product. The Paper Calculator (2014) incorporated a measurement of solid waste in their assessment that included sludge and other wastes generated during pulp and paper manufacturing as well as used paper disposed of in landfills and incinerators.

The outputs from the Paper Calculator (2014) for the 100% recycled content corrugated hex box, the 100% recycled content unbleached paper, and the 60% recycled content corrugated shipping carton were then adjusted based on the weight of each specific packaging material used by Patagonia.

Polybag packaging solution lifecycle data collection and sources

Two main LCA studies were found that address the environmental impacts of the life cycle of a 100% virgin polyethylene bag. Green (2011) completed a study that included a review of three LCA studies from around the world that focused on evaluating the environmental impacts of plastic and reusable bags. In addition to reviewing the existing plastic bag LCAs, Green (2011) expanded upon the existing studies to include reusable polypropylene (PP) and reusable recycled polyethylene (PE) in the study. Green (2011) used the data gathered from Chaffee and Yaros (2007) to represent single use polyethylene bags. The data needs for this research only required information on single use polyethylene bags, so the study by Chaffee and Yaros (2007) was used as it provided more details on the LCA method and calculations used to complete the study.

Chaffee and Yaros (2007) evaluated three types of grocery bags: a recyclable plastic bag; a compostable, biodegradable plastic bag; and a recycled, recyclable paper bag. The recyclable plastic bag product system that they evaluated in their LCA was considered to be a 6-gram single use polyethylene bag. The polybag packaging solution used at Patagonia is made of polyethylene and is similar in weight to the bag Chaffee and Yaros (2007) evaluated. Also, it should be noted that Chaffee and Yaros (2007) found that single-use plastic bags require less energy, fossil fuel, and water than an equivalent amount of paper bags.

The study by Chaffee and Yaros (2007) included the extraction of fuels and feedstocks from the earth, transport of materials, all process and materials operations in the production of high and low density polyethylene resin, converting PE resin into bags, packaging and transport of bags to distribution centers and grocery stores, consumer use, and final disposal. In short, the LCA included all life cycle stages and boundary conditions that were included in the corrugated board and paper assessments done using the Paper Calculator (2014).

The LCA provided measurements of greenhouse gas emissions (kg CO_2 equiv.), energy use (MJ), water use (gallons), and waste generation. These are the same categories and units of measure used in the Paper Calculator's (2014) assessment of the hex box, paper wrap, and corrugated carton. In addition, the measure of GHG emissions in both studies is in terms of CO_2 equivalents. Ensuring that the assessment scope and impact categories used in the LCAs for the paper based products and the polybag were the same was a key factor in comparing the impacts of the various packaging products. Even with the alignment in scope, the assessments were completed by different organizations and for different purposes. Comparing two product systems from different analyses inevitably has a substantial degree of uncertainty.

Chaffee and Yaros (2007) made assumptions for curbside collection and generation and recovery of materials in municipal solid waste based on existing data from government agencies and the EPA. For 2005, the data showed plastic bag recycling at 5.2% and plastic bag MSW for combustion with energy recovery at 13.6%, resulting in 81.2% going to landfill. This assessment indicates that the recycling rate for plastic bags is low. According to Chaffee and Yaros (2007), there are a number of reasons for this, including lack of infrastructure and poor consumer awareness about the inherent recyclability of plastic bags. The paper-based product LCA data also accounted for a portion of the waste being incinerated to produce energy. It was key to see that both sources used for this research addressed the disposal impacts in a similar manner, as one component of this research is to compare the environmental impacts of the packaging options.

The LCA data from Chaffee and Yaros (2007) was used to model both the individual product polybags and the liner polybags used in the transport packaging for the hex box solution, which protects the hex box packaging solution and PBL product during transit. The impact analysis from Chaffee and Yaros (2007) was modified to reflect the weight of each of the polybags evaluated in this research.

The comparative LCA portion of this research assessed energy use, resulting CO_2 equivalents, and water use for the hex box and polybag packaging solution. For the purposes of this study, the assumption was made that the transportation impacts from the packaging manufacturing location to Patagonia's garment manufacturer is accounted for in the LCA studies used. Chaffee and Yaros (2007) noted that the transport to the customer from bag manufacturer is included in the assessment, though the study did not provide details on the shipping distances that were considered in the assessment. Paper Calculator (2014) did not address if transportation is included in the assessment. For the purposes of this research, it will be assumed that the impacts of shipping packaging to Patagonia's manufacturing location are accounted for. Part two of this research will specifically address the environmental impacts that result from shipping products from garment manufacturing factory to a distribution center and from distribution center to retail or wholesale locations.

Once the environmental impacts of both packaging solutions were determined, they were compared to the environmental impacts of an average PBL product. This portion of the research will be done in order to provide a larger context to determine how significant the packaging environmental impacts are in comparison to the environmental impacts of the complete product system. Patagonia has completed preliminary research on the environmental impacts that result from the manufacturing processes required to make its products. The LCA data that has been gathered for Patagonia's PBL products will be used to compare the impacts of the actual PBL product to the impacts of the packaging.

Patagonia's PBL product life cycle analysis accounts for 95 percent of the garment's weight. The boundaries of the supply chain start at the origin of the primary material (in this case, the product is made of a synthetic polymer) and go through each step in the production of a garment, from fiber to yarn to fabric to finished garment. The supply chain ends when the garment reaches the Patagonia Distribution Center in Reno. The analysis also includes the impacts from transporting the product from each life cycle stage to the next. Energy consumption, water consumption, and CO_2 equivalents were measured for the PBL products. Patagonia's supply chain vendors provided the data used to complete the PBL LCA. They requested that vendors provide actual production information specific to their facility. Where vendor data could not be obtained, data from LCA studies was used.

The PBL product LCA used in this research does not include the impacts of the product in the retail, use, or end of use life cycle stages. The comparison of the product impacts to the packaging impacts will be a comparison of the manufacturing and transport life cycle stages. It should be noted that the LCA data collected on the packaging materials include impacts from the end of use life cycle stage. Those impacts, however, are minimal in comparison to the impacts from packaging manufacturing.

Part 2: Operational Analysis

In addition to focusing on the life cycle environmental impacts of packaging that result from extraction and processing of material to manufacture the packaging, Part 2 of the research will examine the impacts that result from Patagonia's current PBL logistics system. In the packaging product life cycle, Patagonia has the most influence over the type of packaging used. This portion of the research will investigate opportunities within Patagonia's logistics system to use the hex box packaging solution to maximize sales while minimizing the use of the box on products and in regions and sales channels where the boxes are less necessary.

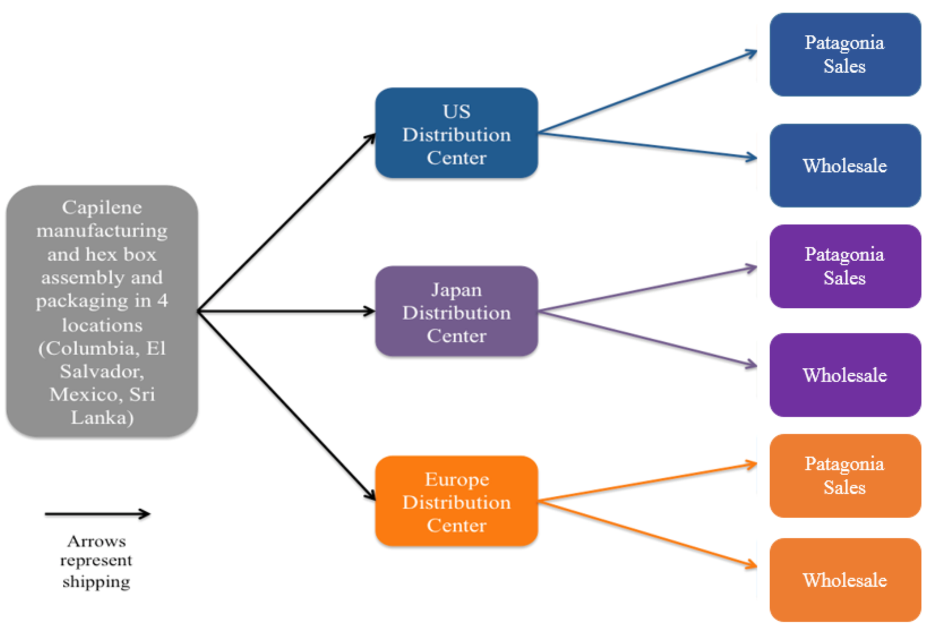
Operational Analysis Scope

Patagonia's logistics system includes transporting the packaging products from the apparel manufacturing facility to Patagonia's global distribution centers (DCs) and from the DCs to Patagonia sales locations and wholesale locations. Environmental impacts will be determined based on the weight of the packaging, the number of products packaged and transported, the number of transport cartons and liner bags needed, the distance of each leg of transport, and mode of transportation.

It can be assumed that by using the hex box packaging solution in fewer sales channels, the overall environmental impacts that result from the packaging will decrease. The answer, however, is not as simple as that. The logistics systems for global companies become complex quite quickly. Adding multiple packaging options and specific packaging options for specific regions increases the complexity of the logistics system even further and can be infeasible. This research will investigate the realities of the logistics system and assess the trade-off between the reduction in impact by limiting use of the hex box and the resulting increase in the complexity of the logistics. The larger contribution of this research will be to illuminate the possibilities of minimizing environmental impacts by changing the logistics of packaging systems.

Patagonia's systems are not completely malleable and there will be limitations to what can realistically be changed. The challenge of determining the optimal packaging scenario is reflective of real world logistics and business decisions. By introducing specific changes to the current PBL packaging system, the supply chain complexities will inevitably increase. In addition, it is important to note that using different packaging for the same product goes against the basic concept of standardization. Standardization is key concept in supply chain and materials management as it can help to maximize quality and efficiency and minimize costs. The flow chart below shows Patagonia's current process flow from packaging a finished product through sales to the customer.

Figure 4.7 Patagonia's current PBL logistics system - Packaging thru Sales



In the paragraphs below, three main factors are highlighted as opportunities to consider when searching for ways to maximize the use of packaging while reducing the need for packaging and resulting impacts.

Sales Channels:

Patagonia has two main sales channels: Patagonia sales and wholesale dealers, shown in Table 4.4. Currently similar products, sold by competitors, are packaged in boxes. The primary need for the hex box packaging solution is in Patagonia's wholesale retailers, where Patagonia products are displayed next to other brand products. Wholesale makes up approximately 60% of Patagonia's total sales. With these factors in mind, the operational packaging assessment will consider opportunities for packaging products only sold in the wholesale channel.

Table 4.4 Sales by sales channel

	% of Total Units Sold
Wholesale	60%
Patagonia Sales	40%

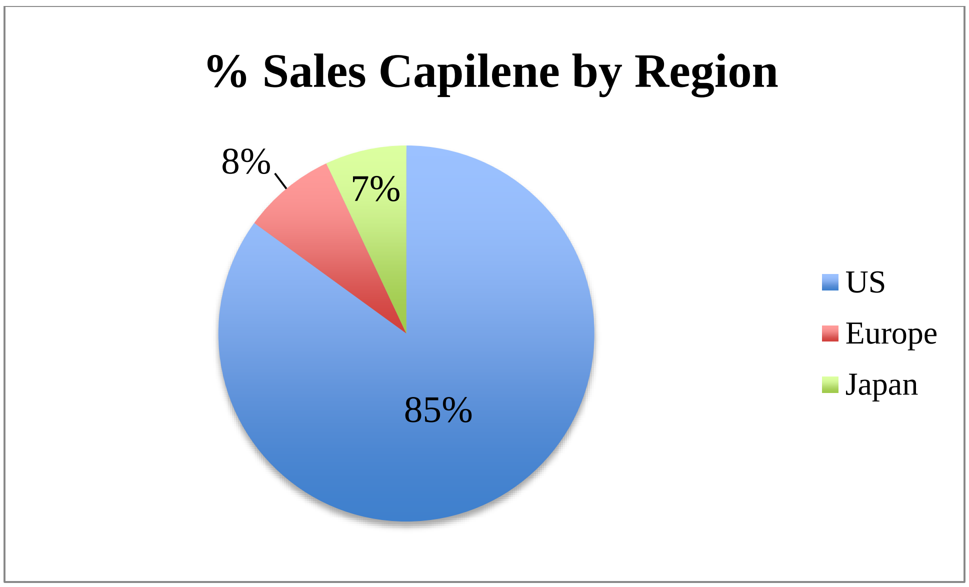
Region:

Patagonia sells products in numerous global regions. The majority of sales are in the US, with Europe and Japan being the next two largest sales regions. The percentages of sales in each region are shown in Table 4.5 and Figure 4.8. These three regions will be the focus of this research. Merchandising and packaging needs in these regions differ. European and Japanese customers prefer that their PBL products be packaged. US customers do not have the same expectations for packaging around their PBL products as European and Japanese customers. These customer preferences were taken into account when creating the analysis scenarios for this portion of the research. Priority will be placed on ensuring that the PBL products sold in Europe and Japan are packaged in the hex box packaging solution.

Table 4.5 Patagonia overall sales by region

	% of Total $	% of Total Units
North America	83%	85%
Europe	8%	8%
Japan	8%	7%
South America	0%	0%
Australia	0%	0%

Figure 4.8 Patagonia's Capilene sales by region



Styles and Factories:

Patagonia currently has 31 PBL styles that are packaged in a hex box. These 31 styles are made in four factories. There are four main weights (fabric thicknesses) in the PBL line: Thermal Weight (TW), Mid Weight (MW), Light Weight (LW), and Daily Weight (DW) (thinnest weight). Each product made is assigned a specific size hex box that best fits the type of the product and the size of the product. The LW and DW are the most underwear-like styles. The TW and MW garments are thicker in weight and are often worn over a first layer of clothing, making their function less like actual underwear. For these reasons it could make sense to not package the TW and MW garments in the hex box packaging solution. The TW and MW garments are made by Vendors A, B, and C located in various locations in Latin America, while all LW and DW styles are made by Vendor D, located in Sri Lanka. This research considers only packaging DW and LW garments in the hex box and using the polybag packaging solution for MW and TW garments.

In contrast to the logic above, the LW and DW PBL styles come in bright colors that are key selling point for the products. It is helpful for the customers to see the colors of the product at the point of sale. With this in mind, it could be helpful to have the products merchandised without the hex box packaging solution covering up the products. The TW and MW garments often come in generic colors like navy blue, black, and grey. There is less of a need for the customer to see the color of the TW and MW garments. This research also explored the option of only packaging TW and MW PBL styles in the hex box packaging solution.

The different styles and their manufacturing locations are listed in Table 4.6 below. These styles and manufacturing locations will be factored in to the assessment to determine if focusing on packaging only the LW and DW or only the TW and MW styles provides a logistically feasible opportunity to minimize the use and impacts of packaging.

Table 4.6 Patagonia PBL styles and manufacturing locations

F15 Product Line			
Style #	**Product Name**	**Vendor**	**Location**
43647	M's Cap TW Crew	Vendor A	Colombia
43650	W's Cap TW Crew	Vendor A	Colombia

43657	M's Cap TW Zip Neck	Vendor A	Colombia
43662	W's Cap TW Zip Neck	Vendor A	Colombia
43667	M's Cap TW Zip Hoody	Vendor A	Colombia
43672	W's Cap TW Zip Hoody	Vendor A	Colombia
43701	M's Cap TW One-Piece Suit	Vendor A	Colombia
43706	W's Cap TW One-Piece Suit	Vendor A	Colombia
43680	M's Cap TW Boot Length Bottoms	Vendor B	El Salvador
43695	W's Cap TW Boot Length Bottoms	Vendor B	El Salvador
43687	M's Cap TW Bottoms	Vendor B	El Salvador
43692	W's Cap TW Bottoms	Vendor B	El Salvador
44425	M's Cap MW Crew	Vendor B	El Salvador
44435	W's Cap MW Crew	Vendor B	El Salvador
44445	M's Cap MW Zip Neck	Vendor B	El Salvador
44455	W's Cap MW Zip Neck	Vendor B	El Salvador
44485	M's Cap MW Bottoms	Vendor C	Mexico
44490	W's Cap MW Bottoms	Vendor C	Mexico
45641	M's Cap LW Crew	Vendor D	Sri Lanka
45646	W's Cap LW Crew	Vendor D	Sri Lanka
45651	M's Cap LW T-Shirt	Vendor D	Sri Lanka
45656	W's Cap LW T-Shirt	Vendor D	Sri Lanka
45681	M's Cap LW Bottoms	Vendor D	Sri Lanka
45686	W's Cap LW Bottoms	Vendor D	Sri Lanka
45260	M's L/S Cap Daily T-Shirt	Vendor D	Sri Lanka
45265	W's L/S Cap Daily T-Shirt	Vendor D	Sri Lanka
45270	M's Cap Daily T-Shirt	Vendor D	Sri Lanka
45275	W's Cap Daily T-Shirt	Vendor D	Sri Lanka
32468	M's Cap Daily Briefs	Vendor D	Sri Lanka
32477	M's Cap Daily Boxer Briefs	Vendor D	Sri Lanka
32487	M's Cap Daily Boxers	Vendor D	Sri Lanka

Factors not taken into consideration in the operational assessment:

Factors influencing the GHG emissions of transport include the transport mode (i.e., truck, ship, train, or aircraft), the size of the vessel or vehicle, speed, load capacity (and proportion of it that is used), transportation time, and distance (Ziegler et al. 2012). Shipping mode and fuel type will not be the focus of this study and will be assumed to be consistent across all channels. This is due to the fact that Patagonia has already completed an analysis on shipping mode and fuel type and understands that shipping by boat is more efficient than plane, train, or truck, and that train transportation is more efficient than by truck. This finding is supported by numerous studies, including the study by Ziegler et al. (2012), which states that airfreight is the most resource-intensive mode of transportation (per tonne∗kilometer [km]) and that shipping in bulk on a freight ship is the most efficient transport mode, closely followed by rail freight. For all cross-continent shipping legs of this assessment, it will be assumed that products are shipped by boat. For all land-based shipment, it is assumed that they are shipped via Class B truck due to the fact that rail transportation is not commonly used in Patagonia's logistics system. Considerable effort was put into confirming reliable distances and fuel emissions factors for use in this assessment.

In addition, reusing the hex box packaging solution in Patagonia or wholesale retail stores will not be considered as an opportunity to minimize packaging. Each hex box identifies the specific style, color and size. This identifying information makes it difficult for retail locations to reuse the boxes for in season and future season styles. Reusing existing boxes for future season styles would not prove to be a likely scenario and will therefore not be considered in the analysis.

<u>Analysis Scenarios</u>

With the details of the three main factors in mind, six analysis scenarios were created to determine the greatest potential to minimize the use of the hex box and the corresponding environmental impacts. The first scenario reflects the present conditions of Patagonia's logistics system for PBL products, in that all PBL products are packaged in the hex box packaging solution. Scenarios two through five incorporate a number of possible alternations in the product specific packaging, regional distribution, and sales stages of the PBL product life cycle. Scenario 6 provides an example of the potential to reduce total impacts by packaging all PBL products in the polybag packaging solution instead of the hex box packaging solution. Table 4.7 shows the list of six scenarios. The columns denote the three key factors that will be adjusted for the assessment and the comments in each row identify where the hex box packaging will be used.

This analysis includes the actual details and complexities of Patagonia's operations. The tradeoffs of the different scenarios were quantified.

Table 4.7 Operational impact analysis scenarios that show where the hex box packaging solution will be used

Scenario	Region	Sales Channels	Styles and Factories
1	All in hex box	All in hex box	All in hex box
2	All in hex box	Wholesale in hex box	All in hex box
3	Japan & Europe in hex box	All in hex box	All in hex box
4	All in hex box	All in hex box	LW and DW in hex box
5	All in hex box	All in hex box	TW and MW in hex box
6	All in polybags	All in polybags	All in polybags

With the three main logistics factors in mind, there are several other potential scenarios that were not evaluated in this research. The intention of this research is to discover realistic and logistically feasible opportunities to minimize the need for the hex box while continuing to meet customers' preferences and sales goals. The key factors that influenced the selection of the six scenarios created above will be reiterated here. Priority was placed on ensuring that the PBL products sold in Europe and Japan are packaged in the hex box packaging. Hence, no US-only scenarios were included. Additionally, the primary need for the hex box packaging is in Patagonia's wholesale dealers, where Patagonia products are displayed next to other brand products. For this reason, a scenario that focused on Patagonia sales only was not included, as it would exclude the hex box packaging on products in the most important market. Lastly, two scenarios focus on evaluating the option of selecting certain products to package. The evaluation will provide insight into which option reduces impacts the most. With that information, the findings from Scenario 2 and Scenario 3 can be used to guide opportunities for additional potential logistics adjustments.

<u>Operational Analysis Data Collection and Sources</u>

The operational analysis for this study required a significant amount of background data from Patagonia's operations. Information on Patagonia PBL sales, locations of PBL manufacturing, number of the various size hex box packaging solutions needed in each manufacturing location, number of hex boxes that could fit in a shipping carton, and distances from manufacturing to DC and from DC to customer were required.

Primary data was collected from Patagonia's operational systems wherever possible. Fuel efficiencies and emissions from fuel types during transportation were modeled using secondary data. Secondary data for the transportation evaluation was gathered from transportation efficiency tools and databases. Energy use and resulting CO_2 emissions, measured in units of CO_2 equivalents, are the environmental impacts that are the focus of this section of the research.

The analysis is based on Patagonia sales and distribution for the 2015 calendar year. Each year, sales, supply chain partnerships, and distribution locations change to some degree.

This research will not perfectly match future years' sales, manufacturing, and distribution, but it will provide educated insight into likely future situations. In order to ensure a consistent analysis across all scenarios, several assumptions were made. These include:

- 2,000,000 PBL products are packaged and sold annually.
- All styles are distributed according to regional and sales channel percentages provided in the first part of the methods section. These percentages include:
    - US sales = 85%
    - Europe sales = 8%
    - Japan sales = 7%
    - Patagonia sales = 40%
    - Wholesale sales = 60%
- The average distance from DC to customer represents shipping distances to Patagonia sales locations and wholesale locations. Appendix B includes the information used to calculate the average distance to customer for each sales region.
- The weight and carton utilization (number of units in each carton) of inbound cartons (shipments from PBL manufacturing locations to DCs) and outbound cartons (from DC to Patagonia sales locations or wholesale locations) are the same. For example, a carton shipped to a DC containing forty-two 10" hex boxes (with PBL products in them) will ship out of the DC to a sales location containing forty-two 10" hex boxes.
- The same size polybag is used for all PBL styles.

The following paragraphs will provide and explanation of the data and the corresponding calculation methods used in this assessment.

In the case of this research, the environmental impacts that result from the logistics systems are based on the energy use and emissions that result from transport. In order to calculate such impacts, the weight of the item being transported, distance traveled, and mode of transport must be known. With this in mind, the data collection portion of this research focused on gathering information on the weight of the packaging materials being shipped to and from various locations in Patagonia's supply chain and distribution network. In addition, it involved gathering transport distances, energy usage, and emissions factors. Calculations were completed for six scenarios to understand if altering the packaging options for PBL products can both reduce environmental impacts and meet regional customer needs.

Step1: Determining weights for all packaging materials

The individual packaging weight for all packaging items involved in this research was gathered from Patagonia's hex box packaging vendor, Patagonia's shipping carton vendor, and by manually weighing polybags. Table 4.8 includes the weights of individual units of each of the packaging materials included in this research.

Table 4.8 Weight of individual units of each packaging type evaluated in this research

	1 polybag	**1 carton liner polybag**	**4" hex box + paper wrap**	**6" hex box + paper wrap**	**10" hex box + paper wrap**	**12" hex box + paper wrap**	**1 16x18x18 corrugated box**	**1 18.5x24.5x16.5 corrugated box**
Mass (kg)	0.006	0.118	0.040	0.055	0.079	0.096	1.188	1.714

Step 2: Quantifying hex box packaging use

The next step was to identify the number of units coming from each manufacturing facility and, more specifically, the number of 4", 6", 10" and 12" hex box packages used in each manufacturing facility. Patagonia selected the four different hex box packaging sizes in order to best accommodate the size of the products needing packaging. The larger and thicker weight PBL products require the larger hex boxes, while the smaller, thinner PBL products are packaged in the small size hex boxes. Data from Patagonia's sales forecast was used to estimate the number of each size hex boxes and corresponding paper wraps needed. Table 4.9 shows the four hex box size options and the percent of each size hex box needed.

Table 4.9 Hex box size options and % of total hex boxes needed

	4" hex box	6" hex box	10" hex box	12" hex box
% of total needed	14.0%	32.2%	47.8%	6.0%

In addition, Patagonia data was used to determine the number of each size hex box size needed at each factory. Once that was established, the destination for each size hex box packaging was determined based on the sales % of each region (US, Europe and Japan).

Table 4.10 Hex box units needed per country

Row #	Hex box sizes	% 4"	% 6"	% 10"	% 12"	Total Boxes
1	Total Units By Size	280,315	643,633	956,041	120,011	2,000,000
2	Columbia	0.00%	0.00%	14.87%	67.45%	223,095
3	El Salvador	0.00%	33.84%	55.06%	32.55%	783,269
4	Mexico	0.00%	19.17%	23.53%	0.00%	348,354
5	Sri Lanka	100.00%	47.00%	6.54%	0.00%	645,282

Table 4.10 shows the number of units for each size of the hex box packaging solution used in each manufacturing location. These numbers and percentages reflect Patagonia's current use of the hex box packaging solution. The percentages included in rows 2-5 were used to calculate the quantity of each size hex box needed at each manufacturing location for the scenarios evaluated in this research.

Step 3: Accounting for polybag product packaging in Scenarios 2-6

Should Patagonia decide to minimize the use of the hex box packaging solution, they will still need to package each product that is not in a hex box in a polybag to protect it during transport, processing in the distribution centers, and in retail storage areas. In addition, all products will still be shipped in a transport carton. Therefore, this assessment included the impacts from packaging and transporting PBL products packaged in the polybag packaging solution. As a reminder, each scenario is based on transporting 2,000,000 PBL units. Each unit requires some sort of product and transport packaging. In scenarios 2-5, the number of products packaged in the hex box packaging solution was reduced from 2,000,000 by varying quantities. Therefore, a component of this analysis was to ensure that the remaining shipping impacts for the products not packaged in hex boxes were accounted for.

Step 4: Carton utilization

Carton utilization refers to the number of products that can fit into a transport carton. The number of PBL products shipped in each transport carton was provided by Patagonia's inbound shipping department. The information provided included the dimensions of the cartons and specific data on how many products fit in each transport carton when packaged in the hex box or when packaged in a polybag. The carton size used to transport products packaged in the polybag packaging solution is smaller than the carton used to transport products packaged in the hex box packaging solution. The difference in carton dimensions was accounted for in the calculations. In addition, the transport carton utilization differed based on the various size hex boxes and if the products were packaged in the polybag packaging solution. These specifics are shown in Table 4.11 below. Once this information was gathered, it was possible to calculate the number of cartons and, in the case of products packaged in the hex box packaging, the polybag liners needed for each scenario.

Table 4.11 Number of units per carton for each product packaging option and dimensions for the two transport cartons used to ship PBL products.

	Units per carton	Carton length (inches)	Carton width (inches)	Carton height (inches)	Carton weight (kg)
Polybag	60	16	18	18	1.188
4" Hex box	108	18.5	24.5	16.5	1.714
6" Hex box	72	18.5	24.5	16.5	1.714
10" Hex box	42	18.5	24.5	16.5	1.714
12" Hex box	42	18.5	24.5	16.5	1.714

Step 5: Calculating the total weight of the packaging materials needed for each scenario

Steps 1-4 of the operational analysis data collection provided the details needed to calculate the total weight that is shipped at every leg of the transportation for each scenario. Table 4.12 below includes the number of packaging units and total weight of packaging for each scenario. Transport packaging including corrugated cartons and liner polybags are included in the table and the total weight calculations.

Table 4.12 Number of packaging units and total weight of packaging for each scenario. Transport packaging including corrugated cartons and liner polybags are included in the table and the total weight calculations.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
# of hex box units needed	2,000,000	1,200,000	300,000	645,282	1,354,718	0
# of cartons needed for products packaged in hex boxes	37,155	22,293	5,573	8,284	28,871	0
# of liner polybags needed	37,155	22,293	5,573	8,284	28,871	0
# of product polybag units needed	0	800,000	1,700,000	1,354,718	645,282	2,000,000

# of cartons needed for shipping products packaged in polybags	0	13,333	28,333	22,579	10,755	33,333
Total weight (kg)	202,243	141,985	74,195	82,933	170,908	51,599

The information displayed in Table 4.12 was then used to complete the two key components to this research. First, the weight measurement was used to determine the energy use and CO_2 emissions from transporting the products from manufacturing facility to DC and from DC to sales location. The details on the method used to complete the transport calculations are included in the following section, Step 7: Transportation impacts calculation method.

Second, the quantities of each type of packaging needed in each scenario were used in conjunction with the LCA data collected in Part 1 to calculate the total environmental impacts that result from the manufacturing, processing, and end of use for each packaging component.

Step 6: Transportation impact calculation method

The following paragraphs describe the approach and data sources used to evaluate the transportation impacts from Patagonia's four manufacturing facilities to three global distribution centers and, finally, to an average distance sales location.

The distances between geographic locations that were calculated for this analysis were done so using two mapping tools. All truck-shipping distances were calculated using Google Maps. All distances traveled between continents were assumed to be traveled by boat. Those distances were calculated using SeaRates.com. All locations relevant to this study were found in the two web based distance tools used.

Four main legs of transport are included in the transportation evaluation. These include:

1.) Transport via truck from manufacturing facility to port.
2.) Transport via boat from the port in the region of manufacture to Patagonia's regional port (i.e. Oakland in the US, Amsterdam in the Netherlands, and Tokyo in Japan).
3.) Transport via truck from the regional port (Oakland, Amsterdam, or Tokyo) to regional DC.
4.) Transport via truck from regional DC to sales location. The sales location distance for all three sales regions was based on average distance to customer sales data gathered from Patagonia staff. Refer to Appendix B to see the distance data used to calculate the average distance to retail sales location for each region.

Table 4.13 shows the four locations where Patagonia's PBL products are manufactured and the distances between those locations and Patagonia's regional DCs and sales locations.

Table 4.13 Vendor locations, transportation distances for all three Patagonia sales regions and mode of transport

Origin and destination	**Shipping Mode**	**Vendor A Valle del Cauca, Columbia**	**Vendor B San Salvador, El Salvador**	**Vendor C Matamoros, Mexico**	**Vendor D Nugegoda, Sri Lanka**
Manufacturing location to local port	Truck (km)	150	110	25	25
Port to US port	Ship (km)	6303	4827	9000	16540
US port to Reno DC	Truck (km)	370	370	370	370

US DC to average distance retail location	Truck (km)	3082	3082	3082	3082
Port to Europe port	Ship (km)	9750	10600	9600	12605
Europe port to Heerenberg, Netherlands DC	Truck (km)	130	130	130	130
Europe DC to average distance retail location	Truck (km)	800	800	800	800
Port to Japan port	Ship (km)	14400	12700	17100	8300
Japan port to Tokyo DC	Truck (km)	50	50	50	50
Japan DC to average distance retail location	Truck (km)	595	595	595	595

Transportation energy was calculated through a combination of identifying transport distances and modes (truck or boat). Originating and destination locations were identified with any intervening waypoints (e.g., trucking from origin to a port, shipping to another port, trucking to destination). The method of transport was identified through research on the supply chain or provided by Patagonia staff. Fuel use was determined using miles per gallon estimates based on the distance one metric ton of freight using one gallon of fuel can be shipped. It is estimated that a truck can travel a distance of 95 metric-ton kilometers per gallon of fuel. It is estimated that a boat can travel a distance of 840 metric-ton kilometers per gallon of fuel (Shipping Comparisons… accessed 2015).

The ton-kilometer per gallon values for truck and boat shipping in the chart above are based on shipping one ton one mile. These numbers reveal that shipping a lot of weight in one shipment can be very efficient. The ton-kilometer per gallon values were then used to calculate the gallons of fuel needed for each mode segment by multiplying the segment distance by the tonnage of material and then dividing by the appropriate mpg estimate. Fuel usage in gallons was then converted to MJ based on the energy content of the fuel. Boats use both Diesel Fuel Oil and Residual Fuel Oil. For the purposes of this research it is assumed that all shipments via truck and boat will use Diesel Fuel Oil.

Table 4.14 Energy content per gallon of diesel fuel conversion factor.

Mode of Transport	Fuel	Energy Content per Gallon in MJ
Truck, Boat	Diesel	146 (Ag Decision Makers 2008)

Energy values were multiplied by gallons of fuel needed for each mode segment, which were then summed to find the total energy needed for transport between the origin location and destination. All energy values are reported in mega joules (MJ) and all CO_2 emissions are measured in kg-CO_2e. CO_2 equivalents were calculated using an emissions factor for diesel truck and ship transport.

Table 4.15 Transport CO_2 equiv. emissions factors

Mode	Kg CO_2 equiv./Metric ton - Kilometer
Truck	0.0947 (Choe et al. 2013)
Boat	0.0132 (GHG Emissions Calculations Tool 2005)

Step 7: Totals Calculations

The last step of the analysis was to total the packaging LCA impacts and operational analysis impacts to determine the total impacts due to packaging for each scenario. Energy and CO_2 equivalents were the only two impact categories that could be totaled due to the fact that the transportation analysis only included measurements of energy use and CO_2 equivalents.

Results

As explained in the *Methods* section, there are two main parts to this research. Part 1 focused on comparing the environmental impacts that result from all steps in the life cycle of the hex box packaging solution and the polybag packaging solution. Part 2 included an analysis of Patagonia's logistical operations to determine the potential to reduce environmental impacts from packaging by tailoring packaging strategies to demands in different global regions and sales channels. The results of these two research components are included in the following sections titled Part 1: Comparative Packaging LCA Findings and Part 2: Operational Analysis Results. The cumulative results, which include the life cycle impacts and the impacts form transportation, will be explained in the section titled Cumulative Results.

Part 1: Comparative Packaging LCA Findings

The LCA data gathered from the literature was used to evaluate individual units of all packaging products included in this assessment. Energy use, CO_2 equivalents, water use, and weight data were collected for each type of packaging.

The results show that the energy demand and resulting CO_2 equivalents from the life cycle of the hex box ranged from 45% (for the 4" hex box) to 79% (for the 12" hex box) greater than the individual polybag. Hex box water use ranged from 3.5 times more (for the 4" hex box) to 9 times greater (for the 12" hex box) than the polybag packaging option. In addition the hex box packaging solution ranges from 6.6 times greater (for the 4" hex box option) to 16 times (for the 12" hex box) the weight of the polybag.

The impacts of the corrugated transport cartons were also evaluated. Two different size cartons were evaluated: one that is used to transport products packaged in the polybag packaging solution and the other to transport products packaged in the hex box packaging solution. The transport cartons had the greatest impacts of the 8 different products used to package and transport PBL products. The impacts of the carton used to transport PBL products in hex boxes had the greatest impacts. The carton used to transport products packaged in hex boxes weighs 30% more than the carton used to ship products packaged in polybags. Table 4.16 shows a side-by-side comparison of individual units of the 8 different packaging components included in the operational assessment.

Table 4.16 LCA impacts for individual packaging products evaluated in this research. Energy use, CO_2 equivalents, Water use and weight data were collected for each type of packaging.

	1 polybag	1 carton liner polybag	4" hex box + paper wrap	6" hex box + paper wrap	10" hex box + paper wrap	12" hex box + paper wrap	1 16x18x18 corrugated box (for products packaged in polybags)	1 18.5x24.5x16.5 corrugated box (for products packaged in hex boxes
Total Energy Use (MJ)	0.509	10.386	0.927	1.292	1.854	2.255	33.841	48.820
CO_2 equivalent (kg)	0.027	0.544	0.057	0.079	0.114	0.139	2.203	3.178
Fresh water use (gal)	0.040	0.816	0.142	0.201	0.285	0.362	11.372	16.406
Mass (kg)	0.006	0.118	0.040	0.055	0.079	0.096	1.188	1.714

Patagonia packages every product manufactured under the Patagonia label in a polybag in order to protect the product from damage during transport and processing in the DC. Patagonia has put much time and effort into trying to find a solution that would eliminate the need for the polybag product packaging but has not been able to find a better alternative. Since the switch to the new hex box packaging solution, the PBL products are the only category of products made by Patagonia that does not require the use of an individual polybag to protect the product. The hex box provides the needed protection instead.

From this perspective, the hex box packaging has enabled Patagonia to reduce the plastic packaging it typically relies on. The hex box does however require the use of one polybag per carton to line the carton and ensure the products and hex box packaging do not get wet during transit. There is a 37% reduction in impacts that result from using 385,875 liner polybags (the number required to ship 2,000,000 hex boxes according to Scenario 1) instead of using 2,000,000 individual polybags. This reduction is shown in Table 4.17 below. The impacts of the liner are shown in contrast to the individual product polybag impacts previously incurred due to the need to package each individual Patagonia product.

Table 4.17 Environmental impacts from product polybags and liner polybags. The table shows that by switching to hex box packaging, Patagonia only needs to use polybags to line transport cartons. This has resulted in a 37% decrease in impacts from plastic polybags.

	2,000,000 product polybags	1 product polybag	37,155 carton liner polybag needed	1 carton liner polybag	% Reduction in impacts from polybag use
Total Energy Use (MJ)	1,018,000	0.509	385,875	10.386	37.9%
CO_2 equivalent (kg)	53,333	0.0267	20,216	0.544	37.9%
Fresh water use (gal)	80,000	0.040	30,324	0.816	37.9%
Mass (kg)	12,000	0.006	4,384	0.118	37.9%

Despite the reduction in impacts from plastic use, the decision to replacing the polybag with the hex box packaging solution for all PBL styles has resulted in an overall 62% increase in environmental impacts. Table 4.18 shows the quantifiable differences between using 2,000,000 units of the two packaging solutions. Although standard polyethylene plastic bags are made from oil, the added requirements of manufacturing energy and transport for the paper-based products far exceed the raw material use in polybag bag system (Chaffee and Yaro 2007).

Table 4.18 Comparison of impacts from polybag packaging and hex box packaging (the hex box packaging solution includes a paper wrap for transit)

	Polybag Total Impacts	Hex Box + Transit Wrap Total Impacts
# of units needed	2,000,000	2,000,000
Total Energy Use (MJ)	1,018,000	3,134,923
CO_2 equivalent (kg)	53,333	192,118
Fresh water use (gal)	80,000	485,421
Mass (kg)	12,000	134,154

The environmental impacts from the lifecycle of the corrugated transport carton were also investigated in this research to determine if they could provide an opportunity to reduce impacts in the PBL product packaging system. In order to give the environmental impacts of the carton context, the details of Scenario 1 were used for the comparison. In Scenario 1, 37,155 transport cartons were needed to contain the 2,000,000 hex box packages during transport. The comparison showed that the corrugated carton made up 32% of the total impacts from using corrugated packaging.

Table 4.19 The 60% recycled corrugated carton used for transporting the hex box packaging (with product in it) is 32% of the total impact from using corrugated packaging

	Scenario 1	
	Carton Impacts	Hex box Impacts
# of units needed	37,155	2,000,000
Total Energy Use (MJ)	1,813,905	3,134,923
CO_2 equivalent (kg)	118,073	192,118
Mass (kg)	63,676	134,183
% of total impact from corrugated packaging	32.2%	77.8%

The total environmental impacts for all packaging components for each scenario are included in Table 4.20. Scenario 6 has the fewest impacts due to the fact that the scope of scenario 6 is that all PBL products are packaged in a polybag. Scenario 6 was used as an extreme example in this research to show the maximum impact reduction potential. The result of the LCA impact calculations show that by eliminating the hex box packaging and instead packaging PBL styles in polybags, it is possible to reduce energy use and CO_2 equivalents from packaging by 62% relative to Scenario 1. Scenarios 3 and 4 have the fewest impacts out of the scenarios that include hex box packaging due to the fact that their scopes require the fewest PBL products to be packaged in hex box packaging. Scenario 3 is based on limiting hex box packaging distribution to Europe and Japan, which together make up 15% of Patagonia's total PBL units sold. Scenario 4 is based on the idea of packaging only LW and DW PBL products in hex box packaging. That scope reduced the need for hex box packaging from 2,000,000 units to 645,282 hex box units. If Patagonia were to switch to a packaging solution that mirrored the scope of Scenario 3, it could reduce its impacts by 54%.

Table 4.20 LCA impacts of packaging required for each scenario. The chart includes both the total impacts as well as the impacts per packaging unit for each scenario.

	Scenario 1 Total Packaging Impacts	**Scenario 2 Total Packaging Impacts**	**Scenario 3 Total Packaging Impacts**	**Scenario 4 Total Packaging Impacts**	**Scenario 5 Total Packaging Impacts**	**Scenario 6 Total Packaging Impacts**
# of polybag units needed	0	800,000	1,700,000	1,354,718	645,282	2,000,000
16x18x18 corrugated box (for products packaged in polybags)	0	13,333	28,333	22,579	10,755	0
# of hex box units needed	2,000,000	1,200,000	300,000	645,282	1,354,718	0
# of 18.5x 24.5x 16.5 corrugated box (for products packaged in hex boxes)	37,155	22,293	5,573	8,284	28,871	0
# of Liner Polybags needed	37,155	22,293	5,573	8,284	28,871	0

Total Energy Use (MJ)	5,334,703	4,059,232	2,624,328	2,710,689	4,770,022	2,146,015
CO_2 equivalent (kg)	330,407	248,949	157,308	163,674	293,493	126,760
Mass (kg)	202,243	141,985	74,195	82,933	170,908	51,598
MJ per unit	2.6674	2.0296	1.3122	1.3553	2.3850	1.0730
CO_2 emissions (kg) per unit	0.1652	0.1245	0.0787	0.0818	0.1467	0.0634

Due to the materials used and the weight of the two packaging options evaluated, it was fairly obvious from the start that the lighter polybag packaging solution would have lower environmental impacts than the hex box packaging solution. The life cycle comparison of the packaging products, however, is not the ultimate goal of this research. Part 1 of this research was considered a building block to use in the logistics assessment in Part 2. Quantification of life cycle impacts were necessary as an input to Part 2 of the research, where trade-offs between increased logistics complexity and reduced impacts from adopting a hybrid of the two packaging solutions were addressed.

The last step in the LCA section of this research was to compare both packaging solutions to the environmental impacts of an average PBL product. The comparison of the product impacts to the packaging impacts focused on comparing the manufacturing and transport life cycle stages. This portion of the research was completed in order to provide a benchmark of the percentage that packaging represents with respect to the total emissions of the PBL product.

There are several different styles of PBL products and several different size hex box packaging solutions. The Men's MW bottoms were chosen as the product for this comparison. In Table 4.21 below, the weight of the Men's MW bottoms are compared to the weight of the 10" hex box and the polybag. The 10" box was singled out, as it is the typical size hex box that the Men's MW bottoms are shipped in. It is important to remember that the environmental impacts of shipping have been factored into the PBL product environmental impact calculations. With this in mind, Table 4.22 shows the environmental impacts of the Men's MW bottoms compared to the per unit impacts for Scenario 1 and Scenario 6 that were identified in Table 4.21. Scenario 1 and Scenario 6 were chosen for this comparison in order to show how the full packaging product system impacts (manufacturing and transport) for the polybag packaging (Scenario 6) and the hex box packaging (Scenario 1) compare to the full apparel product system impacts (manufacturing and transport).

Table 4.21 Weight of packaging and the Men's Medium MW bottoms

	1 MW Men's Bottoms	1 polybag	Polybag weight as a % of the product weight	10" hex box + paper wrap	10" hex box weight as a % of the product weight
Mass (kg)	0.193	0.006	3.11%	0.079	4%

Table 4.22 Environmental impacts for individual units of the polybag, hex box and the Men's Medium MW bottoms. Energy use and CO_2 equivalents data were collected for each type of packaging and for the MW bottoms.

	1 MW Men's Bottoms	Scenario 1 Total Packaging Impacts	Scenario 1 impacts as a % of product impacts	Scenario 6 Total Packaging Impacts	Scenario 6 impacts as a % of product impacts
MJ per unit	66	2.6674	4%	1.0730	1.6%
CO_2 emissions (kg) per unit	3	0.1652	5.5%	0.0634	2.1%

Part 2: Operational Analysis Results

The intention of the operational analysis was to determine if there were opportunities to minimize the environmental impacts that result from transporting Patagonia's PBL hex box packaging through the various transportation stages required to move products from the manufacturing facility to DC and, finally, to a retail location. Four main legs of transportation were included in the transportation evaluation: transport via truck from manufacturing facility to port, transport via boat from the port in the region of manufacture to Patagonia's regional port, transport via truck from the regional port to regional DC, and transport via truck from regional DC to sales location. The distances between each location for each leg of the trip were measured in order to calculate the energy and CO_2 equivalents that result from transporting packaging in Patagonia's logistics system.

Table 4.23 shows the total distance required to transport products by truck in the US, Europe, and Japan. The US transport system has nearly 4 times more truck miles between DC and customer than the Europe distribution system and 5 times more truck miles between DC and customer than the Japan distribution system.

Table 4.23 Total truck miles within Patagonia's sales regions required to get Patagonia PBL products from regional port to final retail location.

Region	Mode	Port to DC	DC to Retail Location	Total Truck Miles
US	Truck	370	3082	3452
Europe	Truck	130	800	930
Japan	Truck	50	595	645

Although the Japan distribution and sales region has the fewest truck miles that need to be traveled to get to the average retail location, it has the greatest distances between PBL product manufacturing facilities and the port nearest Patagonia's Tokyo DC. This is due to the fact that three of the manufacturing facilities for PBL products are located in the Americas region.

Table 4.24 Total distances between each manufacturing location and the ports near Patagonia's Regional DCs. In this analysis it was assumed that the mode for these legs of transport were by boat.

Region	Mode	Vendor A Valle del Cauca, Columbia	Vendor B San Salvador, El Salvador	Vendor C Matamoros, Mexico	Vendor D Nugegoda, Sri Lanka	Total Ship Miles
US	Boat	6303	4827	9000	16540	36670
Europe	Boat	9750	10600	9600	12605	42555
Japan	Boat	14400	12700	17100	8300	52500

The results in Table 4.25 show the total shipping impacts for each scenario. The table includes the total energy use and CO_2 equivalents as well as the energy and CO_2 equivalents on a per unit basis. Again, Scenario 6 has the fewest impacts out of all six scenarios, and Scenario 3 had the fewest impacts out of the scenarios that included the hex box packaging. These results fall in alignment with the results from the LCA portion of this research.

Table 4.25 Total impacts from shipping all packaging products for each scenario

	Scenario 1 Total Shipping Impacts	Scenario 2 Total Shipping Impacts	Scenario 3 Total Shipping Impacts	Scenario 4 Total Shipping Impacts	Scenario 5 Total Shipping Impacts	Scenario 6 Total Shipping Impacts
# of polybag units needed	0	800,000	1,700,000	1,354,718	645,282	2,000,000
# of hex box units needed	2,000,000	1,200,000	300,000	645,282	1,354,718	0
Total Energy Use (MJ)	1,292,233	924,932	412,394	569,332	1,058,747	384,693

CO_2 equivalent (kg)	84,181	60,230	27,329	39,466	62,290	24,805
Mass (kg)	202,241	141,984	74,195	82,933	170,906	51,599
Metric ton -km	2,463,504	2,285,044	951,977	1,254,169	1,878,314	699,146
MJ per unit	0.645	0.508	0.206	0.285	0.529	0.1923
GHG (kg CO_2 equiv per unit)	0.042	0.033	0.014	0.020	0.031	0.0124

In order to ensure that the results shown in Table 4.25 reflected the opportunities in the operational system to minimize impacts, an additional analysis was completed that only considered the scenarios that included shipping hex boxes. The polybag component was eliminated to see if a side-by-side comparison of the impacts from transporting just hex boxes in the different operational scenarios would change the results. As each scenario is based on a different number of hex boxes being shipped, the unit impacts for each scenario were calculated and compared instead of the totals. Scenarios 3 and 4 result in the fewest impacts per unit. Scenarios 1 and 2 have the highest energy use and the same energy and CO_2 equivalents per unit due to the fact that Scenario 2 had no change in the manufacturing and distribution systems and had only a smaller percentage of products packed in a hex box. These variations in the order of which scenarios have the greatest impacts indicate that adjustments to the operational system do have the potential to increase or decrease the environmental impacts of Patagonia's logistics system.

Table 4.26 Evaluations of unit impacts from the transport of the hex box only.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
# of hex box units needed	2,000,000	1,200,000	300,000	645,282	1,354,718
Energy use (MJ)	1,292,233	775,340	102,446	357,536	934,698

CO_2 equivalents (kg)	84,181	50,509	7,194	23,629	53,611
Energy use per unit (MJ)	0.646	0.646	0.341	0.554	0.690
CO_2 equivalents per unit (kg)	0.0421	0.0421	0.024	0.037	0.040

After seeing the total impacts from the transportation of 2,000,000 packaging units, shown in Table 4.25, it is apparent that the weight of the product is the driving factor for the impact results. Table 4.26, however, took a close look at the various adjustments proposed in the five scenarios that include hex box packaging to determine if there were further findings from this research that could inform Patagonia's efforts to minimize impacts. Patagonia's transportation network is quite diverse, and the results shown in Table 4.26 indicate that by adjusting distribution locations to only include Europe and Japan, in the case of Scenario 3, or by adjusting which PBL products are packaged in the hex box, there are opportunities to minimize impacts resulting from transportation.

In order to gain a greater understanding into where the main impacts in the logistics system are, the impacts from each leg of transportation were evaluated to determine which transportation leg results in the greatest energy use and CO_2 equivalents. Percentages were calculated based on moving 1 metric ton of material 1 kilometer. The transportation impacts within the US, traveling between the US Reno DC and the US average distance customer, have the greatest energy use and CO_2 equivalents, making up 34% and 31%, respectively. The boat distances traveled from manufacturing facility to regional port in Japan and Europe have the second and third greatest impacts, respectively. The port-to-port transportation from manufacturing facilities to regional Japan port makes up 17% of the total shipping energy use and 19% of the total CO_2 equivalents. The port-to-port transportation from manufacturing facilities to regional Europe port makes up 13% of the energy use and 15% of the CO_2 equivalents. This information can be used to identify why certain adjustments to the transportation system would result in the greatest impact reductions. Table 4.27 shows the energy use and CO_2 equivalents that result from each leg of transportation.

Table 4.27 Each leg of transportation for each region was evaluated to determine which one results in the greatest Energy use and CO_2 emissions for the entire PBL logistics network. The percentages in the Energy Use and CO_2 emissions columns show the % that each individual transportation leg makes up of the total shipping network, including all manufacturing facilities and all three Patagonia distribution regions.

Region	Transportation leg	Energy Use	CO_2 equivalent
US	Manufacturing location to port (truck)	0.86%	0.79%
	Port to port (boat)	11.54%	12.97%
	Regional port to DC (truck)	4.12%	3.76%
	DC to average distance customer (truck)	34.31%	31.29%
Europe	Manufacturing location to port (truck)	0.86%	0.79%
	Port to port (boat)	13.39%	15.06%
	Regional port to DC (truck)	1.45%	1.32%
	DC to average distance customer (truck)	8.90%	8.12%
Japan	Manufacturing location to port (truck)	0.86%	0.79%
	Port to port (boat)	16.52%	18.58%
	Regional port to DC (truck)	0.56%	0.51%
	DC to average distance customer (truck)	6.62%	6.04%

Cumulative Impacts

The last step of the analysis was to total the packaging LCA and operational analysis impacts to determine the total impacts due to packaging for each scenario. Energy and CO_2 equivalents were the only two impact categories that could be totaled due to the fact that the transportation analysis only included measurements of energy use and CO_2 emissions.

Table 4.28 shows the total environmental impacts of each packaging scenario. Each scenario accounts for 2,000,000 individual units of product packaging as well as the transport packaging. The table includes total impacts as well as per unit impacts for each scenario. When evaluating environmental impacts in terms of overall energy and CO_2 equivalents from transport and life cycle impacts, the polybag-only scenario (Scenario 6) results in 62% less energy use and CO_2 emissions than using the hex box packaging solution. Scenario 3 has the lowest impacts of the scenarios that include the use of hex box packaging. This result was expected, as Scenario 3 had the lowest impacts in both the product LCA data results and the operational analysis data results.

Table 4.28 Total environmental impacts of each packaging scenario. The totals include the packaging LCA impacts and the operational impacts from transporting the packaging materials. Each scenario accounts for 2,000,000 individual units of product packaging as well as the transport packaging.

	Total impacts of Scenario 1	Total Impacts of Scenario 2	Total Impacts of Scenario 3	Total Impacts of Scenario 4	Total Impacts of Scenario 5	Total Impacts of Scenario 6
# of polybag units needed	0	800,000	1,700,000	1,354,718	645,282	2,000,000
# of hex box units needed	2,000,000	1,200,000	300,000	645,282	1,354,718	0
Total Energy Use (MJ)	6,626,936	5,138,042	3,071,518	3,307,749	5,841,977	2,530,708
CO2 equivalent (kg)	414,588	319,100	186,868	204,918	356,630	151,564
Mass (kg)	202,241	141,984	74,195	82,933	170,906	51,599
MJ per unit	3.313	2.569	1.536	1.654	2.921	1.265
CO2 emissions (kg) per unit	0.207	0.160	0.093	0.102	0.178	0.076

On average, the environmental impacts that resulted from transporting the packaging materials from manufacturer through to retail location made up 18% of the total impacts. The following figures show the energy use (Figure 4.9) and CO_2 equivalents (Figure 4.10) from transportation make up between 13% and 20% of the total impacts depending on the scenario being evaluated.

Figure 4.9 Transportation energy use as a % of the total packaging energy impacts

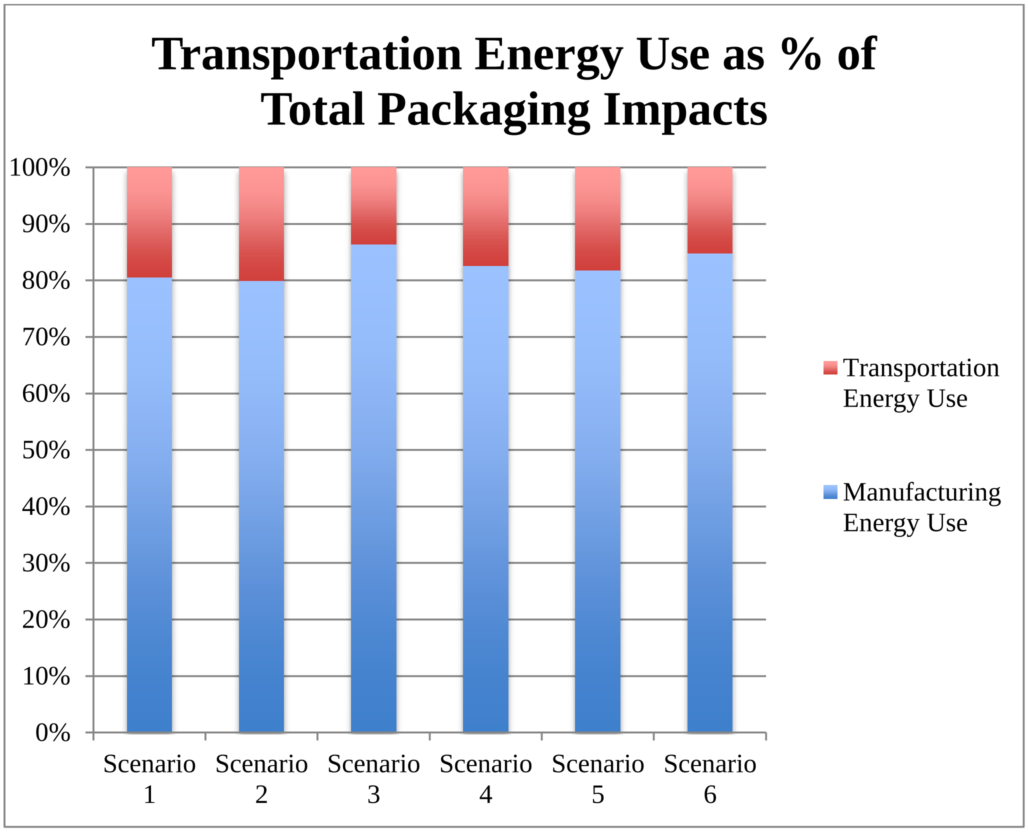
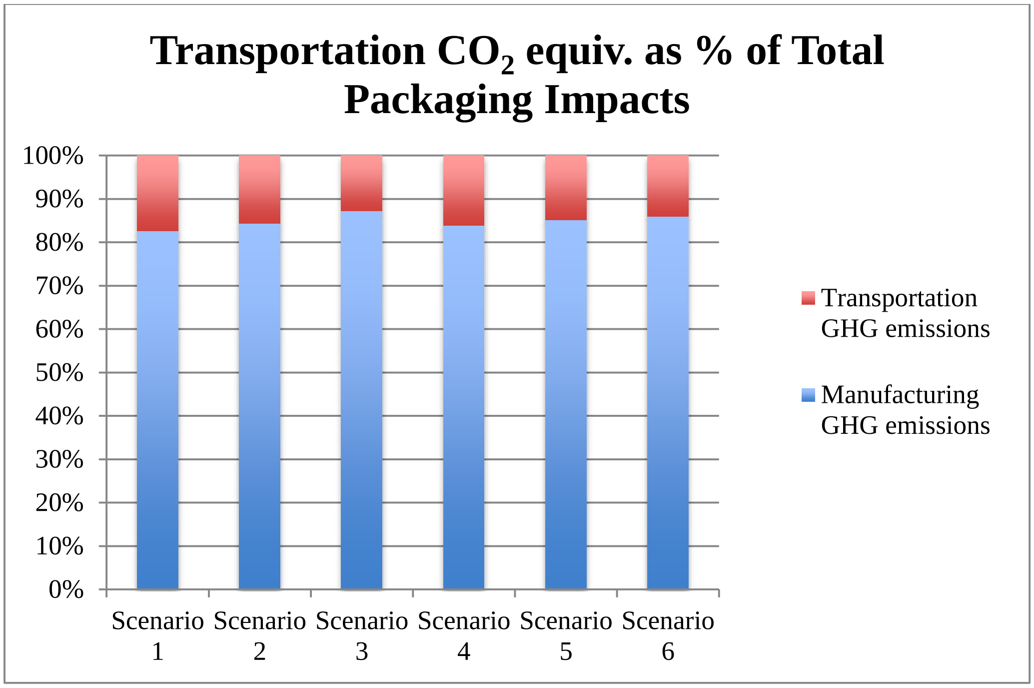


Figure 4.10 Transportation CO_2 equivalents as a % of the total packaging CO_2 impacts



Conclusions and Recommendations

This project combines life cycle assessment and logistics operation details, two areas of research that aren't typically integrated, to evaluate the environmental impacts of product packaging for Patagonia's PBL products. It required a variety of primary and secondary data inputs and provided insight into potential opportunities to minimize environmental impacts.

Overall, life cycle assessment is a very useful tool to quantify the environmental impacts of a product system. The life cycle assessment data was used to provide context for the environmental impacts of the packaging materials. This research clearly showed that the packaging impacts were minimal in comparison to the apparel product system impacts. The comparison showed that at most, packaging impacts are 5% of the product system impacts. These findings provide strong evidence that Patagonia has the greatest potential for impact reduction by focusing on minimizing the impacts of the apparel product system. That said, this research includes a comprehensive analysis of the cumulative impacts of one year's worth of Patagonia's PBL packaging impacts. These findings indicate that, although minimal in comparison to the impact of the product, the cumulative impacts from the packaging system are substantial and worth reviewing to find opportunities to minimize impacts.

The life cycle evaluation that focused specifically on the packaging impacts clearly showed that the polybag packaging solution was the least impactful when compared to the hex box packaging solution. These results were not surprising. The fact that the LCA results lined up with the results of operational analysis indicate that weight, which is a key component of both impact assessments, is an influential factor in causing both life cycle impacts and impacts from transportation. The manufacturing of corrugated boxes requires more material per product in their manufacture than the polybag. The hex box packaging solution ranges from 6.6 times greater (for the 4" hex box option) to 16 times (for the 12" hex box) the weight of the polybag. These aspects result in greater energy use and CO_2 equivalents in both manufacturing and transport of packaging products through a distribution system. With this in mind, finding opportunities to minimize the use of the hex box packaging will ensure environmental impact reductions.

This study explored a number of opportunities to adjust Patagonia's PBL product operational system in order to minimize the need for hex box packaging. The suggested adjustments to the operational system revealed that some actions have a larger reduction potential than others.

Of the options that factored in use of the hex box packaging scenario, Scenario 3 proved to have the greatest impact reductions. The reasons for this were two-fold. First, Scenario 3 considered that only PBL products sold in Europe and Japan would be packaged in the hex box packaging solution. Of Patagonia's total PBL sales, 15% are sold in Europe and Japan. This resulted in the lowest number of PBL products packaged in hex boxes out of the six scenarios. The hex box packaging had the greatest life cycle impacts, and the average weight of the hex box packaging solutions are approximately 10 times more than the polybag packaging scenario. Scenario 3, therefore, has the fewest impacts from both the life cycle of the packaging products and from transporting the products themselves because of the minimal need for hex box packaging. Second, it was found that the US transport system has nearly 4 times more truck miles between DC and customer than the Europe distribution system and 5 times more truck miles between DC and customer than the Japan distribution system. The truck transport is 89% less efficient than the transport by boat. The heavier hex box packaging option was shipped to the two regions with the least truck transport miles required to get to customers. Scenario 3 also eliminated the need to ship the hex boxes in the US transport leg from DC to customer, which has the greatest environmental impacts of all the transport legs. Due to these factors, Scenario 3 had 54% less energy use and 55% fewer CO_2 emissions than the results of Scenario 1, which reflects Patagonia's current packaging and operational system.

The findings from operational analysis completed in this research is in alignment with past research, which has indicated that product transport most often makes up only a small portion of the overall product life cycle impacts. Heller and Keoleian (2000) estimate that diesel fuel use accounts for 25% of the total energy consumed within the U.S. food system. These results account for the weight of the actual product being shipped, but are reflective of the findings from this operational analysis.

The impacts from transport were approximately 1/5 the impacts from the total packaging product system and the theoretical adjustments made to the existing logistics system did not prove to have the ability to substantially reduce environmental impacts calculated in the operational analysis. Despite this, there is still important information that was gained from the analysis. Truck transportation between the US DC and the US retail location was by far the greatest impact in the entire Patagonia distribution network. With regards to the Japan-specific distribution network, the boat transport from manufacturing location to Tokyo port resulted in the greatest energy use and CO_2 equivalents. These pieces of information can be used by Patagonia to adjust certain transportation legs to try to minimize impacts. For example, if Patagonia looks at only distributing products in hex boxes in Japan, then it may also want to examine the opportunity to only package LW or DW PBL products in hex boxes. The logic behind this is that the greatest transport distances in Patagonia's logistics system are between manufacturing facility and Tokyo port due to the fact that three of the manufacturing facilities for PBL products are located in the Americas region. The LW and DW PBL products, however, are manufactured in Sri Lanka, reducing the boat transport distance by more than 50%.

The aim of this study was to explore if there are further ways of reducing the impact without changing the existing packaging material selection. Our conclusion is that there are feasible ways to minimize environmental impacts by making adjustments to the type of packaging used in different regions and sales channels.

Prior to proposing recommendations, it should be noted that the data presented in this report is subject to large uncertainties. This is partly a consequence of conducting the LCA calculations on the basis of openly available data sources. There is an inherent uncertainty with all the data inputs and even more uncertainty due to comparing the results of two independent LCA sources, Chaffee and Yaros (2007) and Paper Calculator (2014). A further reason for the uncertainties is the nature of any product and logistics system characterized by diverse and often changing practices.

One substantial assumption made in this research was that the average distances to retail locations represented the actual transport distances annually. The transport distances calculated took into consideration point A to point B shipments. Most often freight routes have the opportunity for much variability. The average distances used in this study could be either an overestimation or an underestimation. More detailed shipping data would need to be accessed and evaluated to determine if the average distances used in this research are an accurate representation of the actual truck distances Patagonia products travel to get to regional retail locations.

Recommendations

The objective of this research was to develop recommendations for reducing Patagonia's environmental impacts that result from PBL packaging and transporting the packaging in Patagonia's operational system. The improvement actions with the greatest reduction in energy use and CO_2 equivalents are, again, minimizing the weight of packaging and energy used to make the packaging products and reducing truck transport. More specifically, Patagonia has the opportunity to minimize the environmental impacts of its PBL packaging by utilizing this research and reevaluating its packaging needs. The two scenarios with the greatest impact reductions were Scenario 3 and Scenario 4.

Scenario 3 was scoped to meet the cultural demand for packaging. European and Japanese customers prefer that their PBL products be packaged to ensure that few people are touching their garments. US customers do not have the same expectations for packaging around their PBL products as European and Japanese customers. These customer preferences were taken into account when creating Scenario 3. This scope not only addressed the European and Japanese customer's demand for product packaging, it also tremendously reduced the number of hex boxes needed to package PBL products, as Europe and Japan sales make up just 15% of Patagonia's total sales. In addition, it resulted in minimizing the weight of PBL shipments being transported from the US Distribution Center to US sales locations, which was the leg of truck transport in the logistics system that resulted in the greatest energy use and CO_2 equivalents.

If Patagonia were to switch to a packaging solution that mirrored the scope of Scenario 3, it could reduce its impacts by 54% in comparison to the impacts of Scope 1. The 54% reduction is equivalent to approximately 2.7 million MJ of energy saved. In 2014, the average annual electricity consumption for a U.S. residential utility customer was 141,678 MJ (EIA 2015). The amount of energy saved in one year by Patagonia reducing its hex box packaging is enough energy to power 1 US house for 19 years or 19 US houses for 1 year.

The drawback to recommending implementing Scenario 3 is that it would likely create additional complexities at the garment manufacturing factory due to the fact that some products being made will be shipped to Europe and Japan and will need to be packaged in a hex box, whereas others, destined for the US, would be packaged in a polybag. This recommendation to use different packaging for the same product made in the same factory goes against the basic concept of standardization and has the potential to create unintended inefficiencies and errors. For example, the added complexities of using two different packaging types in one factory may increase the likelihood that products are incorrectly packaged. That said, this recommendation is a potentially feasible option and the complexities can be addressed through clear communication between Patagonia and the manufacturing vendors. If the primary need for packaging is to meet the preferences in the Europe and Japan regions, it would make sense for Patagonia to consider using the hex box packaging in only Europe and Japan.

The scope of Scenario 4 included only packaging Patagonia's Light Weight (LW) and Daily Weight (DW) PBL garments. The scope of this scenario meant that only 32% of the total PBL products would be packaged in hex boxes. The LW and DW PBL products are made using the thinnest fabric and are packaged in the 4", 6" and 10" hex boxes. The largest and heaviest 12" hex boxes are not used for LW and DW styles. In addition, manufacturing the LW and DW PBL products takes place only in Sri Lanka. Scoping Patagonia's PBL packaging needs to LW and DW styles only eliminated the need to ship hex boxes from manufacturing locations in Columbia, El Salvador, and Mexico. In this scenario, all the PBL products made in one manufacturing location would be packaged in the hex box. The remaining three manufacturing locations would then not need to use the hex box packaging. This would be an easy change to make within Patagonia's internal operations. In addition, it would not create any added complexities at the garment manufacturing locations due to the fact that it will allow for all of the same type of products to be packaged the same way and would allow for standardization of packaging type within each of the PBL factories.

Sales and finances drive decisions in most corporations. Patagonia, like any other business, will evaluate decisions to ensure that they make financial sense. By evaluating regional sales data from both Patagonia sales locations and wholesale locations alongside the results of this research, Patagonia would be able to make a very informed decision on how best to package the PBL products. In addition, conducting customer surveys regarding their preference for the hex box packaging could provide valuable added insight and should be considered prior to making any changes to Patagonia's current PBL packaging system. It is important to understand where and why products packaged in the hex box packaging solution currently sell well and where and why they don't. Once that information has been evaluated, it will be possible to determine if the recommendation to implement Scenario 3 or Scenario 4 from this assessment lines up with customer preferences.

Patagonia may find that Scenario 3 and/or Scenario 4 prove to be viable solutions that meet sales needs and minimize the need for the hex box packaging solution. Ultimately, however, it should be acknowledged that all the results showed that Scenario 6, which entailed packaging all PBL products in the polybag packaging solution, results in the fewest environmental impacts. Approximately 82% of the total environmental impacts calculated in this research resulted from the manufacturing, processing, and end of use life cycle stages of packaging materials. By eliminating the hex box packaging, not only are the life cycle impacts of the hex box avoided, but the energy used in transporting the product packaging decreases by 30% and the CO_2 equivalents that result from transporting the products decrease by 36% in comparison to Scenario 1.

The result of this research will be used to provide insight to Patagonia on opportunities to minimize the environmental impacts of the hex box packaging solution. Although the findings from this research were fairly obvious, the impacts from packaging are often overlooked. This study provided quantifiable data that can be used by Patagonia to understand the overall impacts from packaging and how significant the impact reductions can be by adjusting the regions or the styles that require hex box packaging.

In addition, these results can be used to inform the decisions of other apparel brands and the broader corporate sector. Packaging is a factor in most industries. This research shows that if packaging preferences differ between markets, it can be worthwhile using different packages for different markets, as the environmental savings have the potential to be substantial. The research also provides a way of comparing different types of scenarios, where different packaging options can be used for different regional markets, different vendors, and/or different sales channels. As other brands work to address their own use of packaging, the data generated in this research will help to guide informed decision-making across any industry that relies on packaging to protect and market their products.

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Chapter 5: Conclusions

Across industries, companies make difficult decisions about how to source materials, manufacture products, and ship them around the world to be sold. Most often, these decisions are driven by economic factors alone. More and more, however, industries are looking for ways to reduce environmental impacts from the goods and services they make. In order to make decisions that result in reducing environmental impacts, it is important to understand the cause of the impacts. Life Cycle Analysis (LCA) is one tool that can be used to provide an environmental assessment of goods and services.

In addition to being used as a tool for decision-making aimed at improving environmental performance of products and supply chains, the use of LCA for policy-making in both industry and the public sector is continuously increasing (Manda 2014). With this in mind, it is important that LCA is developed further to enhance its applicability and reliability as a methodology for the textile industry (Roos et al. 2015).

This purpose of this research was to investigate different ways of approaching LCA that could be useful in the corporate sector. The hope was to find efficient, affordable, and reliable ways to gather product-specific LCA information.

Insights gained from the research

The three objectives of this research were aimed at addressing different opportunities and challenges to gathering LCA data. The purpose of Objective 1 was to review the existing LCA research focused on the textile and apparel industry to determine if the data available could be used by brands and manufacturers to quantify the environmental impacts of their own products and processes. The hope was that by conducting a systematic review focused on LCAs in the textile and apparel industry, this research could provide the industry with valuable data that could be both easily understood and easily used by companies.

The goal of Objective 2 was to determine if a collaborative approach to gathering life cycle data and completing a LCA for a product system could produce credible results. The concept of a collaborative approach refers to the idea that industry partners, which each play a role in producing a single product, gather data specific to the processes that they control, own, or operate and share that data with the other businesses involved in the manufacturing of the product. The hope is that sharing data across the supply chain will stimulate an open discussion between companies, consultants, and suppliers about how best to manage environmental impacts. Ultimately, such data sharing has the potential to increase the amount of LCA data that is publicly available, giving more brands and supply chain partners access to environmental impact data.

The research in Objective 3 shifted away from a focus on textiles and instead addressed the role of packaging in the apparel industry. The research proposed that adding an evaluation of logistics systems to an overall quantification of environmental impacts would provide added insight into the true environmental impacts of packaging used for apparel products. The findings from Objective 1 indicated that there is a substantial amount of existing LCA data. With that in mind, existing LCA data was used to quantify and compare the environmental impacts of two different apparel-packaging options. Patagonia’s logistics systems were then evaluated to determine if there were opportunities to change Patagonia’s current approach to performance baselayer (PBL) product packaging in order to minimize environmental impacts. The research provided an example to the larger LCA community on how LCA data and existing logistics systems information could be used together to determine operational adjustments that have the greatest potential to result in environmental impact reductions.

The data gathering, literature reviews, and analysis completed for each of the three objectives resulted in three main takeaways that support the idea that LCA is resource that can be used in a variety of ways by both academia and the corporate sector to determine quantifiable environmental impacts.

First, there is an opportunity to be resourceful when gathering LCA data. LCA is a growing area of research and there is a tremendous amount of work being done to improve the science of LCA. In addition, there is a substantial amount of data that has already been collected and shared via peer-reviewed publications, databases, and industry research. Publically available data is truly valuable, and academics and industry professionals can utilize this existing data to evaluate their own products and processes.

The early apparel LCAs often used specific products as the functional unit of the assessment and therefore resulted in inventory data that was reported by unit of product. Many of the assessments that used a product as the functional unit included the impacts from consumer use and washing. Numerous assumptions are made for the consumer use life cycle stage that can reduce accuracy, comparability, and usability of the LCA. The more current textile and apparel LCAs have more consistently used a functional unit based on a standard measurement of the weight or yardage of material for each process being analyzed. This shift in approach shows how the field of LCA has evolved over time. The current approach of evaluating a system by unit process allows for more comparisons across independent LCAs.

Going forward, the hope is that LCAs focused on textiles and apparel will focus on providing process-level environmental impact information in a standard unit of measurement.

Second, a collaborative LCA approach that engages supply chain partners to gather LCA data specific to the processes that they control proved, in this research, to be a potentially effective way to model a product system. Thabrew et al. (2009) proposed that the fundamental concept of life cycle thinking can be effectively used to incorporate stakeholders in the research and decision-making process, which can lead to more comprehensive, yet achievable, life cycle assessments. A collaborative approach to LCA could help to support the theory proposed by Thabrew et al. (2009).

The concept of life cycle thinking can be effectively used to analyze upstream requirements and downstream consequences of decisions while improving collaboration in joint projects (Thabrew et al. 2009). By breaking down the life cycle into a series of sequential phases such as raw material extraction, processing, use phase, and end of life, brands and supply chain partners can potentially provide primary data at all steps of a product's life cycle. This approach to incorporating product-specific data provides an opportunity for supply chain vendors and brands to work more closely together. Not only will such stakeholder involvement help to increase the availability of process-level LCA data, it could also potentially speed up the data gathering steps needed to make informed decisions that reduce environmental impacts in a product system.

Combining inventory data from different sources and prepared by different individuals using different LCA software systems, however, has the potential to result in discrepancies and inconsistencies in data. In order to minimize data discrepancies and inconsistencies, there are four key factors that, if used, can help to ensure successful execution of the collaborative approach to LCA. Failing to think through and agree upon any of these four factors would likely result in inconsistent data points across life cycle process steps that prevent the data from being summed to create an assessment of an entire product system. The factors are:

1. All parties involved should agree upon the methodology that will be used to gather data and conduct the analysis. Functional unit and boundary conditions should be agreed upon before starting a project.
2. Data sharing should happen at the inventory level and should include a relatively complete documentation of background processes included in the data points.
3. The impact characterization models that will be used in the LCA should be agreed upon from the start of the project. All parties should decide ahead of time which impact characterization models will be used and use those consistently across all life cycle stages. It is recommended to use the most current versions and most widely accepted impact models to ensure the best results.
4. If at all possible, utilize the same LCA practitioner to complete all parts of the LCA. This factor can be a bit more challenging to achieve, but will result in a more consistent and accurate end product.

Third, the use of packaging results in environmental impacts, just like any other product system. Although often overlooked, the resources required, the manufacturing stages to create the packaging, and the transport of packaging can result in substantial environmental impacts. In addition, packaging contributes to waste generation. If the goal for a company is to minimize environmental impacts of packaging, it is recommended that they first investigate ways to eliminate any unnecessary packaging.

If packaging cannot be eliminated entirely, opportunities to reduce environmental impacts within the product system should be investigated. The product manufacturing and processing stages of the life cycle have the greatest potential for substantial improvements. The packaging manufacturing and processing has been shown consistently to have the greatest impacts in a product supply chain. If, however, the company does not have control over the manufacturing and processing in a product system, their opportunities to minimize impacts lie in the operations they do have control or influence over. The example of an area that a company may have control over used in this research is Patagonia's logistics system. Although, as shown in this research and in previous studies, the impacts that result from transportation are less substantial than those from product processing and manufacturing, the logistics system is something that Patagonia has influence over and could make adjustments to minimize environmental impacts.

An additional opportunity for a company to make environmental improvements is to ensure that customer demand and sales data are well understood. Reevaluating customer needs in certain regions may provide added insight that allow for reduction or even elimination of packaging in certain regions or on certain products.

<u>Limitations of this research and LCA results in general</u>

It is important to note that the data and results presented in this report are subject to large uncertainties. This is partly a consequence of conducting much of the analysis on the basis of openly available data and voluntary contributions of supply chain partners. A further reason for the large uncertainties is the nature of the textile sector in general, which is characterized by very diverse products and practices, each with their own unique causes of environmental impacts. Last, it is due to the inherent uncertainties that exist within the field of LCA.

There are established uncertainties and ambiguities within the field of LCA that can limit its utility as a scientific tool. These shortcomings apply to the field of LCA as a whole, not to any specific method or study. It is therefore important to acknowledge that results from LCA studies should be regarded as having a high uncertainty in all cases. One of the key challenges in LCA is solving the “it depends” problem. A typical LCA study starts with the question, “What is the environmentally preferable choice?” The answer to that question is almost always “it depends”: it depends on the framing of the question, the boundaries of the system investigated, and the options available (Lifeset 2012). The reason for each LCA study is to accomplish a specific and likely unique intended purpose. The variations across studies in the methods used, processes and impacts measured, and comparisons made result in substantial uncertainty in the LCA results.

The level of uncertainty in the field of LCA has characterized it as being a tool that is most useful for detecting order of magnitude effects, such as the importance of a specific life cycle stage in overall energy resource demand in a product system. Smaller effects and differences in the models are generally indicative but not conclusive. Additionally, making comparisons between LCAs is challenging and comes with a high level of uncertainty for a number of reasons. The most significant of these reasons is that different organizations and researchers have completed the various textile and apparel LCAs. Each of these LCAs likely to have used different methods and boundary conditions, LCA software systems, and environmental impact characterization factors in their product or process assessments.

In addition to inconsistencies in the approach taken to completing LCAs, the field has not developed a thorough mechanism for critical review and quality validation of the data used in LCA software systems and databases. If data quality validation improves, LCA results will be viewed with more confidence.

The general lack of available chemical use and resulting toxicity data is also a limitation in LCA that is worth noting. Roos et al. (2015) commented that typically research does not report on quantity of chemicals used, whether or not the substances are used in closed systems or otherwise, whether emissions and waste are properly treated, and which substances are used instead of the regulated ones. The absence of such important environmental aspects makes LCA findings much less informative as tools for environmental decision-making.

The significance of chemicals in terms of environmental and health impacts in a life-cycle perspective is a complex equation in which exposure must be considered in addition to chemical effects such as toxicity, acidification, eutrophication, and even greenhouse emissions from the degradation products (van Zelm et al. 2010). It was clear from reviewing the existing LCA studies in Objective 1 of this research that much confusion and uncertainty still remains regarding assessing the toxicity of a substance or process.

Despite these limitations, when calculated and interpreted correctly, LCAs can be a powerful tool for measuring the environmental profile of products and for understanding where the large environmental impacts occur in a product's life cycle. The field of LCA has come a long way in the past two decades and there is still much opportunity for improvement. As the field continues to grow and gain interest, it will only progress further and become a more accurate and useful tool.

<u>Application to the larger apparel and textile industry and to Patagonia</u>

Brands in the apparel industry are continually increasing their commitment to utilizing more environmentally friendly materials. Recently, there has been a shift of emphasis in India cotton from inputs-based farming to environmentally friendly organic cotton farming as a remedial measure. The continued rapid expansion of the global organic cotton market is driven in large measure by consumer interest in 'green' products, significant expansion of the existing organic cotton programs by brands and retailers, and the launch of organic cotton programs by new entrants to the market. For example, a number of brands and retailers are buying organic cotton, including H&M, C&A, Nike, Zara, Anvil Knitwear, prAna, Puma, Williams-Sonoma, Target and Otto Group (Babu and Selvadass 2013). In addition, brands like The North Face have committed to using 100% recycled polyester in their polyester garments by 2016, indicating a growth in the demand and application of recycled polyester.

These preferences for more environmentally friendly materials indicate a level of environmental consideration that is being practiced by these brands and potentially the apparel industry as a whole. With that commitment comes an interest in finding new innovations and existing opportunities to minimize impacts while continuing to provide the types of products their customers demand. LCA is a viable tool that could help identify future environmental reduction opportunities.

In order for LCA to be used as an effective mechanism for educated decision-making within industry, the approach to gathering LCA data and conducting the analysis needs to work within the structure of corporate operations. It is important to recognize that not all companies interested in using LCA have expertise in the subject or even at a moderate level of understanding of the complexities inherent to LCA.

The systematic review in Objective 1 of this research focused on gathering and organizing as much of that information as possible, with the hope that it could be easily used as a resource by the larger apparel and textile industry to foster continued environmental improvements. For those brands that prefer to complete their own LCAs, the three main insights explained in the preceding paragraphs can be used as guidance to help to inform a typical non-expert LCA project manager how to use existing resources to gather LCA data and potentially complete a successful collaborative LCA.

The LCA data that has been gathered and analyzed for this project will be used by Patagonia as foundational environmental impact information on which to build a strategy for reducing environmental impacts in the supply chain. The intention of gathering such LCA information is to use it to identify environmental impact reduction opportunities within the company's operations. In addition, this information will help guide Patagonia's approach to meeting the potential future European Union environmental regulations focused on requiring brands that sell in Europe to measure the life cycle impacts of consumer goods.

Closing Remarks

The work presented here takes a significant step beyond a qualitative review of LCA to provide tangible data and tools that can be used by corporations to develop their own approach to LCA. This research provides both academic (theoretical) findings in regard to the evolution of LCA practices and practical insight that can be applied to the corporate sector. In addition, it contributes very specific information to the LCA community on the ways that companies, specifically in the apparel industry, are using LCA to assess the environmental impacts of products. This project is unique in that an employee of an apparel brand has completed the research using both an academic approach and specific primary data that reflects a company's actual operations. This approach helps to bridge the gap between the academic approach to LCA and use of LCA within industry.

Although this research focused specifically on the apparel industry, the field of LCA has a broader reach and can apply to most other industries and product systems. Corporations have an opportunity to benefit from identifying the environmental impacts in their supply chains. Across industries, process improvements could lower energy and water usage and save operational costs (Worrell et al. 2003). Increased scarcity of raw materials such as water can lead to disruption of operations or lost production activity, which will impact the revenue earning capacity. Such risks can be avoided by sustainability performance improvements in the supply chain (Koplin et al. 2007).

If made available to the broader corporate sector, this research has the potential to increase the use of LCA across industries. Once corporations have a clear and accurate understanding of the environmental impacts of their supply chains and operations, the next step is to develop programs and initiatives that drive environmental impact reductions.

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Appendix A: Initial List of LCA Studies

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
1	Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling	Li Shen, Ernst Worrell, Martin Patel	Resources, Conservation and Recycling	2010	Yes
2	An Environmental Product Declaration of Jeans		ADEME and bio intelligence service	2006	
3	Reference Document on Best Available Techniques for the Textile Industry		European Commission/ Integrated Pollution Prevention and Control (IPPC)	2003	
4	Apparel Industry Life Cycle Carbon Mapping		BSR	2009	
5	Manufacturing focused emissions reductions in footwear production	Lynette Cheah, Natalia Duque Ciceri, Elsa Olivetti, Seiko Matsumura, Dai Forterre, Richard Roth, Randolph Kirchain	Journal of Cleaner Production	2013	Yes
6	CO_2 footprints illustrate the benefit of textile services - Comparing industrial vs domestic laundry		ETSA Europe		
7	The Carbon Footprint of a Cotton T-shirt		Continental Clothing Co. Ltd	2009	
8	Life Cycle Assessment for Cultivation of Conventional and Organic Seed Cotton fibres	K Babu, M Selvadass	International Journal of Research in Environmental Science and Technology	2013	Yes

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
9	Life Cycle Assessment of Cotton Fiber and Fabric		Cotton Incorporated	2011	
10	Recycling of Low Grade Clothing Waste		Defra, Oakdene Hollins Ltd, Salvation Army Trading Company Ltd, Nonwovens Innovation & Research Institute Ltd	2006	
11	Mapping of Evidence on Sustainable Development Impacts that Occur in the Life Cycles of Clothing		ERM, Defra	2007	
12	Maximising Reuse and Recycling of UK Clothing and Textiles EV0421		Oakdene Hollins, Defra	2009	
13	Water and Chemical Use in the Textile Dyeing and Finishing Industry		Entec UK Ltd	1997	
14	Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester	Nia Cherrett, John Barrett, Alexandra Clemett, Matthew Chadwick and MJ Chadwick	BioRegional Development Group and WWF Cymru, SEI (Stockholm Environment Institute)	2005	
15	An Approach for the application of the ecological footprint as environmental indicator in the textile sector	M Herva, A Franco, S Ferreiro, A Alvarez, E Roca	Journal of Hazardous Materials	2008	Yes
16	Life cycle energy and GHG emissions of PET recycling: change-oriented effects	Li Shen, Evert Nieuwiaar, Ernst Worrell, Martin K Patel	International Journal of Life Cycle Assessment	2011	Yes

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
17	Life cycle analysis of a T-shirt	Francesc Colom Alcover	ENSISA, UHA	2011	
18	Quantification of environmental impact and ecological sustainability for textile fibres	Subramanian Senthilkannan Muthu, Y. Li, JY Hu, PY Mok	Ecological Indicators	2011	Yes
19	Environmental Improvement Potential of Textiles (IMPRO-Textiles)	Adrien Beton, Debora Dias, Laura Farrant, Thomas Gibon, et al	JRC Scientific and Technical Reports, Bio Intelligence Service, European Comission, Ensait		
20	LCA of Clothes Washing Option for City West Water's Residential Customers		EPA Victoria and City West Water	2010	
21	Environmental assessment of textiles	Soren Laursen and John Hansen, Hans Knudsen and Henrik Wenzel, Henrik Larsen, Frans Kristensen	EPIDEX	2007	

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
22	Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer containers and packaging	Franklin Associates	The Plastics Division of the American Chemistry Council Inc., The Association of Postconsumer Plastic Recyclers (APR), The National Association for PET Container Resources (NAPCOR), and the PET Resin Association (PETRA)	2010	
23	Life Cycle Assessment of raw materials for non-wood pulp mill: Hemp and Flax	S. Gonzalez-Garcia, A Hospido, G. Feijoo, M.T. Moreira	Resources, Conservation and Recycling	2010	Yes
24	Life cycle assessment of a GORE branded waterproof, windproof and breathable jacket		W.L. Gore and Associates	2013	
25	LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastine	Natascha M. Van Der Velden, Martin K. Patel, Joost G. Vogtlander	International Journal of Life Cycle Assessment	2012	
26	Life cycle assessment Environmental Profile of Cotton and Polyester-Cotton Fabrics	Eija M. Kalliala, and Pertti Nousiainen	AUTEX Research Journal	1999	Yes

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
27	The life cycle assessment of clothes washing options for city west water's residential customers	Melanie Koerner, Matthias Schulz, Sally Powell, and Mae Ercolani	ARUP, Sydney Sustainability Assessment Program, Water Research Center, UNSW, Sydney City West Water, Service and Sustainability, Melbourne Service Growth Unit, EPA Victoria		
28	Life cycle analysis of a polyester garment	G.G. Smith, R.H. Barker	Resources, Conservation and Recycling	1995	Yes
29	Life Cycle Analysis and Sustainability Report - Levi LCA	Scott Camp, Gordon Clark, Laura Duane & Aaron Haight	Levi Strauss	2010	
30	Dissertation: Bio-based and Recycled Polymers for Cleaner Production: An assessment of plastics and fibers		Li Shen - Utrecht University	2011	
31	Streamlined Life Cycle Assessment of Two Marks&Spencer Apparel Products	Environmental Resource Management, Michael Collins, Simon Aumonier	Marks and Spencer	2001	
32	Made-by Environmental Benchmark for Fibres	Mike Brown, Eric Wilmanns	Made-by, Brown & Wilmans	2013	
33	The Linen Shirt Eco-Profile		Masters of Linen and Bio Intelligence Service		

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
34	Review of Life Cycle Assessments of Clothing	Dr. Adrian Chapman, Oakdene Hollins Research and Consulting	Mistra - The Foundation for Strategic Environmental Research	2010	
35	EU Cost Action 628: life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing	Eija Nieminen, Michael Linke, Marion Tobler, Bob Vander Beke	Journal of Cleaner Production	2007	Yes
36	Patagonia's Common Threads Garment Recycling Program: A Detailed Analysis	Elissa Loughman	Patagonia	2005	
37	Environmental impact assessment of man-made cellulose fibres	Li Shen, Ernst Worrell, Martin K. Patel	Resources, Conservation and Recycling	2010	Yes
38	Environmental Assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics	N.Terinte, BMK Manda, J. Taylor, K.C. Schuster, M.K. Patel	Journal of Cleaner Production	2014	Yes
39	A spatially explicit life cycle inventory of the global textile chain	J. Steinberger, Damien Friot, Olivier Jolliet, Suren Erkman	International Journal of Life Cycle Assessment	2009	Yes
40	The Sustainability of Cotton	Karst Kooistra and Aad Termosrshuizen	Biological Farming Systems, Wageningen University	2006	

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
41	The environmental impacts of the production of hemp and flax textile yarn	Hayo M.G. van der Werf, Lea Turunen	Industrial Crops and Products	2007	Yes
42	Moving down the cause-effect chain of water and land use impacts: An LCA case study of textile fibres	Gustav Sandin, Greg M. Peters, Magdalena Svanstrom	Resources, Conservation and Recycling	2012	Yes
43	Wool in Life Cycle Assessments and Design Tools	Kjersti Kviseth	2025 Design	2011	
44	Energy use pattern of some field crops and vegetable production: Case study for Antalya Region, Turkey	M.Canakci, M.Topakci, I. Akinci, A. Ozmerzi	Energy Conversion and Management	2005	Yes
45	Rationale for integrating a heat and power generating unit in a cotton gin fueled by cotton gin trash	Sergio Capareda, Greg Holt, James Diehold, Calvin Parnell, Robb Walt and Art Lilley	Beltwide	2006	
46	Life Cycle Assessment (LCA) of Organic Cotton		PE International & Textile Exchange	2014	
47	Eco-profiles of the European Plastics Industry Polyamide 6 (Nylon 6)	I Boustead	Plastics Europe	2005	
48	Eco-profiles of the European Plastics Industry Polyamide 66 (Nylon 66)	I Boustead	Plastics Europe	2005	

	Title	Author	Journal/ Organization	Year	Peer Reviewed Journal
49	Energy-Efficiency Improvement Opportunities for the Textile Industry	Ali Hasanbeigi	China Energy Group, Energy Analysis Department, Environmental Energy Technologies Division	2010	
50	Is Unbleached Cotton Better than Bleached? Exploring the Limits of Life-Cycle Assessment in the Textile Sector	Sandra Roos, Stefan Posner, Christina Jonsson, and Greg M. Peters	Clothing and Textiles Research Journal	2015	Yes

Appendix B: Average Transportation Distances
Average US State Distances from Reno DC

State	Weighted Average Distance (miles)
Alabama	2296
Alaska	2487
Arizona	781
Arkansas	1855
California	496
Colorado	1078
Connecticut	2771
Delaware	2659
Florida	2832
Georgia	2444
Idaho	421
Illinois	1915
Indiana	1867
Iowa	1664
Kansas	1579
Kentucky	2128
Louisiana	2079
Maine	3056
Maryland	2599
Massachusetts	2895
Michigan	2168
Minnesota	1926
Mississippi	2110
Missouri	1707
Montana	926
Nebraska	1442
Nevada	366
New Hampshire	2933
New Jersey	2687
New Mexico	1042
New York	2682
North Carolina	2597
North Dakota	1443
Ohio	2210
Oklahoma	1631
Oregon	511
Pennsylvania	2614
Rhode Island	2899

South Carolina	2658
South Dakota	1431
Tennessee	2118
Texas	1806
Utah	533
Vermont	2808
Virginia	2767
Washington	723
West Virginia	2325
Wisconsin	1949
Wyoming	939
Average Distance	3082

Reference: Choe et al. (2013)

Europe Average Distance from Patagonia DC in Heerenberg, Netherlands

Origin	Destination	Distance (km)
Heerenberg, Netherlands	Dublin, Ireland	1050
Heerenberg, Netherlands	San Sebastian, Spain	1380
Heerenberg, Netherlands	Munich, Germany	720
Heerenberg, Netherlands	Milan, Italy	1000
Heerenberg, Netherlands	London, England	590
Heerenberg, Netherlands	Amsterdam, Netherlands	130
Heerenberg, Netherlands	Chamonix, France	1000
Heerenberg, Netherlands	Paris, France	565
Heerenberg, Netherlands	Prague, Czech Republic	780
Average Distance		802

Japan Average Distance from Tokyo DC to Retail Locations

Prefecture	Distance (km) from warehouse (1-4-2 Center-Minami, Misato-shi, Saitama) to other prefectural capitals
Hokkaido	1,327.0
Aomori	681.0
Iwate	508.0
Miyagi	352.0
Akita	577.0
Yamagata	366.0
Fukushima	275.0

Ibaraki	93.3
Tochigi	116.0
Gunma	126.0
Saitama	23.4
Chiba	43.3
Tokyo	29.8
Kanagawa	55.4
Niigata	334.0
Toyama	437.0
Ishikawa	490.0
Fukui	574.0
Yamanashi	155.0
Nagano	244.0
Gihu	428.0
Shizuoka	213.0
Aichi	391.0
Mie	451.0
Shiga	486.0
Kyoto	491.0
Osaka	536.0
Hyogo	565.0
Nara	501.0
Wakayama	597.0
Tottori	694.0
Shimane	805.0
Okayama	696.0
Hiroshima	850.0
Yamaguchi	976.0
Tokushima	680.0
Kagawa	724.0
Ehime	856.0
Kochi	825.0
Fukuoka	1,117.0
Saga	1,181.0
Nagasaki	1,270.0
Kumamoto	1,231.0
Ooita	1,179.0
Miyazaki	1,411.0
Kagoshima	1,402.0
Average Distance	595.0