MASTER

Evaluating the impact of closed loop supply chains on Nike's environmental performance and costs

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Evaluating the impact of closed loop supply chains on Nike's environmental performance and costs

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Abstract

In this master thesis project the impact of closed loop supply chains on environmental performance and costs is assessed. A framework is developed in order to help decision making on closing the loop in Nike's supply chain. This framework is used to assess the environmental and cost impact of several scenarios with different recycling processes and network designs.

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Management Summary

Sustainability is an important part of Nike's business strategy. Sustainable thinking is included in decisions made for the future. One of the sustainable initiatives within Nike is the recycling of apparel, creating a closed loop supply chain. Closed loop supply chains give the opportunity to use more environmental friendly materials, and to use the post-consumer waste created. In order to maximize this possible benefit, this project evaluated the CO_2 emissions, energy use and the cost impact created by transportation and recycling processes in such a closed loop supply chain.

Research Design

The following research question and sub-questions are stated in this project:

How can the impact of closed loop supply chains on environmental performance and costs be determined?

- *How can the environmental performance be determined?*
- *What is the environmental performance of current yarn supply chains?*
- *How can the impact of recycling processes on the environmental and cost impact be demonstrated?*
- *How can a closed loop supply chain network be designed and what is the impact on environmental performance and costs?*

In this project the apparel category of Nike is considered for closed loop recycling. Apparel is made of few materials, often cotton or polyester. The technology for closed loop recycling of these materials is available, and consumers in Europe are used to donate post-consumer clothing. Energy use and CO_2 emissions are taken into account, since they have considerable impact on the environment. These are also acceptable measures in academic papers, so data is more easily available. For the recycling processes, data from academic papers is used, and for transport, the NTM methodology is used to assess the CO_2 emissions and energy use.

A framework is developed for the evaluation of the impacts. In this project, collecting post-consumer apparel, sorting the material based on fiber type and recycling the material into new yarn are the most important processes. All the transportation in between is included. Comparisons are made with the normal production process for polyester, and the end-of-life procedure for collected material, incineration. Objectives are selected for minimizing the energy used, CO_2 emissions and costs.

Results

Based on information from a life cycle analysis of Nike, the environmental impacts of the current production process for cotton and polyester are determined. In an initial scenario, five stores are selected in Western Europe for the collection of post-consumer material. The material is transported to a sorting facility in the Netherlands. Three standard scenarios for polyester recycling are included, mechanical recycling in China, back-to-monomer recycling in Japan and back-to-oligomer recycling in Taiwan. The output is polyester yarn that can be used in the production of new apparel.

In the first assessment it is shown that in all three recycling processes more energy can be recovered and less carbon dioxide emitted than with the incineration of polyester waste. When comparing these recycling methods with the normal production of polyester yarn, they score significantly better on both energy use and CO_2 emissions. Up to 68% of the energy use can be reduced when one kilogram of yarn is produced via mechanical recycling instead of virgin production. The results are dependent on the amount of input needed for the recycling process, to get one unit of output. This yield is initially assumed to be 60% based on previous tests with recycling polyester. With a lower yield, more material need to be collected, sorted and transported. The actual yields of the processes are unknown. However it is unlikely they are low enough to prefer virgin produced yarn instead of recycled yarn based on environmental impacts.

The impact of transport is relatively small compared to the total environmental impact. However abating the impact of transport is still interesting, since it can be realized easy by changing the network design for example. Several options for sorting and recycling locations are assessed in this project. When scenarios are optimized based on energy use and CO_2 emissions for the stores selected in this project, sorting should take place in Switzerland and recycling in Turkey. If costs are minimized, both for the sorting and recycling location India is selected.

Costs for the recycling of yarn are higher than virgin produced yarn in this project. The costs for sorting and transportation have a relative high impact on total cost, compared to the environmental impact created by sorting and transportation. Especially the first transportation move from store to sorting facility is expensive due to the use of 3PL.

Further research

More research is needed on processes for closed loop recycling of apparel. This allows for a better decision on the recycling method that will be used. The yield and output quality in these processes are still uncertain factors. Also the effects on other environmental measures in the closed loop supply chain can be assessed. Another option is the extension of the optimization model used in this project.

Contents

1. Introduction

This document is the report for a master thesis project in Operations Management and Logistics at Eindhoven University of Technology. The master thesis project is made in cooperation with Nike, under supervision of dr. Tarkan Tan from Eindhoven University of Technology and Aad Ramondt of Nike. In this project the impact on environmental performance and costs of closed loop supply chains is studied. A framework is developed in order to assess different scenarios.

In section 1.1 general background information of the research area is given. A description of Nike, the cooperating company is given in section 1.2. Section 1.3 briefly introduces closed loop recycling and the structure of the report is given in section 1.4.

1.1   General background

1.1.1 Research area

Concerns of environmental issues have gained interest by many parties, including universities, governments and companies in recent years. This is due to resource exhaustion and environmental deterioration. Carbon footprints in firms have to be reduced either voluntary or by regulation like the EU ETS. This has led to an increase in operations research on sustainable supply chains. Research is needed to explore the effects of sustainable operations and to provide ways of combining them with regular supply chain management. The first stream of research on green supply chain management has been reviewed by Srivastava (2007) who described the topic as: "integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the customer as well as end-of-life management of the product after its useful life." Another review by Seuring and Müller (2008) define sustainable supply chain management as: "management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainability, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements." Both reviews indicate that existing supply chain management is extended with environmental concerns. Srivastava's (2007) reasons therefore are regulations imposed by governments in order to reduce emissions, the environment worsened by human activities and increasing pressure on companies. Other reviews that show the increase in operations research on sustainable supply chains is done by Corbett and Klassen (2006) and Kleindorfer et al. (2005).

Life Cycle Assessment (LCA) of products is an important aspect of this project and is a specific stream of research within green supply chain management. It can be defined as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product

system throughout its life cycle" (ISO, 1997). An LCA consists of four phases: Goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and Interpretation (Finnveden, 2009). In the first phase the reasons for the study and its boundaries are given, as well as a functional unit which is a qualitative measure to compare goods. LCI is the phase in which data is collected on the involved processes. The LCIA is used to understand and evaluate the environmental impact. In the interpretation phase the results of all previous phases is used to draw conclusion and give recommendations. There are two kinds of LCA, attributional and consequential (Finnveden, 2009). Attributional LCA's are defined as: "focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems" (Finnveden, 2009). Therefore this is mainly to describe the environmental impacts of the entire lifecycle of a product. Consequential LCA's are defined as: "aim to describe how environmentally relevant flows will change in response to possible decisions" (Finnveden, 2009). These are to determine the environmental impacts of a change in the system.

In closed loop supply chains the process of taking back products from customers is studied in order to recover value by reusing the product or parts of it. Closed loop supply chains are defined by Guide and Van Wassenhove (2009) as "*the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time".* The main steps of a closed loop supply chain are product collection, return logistics, inspection/separation, remanufacturing/recycling and redistribution (Guide et al., 2003). Closed loop supply chains are often believed to be sustainable operations, since waste is reduced, the use of new resources and energy intensive production processes avoided.

1.1.2 Previous research at the TU/e

Useful research at the TU/e for this project is the carbon regulated supply chain research by Van den Akker et al. (2009). They developed the TERRA (Transport Emission Reporting and Reduction Analysis) tool based on the NTM method (NTM) for an accurate evaluation of emissions from transport.

Other interesting research is a master thesis by Koomen (2012). In this thesis emission reduction options are evaluated for transport and process decisions in a chemical company. Earlier research mainly focused on reducing emissions from transport only. The resulting transport decisions however might have a negative effect on the emissions from other processes. The thesis by Koomen (2012) showed which transportation and processes needed to be included in the boundaries of the system, by developing a general framework. This framework identified the effect of reduction options on emissions. The framework was used to analyze three changes in the business process. Also insights where given on promising emission

reduction options. The research by Koomen (2012) is interesting for this master thesis since LCA was used to determine the emissions for the supply chain of the chemical company.

1.2   Company description

In this section a short description of Nike, the company where this project is performed is given.

1.2.1 Nike

Nike, Inc. is an athletic footwear, apparel and equipment company. The company is founded in 1964 as "Blue ribbon sports". The name changed in 1978 to Nike, named after the Greek goddess of victory. It is the world market leader in in sports shoes and apparel with its highly recognized logo, the Swoosh. They sell products under their own name, as well as under affiliate brands: Jordan, Converse Inc., Hurley International and Nike Golf. In 2012, more than 44,000 people worked at Nike and they had sales revenue of $24.1 billion. The world headquarters is situated in Beaverton, Oregon, USA, and the Europe headquarters in Hilversum, the Netherlands. The products Nike manufactures can be divided in three broad categories: Footwear, apparel and equipment. These are sold directly to customers or to wholesale customers.

1.2.2 Sustainability at Nike

15 years ago sustainability was seen as a risk management issue that is a cost on business and a drag on performance. Nowadays sustainability is one of the most important business strategies at Nike. It is viewed as an innovation opportunity and a competitive advantage in their vision: "our vision is to build a sustainable business and create value for Nike and our shareholders by decoupling profitable growth from constrained resources". This means sustainability is needed to remain competitive in the long term. An example of a view Nike has that threatens their future is that resources will run out and this will have an effect on the cost and availability of these resources. Also traditional production and transportation models might no longer be useful with increasing energy costs and greenhouse gasses. However the demand for Nike's products is not believed to decrease so sustainable operations are needed. In order to ensure the commitment of the management, there is a vice president sustainable business and innovation.

In order to be more sustainable on the environmental dimension, detailed targets and commitments are set for Nike's environmental performance. Accurate measurement of factory and environmental performance is needed. Therefore Nike has developed their manufacturing index. Targets are set for energy use, waste, water, toxics. This way the performance of innovation of products, processes and transportation can be measured. For example, there are sustainability indexes within Nike to help design products with more environmental friendly materials, such as organic cotton, and with more sustainable processes and less waste. Another sustainable example is apparel made from polyester of recycled PET bottles.

1.3 Closed loop recycling

Closed loop recycling of textiles includes the collection of post-consumer material for the production of yarn that can be used in new clothing. The most dominant form of recycling nowadays is open-loop recycling. The quality of the output material from the recycling process is too low to be used as input for new clothing, and therefore it is downgraded. Recycled material can for example be used as mattress upholstery or isolation material in cars. This way the value is partly recovered from textile waste. Otherwise it would have been incinerated. However this does not reduce the need for raw materials in the production of apparel. Therefore closed loop recycling is an interesting option.

Companies are gaining interest in closed loop recycling of textiles (Oakdene Hollins, 2013). One reason is the increasing awareness of the environmental impact of textile by consumers. There are initiatives by both governments and retailers or brands to increase the collection of post-consumer textile. For example Puma, H&M and Jack & Jones started in-store collection programs.

1.4 Report structure

After an introduction in sustainable supply chains, the cooperating company and closed loop recycling in chapter 1, in chapter 2 the research design is given with the problem description, research questions answered and the research approach. The framework used in this project and the measurement of environmental impact and costs is discussed in chapter 3. Chapter 4 describes the current production process for yarn. Different recycling methods are discussed in chapter 5. In chapter 6 the results are given for the environmental and costs impact of several scenarios. Furthermore sensitivity analyses are conducted. Chapter 7 shows the main findings of the master thesis project and the implementation of the findings are discussed in chapter 8.

This master thesis report contributes to the literature in the following way. Instead of focusing solely on reducing impacts by recycling, or reducing impacts from transport, this study combines these two aspects of closed loop supply chains in textile. In order to minimize the environmental impact with closed loop supply chains both aspects are important. The right recycling process is selected, and the network design optimized to minimize energy use, CO_2 emissions and costs. Only focusing on one of these aspects might lead to suboptimal decisions.

2. Research design

In this chapter the design of the research is given. The problem description is given in section 2.1, the research question in section 2.2, and the research approach for the problem in section 2.3.

2.1   Problem description

Sustainable innovation is one of Nike's most important business strategies. In their apparel product category the most used fibers are cotton and polyester. There are a number of sustainability issues with these materials, such as energy intensive production processes, excessive water, land and chemical use and the depletion of valuable resources. A promising option to avoid resource depletion and to reduce post-consumer waste is to close the loop in supply chains, by recycling. Post-consumer apparel has to be collected, sorted and recycled into yarn which can be used for the production of new apparel. The aim is to produce a product of equal quality from recycled fibers. This primary recycling is the most beneficial form of recycling in resource perspective, since it will decrease the demand for virgin fibers. The main driver in this field is to maximize the economic benefits by recovering value from used products. In the last decade closed loop supply chains are often also associated with sustainability (Srivastava, 2007). It is believed that the environmental impact is reduced by avoiding waste and raw materials. At end of life, products are used instead of being disposed.

However closing the loop does not always lead to a "win-win" situation where both the business objectives of a company and the environmental performance will benefit. Often a tradeoff has to be made between economically rational decisions and environmental performance. The main problem is how to select the right transportation and processes in order to make the supply chain feasible and sustainable. Therefore several objectives are needed, environmental objectives for energy use and carbon dioxide emissions and an economic objective. In Guide et al. (2003) the main steps of a closed loop supply chain are described. These are product collection, return logistics, inspection/separation, remanufacturing/recycling and redistribution. Decisions have to be made on all these steps. It is not straightforward that closing the loop is more sustainable than the virgin process for raw materials. In a closed loop supply chain first used products need to be collected somewhere, for example at the store. Then a reverse logistic network has to be set up, in order to bring the used products back to the factory. At the factory the product needs to be disassembled and materials made ready for recycling and the production of new apparel. These extra transportation moves and processes are likely to be energy intensive and resources have to be put in. A framework based on life cycle assessment (LCA) has to be made in order to assess if closing the loop is more sustainable than the current supply chain. Also the economic feasibility has to be assessed.

2.2 Research questions

From this problem description in section 2.1 the following research question is derived:

How can the impact of closed loop supply chains on environmental performance and costs be determined?

In order to answer the main question of the master thesis project, the following sub-questions have to be answered.

1. *How can the environmental performance be determined?*

   As stated in the problem description Nike is investigating the option to close the loop in their apparel supply chain. A framework is developed in order to assess the performance of several closed loop scenarios. The right goal and boundaries have to be chosen in order to make an assessment. The framework is used to calculate the costs and environmental impact for several impact areas.

2. *What is the environmental performance of current yarn supply chains?*

   In order to compare the environmental performance and costs of closed loop options in the supply chain, a reference scenario is needed. This is the current production process of polyester and cotton yarn.

3. *How can the impact of recycling processes on the environmental and cost impact be demonstrated?*

   The main benefit of a closed loop supply chains is recovering the value from used products. This will be done in a number of recycling steps. The framework is used to assess the environmental impact and costs of all the steps in a closed loop supply chain with recycling. The impact of recycled yarn is compared with yarn from the normal supply chain.

4. *How can a closed loop supply chain network be designed and what is the impact on environmental performance and costs?*

   In order to help decision making in a closed loop supply chain, the impact of different locations in a closed loop supply chain is assessed.

2.3 Research approach

In this section the approach is provided that is used to answer the questions of the previous section. First a framework is developed using life cycle assessment in order to determine the environmental performance and costs of alternatives. Using a desk search alternative options for recycling post-consumer clothes are collected. Data is gathered on the current supply chain, transportation and recycling processes. With use of the framework an assessment is made of a closed loop supply chain for polyester and cotton products. It is important to note that this is different from a complete LCA for a product system. In this project the goal is to compare different closed loop supply chain alternatives with each other and the current supply chain, on environmental measures. Only a part of the supply chain has to be included for this evaluation.

After the impact assessment is made for a certain recycling supply chain, a number of comparisons are made. They are compared with end-of-life options for post-consumer textile. Normally clothes will be incinerated or landfilled for example. It is interesting to see if recycling is preferred. The recycling scenarios are also compared with the current production of yarn, which is produced with virgin materials.

Next sensitivity analyses are included to show the impact of uncertain data. Then the feasibility of economic and other considerations is given. Also the impact of using different locations in a CLSC is shown in the supply chain design.

Data collection of LCA is very time consuming. For example it is also difficult to gather data on some processes in a closed loop supply chain in this industry. These processes are not yet common in the industry, and therefore not included in general databases. Also companies are reluctant to publish data due to confidentiality issues. A hybrid data collection method is used, where specific data is used if available, and generic data from literature or databases otherwise.

3 Environmental impact and cost measurement

In this chapter the determination of the environmental and cost impact is introduced. In 3.1 the environmental measures are discussed. Section 3.2 introduces the processes included in this project and section 3.3 describes the impact measurement of transport. In 3.4 a framework is made for environmental and cost impact measurement.

3.1 Evaluation

At Nike there are three main product categories, footwear, apparel and equipment. For the master thesis project, the apparel category is chosen with cooperation of Nike, since the materials used in apparel are most likely targets for closed loop recycling. The natural fiber cotton and the synthetic fiber polyester, or polyethylene terephthalate (PET) are the most common raw materials in the apparel industry. Cotton and polyester represent 34% and 45% of the global fiber production (Bartl, 2011). The consequences of producing cotton on the environment are the water, land, energy consumption and pesticides that are used (TNO, 2010). The dominant contributions of polyester are the use of energy intensive resources and the energy use for production (TNO, 2010).

There is no scientific consensus about environmental impact measures. Based on the main contributors on the environmental impact for cotton and polyester and Nike's LCA, measures are chosen. In Nike's LCA of the current supply chain, water and land use, chemistry and waste are used next to energy demand and carbon emissions. For the framework in this project energy use (non-renewable) and global warming potential are used as impact categories. For GWP, CO_2 equivalent emissions are the most common reference (IPCC, 2007). In this report CO_2 equivalent emissions are used. These measures are commonly accepted, which increases the availability of reliable data. Non-renewable energy use is called energy use in this report. CO_2 equivalent emissions are called CO_2 emissions in this report.

Multi-criteria analysis is used to analyze the impact of recycling polyester and cotton. The criteria will be compared with each other directly. It is not straightforward what decision to make based on this approach. A holistic view is needed to compare different alternatives on multiple criteria. Two functional units are chosen for the assessment. To compare end-of-life scenarios for post-consumer clothes 1 kg of cotton or polyester waste is used. To compare yarn production, 1kg of yarn is used as a functional unit.

3.2 Processes

Not the entire life cycle of Nike products is included in the assessment. This is not necessary since it is not likely all the stages are influenced by closing the loop.

Defining the boundaries of the system is important in order to make the right decisions on recycling. For the current supply chain of polyester and cotton the scope is from the farm or wellhead (cradle), to the finished yarn (gate). See Figure 1 for an overview of the supply chain. In order to make a comparison, the gate is finished yarn. The steps after the yarn manufacturing are not necessary for the comparison of recycling options, since they will not influence the production process, distribution and use. Only the processes and transport that are likely to be changed or added are included in the system boundaries. Note that the impact of normal end of life processes of used apparel is also included in this project. For example energy is recovered from incinerating used apparel. The cradle of the closed loop supply chain is textile waste and the gate is finished yarn. The processes included are collecting, sorting, fiber recycling, yarn processing and the transportation in between.
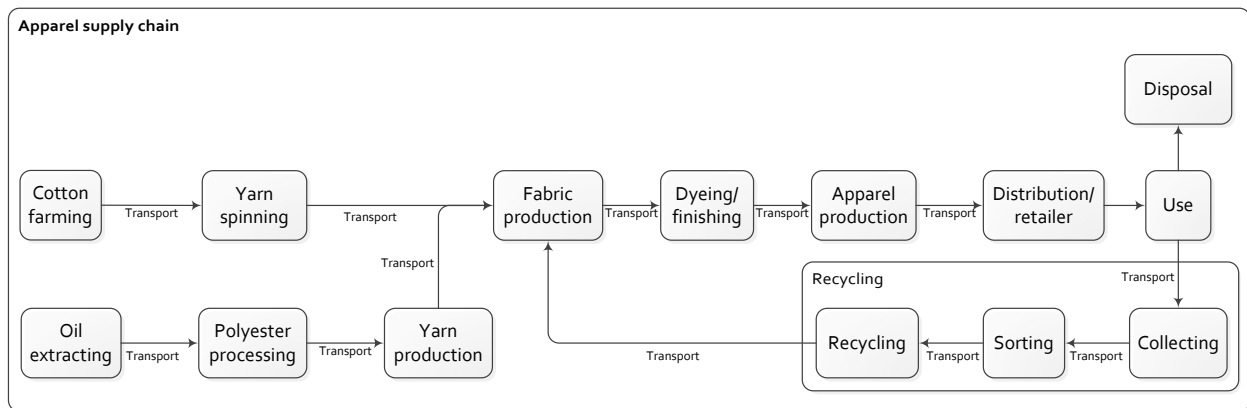

Figure 1: Apparel supply chain

3.3 Transport

The main environmental impacts from transportation are CO_2 emissions and cumulative energy demand. As primary impact category CO_2 equivalent emissions will be used, since this is the most common reference to the Global Warming Potential (GWP) (IPCC, 2007). Other greenhouse gasses from transportation include methane (CH_4) and nitrous oxide (N_2O). However their relative impact is very limited. CO_2 has an emissions factor of 70.101 kg/GJ, CH_4 0.0028 kg/GJ and N_2O 0.00057 kg/GJ (EPA, 2009). Therefore CO_2 emissions in transport are used as reference for CO_2 equivalent emissions.

The energy demand can be calculated based on the CO_2 emissions. The NTM (Network for Transport and Environment) methodology is used in to calculate the environmental impact from transport. This method provides a high level of detail for an accurate evaluation of transport emissions. This method also provides estimates for data that is not available in companies. NTM is cooperating with the European Committee for Standardization (CEN) in

order to develop a European standard for the calculation of the environmental impact from transportation. Other methods for the calculation of transport emissions are Artemis, STREAM, EcoTransIT and the GHG Protocol. They all have well described background but are less suitable for the assessment in companies for the reasons explained in Van den Akker et al. (2009).

For the four main transportation modes, road, rail, air and water there are different calculation methods. In this project air transport is not considered, since transport will be done sustainable. Water and road transport are the most suited in textile transport, since these modes can be used flexible.

For road the fuel consumption of the vehicle depends on the distance and load factor. For water, the fuel consumption is assumed to only depend on distance. Also vertical handling is included for the impact of cranes and reach-stackers (Van den Akker et al, 2009).

Parameters:

D : Distance travelled
FC_{empty}^m : Fuel consumption for empty transport mode m
FC_{full}^m : Fuel consumption for full transport mode m
FC^m : Fuel consumption for mode m
LF : Load factor based on weight
EF^m : Emission of fuel used in transport mode m
TF : Terrain factor
Cap_{max}^m : Maximum weight capacity of transport mode m
E_{road}^m : Emission for transporting 1kg of material via road with transport mode m
E_{water}^m : Emission for transporting 1kg of material via water with transport mode m

$$E_{road}^m = D * \left(FC_{empty}^m + \left(FC_{full}^m - FC_{empty}^m\right) * LF\right) * EF^m * TF * \frac{1}{Cap_{max}^m * LF}$$

$$E_{water}^m = D * FC^m * EF^m * \frac{1}{Cap_{max}^m * LF}$$

3.4 Framework

The potential environmental and economic benefits of a closed loop supply chain should be investigated before a decision is made on recycling. Often reducing the environmental impact of companies focusses on decreasing the impact of one specific business aspect. For example transport emissions are reduced or equipment is replaced for more environmental friendly options. While there might be an environmental benefit in these efforts, it is crucial a company takes a broader view, and also includes processes before or after their own part of the supply chain. For carbon emissions, these are Scope 3 emissions (Bhatia et al, 2011). Scope 1 emissions are emissions created directly from company processes. Scope 2 emissions are indirect

emissions from electricity used by the company. Scope 3 emissions are all other indirect emissions, created up and downstream in the supply chain.

This extended view is the basis of the entire assessment in this project. If recycling used apparel has to be assessed, all the added processes and transportation of both Nike and other players in this closed loop supply chain should be included. A network design model is developed in order to help decision making. The overall goal is to optimize the environmental performance of all the processes in the closed loop supply chain.

3.4.1 Objective

In order to support decision making in a closed loop supply chain, an objective is needed. In this project only option 1 and option 2 of Table 1 are considered. In option 1 either one of the environmental impacts (j) considered in this project can be minimized. In this objective (j) is either energy use or CO_2 emissions. In option 2 the cost of a closed loop supply chain can be minimized.

However other objectives could also be interesting. One of the environmental impacts can be minimized subject to a maximum of the total costs in the system in option 3. This maximum is for example the current price of yarn. It can also be the current price multiplied with a certain percentage that a company is willing to pay for recycled yarn (option 4). In the last option, the cost impact of the closed loop supply chain is minimized, but the environmental impact of recycled yarn should be smaller or equal than the current impact of yarn.

Objectives	
Option 1	$\min Environmental\ impact\ (j)$
Option 2	$\min Cost\ impact$
Option 3	$\min Environmental\ impact\ (j)$ $s.t.Cost\ impact\ \leq current\ price$
Option 4	$\min Environmental\ impact\ (j)$ $s.t.Cost\ impact$ $\quad \leq current\ price * percentage$
Option 5	$\min Cost\ impact$ $s.t.Environmental\ impact$ $\quad \leq current\ impact\ of\ yarn$

Table 1: Objectives

3.4.2 Model

The approach of the model described below takes potential decision criteria into account in order to systematically show the optimal closed loop supply chain. By selecting the right locations and transport movements, this model can minimize the environmental impact or the costs of the system.

Index sets:

C : Set of collection locations c
S : Set of sorting locations s
R : Set of recycling locations r

Parameters:

C_{cs} : Costs for transport between c and s
C_{sr} : Costs for transport between s and r
C_c, C_s, C_r : Costs for collecting at c, sorting at s and recycling at r
I_{cs} : Environmental impact for transport between c and s
I_{sr} : Environmental impact for transport between s and r
I_c, I_s, I_r : Environmental impact for collecting at c, sorting at s and recycling at r

Decision variables:

X_c, X_s, X_r : Decision for using collection facility c, sorting facility s and recycling facility r
$\{0, 1\}$
X_{cs}, X_{sr} : Decision for transport between c and s and between s and r
$\{0, 1\}$

Objective functions:

$$Min \sum_C C_c * X_c + \sum_C \sum_S C_{cs} * X_{cs} + \sum_S C_s * X_s + \sum_S \sum_R C_{sr} * X_{sr} + \sum_R C_r * X_r \ (1)$$

$$or$$

$$Min \sum_C I_c * X_c + \sum_C \sum_S I_{cs} * X_{cs} + \sum_S I_s * X_s + \sum_S \sum_R I_{sr} * X_{sr} + \sum_R I_r * X_r \ (2)$$

$s.t.$

$\sum_C X_c \geq 1 \ (3)$
$\sum_S X_s \geq 1 \ (4)$
$\sum_R X_r \geq 1 \ (5)$
$\sum_S X_{cs} = 1 \ \forall i \ (6)$
$\sum_R X_{sr} = 1 \ \forall i \ (7)$
$X_c \in (0,1), \ X_s \in (0,1), \ X_r \in (0,1), \ X_{cs} \in (0,1), \ X_{sr} \in (0,1) \ (8)$

Note that in this model the environmental impact is either energy use or CO_2 emissions. The cost impact is minimized in (1). One of the environmental impacts is minimized in (2). The minimization of the environmental impacts is subject to the following constraints. Constraint (3-5) guarantee there is always at least one location opened. Constraint (6-7) ensure transport only goes to one destination. Constraint (8) guarantees the domain of the decision variables.

4 Current supply chain

In this part the current supply chain for virgin cotton yarn and polyester yarn is evaluated. For the current supply chain of yarn, the processes and data of an LCA in Nike's Material Sustainability Index (MSI) are used (Nike, 2012).

4.1 LCA current supply chain

The processes in Nike's LCA are representative for the yarn used in Nike products. For the MSI a LCA is conducted for fabrics used by Nike. The cradle to gate scope of this lifecycle starts with the raw materials and ends with dyed fabric. Only the first part of the life cycle, until finished yarn, will be used in this assessment.

The most interesting impact categories in Nike's LCA for this project are GHG emissions, cumulative energy demand and water use, since they use typical LCI conventions for the calculation of these measurements. As a reference for GHG's, kg of CO_2 emissions is used for all the transportation and processes according to the GHG protocol method. Cumulative energy demand is all the energy in MJ from transportation and processes, including feedstock energy embodied in raw materials. Water use is all the water in liters added during processes, for example irrigation during crop growing and cooling water. Data is gathered mainly from literature and LCI databases.

The other impact areas in Nike's LCA are land use, chemistry and waste. There is no standardized method for measuring these impact areas. However they are important for Nike's business. Land use is the kg of raw material that can grow on one hectare of land. Chemistry is divided in four categories, carcinogenicity, acute toxicity, chronic toxicity and reproductive toxicity. For all the substances used in different processes for each material, a score is given from 1 for moderate to high hazardousness, to 4 which is generally recognized as safe. The average score for each category is used. Waste is divided in five categories, hazardous waste, municipal solid waste, industrial waste, recyclable/compostable waste and mineral waste. They are measured in mg/kg fabric.

4.2 Processes

The cotton yarn process contains a few key processes that have an environmental and cost impact. See Figure 2. The first process is the conventionally growing of cotton in different parts of the world. Also ginning, the process of separating cotton fiber from the seed, is included in the farming step. The next step is the spinning of yarn from cotton fibers. This step includes carding, drawing and ring spinning of yarn. The fineness of cotton is measured in cotton count, expressed as singles. This is the linear density of the yarn. The higher the singles, the finer is the

yarn. Cotton used in shirts by Nike is often between 20s and 40s. See Appendix III for the energy, CO_2 and water impact.
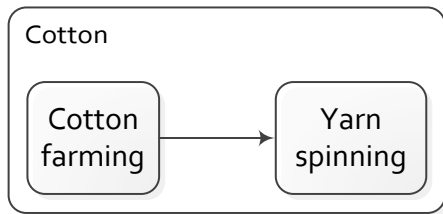

Figure 2: Cotton production

Also polyester has a few steps for the yarn production. The first step is the extraction of crude oil, the raw material for polyester. There are two main methods for the production of PET. Oil can be refined and via reaction steps either dimethyl terephthalate (DMT) or terephthalic acid (TPA) is made. The classic method is to produce PET from DMT, but nowadays the TPA route is more common. DMT or TPA is first combined with the monomer ethylene glycol (EG) to produce an intermediate product, the oligomer BHET. This oligomer is then polymerized into PET, and a part of the EG is recovered again.

The end product of the previous steps is polymerized PET pellets. The MSI uses a TPA route for the production of PET pellets. In the following step the pellets are melt-spun into filament yarn, also known as partially oriented yarn (POY). This yarn is often texturized in drawn texturized yarn (DTY). See Figure 3 for the overview of process steps. The fineness of polyester yarn is commonly expressed as denier/filaments. Denier is the total linear mass of the yarn, and the filaments are the number of fibers in the yarn. The lower the amount of denier/filament, the finer is the yarn. A polyester yarn commonly used by Nike has the specification of 75D/72f. See Appendix III for the energy, CO_2 and water impact of polyester production.
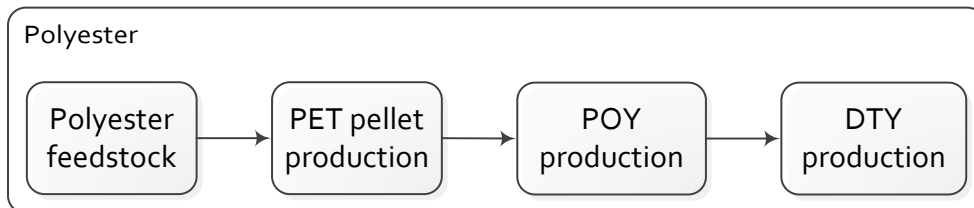

Figure 3: Polyester production

5 Closed loop supply chain

In this chapter the different processes in a closed loop supply chain are described. There are three main steps, collecting, sorting and recycling. As a reference end-of-life option incineration is included. In Appendix II and overview is given of the data sources, and in Appendix III an overview of the environmental impacts of these processes.

5.1 Collecting

The first part of a closed loop supply chain in apparel is to get products back after a consumer has used them.

A likely option to collect post-consumer apparel is by using an in store collection box. Nike has experience with this type of collection from their shoe recycling program Reuse-a-shoe. The boxes can be placed in stores owned by Nike or other retailers. In order to demonstrate the environmental impact for this collection option five stores are selected. The stores in Amsterdam, Paris, Hamburg, Barcelona and Rome are selected since they are situated in different parts of Western Europe. The environmental impact from the user to the collection point will not be taken into account. It is assumed the user will only return used clothes when already going to the store, therefore this trip is not allocated to the collecting. The environmental impact from heating and electricity in the store will not be allocated to the collecting. A collection box will only use a very small part of the store.

Another option for Nike is to make use of the inflow from general collection boxes. These are boxes in public where people return their used shoes and clothing. This alternative has a number of benefits. First people are already used to bring their shoes and clothing to these boxes. They also are a wide spread collection method in Europe. Therefore the inflow of used clothes is probably high when collaborating with a collection organization. Also the return logistics network already exists.

5.2 Sorting

The products have to be separated based on the material of the fabric. For Nike, 100% cotton and 100% polyester have to be separated from the textile waste. The sorting might also be based on the color of the returned product. For example the difference between light, medium and dark colors can be useful further in the process in order to dye or print fabric from recycled material. After the sorting, the post-consumer goods will be compressed in order to increase the load factor of a container. Different locations are considered for the sorting. One facility in Wormerveer in the Netherlands is interesting, since this facility has an automated sorting machine. If this machine can't be used, people with knowledge of fabric separate the cotton and polyester from the inflow manually. The next facility is located in Wolfen, Germany. This is

the largest textile sorting company in Europe. Also sorting in India is considered, since it is on-route to most Asian recycling facilities and labor costs are lower than in Europe. The environmental performance of the sorting is based on electricity and natural gas use of the facility. Only the impact from materials that will be recycled in the next step is allocated. This is assumed since there will be no losses during transport. In the sorting process, material will be separated in other streams, but all the material will be used. For example one kilogram of material is collected and brought to the sorting facility. It exists of 50% cotton and 50% polyester. Only the recycling of polyester is included in this project, so only 50% of the energy used and CO_2 emitted is accounted to the recycling of polyester. This can be assumed since the cotton material will also be further processed, but this is not included in this assessment. The environmental impact from transporting the cotton to the sorting facility is accounted to the cotton processing. The impact of sorting is based on data from a Dutch sorting company.

5.3   Recycling

The used apparel has to be returned into separate fibers in order to make new yarn out of them. This report focusses on the recycling of polyester material, since data for cotton recycling is not available. As a reference to the end-of-life management incineration is included since this is the standard option in Europe. In Appendix II an overview of the data sources is given, and in Appendix III the impacts are shown.

5.3.1 Cotton recycling

For cotton there is only one option, to use a mechanical process, see Figure 4. The first step in this process is to prepare the used product for recycling. All pieces other than cotton have to be cut out, such as zippers buttons and fabric from other material. The next step is the fiberizing process where the material is returned into single fibers. The fibers can be spun into yarn as in the virgin process. In this process it is not possible to remove color from the fibers. This basic recycling method is nowadays mostly done in India and the north of Africa, for shoddy production (Oakdene Hollins, 2013). Post-consumer material is fiberized and re-spun into yarn used for the production of clothing and blankets. In more developed countries post-consumer cotton is often recycled open-loop, where it is downgraded to be used as isolation material for example.

The energy use is estimated to be really small by experts. However the yield is low, since a lot of fibers in the output material are too small to be spun. A high amount of virgin cotton has to be added. The water use is high during the farming process, 2120L/kg cotton. Since no water is used in the recycling process, this amount could be saved for every kilogram of recycled cotton. Also all the chemicals used in the farming of cotton are avoided. The virgin process uses 75.42MJ energy per kilogram cotton. 16.67MJ is used in the farming process, and 58.76MJ in the spinning process. The maximum benefit in cotton recycling is 16.67MJ, since spinning is still

necessary. Both transport and process energy has to be deducted. It is assumed there will be little or no benefit on energy use.
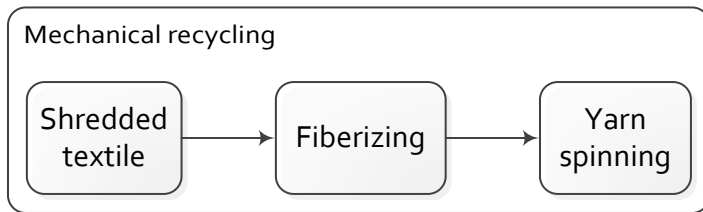

Figure 4: Mechanical recycling of cotton

5.3.2 Polyester recycling

There are a few methods to create polyester drawn texturized yarn (DTY) by recycling. All these methods are able to produce the fineness of polyester yarn that is commonly used by Nike. The technologies available are based on recycling methods used for recycling bottles into fiber. Before the recycling process, first bottles are collected. The collected bottles are then pre-washed, sorted on color and material, chopped into flakes, washed rinsed and dried. In this project post-consumer textile is recycled into fibers. Therefore a similar process is needed to chop the material into smaller pieces and remove all the pieces that can't be recycled. This is a crucial part of the recycling process, since the yield of the process is for a large part dependent on this step. However, no information is available for the pre-treatment of post-consumer textile. Therefore the environmental impact and the yield are initially assumed to be the same as the process for pre-treating bottles. The process in the article by Shen et al. (2010) is used.

One recycling method is a mechanical route, where the polyester is melted, extruded into pellets and subsequently converted into partially oriented yarn (POY). See Figure 5. This is the most common process for the recycling of PET bottles into fibers, and large scale production is available. One of the yarn manufacturers that recycle yarn this way is located in Suzhou, China. The main downside of this process is that color and other pollution of the polyester are not removed. This is no big issue for recycling bottles since clear bottles with little or no contamination are used as input. Apparel is always colored and often contains a few percentage of other material than PET fiber. This process has a grey yarn as output, and therefore can't be used for all the purposes of virgin yarn. Also the polyester is stressed mechanically due to the reheating of the material. This means it technically can't be considered equal quality compared to virgin yarn. The yarn also contains all the contamination that is not removed from the post-consumer material. When the material is recycled multiple times, it is suited for use in apparel. Therefore it is not a full closed loop option on the long term. However the method is commercially available for recycling yarn waste. Nike's internal data for the environmental impact of this process is used.
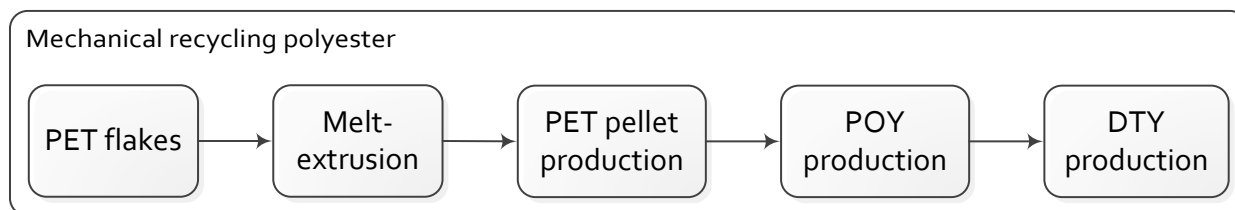
Figure 5: Mechanical recycling polyester

Others methods for recycling polyester are chemical routes. These yield a higher quality of fiber than mechanical recycling, and are comparable to virgin yarn. These methods are full closed loop options, since the input material will be converted into the original raw materials for the production of polyester.

There are a few different processes known, including hydrolysis, glycolysis, methanolysis, ammonolysis, and aminolysis. Glycolysis and methanolysis are the main chemical methods used for PET recycling. In these processes the polyester is depolymerized into smaller pieces. It can be depolymerized partially to oligomers or fully to monomers (Shen et al, 2010). The first process (Figure 6) is used in small scale for bottle-to-fiber recycling in Taiwan. Polyester flakes are depolymerized using glycolysis into oligomers. They are filtered and polymerized into pet pellets. Although the process is for PET bottles, the method will be similar for recycling polyester fibers.

The other process (Figure 7) is used in small scale to recycle post-consumer textile in Japan. In this process, the polyester flakes are depolymerized into monomers using methanolysis. The output is DMT and EG which can be re-polymerized into PET pellets. The waste of both processes is incinerated with energy recovery. Next the pellets can be processed in the normal way to retrieve drawn and texturized yarn. The main benefit is that the color and contamination of other materials can be removed in the process. The output is pure polyester yarn, comparable to the virgin yarn. The data is used from Shen et al. (2010). This article also included transport of PET bottles. The energy and CO_2 emissions are estimated with the NTM method and subtracted. Laursen et al. (1997) is used for the impact of DTY production. The benefit of the glycolysis is that the reaction is on lower pressure and temperature than methanolysis (Achilias and Karayannidis, 2004). On the other hand this process is more difficult to purify, and therefore less suited for textile recycling.
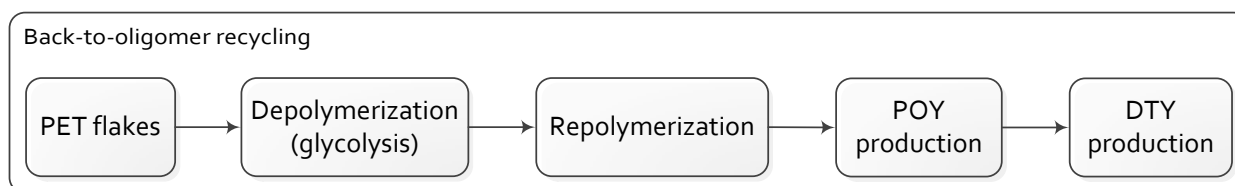

Figure 6: Chemical recycling polyester: back-to-oligomer

Back-to-monomer recycling

PET flakes → Depolymerization (methanolysis) → Repolymerization → POY production → DTY production

Figure 7: Chemical recycling polyester: back-to-monomer

5.4   Incinerating

Normally apparel waste that is not reused or recycled is incinerated in Europe. In combined heat and power (CHP) plants, both energy and heat will be recovered. The main advantage of incineration plants for waste management of textile is that they are used for all types of waste. Therefore textile does not have to be separated from other waste streams. There are numerous of these plants in Europe, so waste doesn't have to be transported over long distances. The main environmental impact from incinerating waste is the emissions to the air. The carbon that is embodied in the material is released to the air. Due to the heat and energy recovery, the energy and CO_2 emission impacts from regular generation can be substituted. This means that the impact of fossil fuels in the normal production of energy is avoided. According to Shen and Patel (2010), in an average European plant 60% of the energy content of the material is recovered.

6 Results

In this chapter the environmental impact and costs of a closed loop supply chain in apparel is shown. In 6.1 the transportation to standard recycling locations is explained. In 6.2 the energy and CO_2 emissions impact is given for the standard scenarios, mechanical recycling in China, back-to-monomer recycling in Japan and back-to-oligomer recycling in Taiwan. Also sensitivity analyses are conducted on uncertain parameters. The impact of changes in the network design is treated in section 6.3. Section 6.4 gives insight in the costs of closed loop supply chains for apparel. In section 6.5 the optimal scenarios for environmental measures and costs are determined.

6.1 Transportation

In this part the environmental impact from transportation between locations in the closed loop supply chain is determined. The NTM method is used for the calculation of CO_2 emissions and energy from this transport (NTM). NTM's fuel consumption data for different transportation types is used. The NTM method is based on European transport, but will also be used to assess the impact of transport in Asia. In Asia trucks are often older than in Europe, and therefore have lower emission standards. Also the roads are worse with a lot of potholes for example. It is likely the NTM method will underestimate the emissions for truck transport in Asia. Truck distances are determined using Google Maps (Google). Nike data is used for ocean distances.

Third party logistics providers will be used for the transportation of the collected material from the stores to the sorting company. The use of 3PL providers is the normal procedure for return logistics in Nike's case. Nike doesn't have its own logistics network, and their stores are widespread in Europe. The collected material is also assumed to be low in volume when transported, since stores do not have much storage capacity. Therefore the use of 3PL services for the transport of collected apparel is chosen.

Whenever a collection box is full, the store triggers a request for transportation. A van picks up the collected clothes, and brings this to a nearby hub. Since 3PL providers combine orders, only the actually driven kilometers are accounted to the package. A small cost-based evaluation is made between UPS and DHL for the shipment between the five chosen stores and Nike's logistics center in Laakdal, Belgium. UPS and DHL are chosen since Nike already has contracts with these providers for reverse logistics. A standard collection box for the collection of post-consumer shoes will be send with 25kg of apparel. Shipping with DHL is three times as expensive as shipping with UPS. The large difference in price can be clarified by the way these providers determine their tariffs. UPS has fixed tariffs for a package, and DHL has tariffs per KG.

No actual data is available from UPS on their processes, so it is assumed the package goes to the hub closest to the store, and can then be transported to the hub near the destination directly by truck and semi-trailer. It is assumed the return logistics are efficient, so materials are not long in inventory at the hubs. The load factor based on weight of UPS collection vans is 40% on average and for UPS trucks with semi-trailer 85% on average. The load factor for UPS trucks is high due to the consolidation of different orders. For the collection vans the road type is urban, and for the truck it is highway. The gradient of the roads are assumed to be zero. If the collected material is sorted in Wormerveer in the Netherlands it is transported directly from the store to the sorting company.

The separated cotton and polyester stream is then shipped to fiber recycling facilities. The maximum weight of sorted material that can be put in a TEU container is determined with data of the sorting facility. This is 10850 kilogram. Sorted material is compressed in bales to maximize the amount that fits in the container. The products are transported directly with a truck with semi-trailer to the Europoort in Rotterdam. Then the container is shipped with a 6000 TEU vessel. For the back-to-oligomer recycling of polyester, the container is shipped to the Kaohsiung port in Taiwan, and by truck to Taipei city. For the back-to-monomer recycling, the products are shipped to Kobe in Japan. From Kobe the TEU is shipped to the recycling company in Matsuyama directly with a 333 TEU vessel. The recycling facility for the mechanical recycling of polyester is situated in Suzhou in China. The container is first shipped to Shanghai, and trucked to the recycler. See Figure 8 and Figure 9 for the overview of the locations in the closed loop supply chain.
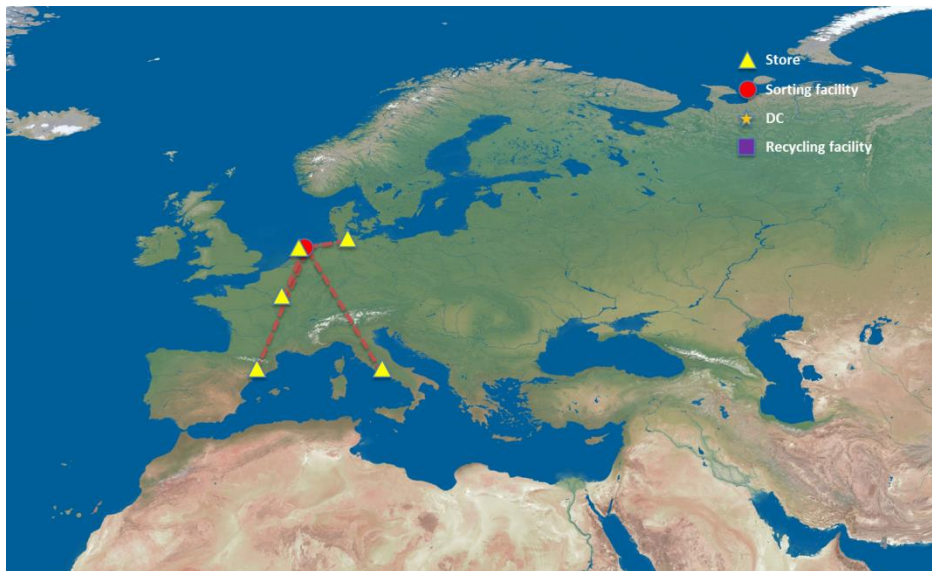

Figure 8: Sorting in Wormerveer

In Table 2 and Table 3 the environmental impacts for the transportation of 1kg of material from store to recycling facility are shown for the standard situation where products are collected in-store, and sorted in Wormerveer in the Netherlands. Since the recycling facilities are located close to each other, and the shipments are of equal size, the CO_2 emissions for all three scenarios are nearly the same.

Transport	Energy (MJ/kg)
In-store – China	3.38
In-store – Japan	3.55
In-store – Taiwan	3.36

Table 2: Energy transport

Transport	CO_2 (kg CO_2/kg)
In-store – China	0.25
In-store – Japan	0.27
In-store – Taiwan	0.25

Table 3: CO2 emissions transport

6.2   Environmental impact with sensitivity analyses

In this part the CO_2 emissions and energy use of both the processes and transportation is combined for three standard recycling scenarios. Several parameters with uncertain values have been chosen that might have an impact on the results. Sensitivity analyses are conducted on these parameters to determine the difference in results with other values.

6.2.1 End-of-life options

In the first assessment the treatment of one kilogram post-consumer material is evaluated. There is a fixed amount of input material in this situation. Normally this material is incinerated with the recovery of energy. Instead of incinerating, recycling polyester is compared as alternative end-of-life option. Three recycling options for polyester are compared on energy use and CO_2 emissions with incineration. Water use is not interesting for polyester recycling, since little water is used in the virgin process. The same amount water also has to be used in the recycling processes. In the standard situation post-consumer material is collected in stores and sorted in the Netherlands. It is then transported to China for mechanical recycling, Japan for back-to-monomer recycling and to Taiwan for back-to-oligomer recycling.

Before the actual recycling processes, the apparel needs to be pre-treated. The removal of unwanted material, cutting the material, washing and drying are examples of such treatments. However the yield of this process is unknown. For PET-bottles the yield is 75% (Shen et al, 2010). For polyester clothing this is likely to be lower. Post-consumer clothing is not a homogenous stream of input, and has more unwanted materials than PET-bottles. Based on previous experiments with recycling polyester material by Nike, initially a yield of 60% is assumed for the total recycling process. The left over material is assumed to be waste, but it is not likely to be incinerated with energy recovery since the recycling facilities are located in Asia. The normal waste management option there is landfill. For the landfill of polyester, there are no CO_2 emissions and no energy is used.

One kilogram of post-consumer material is incinerated, recycled mechanically, entirely broken down chemically or partly broken down chemically. To show the benefit of each recycling process, the environmental impact of producing the same amount of virgin material as the output of the recycling process is subtracted from the impact of recycling. In Appendix I the calculations for the energy use and carbon dioxide emissions for these recycling scenarios are given. In Figure 10 and Figure 11 the impacts for recycling 1kg of polyester waste is compared with incinerating the same material.
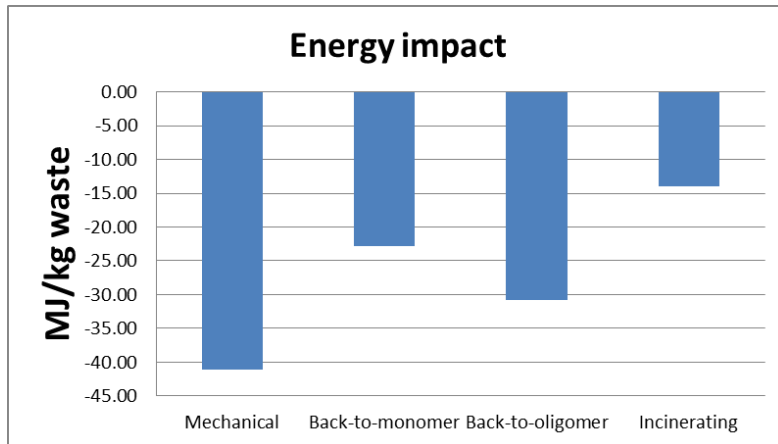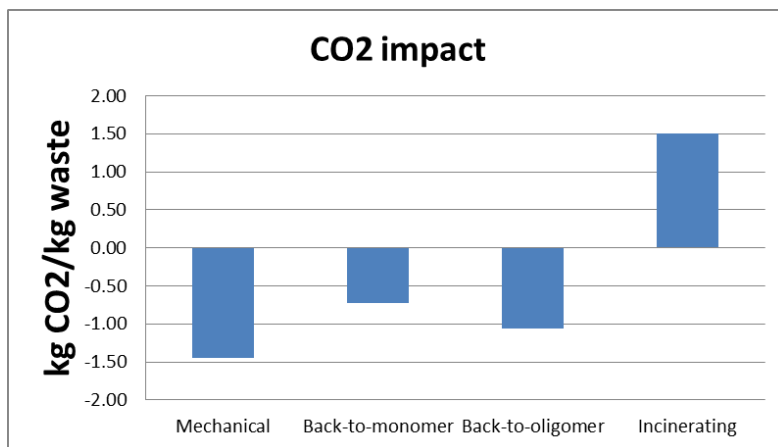
Figure 10: Energy use 1kg of waste

Figure 11: CO2 emissions 1kg waste

From Figure 10 and Figure 11 it becomes clear all the recycling processes are beneficial in terms of energy impact and CO_2 impact compared to incineration. When the yields of recycling are lower than 26%, 44% and 34% respectively for mechanical, back-to-monomer and back-to-oligomer recycling, incineration is preferred when looking at energy use. However with recycling, the yarn can be used for further processing into new clothing. With incineration the energy recovered can be used.

Based on CO_2 emissions, it is impossible to prefer incineration. If the waste is not burned, the carbon remains in the product. The choice for a specific recycling process also depends on the use of the output material. The chemical processes have the least environmental benefit compared to a virgin process, but the quality of yarn is comparable to virgin yarn. The mechanical process is preferred in terms of energy use and CO_2 emissions. The use of this recycled yarn might be limited since the quality is lower than chemically recycled yarn. Mechanically recycled white yarn is for example not possible with this process, since color is not removed.

In Figure 12 and Figure 13 the energy and CO_2 impact is shown for the situation where the waste is incinerated with energy recovery instead of landfilling it. In the near future also countries in Asia will start with waste incineration. This will increase the benefit in energy consumption, but the CO_2 trapped in the waste will be released in the incineration process. Overall, recycling remains the preferred method for the treatment of one kilogram of polyester waste.
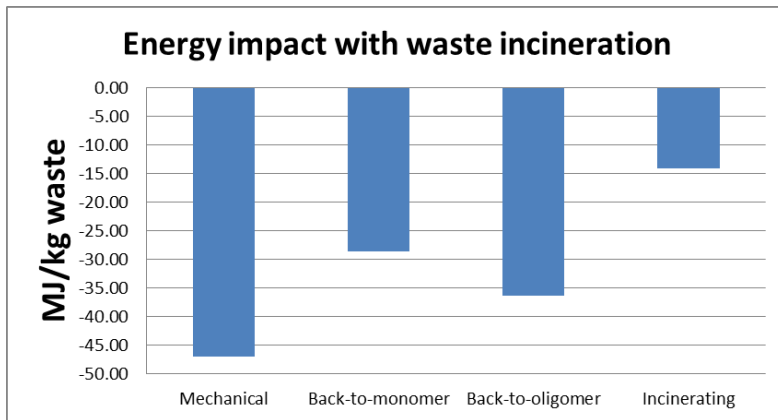

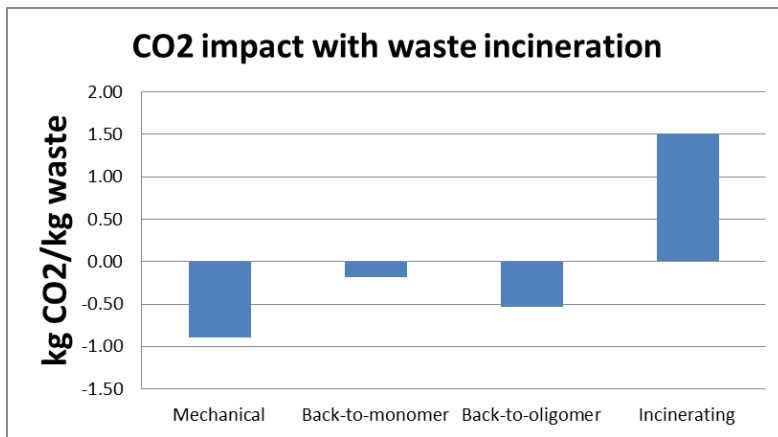**Figure 12: Energy use 1kg yarn with process waste incineration**

Figure 13: CO2 emissions 1 kg yarn with process waste incineration

6.2.2 Yarn production

Instead of a fixed amount of input material as in the previous section, in this situation there is a fixed amount (1kg) of output material. To get a better view on the impacts of recycling, the production of one kg polyester yarn is chosen as a functional unit in this section. It is important to note that no burden is assigned to the waste material used as input. For example, the environmental impact from incinerating waste if it is not recycled is not assigned to the waste. The calculations for the impact of producing polyester yarn are shown in Appendix I. In Figure 14 and Figure 15 the energy and CO_2 impact for transportation, sorting and the recycling process is shown. The total yield is again 60%, and the leftover waste is not incinerated. Based

on the energy and CO_2 impacts all three recycling options are preferred compared to the virgin production of polyester, for this yield percentage. Mechanically recycled yarn uses 68% less energy and emits 43% less CO_2 than virgin produced yarn. Even the recycling methods with the highest impacts, back-to-monomer recycling, uses 38% less energy and emits 22% less carbon dioxide. Back-to-oligomer recycling is in between, and respectively saves 50% and 31% on energy use and CO_2.

When the process waste is incinerated, the energy use will benefit, as seen in Figure 16. Mechanical, back-to-monomer and back-to-oligomer processes use 77%, 46% and 59% less energy. However CO_2 emissions increase in this case. See Figure 17. The processes emit respectively only 26%, 5% and 15% less CO_2 than a virgin process.
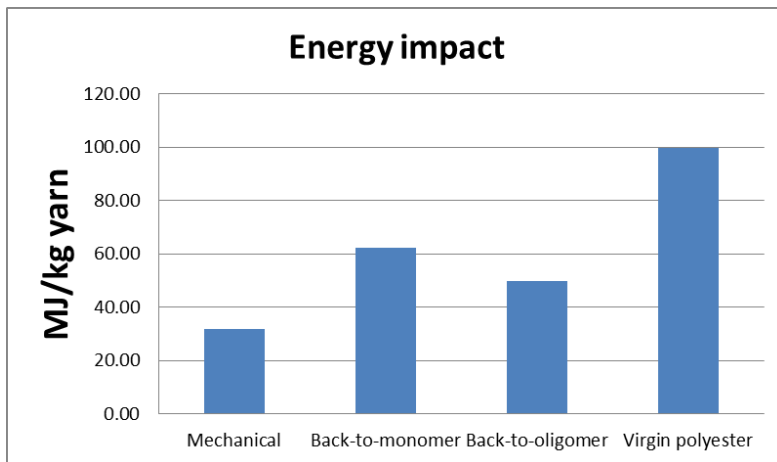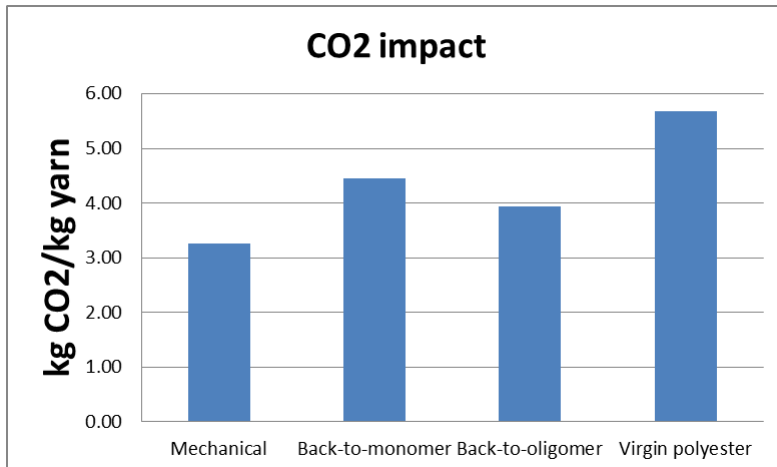

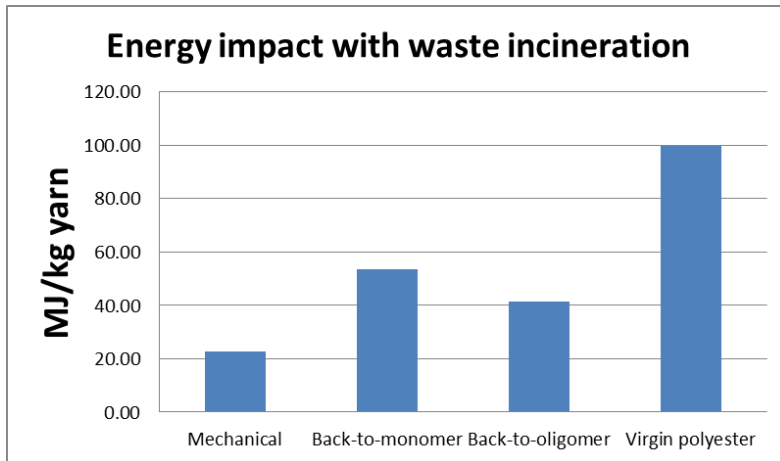**Figure 14: Energy use 1kg yarn**

Figure 15: CO2 emissions 1kg yarn

Energy impact with waste incineration

Figure 16: Energy use 1 kg yarn with process waste incineration
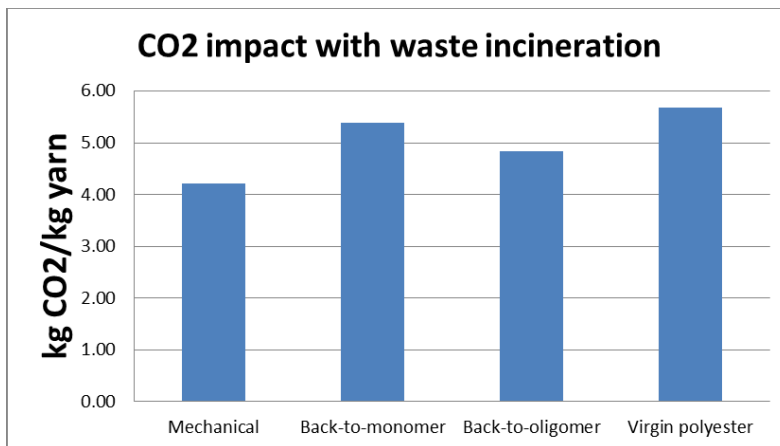

CO2 impact with waste incineration

Figure 17: CO2 emissions 1kg yarn with process waste incineration

6.2.3 Sensitivity analysis yield

A sensitivity analysis is conducted for the yields of the pre-treatment for recycling since they are likely to be lower than in a bottle recycling process. Polyester apparel has more impurities compared to bottles. These might be prints, zippers, buttons, labels and parts of other materials. Before recycling they have to be removed, and less material remains for recycling. If the yield is lower, more post-consumer material needs to be collected sorted and transported and this will increase the environmental impact. In Figure 18 and Figure 19 the impact is shown for efficiencies of 5% to 100%. Only with a very low yield of 10%, the energy for the production of 1kg of polyester yarn via the back-to-monomer process is equal to the energy use in virgin yarn. For CO_2 emissions the threshold level of the yield is 18%. Since higher yields than 18% are likely to be realized in recycling post-consumer polyester, it can be concluded that recycling is beneficial in terms of energy use and CO_2 emissions.
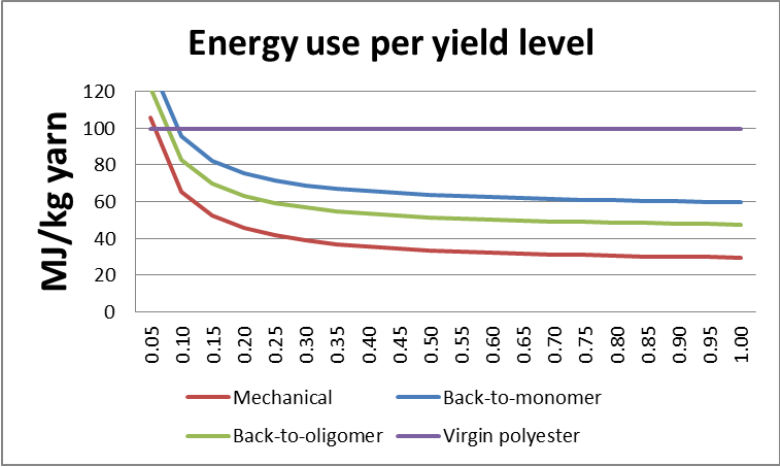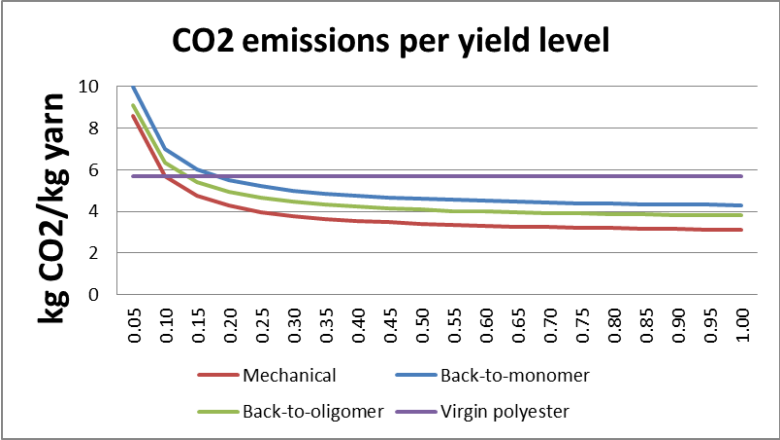
Figure 18: Energy use per yield level

Figure 19: CO2 emissions per yield level

With lower yields, the energy and CO_2 emissions will increase substantially. The reason for this is the increased transportation and sorting needed for the same output. In Figure 20 and Figure 21 the energy use and CO_2 emissions per yield level is shown when the process waste is incinerated. The energy use of recycling will never exceed the energy use of virgin polyester yarn production. With lower yields, there is more waste material. This material is incineration with energy recovery. However this incineration will result in high CO_2 emissions in Figure 21. The break-even point for CO_2 emissions of mechanical, back-to-monomer and back-to-oligomer recycling with a virgin production process, is respectively with yields of 45%, 60% and 50%. These values are not unlikely for recycling processes. In a situation where the yields are lower, a virgin process is preferred based on carbon dioxide emissions. The consideration has to be made between lower emissions on one hand and lower energy use on the other hand.
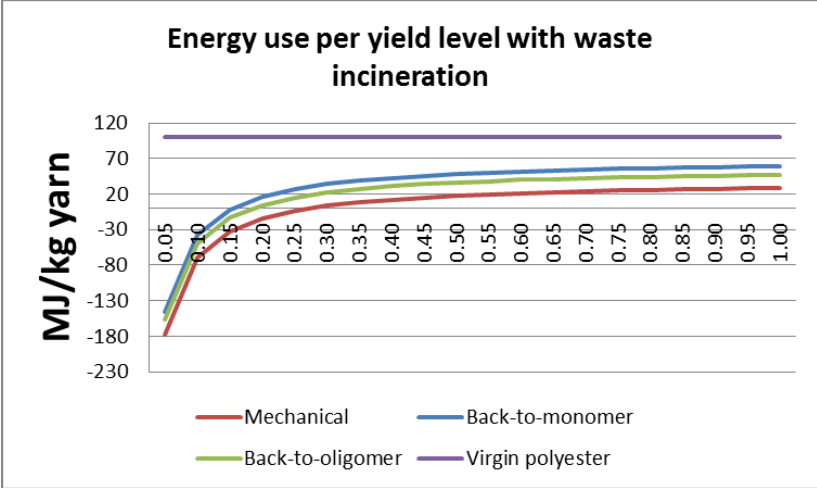
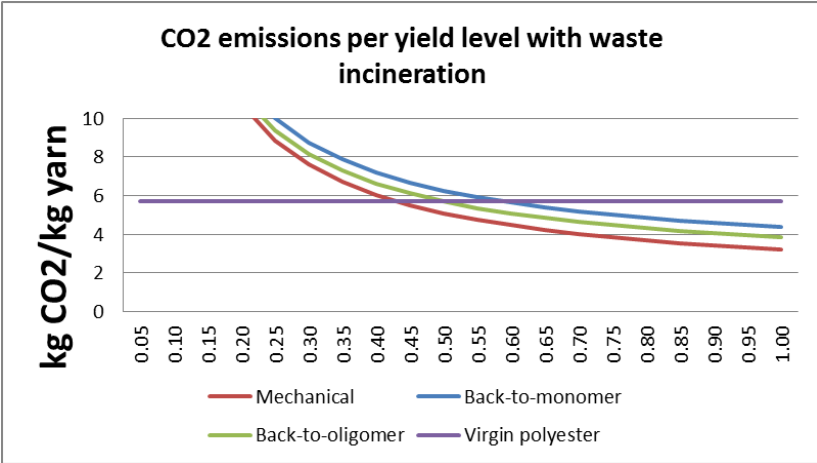**Figure 20: Energy use per yield level with waste incineration**

Figure 21: CO2 emission per yield level with waste incineration

In Figure 22 the total emissions are separated in transport and process emissions. The base scenario is used with in-store collecting and sorting in Wormerveer. It shows that the transport emissions are only a small part of the total. Respectively 13%, 10% and 10% of the total emissions arise from transportation. Although transportation emissions are a relatively small part of the emissions, decreasing these emissions is interesting. Emissions from the recycling processes are more or less fixed. They can only be decreased if processes are scaled up. However for transportation a lot of factors can be changed to decrease emissions. The most obvious options include changing location in the supply chain, the use of more environmental friendly transportation types and increased load factors. Abating of energy and CO_2 emissions is much easier and within Nike's scope.

There is uncertainty in the amount of material needed as input for the recycling process, in order to get the same amount of output. Due to these uncertain efficiencies, the relative

impact of transportation compared with the total emissions change. In Figure 23 the different relative CO_2 impact of transportation is shown. With low efficiencies transportation becomes an important part of the total environmental impact of the system. The abatement of environmental impacts from transportation is more important when yields in the recycling process are low.

CO2 impact
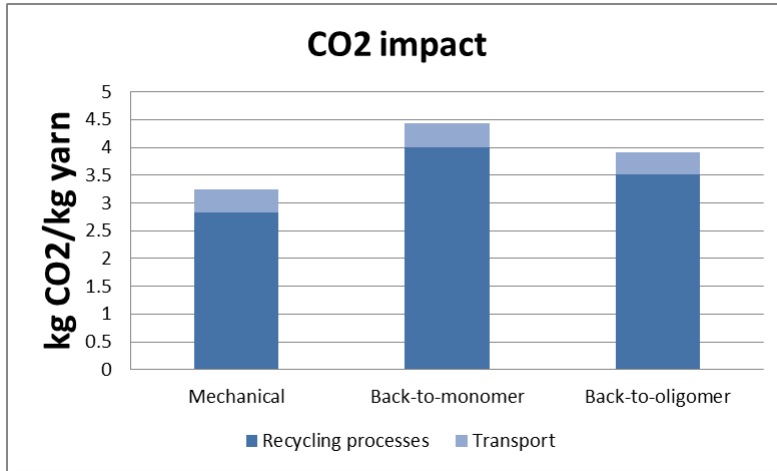
Figure 22: Transport vs. process emissions
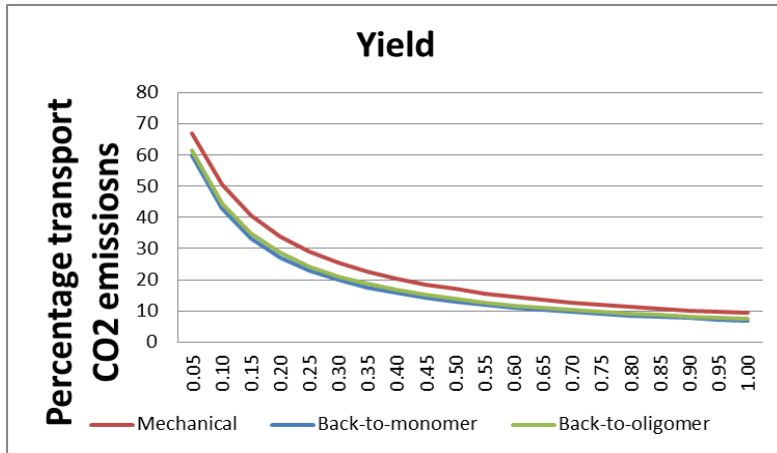
Yield

Figure 23: Relative impact transport

6.3   Network design

In this closed loop supply chain transport has an important impact on the environment depending on the yields of the recycling processes. Besides the choice between recycling processes, the choice of locations for the network is an important decision for Nike. Since this closed loop supply chain not yet exists, network design is a good option to optimize the environmental performance and costs. The impact of several changes to the initial network design will be shown in this part.

6.3.1 Sorting locations

After post-consumer apparel is collected in stores, a suitable location for the sorting has to be selected. In the standard scenario the location is Wormerveer in the Netherlands. Two other possible locations are selected in Europe. Post-consumer goods are shipped directly from the store using a parcel network to these sorting locations. The first one is Wolfen in Germany. This location is selected because it houses the largest sorting facility in Europe. See Figure 24. Sorted material is transported to the port of Rotterdam for further processing.

The other location is in Switzerland, due to its central location for the selected stores Western Europe. This might reduce the distance from stores to sorting facility. The sorted material is then transported to the port of Genoa in Italy for further shipping per vessel. In Figure 25 the overview of the supply chain is showed.

In Figure 26 material is sorted in India. Sorting costs in India are estimated to be only 11% of the sorting costs in Europe. First the items are consolidated in Nike's logistics centrum in Belgium. However the load factor based on weight for the shipment to India is assumed to be 25%, instead of 50% in the normal situation. The load factor is low since the post-consumer material is not yet compressed into bales. This assumption is made based on a compression factor of 2 in the sorting facility. If clothes are compressed before shipping, sorting is not possible. In Figure 27 the CO_2 impact from shipping 1kg of material from stores to the recycling facilities is shown, via all different sorting facilities.
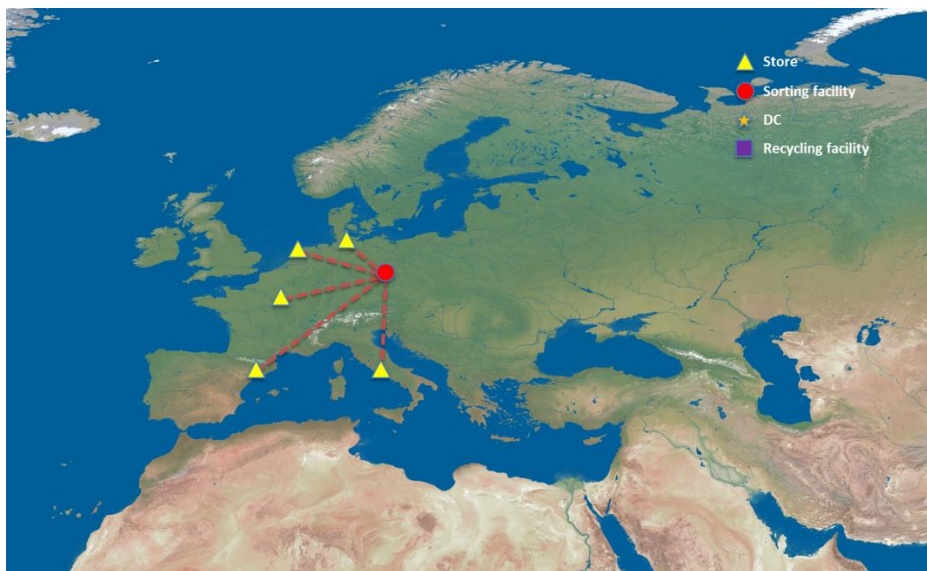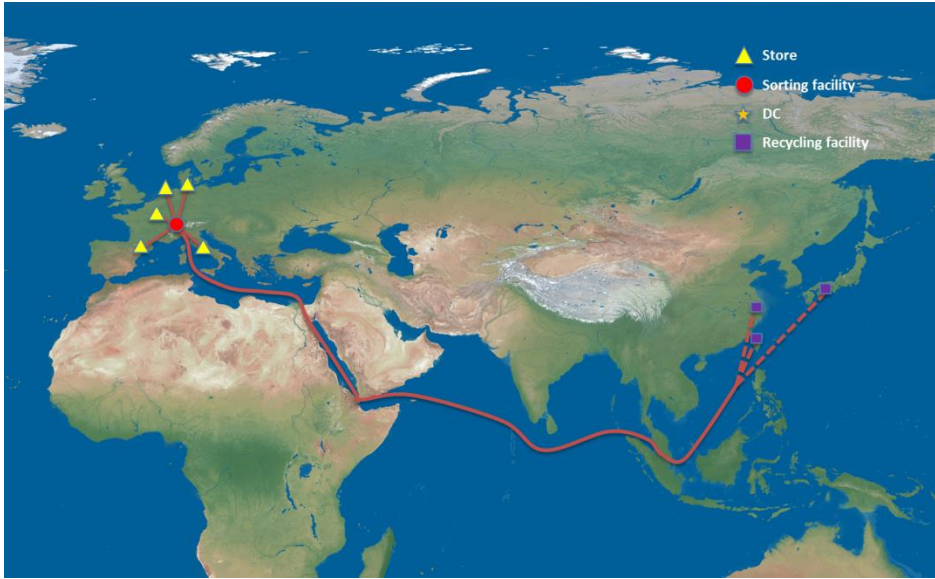

Figure 24: Sorting in Germany

Figure 25: Sorting in Switzerland
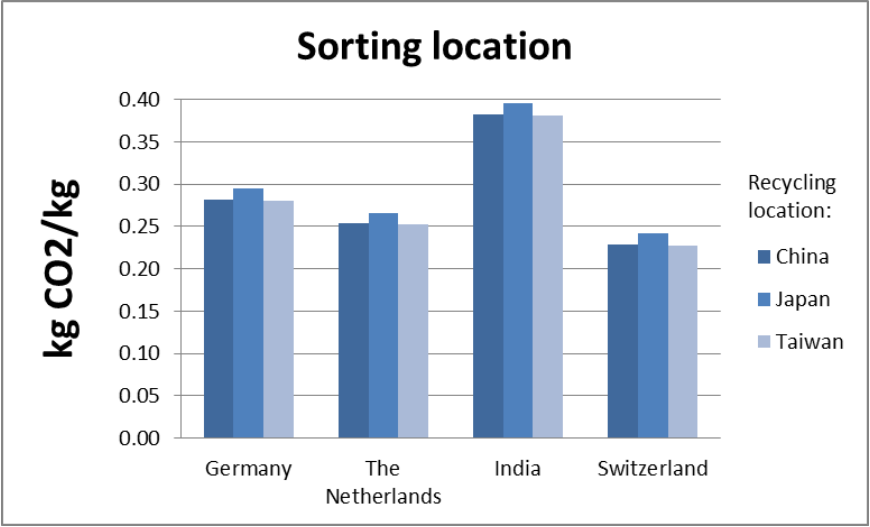

Figure 26: Sorting in India

Figure 27: Sorting locations

The optimal location is dependent on the location of the stores used in this assessment. The best option in terms of CO_2 emissions is to sort the material in Switzerland. CO_2 emissions are reduced with 10% compared to sorting in the Netherlands. The distance from stores to sorting facility is reduced due to its central location. Also the impact from sorting facility to recycling center is reduced, since the vessel departs in Italy instead of Rotterdam. Sorting in Germany increase CO_2 emissions with 11% compared to the standard scenario of sorting in the Netherlands. The main difference is the longer distance from sorting location to the port in Rotterdam.

Sorting in India increases the carbon dioxide emissions with 51% compared to sorting in the Netherlands. Only 5% increase is caused by the extra miles by the vessel. The main contribution to the increase is that post-consumer clothes are not compressed before shipping. If sorting takes place in Kandla, this is not be feasible. Normally, after sorting the clothes are compressed to increase the shipping volume of a container. 10850kg will fit in a TEU after compressing, equal to a load factor of 50% in weight. Less post-consumer material will fit in the container, and the impact of transportation will increase. In Figure 28 the CO_2 impact of shipping with a load factor of 25%, 37.5% and 50% is shown. Emissions increase with 14% for and 43% for load factors of 37.5% and 25% compared to the standard scenario of a 50% load factor based on weight.
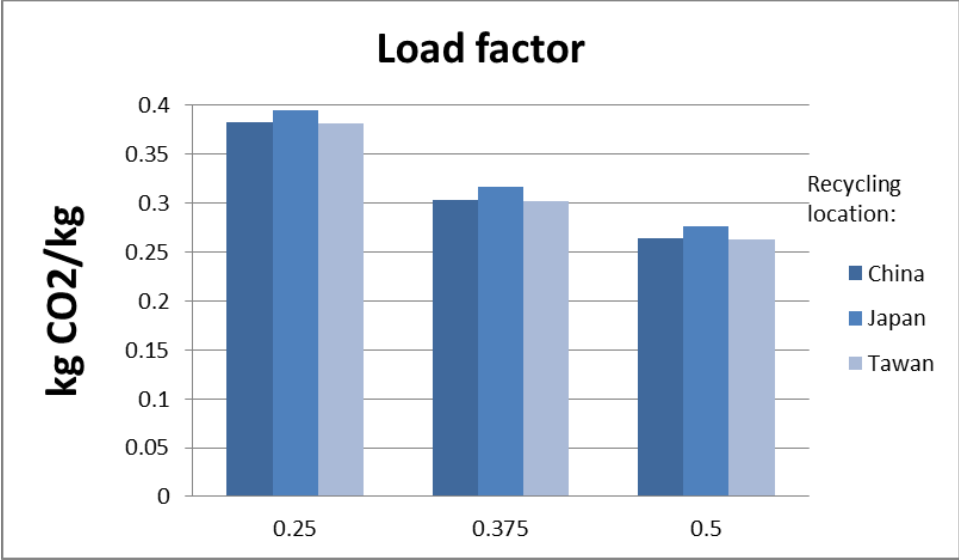
Figure 28: Different load factors

6.3.2 Recycling locations

In the previous scenarios, the locations of companies providing these recycling methods are used. In this section other possible markets for Nike are examined. For sorting the standard scenario is used, it is done in the Netherlands.

An interesting option to consider is to use a recycling facility in India. The material is shipped from the port of Rotterdam to Pipavav in India. Then it is further transported 170km by truck with semi-trailer to a textile area in India. This recycling location is chosen since it is closer to Europe than the location considered previously. There also is a large textile industry in India for the production of apparel. The availability of factories is important, since sub-optimization of distances should be avoided. If recycled yarn has to be shipped to south-east Asia for apparel production, the advantages of near shore recycling are lost. See Figure 29 for the overview of the network.

Figure 29: Recycling in India

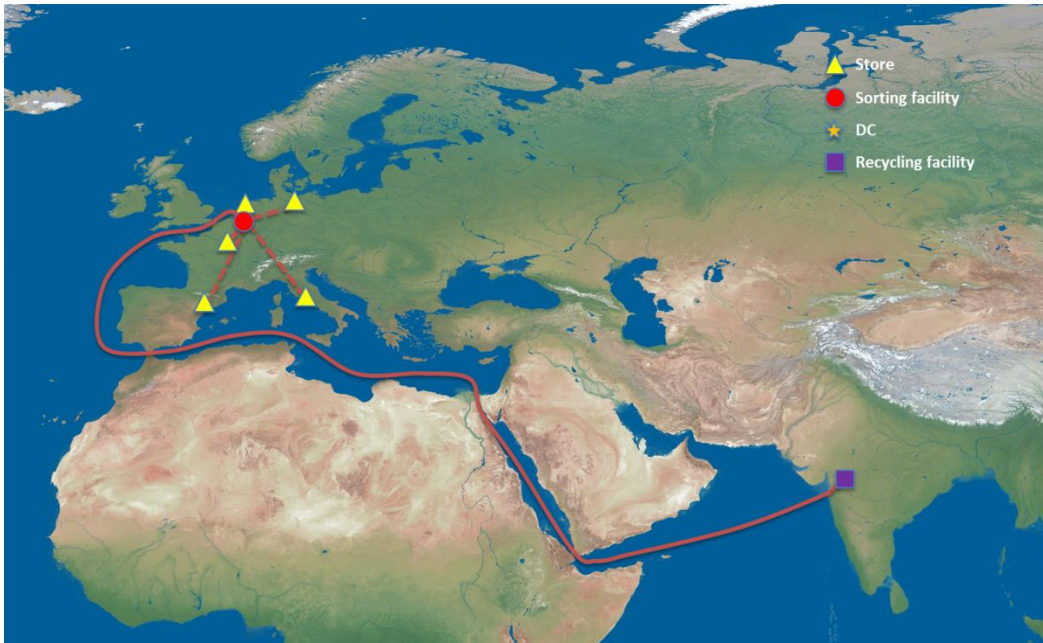Even closer to the collection market Europe, is Turkey. In Turkey there is also a developed textile industry. The material is shipped from the port in Rotterdam to Gemlik in Turkey. There the material is moved 30km by truck to the textile industry in Turkey. In Figure 30 the network is shown.
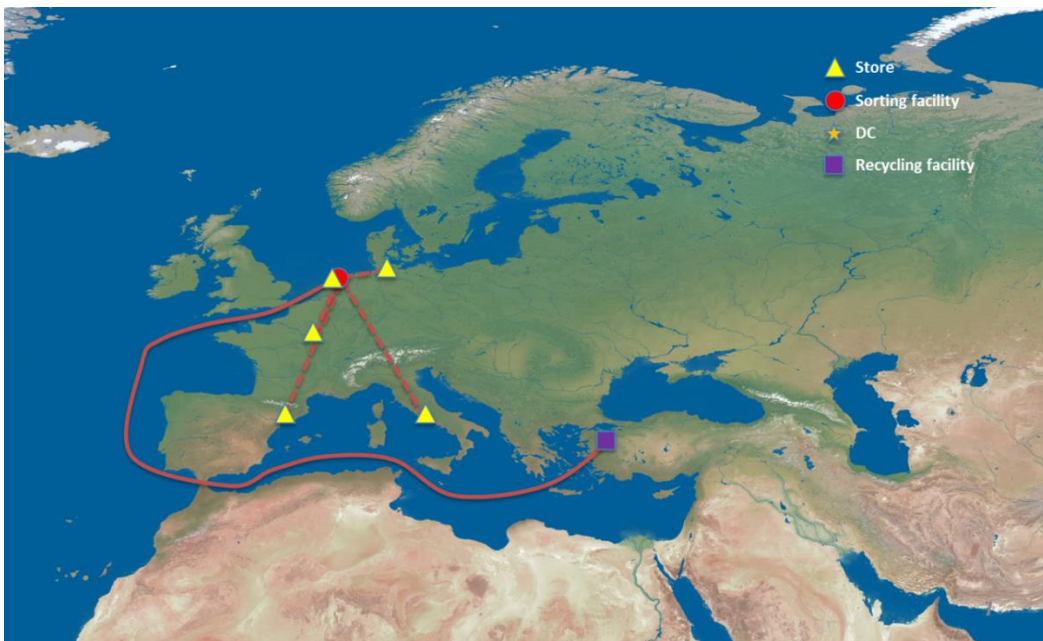

Figure 30: Recycling in Turkey

In Figure 31 the kilograms of CO_2 emissions from transportation to generate 1 kg of recycled yarn is shown. The process yield is assumed to be 60%. Transport emissions for India are 30% lower than the emissions for transport to China. For Turkey, the emissions are 55% lower than the emissions for shipping to China. Even when a mechanical recycling process is included, total emissions can be reduced with 7% when recycling in Turkey, and with 4% when recycling in India.
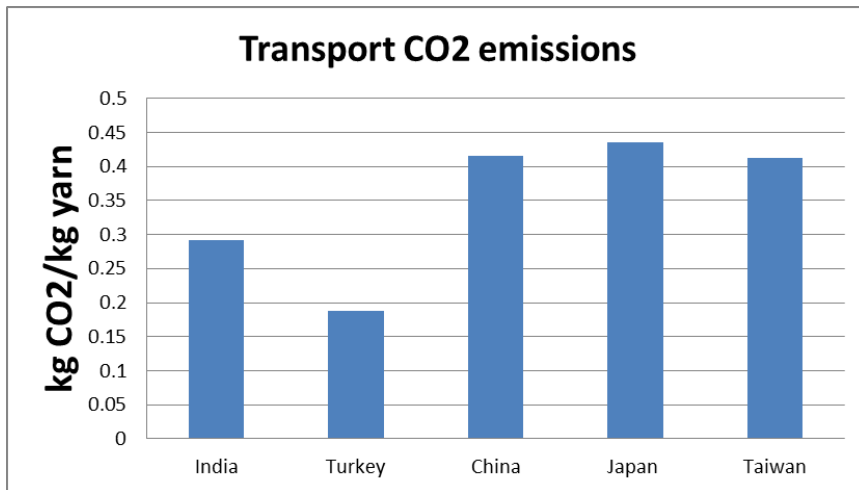

Figure 31: Transport emissions

6.4   Cost impact

Also the cost impact in the closed loop supply chain will be analyzed. The first costs in the closed loop chain are the transportation costs from stores to the sorting facility. For this transport the logistics services of DHL or UPS will be used. They pick up the full collection box at the store, and transport it to one of the sorting facilities or a distribution center. UPS prices are per package, DHL prices per kilogram. It is estimated that on average a collection box will weigh 25 kilograms of post-consumer clothing. Sorting either takes place in Europe or India. Sorting costs in Europe are based on the price of one sorting facility. Sorting costs for India are estimated based on expert data. The costs for shipping a FEU container are based on internal data from Nike. Nike has contracts with Maersk for all their inbound transport by vessel.

Recycling costs are determined indirectly. The polyester recycling processes considered in this project are based on the bottle recycling processes. The price per kilogram of recycled yarn from bottles is used for each vendor. In our case, Nike delivers the material input. Therefore the price of PET bottle bales the vendor pays is subtracted from their price per kg of recycled yarn. The price of baled bottles is based on data from an expert within Nike. This price is divided by the yield of the recycling process for bottles, which is 0.75. The price for the recycling process itself is 6% more expensive than the price of virgin yarn.

36

In Figure 32 the costs impact for the different recycling scenarios is shown. The price of virgin yarn is set to 100%. See Appendix I for the determination of the costs. The price of recycling is only a rough estimate since actual data is unavailable. The main goal of this figure is to shown the division of costs in the system. This is the standard situation with in store collection and sorting in the Netherlands. Note that the only difference between the three recycling options is the difference in transportation costs, since it is assumed the price of the process is the same as the average price over different vendors for the process of recycled yarn from bottles. It is interesting that the relative cost impact of transport and sorting in the closed loop system is much higher than the relative CO_2 impact of transport and sorting in Figure 22. Relative cost impacts of transport and sorting in the closed loop supply chain are 54%, 54% and 56%.
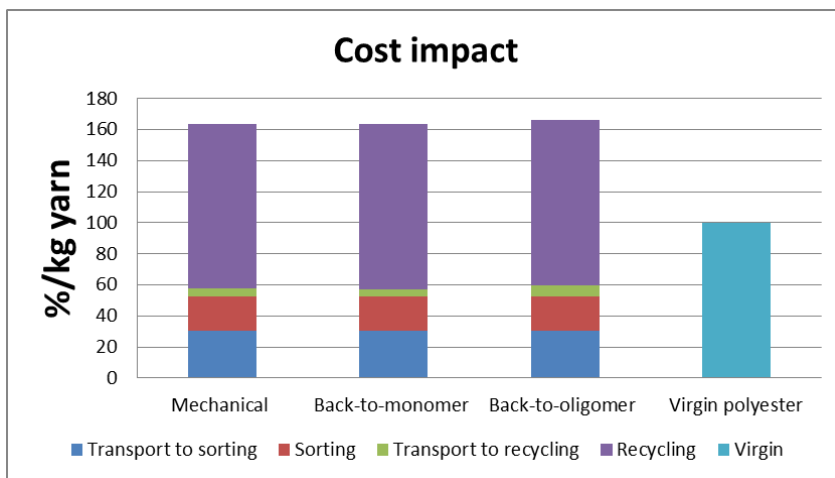

Figure 32: Cost of 1kg yarn

The chemical processes are very likely to be much more expensive. The bottle recycling processes are all mechanical processes which are scaled up. Chemical processes are only in small scale available. In Figure 33 the process costs for the chemical routes are increased with 25%.
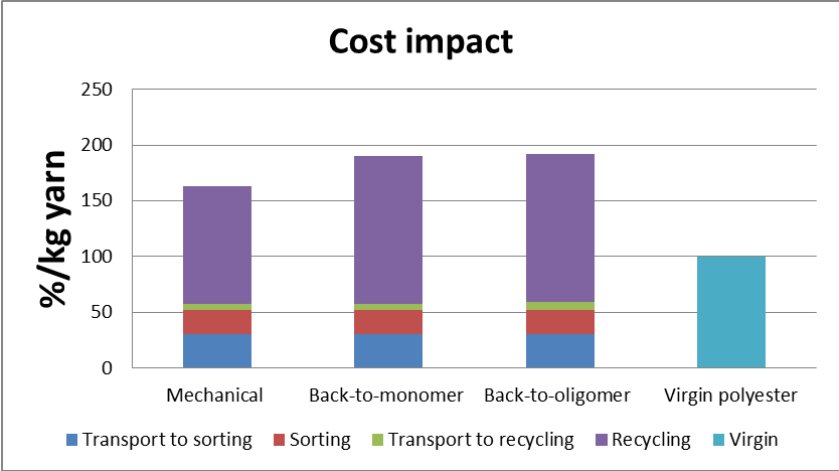
Figure 33: Cost of 1kg yarn

The reference cost of virgin polyester does not show what Nike is willing to pay for closed loop recycled yarn. In Figure 34 the average price of yarn from recycled PET bottles is used as 100%. This is the maximum what Nike currently pays for 1kg polyester yarn. Since this yarn is used in Nike's products, it is known they are willing to pay this amount. For the recycling processes only transport and sorting cost are displayed. Respectively, 130%, 130% and 120% of the transport and sorting costs in these three scenarios can be spent on the recycling process per kilogram.
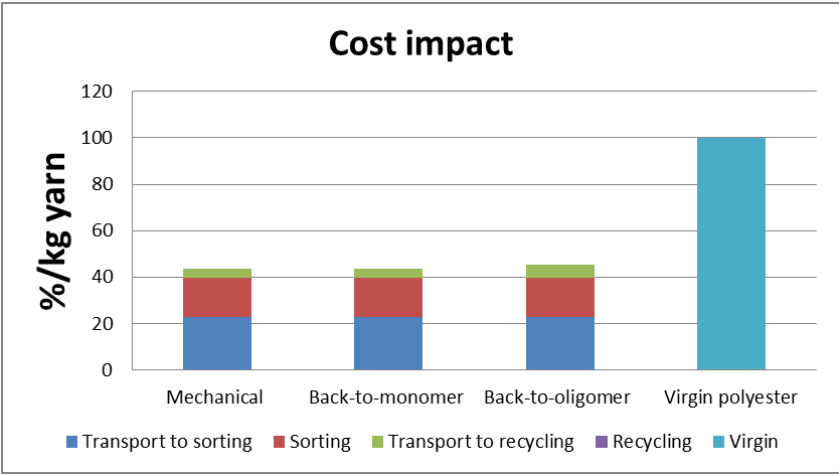
Figure 34: Target cost recycling 1kg of yarn

It is interesting to see that a large part of the cost arise from transportation between stores and sorting. This is a relative small distance, with a limited impact on the environment. However the use of services from DHL or UPS is expensive. It is recommended to look into other options for the transportation of collected material. It might be cheaper to collaborate with companies that collect and sort the post-consumer material before it is returned to Nike. Or even internal transport can be considered when volumes are large enough.

38

The larger relative impact of transportation costs compared to process costs is showed in Figure 35. This causes the line in Figure 36 to be much steeper than the environmental impacts per yield level in Figure 18 and Figure 19.
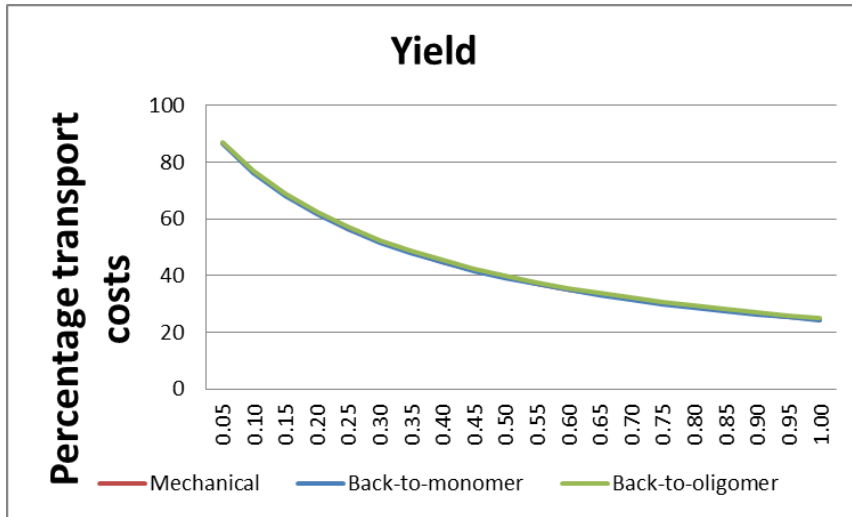
Figure 35: Relative cost impact transport
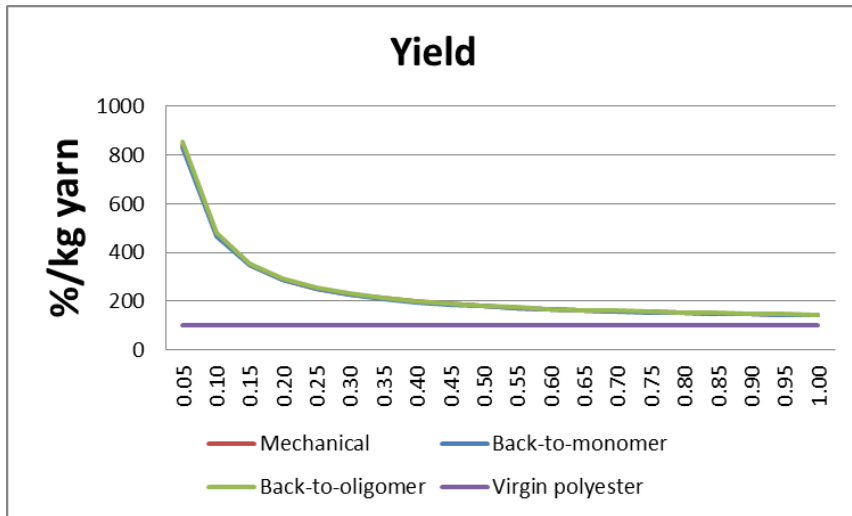
Figure 36: Costs per yield level

A better insight in the costs is given with a comparison to the total cost for the production of a polyester shirt. In Figure 37 the cost for producing a polyester shirt is given. This specific shirt is chosen based on a type of polyester that is used often within Nike. The total material costs, the fabric used, is 44% of total costs. 43% of the total materials, or 19% of total costs is yarn. This is yarn from recycled PET bottles. Assuming the costs of mechanical recycling in Figure 32, the total yarn costs would increase with 5% for the production of a shirt.
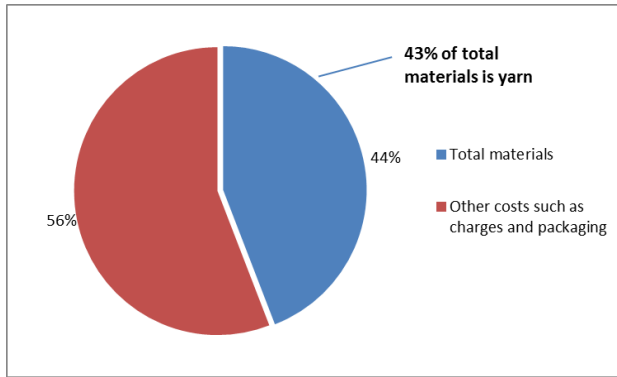
Figure 37: Cost of a shirt

6.5   Optimal scenarios

In this part the framework of chapter 3 is used to determine the optimal scenario based on costs, energy use and carbon dioxide emissions. The price for mechanical recycled yarn of section 6.4 is used. Also a yield of 60% is assumed. The main goal of these optimal scenarios is to show the difference in scenario between objectives. A tradeoff can be made between the price paid for a kilogram of yarn and the environmental impact of that yarn. See Table 4, Figure 38 for the energy use, Figure 39 for the CO_2 emissions and Figure 40 for the cost impact.

In the optimal scenario based on energy and carbon dioxide emissions, sorting will take place in Switzerland and mechanical recycling in Turkey. Energy use is decreased with 72%, and CO_2 emissions are decreased with 47% compared to virgin yarn. This large decrease however increases costs with 63%. Both sorting and mechanical recycling should take place in India when costs are minimized. In this scenario energy use is decreased with 68% and CO_2 emissions with 42% compared to virgin yarn. Costs increase with 50%. In this optimal costs scenario environmental impacts only increase a little compared to the optimal environmental scenario, but the increase in costs compared to virgin yarn decreases significantly. The main reason are the low sorting costs in India, see Figure 40. Compared to the maximum Nike pays for polyester yarn, cost increase 24% in the optimal environmental scenario and 14% in the optimal cost scenario. Even when comparing the optimal environmental scenario with mechanical recycling in China, 12% can be reduced on energy use and 8% on CO_2 emissions, while reducing costs with 1%. In the optimal cost scenario on the other hand, both energy use and emissions increase with 1%, but costs are reduced with 8%.

Scenario	Energy (MJ/kg)	CO_2 (kg CO_2/kg)	Cost (%/kg)
Optimal environmental	28.08	3.00	163%
Optimal cost	32.24	3.31	150%
Mechanical recycling China	31.74	3.27	164%
Virgin polyester	99.69	5.69	100%

Table 4: Optimal environmental scenario
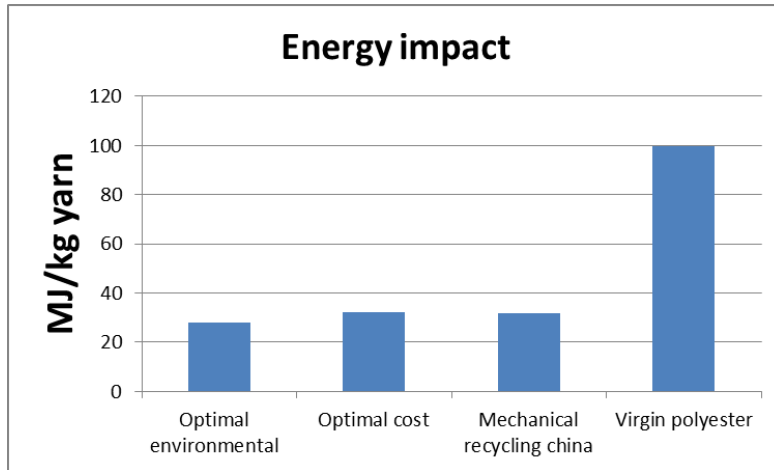
Figure 38: Energy use optimal scenario
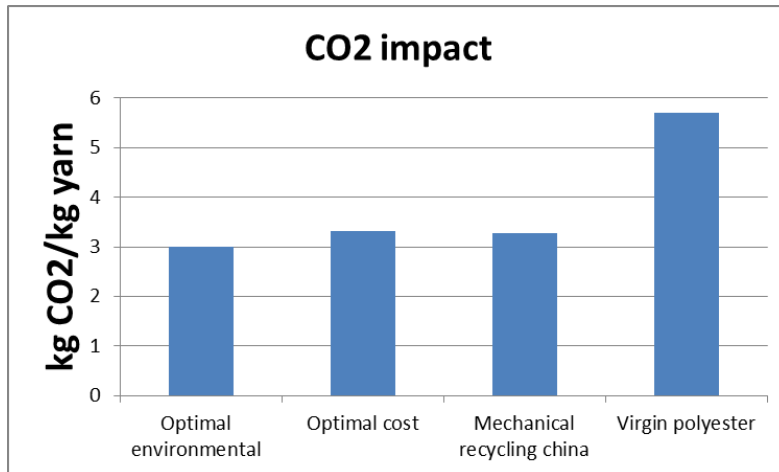
Figure 39: CO2 emissions optimal scenario
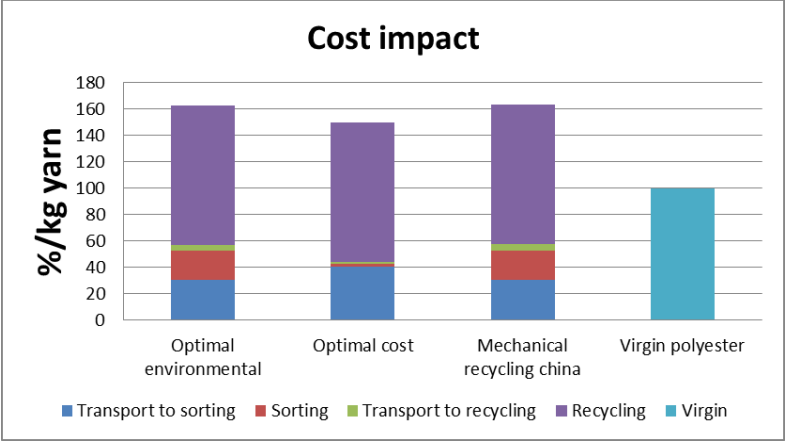
Figure 40: Cost impact optimal scenario

7 Conclusion

In this chapter the main findings and the limitations of the study are presented. Also recommendations are given for further research.

7.1 Main findings

A promising way to decrease both the amount of valuable resources used, and the waste created in the apparel supply chain, is a closed loop recycling system. Recycling is in general seen as a sustainable activity. However both transportation and processes have to be added, which might have a negative impact on the environment. An evaluation is made to give insights in the environmental and cost impact of closed loop recycling.

The standard scenarios are mechanical recycling in China, back-to-monomer recycling in Japan and back-to-oligomer recycling in Taiwan. Post-consumer material is collected and sorted in Western Europe, and the yield of the recycling processes is 60%. In Figure 41 the relative impacts of these methods and virgin polyester are compared, including all processes and transportation in the closed loop supply chain.
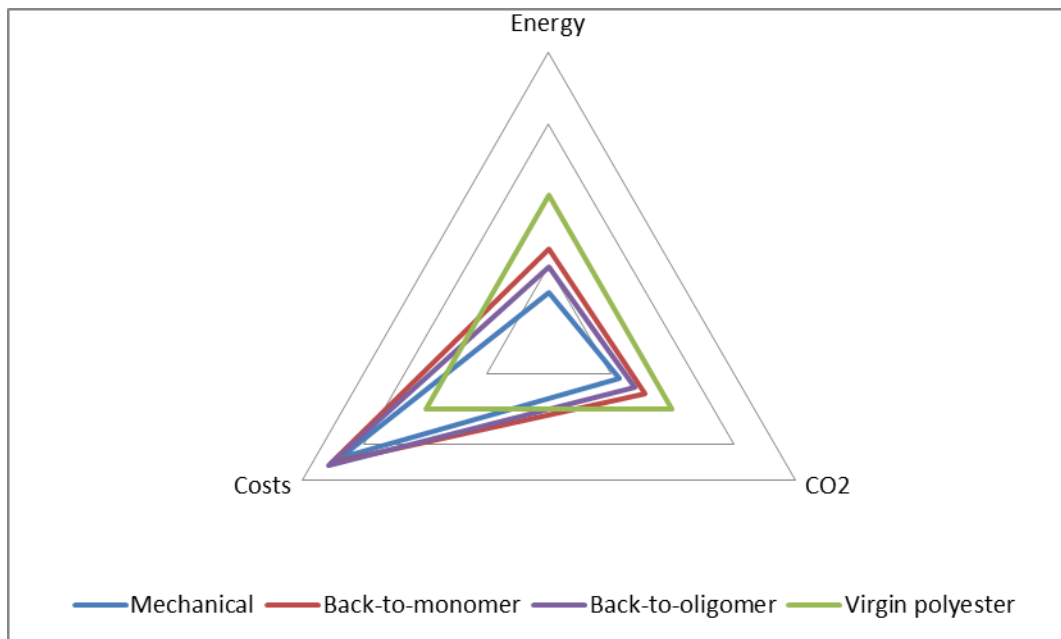
Figure 41: Relative comparison

First one kilogram of polyester waste is either incinerated or recycled with one of the three standard scenarios. Both on energy use and emissions all three recycling methods are the preferred treatment for polyester waste. In an extended scenario, waste created in the recycling process is incinerated instead of landfilled. More energy is recovered from the post-

consumer material, but also more CO_2 is emitted. However all recycling methods are still preferred over incineration.

In the second assessment the focus shifted to the impact of producing of 1kg polyester yarn. Mechanical, back-to-monomer and back-to-oligomer recycling respectively reduce energy use with 68%, 38% and 50% compared with virgin polyester. Enormous reductions can be realized on Nike's environmental impact when recycled yarn is used for their entire demand of polyester yarn. Next a sensitivity analysis is conducted for the yield in these recycling processes, since the value of this parameter is unknown. It is important to note that the results are highly dependent on the amount of input material for the recycling process. With lower yields more material has to be transported from the collection area in Europe to recycling facilities in Asia, and the contribution of transport on both the environmental and cost impacts will be more important. However only with unrealistic low yields virgin methods are preferred for the production of polyester yarn.

In the three standard recycling scenarios, transport accounts for a small amount of the total CO_2 emissions. It still is interesting to abate these emissions, since they can be reduced much easier compared to abating impacts in the recycling processes. The emissions in recycling processes are more or less fixed, while transport emissions can be reduced via numerous routes. In this project locations in the network design are changed to minimize the impact. Locating recycling facilities closer to the collection market is an interesting option. Transport emissions are reduced with 30% with recycling facilities in India, and 43% with recycling facilities in Turkey. Recycling in Turkey can decrease total emissions with 7%.

For the standard scenarios, it is interesting that the relative cost impact of transport and sorting of the closed loop system is much higher than the relative energy and CO_2 impact. Especially the first transport movement from stores to sorting facility is expensive, due to the use of 3PL.

In the last assessment either one of the environmental measures or costs are minimized using the framework. The optimal scenario for the energy use and CO_2 emissions is the same. Energy use can be reduced with 72% and emissions with 47%. The sorting location is Switzerland and the recycling facility is located in Turkey. In the scenario where costs are optimized, both sorting and recycling takes place in India. While energy use and CO_2 emissions will only increase a little in the optimal cost scenario compared to recycling in China, cost are decreased.

7.2   Limitations and further research

For the environmental impact, energy use and CO_2 emissions are included. A downside is that the effects of closed loop supply chains on other environmental measures are unknown. Different sources are used to determine the environmental impacts included in this project.

These sources are all subjected to different scopes and assumptions. Therefore it is possible the impacts might not have the same order of magnitude.

Since closed loop textile recycling is still in an early stage of development, no large scale facilities are available. Important data such as the yield of the total recycling process is therefore not available. Extra data on these processes can be gathered in pilot tests. Large scale recycling techniques are necessary for a feasible system. In order to get the right input material for these processes, advanced collection and sorting systems are also needed. If color isn't removed in the recycling process, the dyeing of the fabric might have a different impact as well.

Also the comparison between recycling methods should be made with care. The only available methods for recycling post-consumer polyester textile are the back-to-monomer process and mechanical process. However mechanically recycled yarn has a lower quality. The strength of the yarn can be lower than virgin yarn, and color isn't removed in the process. The back-to-oligomer chemical process is not available commercially, due to issues with purifying the output. The cost of these processes is not known. In this project costs for recycling are based on PET-bottle recycling methods.

Assumptions have been made on transport aspects as well. Containers are assumed to be full when shipped and transport is efficient, so no long time storage. This research is subject to all the assumptions in the NTM methodology. Transport emissions are based on European vehicles, also for transportation in Asia, where emissions might be higher. A better estimate of transport emissions can be gained when the actual fuel consumption of vehicles from third party logistic providers are included in the assessment. Also only direct emissions and energy use for transport is included. The locations used in the closed loop supply chain need to be chosen carefully, to minimize emissions. An integrated approach is needed where processes further up and downstream are also included. When recycling takes place in Turkey and material can be processed further in Turkey, this will also decrease emissions from factory to distribution. In this project, the carbon emissions based on energy use for the process are not changed per country. In reality not all countries have the same carbon emissions for energy.

Interesting research can be done on optimization models for closed loop supply chains in textile. The model included in this project merely focuses on the decision to use facilities and transportation in between. This can for example be extended with actual quantities transported in the closed loop supply chain. Also capacities of both facilities and transportation modes might be included. Even transport mode selection can be included.

8 Implementation

Sustainability is an important part of Nike's business strategy. Nike takes account of the impacts they create now, and includes sustainable thinking in decisions made for the future. Nike has set specific targets for numerous sustainable topics. For example they aim to reduce CO_2 emissions per unit with 20% between FY11 and FY15. Also they want 100% of their new products to be designed according to standards for considered design.

There are numerous sustainable initiatives in all parts of Nike's business. This project is focused on evaluating closed loop supply chains as a method to reduce the impact of yarn. A general framework and tool is developed in chapter 3 to determine the environmental impact of closing Nike's supply chain by recycling apparel. Several scenarios are examined and compared with each other. The framework can be adapted when new information is available, and new insights can be gained with more reliable data. In this part insights in closed loop supply chains are given based on previous findings.

Closed loop supply chains are considered by Nike for the possibility to reduce the impact of yarn. The largest part of the energy and CO_2 impact in closed loop supply chains are caused by the recycling processes. For the three selected methods in this project, the results show that mechanical recycling has the least impact. However in order to select the best method, pilot tests are needed. These tests will show the actual yield of the recycling processes. When for example the yield is very low in mechanical recycling, and very high with chemical recycling, the last method can still be preferred. Also the quality of the output material can be determined. Without a suitable application for the material in new apparel, no closed loop supply chain is possible. In order to realize the benefits shown in this report, the recycled yarn should be used in apparel that would normally be made of virgin yarn. Cooperation is needed between Nike and companies that provide these recycling methods.

The first step in a closed loop supply chain for polyester material is to collect post-consumer material. This can be done by using in-store boxes. Nike already has experience with this in their Reuse-a-shoe program for the recycling of shoes. Also other apparel retailers are collecting material this way. Since stores have limited capacity, whenever a box is full it has to be transported to the sorting facility. In this project a 3PL service is used. The costs analysis shows this transport has a large impact on the total costs of the closed loop system. Therefore it is recommended to Nike to investigate alternatives for this transportation. They can cooperate with companies that collect post-consumer textile for shared transportation, set up their own transportation, or buy post-consumer material.

Either one of the environmental measures can be minimized as an objective, or costs can be minimized. Nike can also specify more specific objectives, such as the examples in section 3.4. When energy and CO_2 emissions are minimized, the same scenario is selected. The collected material from stores will be transported to a sorting facility in Switzerland for the selected stores in this project. Nike should find the optimal location for sorting if all their stores are included. At the sorting location the polyester material is sorted out and stored until a FEU is full. This will be transported by truck to the port of Genoa in Italy. From there on it is shipped by vessel to the port of Gemlik in Turkey, which is close to the textile industry.

An interesting insight in the optimal scenarios is that when costs are minimized there are still large environmental benefits. 68% of the energy use and 42% of the CO_2 emissions can be reduced compared to virgin yarn. These savings are only a little less than the optimal scenario based on environmental measures. This situation however has the least extra costs compared to virgin yarn. The collected material from stores will be brought to Nike's DC in Belgium for consolidation. There the material will be stored until a FEU container can be fully loaded based on volume. The FEU will be transported to Rotterdam by truck and subsequently put on a 6000TEU vessel to the port of Pipavav in India. In the free trade zones of the port the material can be sorted based on fiber type or color. The price of sorting in India is the main reason for lower costs in this scenario. Only the polyester material will be further processed within the scope of this project. The other materials can also be recycled or sold. The remained polyester is then transported by truck to a textile industry in India, such as Nashik.

Next to the assessment made in this project, the framework can be used to compare other initiatives that can reduce Nike's environmental impact. These can be closed loop recycling options, but also other recycling options. For example the material that can't be recycled in these processes can be treated differently. It can be converted into biofuel, which can be used in Nike's distribution network. Or if waste cotton can't be recycled into new cotton, viscose fibers can be produced.

Also the methodology for calculating transport emissions can be used within Nike for a detailed calculation of their inbound and outbound emissions. Detailed information of the fleet used by Nike's logistic partners can be included. Accurate measurement of the emissions is important to make the right decisions on reduction options. An example of an assessment that can be made is to use emission data of biofuel instead of regular diesel to determine the reduction in emissions for Nike.

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Appendix I Calculations

Parameters

EU_t	: Energy use for transporting 1kg polyester
EU_s	: Energy use for sorting 1kg of polyester
EU_r	: Energy use for recycling 1kg of polyester
EU_v	: Energy use for the production of 1kg virgin polyester
EU_i	: Energy use for the incineration of 1kg polyester
CE_t	: CO_2 emissions for transporting 1kg polyester
CE_s	: CO_2 emissions for sorting 1kg of polyester
CE_r	: CO_2 emissions for recycling 1kg of polyester
CE_v	: CO_2 emissions for the production of 1kg virgin polyester
CE_i	: CO_2 emissions for the incineration of 1kg polyester
C_t	: Cost of transporting 1kg polyester
C_s	: Cost of sorting 1kg of polyester
C_r	: Cost of recycling 1kg of polyester
C_v	: Cost of 1kg virgin polyester
μ_r	: Yield of the recycling process
cf	: Conversion factor for CO_2 emissions to energy use in transport

End-of-life

The energy use for recycling 1kg of polyester waste is calculated by $(EU_t + EU_s) + (EU_r - EU_v) * \mu_r$. The CO_2 emissions for recycling 1kg of polyester waste are determined by $(CE_t + CE_s) + (CE_r - CE_v) * \mu_r$. The first part of these equations $(EU_t + EU_s)$ and $(CE_t + CE_s)$ are the energy used and carbon emissions for all the processes before recycling. This includes transportation from collection in stores to a sorting facility, the sorting process and the transportation from sorting facility to recycling facility. It is assumed there is no loss of material in this process, so the 1 kg collected material will arrive at the recycling facility. In section 5.2 this assumption is explained.

EU_t and CE_t are computed with the NTM method. See section 3.3 for the method and formulas. The NTM method used in this project has CO_2 emissions as output. $EU_t = CE_t/cf$ where cf is a conversion factor to determine the energy used based on carbon dioxide emissions. For diesel this factor is 0.0729 kg CO_2/MJ (Nike, 2012). As input for the NTM calculations, the distance travelled, transport mode and load factor based on weight or the weight transported with the transport mode need to be known. See section 6.1 for details on the transport data.

EU_s and CE_s for sorting in Western Europe are based on data from a sorting company in the Netherlands (direct communication). No energy use or CO_2 emissions are assumed for sorting in Asia, since this process is entirely manual.

The second part of the equation, $(EU_r - EU_v) * \mu_r$ for energy use and $(CE_r - CE_v) * \mu_r$ for CO_2 emissions calculates the impact for the recycling process. $EU_r * \mu_r$ is the energy needed to produce μ_r kilogram output material for every kilogram input material. For the mechanical process EU_r and CE_r are the energy and emissions for the recycling, spinning, drawing and texturizing polyester yarn from internal data of one of Nike's yarn suppliers (Nike internal). For back-to-monomer and back-to-oligomer recycling data from Shen et al. (2010) for the recycling process is used. However they included transportation of bottles as input material. Therefore the energy and emissions for transporting 10t of bottle 225 km with truck and semi-trailer (Shen et al., 2010) is determined using NTM, and deducted from the recycling impact. The energy and emissions for drawing and texturizing yarn (Laursen et al., 1997) are not yet included in Shen et al. (2010) data, and therefore this is added. This resulted in EU_r and CE_r for the chemical recycling processes. $EU_v * \mu_r$ is the energy use and $CE_v * \mu_r$ is the CO_2 emission for the virgin production of μ_r kilogram output material for every kilogram input material. This amount is substituted when material is recycled into yarn, and therefore the amount of energy and carbon emissions can be subtracted from the recycling process. The data for EU_v and CE_v is based on data from Nike's MSI (Nike MSI, 2013). The virgin production process for polyester consists of four main parts, the raw material production and PET pellet production (Boustead, 2005), the filament yarn spinning (Franklin Institute, 1993) and the drawing and texturizing of the yarn (Laursen et al., 1997).

In the situation where the process waste is incinerated, $(1 - \mu_r) * EU_i$ is added to $(EU_t + EU_s) + (EU_r - EU_v) * \mu_r$, and $(1 - \mu_r) * CE_i$ is added to $(CE_t + CE_s) + (CE_r - CE_v) * \mu_r$. $(1 - \mu_r)$ is the amount that is not recycled into yarn. EU_i and CE_i are the energy impact and carbon dioxide emissions from incinerating 1kg of polyester with substitution for normal energy production. The source is Shen and Patel (2010). It is here assumed that all the waste has the same incinerating properties as polyester. In real life, the waste might consist of numerous other materials.

Yarn production

The equations for recycling 1kg of polyester waste can be rewritten to compute the impact for the production of 1kg recycled polyester yarn. For energy use the expression is $EU_r + (EU_t + EU_s)/\mu_r$. For CO_2 emissions it is $CE_r + (CE_t + CE_s)/\mu_r$. The impacts from the recycling processes EU_r and CE_r are now fixed, since the amount of output is fixed to 1kg of yarn. However more material needs to be transported and sorted depending on the input/output coefficient μ_r.

For the situations with waste incineration ($(1/\mu_r) - 1) * EU_i$ is added to the energy use equation and ($(1/\mu_r) - 1) * CE_i$ is added to the CO_2 emissions equation. ($(1/\mu_r) - 1)$ is the amount of material not recycled into yarn.

μ_r levels are changed from 5% to 100% in steps of 5% to gain the energy use and CO_2 emissions graphs per yield level.

Cost impact

Costs in a closed loop supply chain are determined in a similar way as energy use and carbon emissions are determined. $C_r + (C_t + C_s)/\mu_r$ is the expression for the cost of recycling 1kg polyester yarn. C_r is based on the price of recycled PET-bottle yarn minus the cost of PET-bottles as input material. C_s for sorting in Western Europe is based on the price charged by a sorting company in the Netherlands. For sorting in India it is based on an estimate from an expert. C_t for transport from store to sorting facility is based on the price Nike pays for shipping with UPS. The average price for sending 1kg of material in 25kg boxes from the five selected stores to the destination locations is taken. The price of road transport is determined by a price for transporting a FEU per kilometer in Europe. Based on the weight in the FEU the price per kilogram material is determined. This is also used for transport in Asia. For sending a FEU from every port to port used in this project prices are determined by Nike for using Maersk lines. Handling costs in the ports are included. Based on the weight in the FEU the price per kilogram material is determined.

Appendix II Data sources

Data	Data source/assumption
Cotton farming	Cotton Inc. (2012)
Cotton spinning	Cotton Inc. (2012)
Polyester feedstock	Boustead (2005)
Polyester pellet production	Boustead (2005)
Polyester melt-spinning	Franklin Institute (1993)
Polyester yarn processing	Laursen et al. (1997)
Sorting	Sorting company
Mechanical recycling	Nike internal
Chemical recycling (Back-to-monomer)	Shen et al. (2010), Laursen et al. (1997)
Chemical recycling (Back-to-oligomer)	Shen et al. (2010), Laursen et al. (1997)
Polymerization	PlasticsEurope (2011)
Incinerating cotton	Shen and Patel (2010)
Incinerating polyester	Shen and Patel (2010)

Table 5: Sources processes

Data	Data source/assumption
Road distances	Google maps
Ocean distances	Nike internal
Load factor collecting-sorting	Assumption
Load factor sorting-recycling	Sorting company
Fuel consumption	NTM
Transport mode	UPS, Nike internal

Table 6: Sources transportation

Data	Data source/assumption
Cost virgin cotton yarn	Nike internal
Cost virgin polyester yarn	Nike internal
Cost transportation	UPS, Nike internal
Cost sorting	Sorting company
Cost recycling	Nike internal

Table 7: Sources costs

Appendix III Impact tables

Process	Energy (MJ/kg)	Source
Polyester	99.69	Boustead (2005) Franklin Institute (1993) Laursen et al. (1997)
Cotton	75.43	Cotton Inc. (2012)

Table 8: Energy use virgin yarn

Process	CO_2 (kg CO_2/kg)	Source
Polyester	5.69	Boustead (2005) Franklin Institute (1993) Laursen et al. (1997)
Cotton	5.63	Cotton Inc. (2012)

Table 9: CO_2 emissions virgin yarn

Process	Water (L/kg)	Source
Polyester	62	Boustead (2005) Franklin Institute (1993) Laursen et al. (1997)
Cotton	2120	Cotton Inc. (2012)

Table 10: Water use virgin yarn

Process	Energy (MJ/kg)	Source
Sorting	0.283	Sorting company
Mechanical polyester	25.575	Nike internal
Chemical back-to-monomer	55.8	Shen et al. (2010), Laursen et al. (1997)
Chemical back-to-oligomer	43.8	Shen et al. (2010), Laursen et al. (1997)
Incinerating polyester	-14	Shen and Patel (2010)
Incinerating cotton	-10	Shen and Patel (2010)

Table 11: Energy use recycling

Process	CO_2 (kg CO_2/kg)	Source
Sorting	0.017	Sorting company
Mechanical polyester	2.823	Nike internal
Chemical back-to-monomer	4	Shen et al. (2010), Laursen et al. (1997)
Chemical back-to-oligomer	3.51	Shen et al. (2010), Laursen et al. (1997)
Incinerating polyester	1.5	Shen and Patel (2010)
Incinerating cotton	1.1	Shen and Patel (2010)

Table 12: CO2 emissions recycling

Process	Water (L/kg)	Source
Sorting	-	Sorting company
Mechanical polyester	62	Boustead (2005)
Chemical back-to-monomer	62	Boustead (2005)
Chemical back-to-oligomer	62	Boustead (2005)
Incinerating polyester	-	Shen and Patel (2010)
Incinerating cotton	-	Shen and Patel (2010)

Table 13: Water use recycling