

# The Zero-Waste Loafer

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## ***INTRODUCTION***

A shoe is an item of footwear evolved to protect the human foot. Contemporary footwear varies in style, complexity and cost, from the most basic sandal, via high fashion shoes for women sometimes costing thousands of dollars a pair, through to complex boots specially designed for mountaineering or skiing. Shoes have traditionally been made from leather, wood or canvas, but are increasingly made from rubber, plastics and other petrochemical-derived materials.

Americans purchased 2.4 billion pairs of shoes in 2006, eighty-five percent of which come from China. The manufacturing of these shoes use a wide variety of materials, most of which are responsible for some negative environmental impact, including toxic pollution, conventional air pollution and landfill waste. Furthermore, Greenhouse gas emissions from transportation of materials to the manufacturing facility, and subsequent transportation of finished product to the point of sale contribute to global warming.

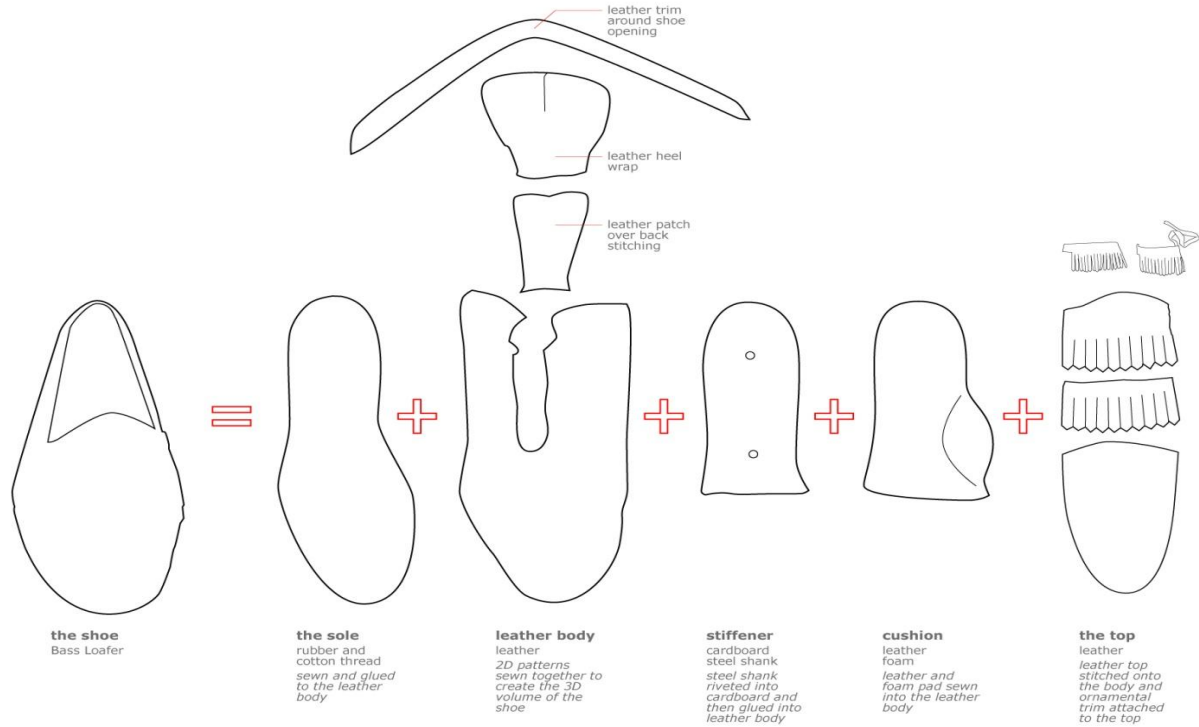
The following report examines a specific type of footwear – the loafer – and provides a detailed redesign for a loafer-type shoe. The overriding objective of this new design is for the shoe to generate zero materials waste over its life cycle. The second objective is the minimization of toxic waste and emissions throughout the life cycle. Climate change impacts and conventional air pollutants resulting from energy use, transportation, and the manufacturing process are also examined, and minimized whenever possible.

## ***PARTS OF A SHOE***

Loafers are low, lace-less, slip-on, shoe that is made of leather. In the United States, the loafer enjoys general use as a casual and informal shoe worn for work and leisure<sup>1</sup>. This style of footwear is most popular in brown and black. See figure one below for a diagram of the elements of a typical leather loafer.

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<sup>1</sup>Antogiovanni, Nicholas (2006). *The Suit: A Machiavellian approach to men's style*. New York: HarperCollins Publishers. p. 92.



**Figure 1: Typical Leather Cutouts for a Loafer-Type Shoe<sup>2</sup>**

## **GENERAL SHOE TERMINOLOGY**

**Sole** - The bottom of a shoe is called the sole.

**Midsole** - The layer in between the top and bottom of the sole that is typically there for shock absorption.

**Upper** - The upper part that helps hold the shoe onto the foot; in leather loafers, this is synonymous to the tongue of the shoe.

## **FUNCTIONAL CRITERIA**

Our shoe will be a loafer style shoe for men. A loafer is a slip on style of shoe that enjoys general use as a casual and informal shoe worn for work and leisure. Our loafer will be built to last at least 500 days under normal use. We define normal use as an average (160lb) person wearing the shoe for ordinary walking, two miles per day, five days per week, for two years. At this time, the shoe will be worn to the point that most people would get rid of it. Others may choose to wear it longer, others less. Either way,

<sup>2</sup> <http://futurecraft.media.mit.edu/rmurphy/files/2007/09/shoe-coming-apart.jpg>

we will take back the used shoe so that it may be recycled into a new shoe, or provide another use.

The loafer will provide a reasonable level of comfort throughout its life, while protecting feet from terrain and climatic conditions. It also needs to hold its structure and appearance, with reasonable fading as it breaks in. This will ensure that the wearer would want to wear the shoe often, and that it is a quality product people would want to buy.

### ***DESIGN GOALS/CRITERIA***

The following are our design goals, in order of importance:

1. Zero materials waste in manufacturing
2. Zero toxic waste or emissions
3. Zero air pollution
4. Carbon neutral

Achieving each of these criteria is our goal; however, we have ranked them in order of importance because we realize that this is not always attainable.

### ***PROCESS MATERIALS OVERVIEW***

There will be opportunities to reduce or eliminate waste and emissions at every stage in the process. For example, at the materials acquisition stage, we can purchase raw materials from local suppliers (to reduce transportation) and make sure that all purchased materials come from eco-friendly processes themselves. We can also choose to purchase recycled materials, which divert waste back into production. We will design the process to require the least amount of material per shoe possible and choose low-toxicity materials. Similar opportunities are available throughout the lifecycle of the product.

Generally, shoes are composed of two main components; the sole and the upper. Bovine hide commonly provides the leather upper for a loafer, and will be our material of choice. Leather is ideal for uppers because it is naturally flexible, durable, and naturally water resistant. Bovine leather is a by-product of the beef industry, and as such its use represents what would otherwise be waste from another system. It is also a material that

can be composted at municipal facilities. We will procure ISO 14001 certified leathers to minimize the environmental impact of this important material.

The sole of a shoe is typically made out of rubber, although some use a polyurethane sole and most shoes have a shank in the sole to keep the shape of the shoe. The shank is usually made from Ethylene Vinyl Acetate, or EVA. The latter two materials mentioned are highly toxic according to the EPA and will not be considered for our shoe because they are not absolutely essential. To achieve our goal of minimal materials waste, we have decided to stick with a basic, durable, rubber sole. Preparing virgin rubber for use in a shoe requires vulcanization, which is a way of curing latex rubber with sulfuric acid to make the end product more durable and elastic. In addition, this process can require some 40 other chemicals to create the desirable end product, or shoe sole, including the highly toxic carbon black. The transportation emissions alone in procuring natural rubber, usually shipped from Malaysia, contribute to global warming. Curing rubber with sulfuric acid is highly corrosive and has detrimental effects on plants, animals, and marine life. We intend to avoid creating more of these negative environmental impacts by tapping into the scrap rubber market. According to the Rubber Manufacturer's Association (RMA) Report of November 2006, there are 300 million scrap tires generated annually in the United States. With an average scrap tire weight of 22.5 pounds, this represents well over 6 billion pounds of predominantly hydrocarbon based materials that we can access.<sup>3</sup>

The sole and the upper of a shoe need to be bound together with stitching and adhesives. Typically, shoes are stitched with nylon 6, thread and/or glued with industrial adhesives. The production of nylon 6 thread requires the input of some highly toxic chemicals that can be detrimental to the environment, specifically their effect on air pollution. This process is explained in greater detail in the Inventory Analysis section. Industrial adhesives are also notoriously toxic as most of these adhesives are hydrocarbon-based. To avert these environmental impacts, we intend to use a natural fiber thread with comparable durability to nylon 6 such as jute or hemp. Jute and hemp

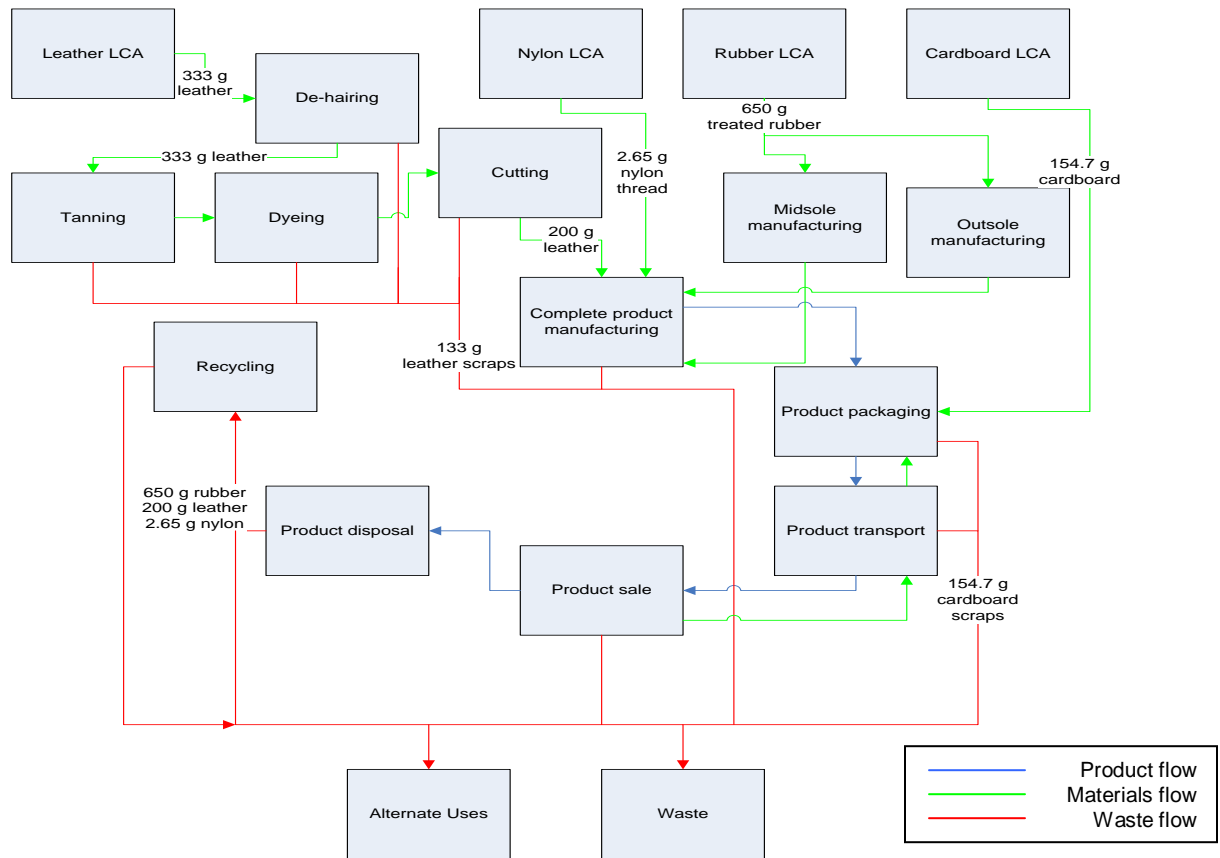
come from plants and are a renewable resource that can be obtained locally, if not from the Americas to reduce transportation emissions, and their processing requires no toxic chemicals. We can also opt to use vegetable-based adhesives. However, these non-toxic alternatives are not as durable as industrial adhesives. There is also the option of melding the upper and sole together and reinforcing with the natural fiber thread

Lastly, the shoe needs to be packaged, used, and recycled or composted. We intend to calculate the minimal required space for packaging to reduce package materials. These materials will have a high post-consumer recycled content and be made from paper. The packaging can be recycled, returned, or composted. In addition, the shoe itself is designed to be recycled and composted. For recycling, we will obtain the used shoes from our retailers and recycle the materials in-house. If not, the shoe can be composted in a municipal composting facility only, however we realize this will take many years to do.

### ***SYSTEM LIFE CYCLE***

The life cycle of our system is depicted below in Figure 2. All values are per pair of shoes. The first step in the life cycle is procurement of input materials for the shoes and packaging. These inputs include tanning materials and dyes, leathers, threads, adhesives, sole materials (latex rubber), and packaging materials. The next step is the manufacturing process, resulting in finished loafers. The finished shoes will then be packaged, shipped and sold to the consumer in a manner that produces minimum waste and environmental impact. At the end of life the product and the packaging will be disposed of in a manner that creates no new waste; e.g. recycling or composting.

Our system is analyzed by combining the results of existing lifecycle assessments, in some cases supplementing with our own models and calculations. Existing LCA data can be found for all raw materials used in the process, either from a specific LCA report or from a data aggregation tool such as EIOLCA or UWME EcoScores.



**Figure 2: Lifecycle process flow diagram for a pair of loafers.**

### **DESIGN STRATEGIES**

Our primary goal is zero net waste throughout the product life cycle, which we will calculate by mass. In calculating net waste, inputs sourced from recycled materials that would have otherwise gone to waste in another system or process will count negatively toward the net total waste. This allows us to design a system that will put no more waste into the environment than it removes, even if it does output some amount.

We will analyze each of the unit processes described in Table 1 below in order to identify the least wasteful method to achieve the goal of each process. Where a zero waste alternative does not exist, we will actively seek to reformulate the process to meet this goal. To this end, we will utilize recycled materials to make our loafer whenever possible. Where we cannot recycle materials ourselves, or purchase recycled materials,

we will strive to purchase new materials from companies that adhere to ISO 14001 certifications. We will also look at ways to improve our product stewardship by managing our product at the end of its life cycle. For example, recycling rubber from our shoes will help eliminate harmful environmental effects of it going into a landfill, even if the leather is chemically treated and the rubber is synthetic.<sup>4</sup> According to the EPA's facts and figures report on municipal solid waste, in 2007, 14.7% of leather and rubber had been successfully recycled.<sup>5</sup>

In addition to our primary goal, we will minimize toxic emissions and waste from the system, and eliminate the use of toxic chemicals and solvents in the manufacturing process. Primary considerations in this category will be the materials used in the tanning and dyeing process, and solvents used in assembling the final product. Our leather will be tanned and dyed using non-toxic vegetable based dyes to eliminate toxic chromium, benzene, aldehydes, solvents, and other toxic chemicals. In the processes of production, we could confine actions such as melting rubber to minimize its escape to the air. Capturing our waste can ensure its use or proper use or treatment later.

Our final goal is to minimize CO<sub>2</sub> emissions at every stage in the design and manufacturing process. We will choose a facility powered with clean, renewable energy such as hydropower, wind or solar. We will also investigate methods of transportation of materials and final products in ways that minimize our CO<sub>2</sub> emissions. Our facility will be located in the Pacific Northwest, and powered with clean, renewable energy such as wind or solar. Our packaging will be as small as we can accomplish without sacrificing the quality of the shoe, will be made from 100% recycled materials, and be 100% recyclable.

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<sup>4</sup> Woolridge, A.C., Ward, G.D., Phillips, P.S., Collins, M., Gandy, S. (2006). Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective. *Resources, Conservation and Recycling*. 46(1), 94-103.

<sup>5</sup>EPA, *Municipal Solid Waste in the United States: Facts and Figures*. 2007. <http://www.epa.gov/osw/nonhaz/municipal/pubs/msw07-rpt.pdf>

**Table 1: Unit Process List**

<u>Process</u>	<u>Sub-process</u>	<u>Conventional method</u>	<u>Alternative methods</u>	<u>Concerns / Remarks</u>
<b>Leather preparation</b>	Obtain leather for shoe uppers	Obtain leather from the meat industry	Obtain recycled leather from another process	May need to incorporate a small amt. of virgin material
	Obtain tanning/dyeing supplies for leather			Lets make this separate process
	Tan/dye leather	Chemical dye	Vegetable-based dye	Chemical dyes are suspected carcinogens. Vegetable dyes are not.
	Cut out shoe patterns	Die cut	Hand cut, laser cut	
<b>Sole manufacturing</b>	Obtain sole material	Natural rubber, synthetics from petroleum	Recycled natural rubber or synthetics, e.g. old tires	May need to incorporate a small amt. of virgin material
	Melt sole material			
	Manufacture soles	Injection molding	Casted, cut out	
<b>Last manufacturing</b>	Obtain last material	Plastic	Wood/Recycled plastic/Biodegradable plastic	
	Manufacture last	Injection molding of plastic	Machine wooden block into correct shape, repurpose shavings as fuel	
<b>Shoe assembly</b>	Obtain thread	Nylon thread	Hemp, jute, recycled synthetics	
	Obtain adhesive	Solvent-based adhesive	Water-based adhesive, or melt sole directly to upper and don't use adhesive	Could fall apart faster. Best to reinforce with stitching.
	Stitch together uppers on last	Sewing machine (automated?)	Glued	
	Attach sole to uppers	Glued	Sewn, melted, welted	
<b>Packaging</b>	Obtain material for packaging	Corrugated cardboard, all new material	Recycled plastic, scrap or excess lumber, recycled cardboard	
	Print identifying information on product	Print on cardboard with laser printer or apply pre-printed stickers	Vegetable based inks.	
	Package product in consumer container	Single-use cardboard shoebox	Minimal packaging; offer discount for not getting a box, maybe? Or we could provide a super durable	

			box and give credit for returning it at shoe end of life, but I don't know how successful that would be.	
	Package product in delivery container	Single-use cardboard carton	Reusable plastic or wooden tote, or durable reusable cardboard box	
<b>Product transport</b>				
		Truck it across the country	Sell nearby manufacturing plant only. Use biodiesel automobile run on recycled vegetable oil.	
<b>Product sale</b>				
	Product advertisement and sale to consumer			
	Disposal of delivery container	Throw away or recycle cardboard box	Return reusable tote to manufacturing center	
<b>Product end-of-life</b>				
	Disposal of shoes	Throw in garbage	Recycle: leather maybe back into process + for dog toys, soles back into process. Offer a discount on a new pair of shoes for turning in your old ones for recycling.	
	Disposal of shoebox	Throw away or recycle cardboard box	No shoebox in the first place, or return box to manufacturer.	

### ***DATA SOURCES***

All of the data used in this report came from various life-cycle analyses (LCA's). Life cycle analysis is a technique used to estimate the entire environmental impact of a product by examining all of the resources used to produce, use and dispose of the product. This is in contrast to many environmental studies which look only at a specific phase of the product life cycle. Whenever possible, we used existing LCA's for specific portions of our product from reputable sources to estimate the environmental impact of each portion of our product.

When a specific LCA was not available, data was obtained from an aggregated source of LCA data. Two sources of aggregated data were used; EIOLCA (economic input-output life cycle analysis) and UWME EcoScores. EcoScores gives figures for all common environmental impacts and indicators based on a certain unit, which for

materials is mass in kg or tonnes, for energy use or generation is energy in kWh or MMBTU, and for transport is typically tkm (tonne-kilometers). This makes EcoScores very straightforward to use and understand.

EIOLCA, by contrast, tracks all impacts via economic activity; i.e. if you buy \$1 million worth of a material or process in some economic sector, another sector gets \$0.4 million worth of business, and so on. All of the sectors that see economic activity due to the original activity have their environmental impacts/indicators added up to calculate aggregated environmental impacts/indicators. To use EIOLCA, the economic value of a functional unit of the material or process under consideration must be calculated before EIOLCA can be used. The US Consumer Price Index ([www.bls.gov/CPI](http://www.bls.gov/CPI)) and various internet shopping resources are useful in this regard.

Another tool that was used in conjunction with the lifecycle analysis was TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts), developed by the US EPA. TRACI provides conversion factors for specific toxic emissions into environmental impact indicators (eutrophication, acute human toxicity, etc.) Since there are thousands of specific toxic chemicals that could potentially come out of a process, this was very useful to compare and present toxic emissions in a manageable format.

## **INVENTORY ANALYSIS**

The following sections examine each section of our shoe's life cycle in detail. For each material used to manufacture the shoe, mass flows per pair of shoes is determined and the environmental impacts of that mass of material. This will allow us to quantify the impact of each portion of our shoe, which will allow us to compare alternatives and calculate the impact of our final design. System alternatives are also discussed for each material.

## ***LEATHER***

By far the biggest GHG contributor is the shoe's raw material. "For most Timberland shoes," says Betsy Blaisdell, Timberland's manager for environmental stewardship, "leather really drives the" carbon emissions.

The average dairy cow produces, every year, an amount of greenhouse gas equivalent to four tons of carbon dioxide, according to U.S. EPA. The cow's impact on the atmosphere is due largely to "enteric fermentation" - burping. A cow's multiple stomachs produce lots of methane - a highly potent greenhouse gas. But Timberland has determined that 7% of the financial value of a cow lies in its leather.

Life-cycle-analysis guidelines used by Timberland say the company should apply 7% (their estimate of leather to the entire financial value of the cow) to compute the share of a cow's total emissions attributable to the leather.

After accounting for the animal's life cycle, we still need to account for the environmental impact of the tanning process that turns animal hide into leather. The first stage is the preparation for tanning. The second stage is the actual tanning and other chemical treatment. The third stage, known as retanning, applies retanning agents and dyes to the material to provide the physical strength and properties desired depending on the end product. The fourth and final stage, known as finishing, is used to apply finishing material to the surface or finish the surface without the application of any chemicals if so desired.

Preparing hides begins by curing them with salt to prevent putrefaction while waiting to be processed. When they are ready to be processed, the hides are then soaked in clean water to remove the salt and bring back the moisture content. After soaking, the soaked hides and skins are treated with milk of lime with chemical additives. The objective of this operation is to:

- Remove the hairs, nails and other keratinous matters
- Remove some of the interfibrillary soluble proteins like mucins
- Swell up and split up the fibers to the desired extent
- Remove the natural grease and fats to some extent

- Bring the collagen to a proper condition for satisfactory tannage

The weakening of hair is dependent on the breakdown of the disulfide link of the amino acid called cystine, which is the characteristic of the keratin class of protein like hair and wools. Some of the chemical “dehairing” additives used include:

- Sodium sulfide
- Sodium Hydroxide
- Sodium Hydrosulfite
- Arsenic sulfide
- Calcium Hydrosulfide
- Dimethyl Amine
- Sodium Sulphhydrate

The majority of hair is then removed using a machine, and the remaining hair is removed by hand using a dull knife. Next, the hide is treated with a mixture of common salt and sulfuric to facilitate the penetration of tanning agents in the next step.

A new alternative to these dehairing methods has been developed which utilizes a bacterial alkaline protease preparation. It is just as effective at dehairing the hides, and eliminates the use of lime and sulfides and reduces the total amount of effluent produced in the process.<sup>6</sup>

Modern tanning usually uses chromium sulfate because it is much faster than vegetable tanning. Vegetable tanning uses tannin that occurs naturally in bark of trees. Hides are stretched on frames and immersed for several weeks in vats of increasing concentrations of tannin. Depending on the finish desired, the hide may be further waxed, rolled, lubricated, injected with oil, split, shaved and, of course, dyed.

FYI: Timberland Co. has found that transportation typically accounts for less than 5% of the carbon footprint even though they produce shoes in Asia for the U.S. market.

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<sup>6</sup> Sivasubramanian S et. al. *Ecofriendly lime and sulfide free enzymatic dehairing of skins and hides using a bacterial alkaline protease*. Chemosphere 70 (2008) 1015-124. Published by ScienceDirect, 2008.

There are two primary considerations for end-of-life management from the perspective of leather. The first consideration is the manner in which the shoes will be disposed at the end of their useful life, and the second is the toxicity of the remnant chemicals contained in the disposed shoes and the subsequent effect on the local environment. In our process we have described environmentally safe alternatives to commonly used chemicals in the shoe manufacturing process to eliminate the toxicity of our product. For example,

1. Our process will utilize vegetable based tannins instead of chromium based tanning materials (see leather procurement section).
2. Water-based adhesives instead of more toxic industrial strength adhesives (see assembly section).
3. The dehairing process will be accomplished using a bacterial alkaline protease instead of the more harmful chemicals involved in the industry standard methods. (see leather procurement section).

Utilizing these materials will help to ensure that regardless of the method of disposal, our product will not be toxic to any local environment.

Returning to our first consideration is disposal of the product, and for this there are two possibilities that meet our design goals: recyclable and/or compostable. These options are not mutually exclusive, and so the product will be designed with both of these options in mind. The Central Leather Research Institute has conducted research in and described the process of biodegradation of leathers tanned using various methods, including vegetable tanning.<sup>7</sup> They have also detailed the by-products of biodegradation of leathers. Latex rubber is also biodegradable under the right conditions, and chemists are working towards better biodegradable rubber-alternatives.<sup>8</sup>

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<sup>7</sup> Dhayalan, K. et al. Biodegradability of leathers through anaerobic pathway. *Waste Management*. Vol 7, Issue 6, 2007. Pp 760-767.

<sup>8</sup> Xu, Jingyuan et al. *A potential biodegradable rubber – Viscoelastic properties of a soybean oil-based composite*. *Journal of the American Oil Chemists' Society*. Vol 79, No 6, June 2002.

The consumer alternative to composting their old shoes is recycling, and there are many databases of shoe and leather recyclers<sup>9</sup>. Contained in the shoebox packaging will be information detailing the available alternatives for disposal at the end of life.

The functional unit for this analysis is one pair of leather loafers. After consulting with shoe designers and creating mock ups of leather sections for the upper part of the loafer, we were able to conclude that we will likely need between three to four square feet of leather to produce the leather pieces necessary. (See figure 2 below for details of typical shoe cutouts.) Websites of cowhide vendors such as [cowhidesinternational.com](http://cowhidesinternational.com)<sup>10</sup> confirm that cow hides typically run between 35 to 45 square feet in size. We estimate that on average we can produce a dozen pairs of shoes from each cowhide with 40% of the hide rejected as scrap leather. We also estimate that each shoe on average contains 0.2 kg of leather and causes 0.133 kgs of leather to be scrapped. Therefore every pair of shoes produced requires the purchase of a third of a kilogram of leather.

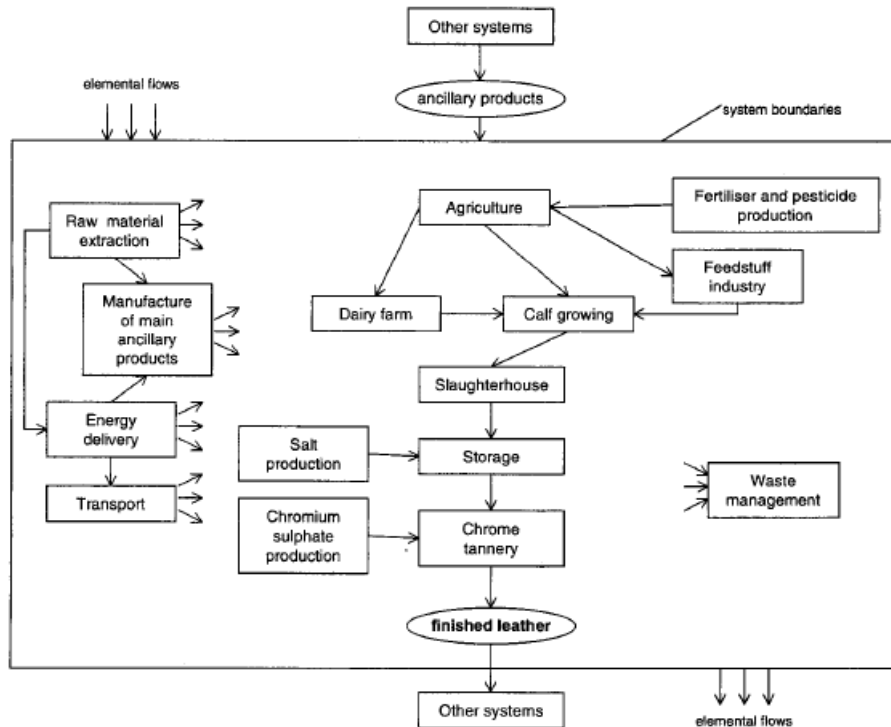
Our main source for lifecycle data on leather was a detailed LCA study<sup>11</sup> based on Spanish Catalan leather. We recognize that cattle industry practices may be different in Europe than from the United States. However, those differences are not likely to be significant and this study provides the clearest documentation of leather life cycle impacts we were able to find. Figure 3 below, from this paper, clearly shows the complex life cycle impacts of the bovine industry:

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<sup>9</sup> <http://www.recycle.net/Textile/footwear/index.html?affilid=100029>

<sup>10</sup> <http://cowhidesinternational.com/index.asp>

<sup>11</sup> Mila i Canals L, Domenech X, Rieradevall J, Puig R, Fullana P (2001): Use of Life Cycle Assessment in the Procedure for the Establishment of Environmental Criteria in the Catalan Eco-label of Leather. Int J LCA-Online First [DOI: <http://dx.doi.org/10.1065/Ica2001.07.059>.]



**Figure 3: Life Cycle of the Bovine Industry**

Table 2 below, also excerpted from this paper, shows their calculated environmental impacts:

**Table 2: Calculated impacts from leather LCA**

**Table 1: Environmental profile of the life cycle of chrome-tanned leather. Fig.s for the tanning of 1000 kg of salted hide**

	Unit	Agriculture	Cattle Raising	Slaughterhouse	Storage	Tannery	TOTAL	
Indicator	BRC	kg	3.00E+04	8.61E+03	0.00E+00	0.00E+00	3.86E+04	
	ARC	kg	1.16E+02	1.90E+01	1.20E-02	4.54E+02	8.87E+02	
	WC	kg	1.12E+06	3.38E+04	2.30E+03	0.00E+00	1.18E+06	
	Fossil Fuels	MJ	1.14E+04	2.87E+03	5.41E+02	5.84E+02	1.89E+04	
	Electricity	kWh	6.59E+02	1.50E+01	3.92E+00	1.78E+01	1.03E+03	
Impact	GW	eq kg CO <sub>2</sub>	5.54E+03	6.99E+03	5.87E+02	7.32E+01	6.59E+03	1.98E+04
	HT	eq kg Pb <sub>av</sub>	5.49E-01	3.11E-02	1.44E-02	2.16E-02	1.95E+00	2.56E+00
	AET	eq kg Zn <sub>water</sub>	2.38E-01	9.56E-03	1.60E-03	2.31E-03	7.00E-03	2.59E-01
	TET	eq kg Zn <sub>soil</sub>	1.35E-01	2.01E-06	1.56E-03	5.73E-04	1.61E+00	1.75E+00
	POF	eq kg ethene	1.72E+00	1.28E+00	1.33E-01	1.20E-01	1.30E+00	4.55E+00
	A	eq kg SO <sub>2</sub>	7.34E+01	8.15E+01	5.47E+00	9.00E-01	6.68E+01	2.28E+02
	N	eq kg PO <sub>4</sub> <sup>3-</sup>	4.22E+01	1.43E+01	1.04E+00	1.65E+00	1.29E+01	7.21E+01

BRC: Biotic Resources Consumption; ARC: Abiotic Resources Consumption; WC: Water Consumption; Fossil Fuels: Fossil Fuels Consumption; Electricity: Electricity Consumption; GW: Global Warming; HT: Human Toxicity; AET: Aquatic Ecotoxicity; TET: Terrestrial Ecotoxicity; POF: Photochemical Ozone Formation; A: Acidification; N: Nitrification

In the leather industry, weights are often reported for wet salted hides instead of “finished” leather. The wet salted weight of leather is nearly 4.5 times that of the final product (typical of Spanish leathers). Since salted cow hides from Spain usually weight 28 kilograms, and we can expect to make a dozen shoes from a single such hide, we

would expect the that 2.33 kilograms of weather slated leather must be procured for each shoe. Therefore, the impacts to be attributed from the leather procurement process to each pair of shoes is only 0.00233 times the total reported above. Therefore, for each of our shoes, the impacts are as follows:

***Table 3: Environmental Impacts due to Leather***

INDICATOR / IMPACT	UNIT	PER PAIR of SHOES
Biotic Resources Consumption	Kg	9.0E+01
Abiotic Resources Consumption	Kg	2.1E+00
Water Consumption	Kg	2.8E+03
Fossil Fuels Consumption	MJ	4.4E+01
Electricity Consumption	kWh	2.4E+00
Global Warming	eq kg CO <sub>2</sub>	4.6E+01
Human Toxicity	eq kg Pb (air)	6.0E-03
Aquatic Ecotoxicity	eq kg Zn (water)	6.0E-04
Terrestrial Ecotoxicity	eq kg Zn (soil)	4.1E-03
Photochemical Ozone Formation	eq kg ethene	1.1E-02
Acidification	eq kg SO <sub>2</sub>	5.3E-01
Nutrition	eq kg PO <sub>4</sub> <sup>3-</sup>	1.7E-01

The authors go on to summarize the impacts and possible improvements:

**Table 4: Qualitative Impacts and Potential Improvements for Leather**

**Table 2:** Summary of impacts and possibilities for improvement in the life cycle of leather

Impact	Phase*	Subst.	Origin	Possibilities for improvement
Energy Consumption	Agriculture (60-65)		field operations	reduction of energy intensity
			mineral fertilisers production	reduction of mineral fertilisers use
Global Warming	Cattle Raising (36)	CH <sub>4</sub>	rumen	stable gas collection
	Tannery (33)	CH <sub>4</sub>	landfill biogas	biogas collection, wastes reduction
	Agriculture (28)	N <sub>2</sub> O	denitrification	fertilising management (timing, dose, type of fertiliser, etc.)
Human Toxicity	Tannery (76)	Cr	wastes in landfill	wastes reduction, incineration of wastes with Cr recovery
	Agriculture (21)	NO <sub>3</sub>	leaching from fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
Aquatic Ecotoxicity	Agriculture (92)	Hg, Cd	mineral fertilisers production	reduction of use of mineral fertilisers
		NO <sub>3</sub>	leaching from fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
Terrestrial Ecotoxicity	Tannery (92)	Cr	wastes in landfill	wastes reduction, incineration of wastes with Cr recovery
Photochemical Ozone Formation	Agriculture (40)	NM VOC	energy consumption	reduction of energy intensity
	Cattle Raising	CH <sub>4</sub>	rumen	stable gas collection
	Tannery (23)	CH <sub>4</sub>	landfill biogas	biogas collection, wastes reduction
Acidification	Cattle Raising (37)	NH <sub>3</sub>	volatilisation from animal wastes	animal wastes management with the aim of N emissions reduction
	Agriculture (32)	NH <sub>3</sub>	volatilisation from organic fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
	Tannery (29)	NH <sub>3</sub>	anaerobic degradation in landfill	biogas collection, wastes reduction
Nitrification	Agriculture (59)	NH <sub>3</sub>	volatilisation from organic fertilisers	fertilising management (timing, dose, type of fertiliser, etc.)
		NO <sub>3</sub>	leaching from fertilisers	
	Cattle Raising (20)	NH <sub>3</sub>	volatilisation from animal wastes	animal wastes management with the aim of N emissions reduction
	Tannery (18)	NH <sub>3</sub>	anaerobic degradation in landfill	biogas collection, wastes reduction

\*: in parentheses, relative contribution of the phase to the impact (%)

## ***RUBBER***

Rubber will be used for the majority of the outsole. We can either use virgin or recycled rubber. Virgin rubber, in either synthetic or natural form, presents larger emissions, energy use, waste, and toxicity than using recycled rubber.<sup>12</sup> Most natural latex rubber comes from Indonesia, which results in a significant transportation emissions. Synthetic rubber is made from unsaturated hydrocarbons from petroleum, and can be manufactured in the US; over 20% of US production is from Texas.<sup>13</sup> However, this method emits more toxins.

Recycling rubber can be a simple or a complex process. For our system, we will consider recycling rubber tires and common vulcanized rubber. At its simplest, recycling rubber can be manually broken down and re-shaped with simple tools such as knives and hammers, or mechanically cut. As our facility will be powered by low-waste means, either of these methods would create virtually no toxic waste. Excess rubber from the cutting process can be converted to crumb rubber can also be used in our midsole for cushion. This material is rubber grinded down to granules that can be melted together or packed into the midsole. A more complex way to break down rubber is by machine and heat. This would consist of melting the rubber to the point it is pliable, shaping it, and letting it cool.

Most shoes either use a vulcanized rubber sole or a polyurethane sole with EVA as a midsole. Vulcanized rubber is natural rubber that has been cured to improve durability against temperature, bacteria and general use. The most common way to vulcanize rubber is by hot process, curing with sulfur. The ratio of sulfur to rubber used is between 1:40 and 1:1.<sup>14</sup> For the purpose establishing a baseline system, we will use a ratio of 1:1.43, which is common. For each pair of average sized shoes, we can assume 650g of rubber for the sole, and 455g of sulfur, heated to 284°F for 60 minutes.

EVA, commonly used in the midsole, is a copolymer of ethylene and vinyl acetate. EVA soles are shaped using injection molding. Even though vinyl acetate is a

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<sup>12</sup> The Schumacher Center for Technology and Development, UK. 2000?  
[http://www.itdg.org.pe/fichastecnicas/pdf/recycling\\_rubber.pdf](http://www.itdg.org.pe/fichastecnicas/pdf/recycling_rubber.pdf)

<sup>13</sup> <http://www.eiolca.net/>

<sup>14</sup> <http://www.history.com/encyclopedia.do?articleId=221032>

hazardous material, EVA is not considered hazardous to human health. According to MSDS data:

- LD50 information for EVA: 2900mg/kg of rat taken orally.
- LD20 info for EVA: 11400mg/kg of rat inhaled over 4hrs.

This is enough for us not to want to consider using EVA, and stick to rubber. We consider two methods of obtaining rubber: virgin natural latex rubber, and recycling of car tires. The following chemicals are used in the production of natural rubber, and are likely to have significant environmental impacts:

1.) Permethrin (or Permetrin; insecticide)

- Toxic to fish and cats, used in flea treatment also for dogs.
- Likely carcinogen to humans based on mice studies. The mice developed tumors on their liver and lungs. Also, 'carcinogenic action' and depletion of nasal mucosal cells in humans has been recorded. (DEET)

2.) Tridemorph (fungicide)

- WHO classified as 'moderately hazardous' (class II)
- 650mg/kg rat (dose required to kill half the population of lab rats)
- Prolonged exposure can cause dermitities or conjunctivitis.
- Reproductive effects (in unborn fetuses of rats) are recorded.
- Widely used despite these lab studies. Not a lot of information produced about this fungicide

3.) Copper oxychloride and Chlorothalonil (fungicides)

- WHO classifies both as 'slightly hazardous' (class III)

The production of virgin latex also requires inputs of heavy oil, electricity, raw rubber, and diesel fuel.

The main additional ingredient in car tires that may impede a recycling process is carbon black, which is added to natural latex to improve its overall strength. Carbon black is formed by the incomplete combustion of heavy petroleum products such as FCC tar, coal tar, and ethylene cracking tar. The Internal Agency for Cancer Research says carbon black is possibly carcinogenic to humans and short term exposure to high

concentrations may at least cause upper respiratory problems. There are ways to make carbon black from vegetables rather than petroleum, used in Europe.

More fuel is needed to decompose a tire than to make a new one. However, especially if we do not need to completely break down the tire, recycled tires for the soles of the shoes is a great option to offset emissions to gain credit. In the U.S we throw away 300 million tires per year (Europe and LA have roughly the same stats). Car tires are about 35 percent natural rubber and 65 percent synthetic rubber, and one tire weighs about 9.1 kg.<sup>15</sup>

Here is a table depicting pollutants caused by the synthetic rubber industry. These are some of the environmental impacts we hope to avoid by using recycled rubber.

**Table 5: Environmental Impacts of Synthetic Rubber Manufacturing<sup>16</sup>**

<u>Sector</u>	<u>Non-Point Air kg</u>	<u>Point Air kg</u>	<u>Tot Air Releases kg</u>	<u>Water Releases kg</u>	<u>Land Releases kg</u>	<u>U'ground Releases kg</u>	<u>Total Releases kg</u>	<u>POTW Transfers kg</u>	<u>Offsite Transfers kg</u>	<u>Total Rel/Trans kg</u>
Synthetic rubber manufacturing	541.0	618.0	1160	43.4	2.64	113.0	1320	10.6	20.0	1350

Here is another table showing the amount of energy used and/or emitted during the production of synthetic rubber:

**Table 6: GREET Data on Energy Consumption and Emissions**

Total Energy mmBTU	Fossil Fuels mmBTU	Coal mmBTU	Natural Gas mmBTU	Petroleum mmBTU	NMVOC g	CO g	NOx g	PM10 g	PM2.5 g	SOx g	CH4 g	N2O g	CO2 g
-4.11E-02	-4.09E-02	-9.64E-04	-2.05E-02	-1.94E-02	6.08E+00	9.57E-01	4.61E+00	1.09E+00	6.68E-01	4.49E+00	5.59E+00	3.24E-02	3.02E+03

<sup>15</sup> <http://www.tfrc.gov/hnr20/recycle/waste/st1.htm>

<sup>16</sup> Chart taken from <http://www.eiolca.net>

## **RUBBER ALTERNATIVES**

De-vulcanizing rubber has been touted as the best way to recover, or recycle, used rubber products.<sup>17</sup> Many companies have developed a process for de-vulcanization, including Goodyear, but none claim to be free from adverse environmental impacts. Recently, I have come upon a product called Green Rubber. This product boasts the ability to de-vulcanize rubber by combining vulcanized rubber with a concoction called DeLink, which essentially turns it back into virgin rubber. This product also claims to be a zero waste product. Unfortunately, I cannot locate the exact materials used in DeLink to give it a proper critique. Assuming their claims go beyond true, that is, it really is a zero waste product and non-toxically reverses the vulcanization process, we would love to be able to use it in making the sole of the shoe. Timberland has just signed a deal with the Petra Corporation, who handles DeLink, to manufacture 50% of each shoe sole from Green Rubber which gives it some clout, but we are still unable to prove the claim of zero waste for ourselves. However, if it is in fact a zero waste way to de-vulcanize rubber, this would be an example of “up-cycling” a recycled material so that it becomes at least as good as the new material.

Another consideration for the sole of the shoe is a blend of rubber and cork. Recycled cork is not as abundant as rubber, but it is a fairly non-toxic material and is durable. However cork will degrade over time, drying out, and so it must be treated with something to make it last. If we had more time, the option of treating and using cork as a material for the sole might have been explored further.

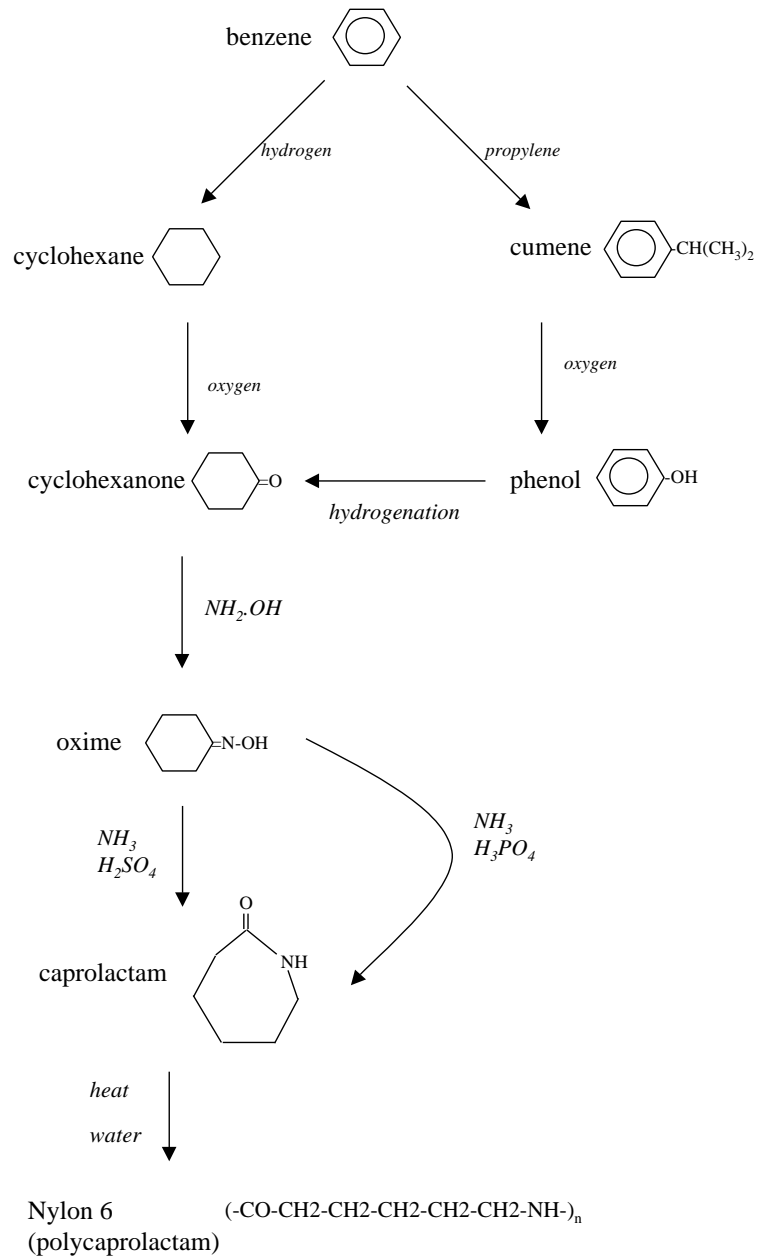
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<sup>17</sup> [www.ejn.com](http://www.ejn.com)

## NYLON

The assembly process that will be used for the construction of the shoe includes the stitching used to connect the pieces of the upper together as well as the method in which the upper is attached to the sole. The current methods that are most commonly used is to stitch the uppers together with nylon 6,6 thread and to use an industrial strength adhesive, and sometimes additional stitching, to attach the upper to the sole. In order to minimize the environmental impacts of the assembly process some companies have moved to other types of stitching material, commonly either jute or cotton with a wax coating. A few companies, such as Simple and Timberland, have also moved towards using water-based adhesives, which are much more environmentally safe; in addition, depending on the sole material, the sole may be melted/fused directly to the upper with no adhesives and then reinforced with stitching.

Nylon is a polymer of the group polyamides which can be characterized by a carbon chain with  $-\text{CO}-\text{NH}-$  groups at regular intervals. The most common way of producing nylon is by the direct polymerization of amino-acids, this can also be done by the reaction of a diamine with a dibasic acid. There are a few routes to the production of nylon 6, which is the type of nylon used in thread. The starting chemical is benzene, which is used to produce cyclohexanone which can be done in two



different ways. The first way hydrogenates the benzene in order to produce cyclohexane, and then oxygenated to produce cyclohexanone. The second way is to react the benzene with propylene to give cumene. The cumene can be oxygenated to phenol, also creating acetone, and then hydrogenated to cyclohexane.

The cyclohexane is then reacted with hydroxylamine to make oxime. The oxime is converted to caprolactam by an acid catalyst reaction called the Beckmann rearrangement. This can be done in two ways, one involves sulfuric acid and the other phosphoric acid. During this process there is a large amount of ammonium sulfate created. In practice an excess amount of ammonia is used in the process and then neutralized with sulfuric acid. The end amount of ammonium sulfate can be between 4.0kg to 2.9kg of ammonium sulfate to caprolactam. This excess ammonium sulfate is typically sold to be used in fertilizer.

Figure 4 shows the process flow of manufacturing of Nylon 6 and its alternate routes. An estimate of 2.65 grams of nylon is used per pair of shoes. The raw materials used to make this amount of nylon are shown in Table 5 below.

***Table 7: Raw Materials of Nylon-6***

<b>RAW MATERIALS</b>	Input in mg
Air	3713.073
Biomass (including water)	37.13073
N <sub>2</sub>	928.2682
O <sub>2</sub>	716.0926
S (elemental)	901.7462
Sodium chloride (NaCl)	151.1751

The air emissions for the process of nylon are where the biggest problems come from. Table 6 shows the top air emissions for the production of nylon for one pair of shoes.

**Table 8: Air Emissions Resulting from Nylon Production**

<b>Emission</b>	<b>Total per pair (mg)</b>
CO2	19449
CH4	166
NOX as NO2	67
SOX as SO2	60
CO	34

There are also a lot of water and ground emissions that need to be taken into account. Table 7 shows the Water Emissions and Table 8 shows the Solid Emissions for the production of nylon for one pair of shoes. It is clear that an alternative would be ideal for the use of Nylon thread, or a way to recycle nylon from another source.

**Table 9: Water Emissions Resulting from Nylon Production**

<b>Emission</b>	<b>Total per pair (mg)</b>
SO4--	99.01527
Na+compounds as Na	34.30172
COD	12.73053
NO3-	9.901527
Cl-	9.547901

**Table 10: Land Emissions Resulting from Nylon Production**

<b>Emission</b>	<b>Total per pair (mg)</b>
Waste returned to mine	190.96
Mineral waste	180.35
Slags & ash	109.62
Regulated chemicals	77.80

Unspecified refuse	22.28
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Table 9 shows the CO2 equivalents for production of nylon and transportation for incoming materials. This study was done in Europe so the transportation and other numbers may be a little different, but this is a good baseline to look at for comparison.

**Table 11: GHG impact of Nylon Production**

Type	From Fuel prod'n	From fuel use	From transport	From process	From biomass	From fugitive	Totals
	(mg)	(mg)	(mg)	(mg)	(mg)	(mg)	(mg)
<b>20 year equiv</b>	9813	8752	154	9813	-24	0	29174
<b>100 year equiv</b>	5304	8752	154	10078	-24	0	24135
<b>500 year equiv</b>	3448	8752	154	6630	-24	0	19096

## **PACKAGING**

The default method of packaging shoes is to package them in cardboard boxes that may be polyurethane coated for water resistance. The boxes are labeled by some method and may be put together by glue, staples, or simply folding. Typically, paper, cardboard or plastic “shoe stuffers” are inserted into the shoes to help them keep their shape, and a small amount of dessicant material is placed in the shoebox to remove moisture. Excess moisture during storage can cause shoes, especially those made of natural materials, to mildew. This analysis includes some innovations that we know we wish to incorporate into our finished product, and as such represents somewhat of a departure from traditional methods. This was done to reduce unnecessary computation, since we already know these methods are preferable, and there are no “trade-offs” that require quantitative comparison.

Single-layer cardboard is used for three purposes: shoeboxes, labels, and shoe stuffers. Flows were estimated by analysis of an average sized shoebox.

The box is made of 1 piece of cardboard and is held together by folding, no glue. This reduces the number of materials and toxics inherent to the process, so it is something we want to incorporate into our finished product. The cardboard can be made from 100% recycled material, and can be unbleached brown paperboard/cardboard, since this is the simplest product to manufacture and is devoid of the toxic emissions associated with paper bleaching.

The surface area of the box is  $0.339 \text{ m}^2$ . It was estimated that if it was cut out of a rectangular piece of cardboard, it would be approximately a  $0.415 \text{ m}^2$  piece. The box's volume is 6.768 L, and the empty box weighs approximately 227 g.

In addition, labels will be needed to identify the shoes in the box. Labels can be made out of the same material as the shoe boxes, cut from the waste material from the shoebox manufacturing, and simply folded over the end of the shoebox and tucked inside the existing cardboard folds. This way there are no toxic adhesives used. The labels would be approximately  $3 \text{ cm} \times 6 \text{ cm} = 18 \text{ cm}^2 = 0.0018 \text{ m}^2$ .

Cardboard or plastic inserts are commonly used to help shoes keep their shape while in the box. Use of such items is consistent with maintaining an acceptable quality of service, but as their cosmetic appearance and long-term durability are both unimportant, they can be manufactured out of 100% re-purposed cardboard without the need for recycling processes. Scrap cardboard will be mechanically torn into pieces a few square inches in area, then mechanically crushed in a mold to form a packed paper insert to hold the shape of the shoe. From sample measurements, the average pair of stuffers will use approximately  $2,750 \text{ cm}^2$  or  $0.275 \text{ m}^2$  of cardboard.

These are converted into mass flows by calculating the linear density of single-layer cardboard from the sample shoebox, then multiplying each value by it:

$$\rho_l = \frac{227 \text{ g}}{0.339 \text{ m}^2} = 669 \text{ g/m}^2.$$

These figures are assuming that the process works correctly 100% of the time. This doesn't really happen, so we will introduce a 1% accidental waste factor for the incoming single-layer cardboard to account for equipment malfunctions, etc.

Using these figures, the following inputs are needed:

280.4 g single-layer cardboard - box and labels

184.0 g cardboard scraps - stuffers

The following outputs are generated:

226.8 g - finished box

1.2 g - finished label

184.0 g - finished stuffers

52.4 g - waste

We plan to implement a program where consumers, upon receipt of a shoebox, will be able to receive a credit towards their purchase for returning it at the point of sale. The credit will be reduced if the box is returned at a later date in too poor of condition to be reused. The exact dollar amount of credit is beyond the scope of this report, but it is assumed that it will be substantial enough that 50% of consumers will return boxes in good enough condition to be re-used, while another 40% will return boxes in poor condition. This means we have to manufacture 50% less boxes than we would have if we did not re-use boxes, which means all of the flows will be cut by 50%.

This is equivalent to saying each box can be used an average of twice, because the average number of times a box can be re-used is equal to the sum of the infinite series:

$$\# \text{ of uses} \quad \text{probability of that \# of uses} = 1 \cdot 0.5 + 2 \cdot 0.5^2 + 3 \cdot 0.5^3 + \dots = 2$$

This is a very reasonable expectation with regards to the durability of the box.

This means a few things for the flows. First, it means that each box and pair of shoe stuffers can be used for two pairs of shoes. This means that the flows for boxes and shoe stuffers are cut in half. (The flow for labels will remain the same because a new label is needed for each pair of shoes.) Second, the material from the shoe stuffers can be obtained from the recovered poor-quality boxes, labels and shoe stuffers. Applying the first change gives these flows for cardboard:

In:

140.2 g single-layer cardboard - box and labels

92.0 g cardboard scraps - stuffers

Out:

113.4 g - finished box

1.2 g - finished label

92.0 g - finished stuffers

25.6 g - waste

Each box is used for 2 pairs of shoes, and we ultimately reclaim 90% of boxes, so per pair of shoes we reclaim 45% of the box and stuffer material used. We reclaim 90% of labels per pair, because new labels are used for each pair of shoes. This is an available flow of 93.5 g, which is just enough for the stuffers. The rest of the cardboard eventually makes its way into the municipal recycling stream. The final flows for cardboard are thus:

In:

140.2 g single-layer cardboard

Out:

140.2 g cardboard scraps

Corrugated cardboard – Corrugated cardboard is used for shipping cartons, and can also be made out of 100% recycled materials. An average shipping carton would be about 25” x 23” x 23” and fit 30 boxes of shoes. Converting to metric units, this is 0.635 x 0.584 x 0.584 m. The surface area of such a box would be 2.16 m<sup>2</sup>, and the volume would be 0.216 m<sup>3</sup>. The linear density of a typical sample of corrugated cardboard was found to be 2,007 g/m<sup>2</sup>, so the amount of corrugated cardboard by mass per box is 4,335g.

A box can be shipped back to the manufacturer and re-used an average of 10 times, and holds 30 pairs of shoes per shipment, so one box can be used for 300 pairs of shoes. The average mass of corrugated cardboard used per box is thus 4335/300 = 14.45g.

A variety of substances, such as clays, chalks and silica gel, can absorb water into their chemical structure and are thus used as a dessicant. Most of these can be indefinitely “recharged” by heating to drive off the water. Dessicant packets are often lost or thrown out, so we will assume our reclaim rate is the same as for re-usable shoeboxes, 50%. Approximately 1 g of dessicant is used per shoebox, so this is equal to 0.5 g per pair of shoes.

For this analysis the dessicant calcium sulfate is used. Its hydrated form is known as gypsum, which is used for drywall and blackboard chalk among other things. In its anhydrate (water-free) form, it is an effective dessicant, slowly absorbing moisture and reverting back to its hydrate form. “Used” calcium sulfate dessicant can be “recharged” by heating to 180°F for about two hours. Thus, the impact of calcium sulfate is equal to the impact of gypsum plus the impact of the heating process. The energy used to heat one gram of gypsum from ambient temperature (assume 60°F) to 180°F is equal to:

$$E = cm\Delta T = \left(0.26 \frac{BTU}{lb \cdot F}\right) 1g \left(\frac{1lb}{453.59g}\right) 120^\circ F = 0.07 BTU_{18}$$

This is done once per pair of shoes, either to convert gypsum into anhydrate calcium sulfate, or to recharge, so the total energy used per pair of shoes is equal to 0.07 BTU, or 7\*10<sup>-8</sup> MMBTU. This is a quite insignificant amount.

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<sup>18</sup> [http://www.engineeringtoolbox.com/specific-heat-solids-d\\_154.html](http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html)

The impacts of cardboard production, dessicant production, heating, and transport are shown below on a per-pair basis. Data for cardboard and dessicant were obtained from EIOLCA<sup>19</sup>. Data for heating and transport were obtained from UWME EcoScores.

**Table 12: Impacts of Cardboard Production**

	<b>Material Flow</b>	<b>Energy Use</b>	<b>GWP (CO2 equiv.)</b>	<b>VOC emissions</b>	<b>PM10 emissions</b>	<b>PM2.5 emissions</b>
<b>Cardboard</b>	154.7 g	277 KJ	22.5 g	35 mg	13 mg	Unavail.
<b>Calcium sulfate production</b>	0.5 g	38 KJ	3.1 g	10 mg	1 mg	Unavail.
<b>Calcium sulfate heating (w/ NG)</b>	N/A	0.07 BTU	7.12 mg	400 ng	60 ng	36 ng
<b>Transport</b>	N/A	N/A	6.21 g	4.2 ng	1.9 ng	1.2 ng

### ***END OF LIFE***

In the year 2000, the primary components of the footwear industry (leather and rubber) composed 1-2% of municipal solid waste in the U.S.,<sup>20</sup> and it is estimated that it takes 40-50 years for a pair of leather shoes with rubber soles to decompose in standard aerobic landfill conditions. This time frame depends largely upon the climate of the region in which the shoe decomposes.

Since we were unable to find source specific data for the products of decomposition of shoes in aerobic conditions (as in a landfill), we will utilize general landfill characteristics to approximate the most significant outputs for our consideration. If we assume that our average pair of shoes, from size seven to size thirteen is 1 kg in weight, then we can specify the output products of biodegradation. Since historically

<sup>19</sup> Economic Input-Output Life Cycle Analysis. <http://www.eiolca.org>

<sup>20</sup> Palanathakumar, Balasingam. *Modeling of Methane Generation, Oxidation and Emission in Landfills*. Asian institute of Technology; School of Environment, Resources and Development. Bangkok, Thailand; 1999.

there has been no alternative disposal method to landfilling old shoes, this will be our baseline system and will assume a vegetable tanned leather shoe with a latex rubber sole.

For our baseline system, we will consider airborne emissions only since the water emissions data from landfilling our shoes are unavailable. We will also be working with the assumption that the primary elemental makeup of leather is carbon, nitrogen, hydrogen, and oxygen, and latex rubber is a hydrocarbon with a few other trace minerals. There may be other trace minerals resident in the leather from tanning or unhairing, but we will ignore them for now.

For 1 kg input, in a typical landfill situation we expect there will be approximately 21 g of CH<sub>4</sub>, 178 g of CO<sub>2</sub>, 119 mg of CO, and 107 mg NO<sub>x</sub> air emissions. These values are an estimation based on typical landfill situations, and we might expect these values to be slightly higher, but they are not likely much lower.

If we convert these all to CO<sub>2</sub> equivalents so that the units can be compared, we arrive at 1.1 kg of CO<sub>2</sub> equivalents for a 1 kg input over the course of its approximately fifty year decomposition. If we assume a steady state of decomposition and proportionate values throughout, the shoes emit about 20 g of CO<sub>2</sub> equivalents per year. To put this output in perspective, a gallon of gasoline burned will emit approximately 8.8 kg of CO<sub>2</sub>. To further the comparison, it would take roughly 440 pairs of shoes decomposing in a landfill for a year to produce as much CO<sub>2</sub> equivalent as a gallon of gas. In terms of our system, this output is relatively minor.

### ***ALTERNATIVES FOR END OF LIFE***

We assumed for our baseline that shoes are traditionally sent to landfill. However, as mentioned before, many waste management facilities are becoming equipped to recycle and/or compost non-toxic shoes. These are the alternatives for the end of life for our product that we will consider.

In the case of recycling, there are two different types of recyclers on the market. The first type is known as charity recycling, which is simply redistributing used shoes to the needy, often in developing nations. There are a number of social and environmental issues that arise from this practice, and from an environmental standpoint this is the least desirable outcome for the end of life for our shoes. This is because many shoes are

disposed of when they are near but not at the end of their useful life. At the point of donation, they are shipped to places all over the globe, incurring additional emissions that must be considered. They are given to the needy, who use up the last few percent of their useful life, mend and repair them as best as possible, and then discard them. In reality, the life of one of these 'recycled' shoes is much shorter than a new pair of shoes, and they must be disposed of in places that are often lacking adequate waste management facilities. This is a difficult issue in terms of social welfare and economics as well; some argue that it depresses local retail economies further when residents are able to receive free goods rather than purchase new products. However, our scope is limited to the environmental arena, and from that standpoint, this type of program is not desirable due to the transportation involved and the conditions of the end of life disposal.

The second type of recycling involves breakdown of the materials by various processes so that they can be used as inputs in another system. This process typically involves a splitting phase, where the upper is separated from the sole of the shoe, and a grinding or shredding phase where the materials are broken down into tiny pieces. Both of these processes require heavy equipment that uses electrical energy, however, many are located in the pacific northwest, and as such they derive their energy from hydropower. Once ground, the materials can be used in a number of different products and materials, including sports courts and playground surfaces, leather tiles for flooring, and reprocessed leather that can be used for consumer goods like shoes, handbags, & other leather products. Reprocessing leather uppers in this way requires glue, and we would have to determine whether our water-based adhesive would be strong enough for this purpose. This type of recycling produces leather that we could keep within our supply chain to reduce the need for new materials while reducing our waste.

The final alternative for our end of life is composting the shoes, and this option depends upon the use of natural tannins, biodegradable stitching, non-toxic adhesives, and latex rubber in our product to ensure its compostability. It also depends upon the location of end-use, as composting shoes requires a special facility. We contacted Northwest Waste Management and found that they have two local facilities capable of composting our non-toxic shoes (their Maple Valley and Everett hi-tech facilities). The shoes spend 18 months composting before they are transformed into nutritious soil,

which is then used in local public parks and gardens. Composting does utilize energy, some of which is fossil fuel based, but it gives the parks and recreation department an alternative to using chemical fertilizers that end up in waterways and cause serious problems with dissolved oxygen levels.

The crucial factor in our process is giving the customer the right incentive and the right information to dispose of our shoes properly. The most feasible incentive is convenience, so we could allow old shoes to be dropped off at the retail locations where our products are sold, and pick up shoes when we make deliveries. Of course, the customers could recycle or compost the product themselves, and we would have to provide them the right information. We would compile a directory of the proper facilities and ways in which the shoe ought to be disposed, and make sure the customer receives the information through the salespeople and also from information contained on our packaging.

## **ANALYTICAL LIMITATIONS**

The environmental impacts of some of our alternative processes are not well documented. For example, the emissions from the machinery involved in the composting of our shoes are not well documented, and in order to complete a full assessment of end of life options, we would need a few pieces of critical information about energy use and emissions at the facility. This is also the case for the shoe recyclers; it is a fairly new system with only a few facilities in the region, and the process and equipment involved is also not well documented. To complete a proper impact assessment a more thorough understanding of each of these processes would be required, but this was beyond the scope of our analysis. In addition, it requires an evaluation of the emissions involved in transportation of shoes to these facilities and the products to their next or final destination so that a more accurate assessment of impacts can be attained.

Human behavior is also a limiting factor in our analysis. It is difficult to predict what consumers will actually do with the product after it leaves the store. As we mentioned, we would provide as much incentive as is possible, and these incentives may need to be evaluated in time and adjusted to make them more effective.

We also have to account for performance limitations of some of our alternative materials. In some cases, performance of the materials was sacrificed for environmental improvements, and these cases need to be weighed carefully in order to develop a competitive product that meets our functional criteria. If our shoes wear out more quickly than they are supposed to, then environmental improvements will be negated by the discrepancy between actual performance and intended performance.

Finally, and maybe most importantly, are the economic limitations. Our system must be developed in accordance with cost objectives that were not covered here to account for profitability. A superior system may be attainable, but if the cost of developing superior alternatives puts it out of reach for our customers, we will not be able to continue to develop new products. This is why many companies have an ongoing process of development that strives to make progress in small increments to reduce the financial burden of developing new technologies and processes.

## **SYSTEM GUIDELINES TOWARD ZERO WASTE**

Our system design philosophy is guided by principles of closed loop design, one in which waste is not an option. Every bit of material and energy should be utilized to its full potential. Our design process will be inclusive of any excess materials in the process, and we will use them within the system. We have developed a series of questions in the design phase that must be critically answered throughout each of our processes. The answer to each question should be yes, and if it is not we must start again by selecting new materials or processes until we have progressed as far down the list as we possibly can. Each question assumes our functional criteria are also met.

1. Is this the least wasteful material/process available?
2. Can excess material be reused, recycled, or composted? If the answer is no, we must try to find another input before moving on.
3. Is this the least toxic material/process available?
4. If toxics are present, can they be captured within the current system for reuse or neutralized to prevent harm?
5. Is this the lowest GHG emitting material/process available?

6. Can we redesign any of aspect of this system to further reduce any of our impact categories?

By critically answering these questions at every process, we will be able to continuously move our system toward zero.

## ***SUMMARY***

In conclusion, our design eliminates material waste for all processes except the procurement of leather. 40% of the leather procured would have gone to waste. However, we found a way to reuse half of that leather as a component for midsole. Some of the remaining scraps can be donated or sold to other leather user for purposes such as bog toy and crafts. However, 10% of the leather purchased remains manufacturing waste. The majority of emissions and environmental impacts are attributable to the leather used in leather loafers; however, no less harmful alternative material currently exists that satisfies our functional requirements.

However, reduction of the wastage of leather raw materials reduces most emissions and impacts by 30% across the board. We were also able to achieve a 20% reduction of toxics from use of natural dehairing and tanning agents instead of the more conventional harsh chemicals. In addition, use of leather and rubber composites eliminates toxics attributable to the mid sole by eliminating use of EVA.

The shoebox recycling program will help us achieve a 50% Energy and emissions reduction attributable to shoebox recycling. In addition, 15% additional reduction of toxics and energy consumption from elimination of resin coating and choice of a non-toxic desiccant.

The use of recycled rubber instead of virgin rubber also reduces the toxic impacts attributable to rubber components by 75% and reduces air emissions attributable to the same components by 50%. Please find the resulting net remaining environmental impacts of our loafer design in the following summary tables:

**Table 13: Summary of Indicator Impacts of Loafer Production**

<b>INDICATOR / IMPACT</b>	<b>UNIT</b>	<b>PER PAIR of SHOES</b>
Biotic Resources Consumption	kg	9.00E+01
Abiotic Resources Consumption	kg	2.10E+00
Water Consumption	kg	2.80E+03
Fossil Fuels Consumption	MJ	4.40E+01
Electricity Consumption	kWh	3.28E+00
Global Warming	eq kg CO <sub>2</sub>	4.71E+01
Human Toxicity	eq kg Pb (air)	6.00E-03
Aquatic Ecotoxicity	eq kg Zn (water)	6.00E-04
Terrestrial Ecotoxicity	eq kg Zn (soil)	4.10E-03
Photochemical Ozone Formation	eq kg ethene	1.10E-02
Nitrification	eq kg PO <sub>4</sub> <sup>3-</sup>	1.70E-01
VOC emissions	kg	4.49E-04
PM10 emissions	kg	7.85E-04
PM2.5 emissions	kg	3.72E-05

**Table 14: Summary of Chemical Impacts of Loafer Production**

<b>CHEMICAL</b>	<b>PER PAIR OF SHOES (kg)</b>
Sox	5.33E-01
CH <sub>4</sub>	2.48E-02
Nox	3.18E-03
CO	7.75E-04
S (elemental)	9.02E-04
Sodium chloride (NaCl)	1.51E-04
Na+compounds as Na	3.43E-05
COD	1.27E-05
Cl <sup>-</sup>	9.55E-06

More detailed information can be found in Appendix Table A3 and A4.

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- a. (This study provides some great, concrete numbers for us to base further thoughts and research. There are a couple tables that break down the weight of each material in a typical shoe, and the environmental impacts of each. The main name behind this study is T. Staikos who's name appears on a lot of life cycle assessment studies regarding consumer waste products.)
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## APPENDIX

TABLE A1: Baseline

INDICATOR / IMPACT	UNIT	PER PAIR of SHOES	Leather	Nylon	Packaging	Rubber	End of Life
Biotic Resources Consumption	Kg	9.00E+01	90				
Abiotic Resources Consumption	Kg	2.10E+00	2.1				
Water Consumption	Kg	2.80E+03	2800			3.71E-05	
Fossil Fuels Consumption	MJ	4.40E+01	44				
Electricity Consumption	kWh	3.28E+00	2.4		8.82E-01		
Global Warming	eq kg CO 2	4.91E+01	46	1.94E-02	3.18E-05	1.96E+00	1.10E+00
Human Toxicity	eq kg Pb (air)	6.00E-03	0.006				
Aquatic Ecotoxicity	eq kg Zn (water)	6.00E-04	0.0006				
Terrestrial Ecotoxicity	eq kg Zn (soil)	4.10E-03	0.00041				
Photochemical Ozone Formation	eq kg ethene	1.10E-02	0.011				
Nutrication	eq kg PO43-	1.70E-01	0.53				
VOC emissions	kg	4.40E-03			4.49E-04	3.95E-03	
PM10 emissions	kg	7.85E-04			7.59E-05	7.09E-04	
PM2.5 emissions	kg	4.38E-03			3.71E-05	4.34E-03	

TABLE A2: Baseline

Chemical	UNIT	PER PAIR of SHOES	Leather	Nylon	Packaging	Rubber	End of Life
Sox	kg	5.33E-01	5.30E-01	6.00E-05	9.90E-05	2.92E-03	
CH4	kg	2.48E-02		1.66E-04		3.63E-03	2.10E-02
Nox	kg	3.17E-03		6.70E-05		3.00E-03	1.07E-04
CO	kg	7.75E-04		3.40E-05		6.22E-04	1.19E-04
S (elemental)	kg	9.02E-04		9.02E-04			
Sodium chloride (NaCl)	kg	1.51E-04		1.51E-04			
Na+compounds as Na	kg	3.43E-05		3.43E-05			
COD	kg	1.27E-05		1.27E-05			
Cl-	kg	9.55E-06		9.55E-06			

TABLE A3

<b>INDICATOR / IMPACT</b>	<b>UNIT</b>	<b>PER PAIR of SHOES</b>	<b>Leather</b>	<b>Nylon</b>	<b>Packaging</b>	<b>Rubber</b>	<b>End of Life</b>
Biotic Resources Consumption	Kg	9.00E+01	9.00E+01				
Abiotic Resources Consumption	Kg	2.10E+00	2.10E+00				
Water Consumption	Kg	2.80E+03	2.80E+03			3.71E-05	
Fossil Fuels Consumption	MJ	4.40E+01	4.40E+01				
Electricity Consumption	kWh	3.28E+00	2.40E+00		8.82E-01		
Global Warming	eq kg CO <sub>2</sub>	4.51E+01	4.60E+01	1.94E-02	3.18E-05	1.96E+00	1.10E+00
Human Toxicity	eq kg Pb (air)	6.00E-03	6.00E-03				
Aquatic Ecotoxicity	eq kg Zn (water)	6.00E-04	6.00E-04				
Terrestrial Ecotoxicity	eq kg Zn (soil)	4.10E-03	4.10E-03				
Photochemical Ozone Formation	eq kg ethene	1.10E-02	1.10E-02				
Nitrification	eq kg PO <sub>4</sub> <sup>3-</sup>	1.70E-01	1.70E-01				
VOC emissions	kg	-3.50E-03			4.49E-04	3.95E-03	
PM10 emissions	kg	-6.33E-04			7.59E-05	7.09E-04	
PM2.5 emissions	kg	-4.30E-03			3.71E-05	4.34E-03	

TABLE A4

<b>Chemical</b>	<b>UNIT</b>	<b>PER PAIR of SHOES</b>	<b>Leather</b>	<b>Nylon</b>	<b>Packaging</b>	<b>Rubber</b>	<b>End of Life</b>
Sox	kg	5.27E-01	5.30E-01	6.00E-05	9.90E-05	2.92E-03	
CH <sub>4</sub>	kg	1.72E-02		1.66E-04		3.63E-03	2.10E-02
Nox	kg	-2.96E-03		6.70E-05		3.00E-03	1.07E-04
CO	kg	-5.37E-04		3.40E-05		6.22E-04	1.19E-04
S (elemental)	kg	-9.02E-04		9.02E-04			
Sodium chloride (NaCl)	kg	-1.51E-04		1.51E-04			
Na+compounds as Na	kg	-3.43E-05		3.43E-05			
COD	kg	-1.27E-05		1.27E-05			
Cl-	kg	-9.55E-06		9.55E-06			