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Manufacturing-focused emissions reductions in footwear production

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Title: Manufacturing-focused Emissions Reductions in Footwear Production

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Abstract

What is the burden upon your feet? With sales of running and jogging shoes in the world averaging a nontrivial 25 billion shoes per year, or 34 million per day, the impact of the footwear industry represents a significant portion of the apparel sector's environmental burden. This study analyzed the carbon footprint of a familiar consumer product, a pair of running shoes. A single shoe can contain 65 discrete parts that require 360 processing steps for assembly. While brand name companies dictate product design and material specifications, the actual manufacturing of footwear is typically contracted to manufacturers based in emerging economies. Using life cycle assessment methodology, this effort quantified the global warming potential burden of a pair of shoes and mitigation strategies were proposed focusing on high leverage aspects of the life cycle.

Using this approach, it was estimated that the carbon footprint of a typical pair of running shoes made of synthetic materials is 14 ± 2.7 kg CO₂-equivalent. The vast majority of this impact is incurred during the materials processing and manufacturing stages, which make up around 29% and 68% of the total impact, respectively. By comparison, a person emits the equivalent amount of carbon by using a 100-watt light bulb for a week.

For consumer products not requiring electricity during use, the intensity of emissions in the manufacturing phase is atypical; most commonly, materials make up the biggest percentage of impact. This distinction highlighted the importance of identifying mitigation strategies within the manufacturing process, and the need to evaluate the emissions reduction efficacy of each potential strategy. By postulating the causes of manufacturing dominance in the global warming potential assessment of this product, this study described the characteristics of a product that would lead to high manufacturing impact. Thereby, the work explored how relying solely on the bill of materials information for product life cycle assessment may underestimate life cycle burden and ignore potentially high impact mitigation strategies.

Keywords

Manufacturing vs. materials, uncertainty; life cycle assessment; footwear; carbon footprint

1. Introduction

In 2010 the world produced and purchased almost 25 billion shoes, nearly all of which (more than 90%) were manufactured in developing and transitional economies (IBISWorld, 2010; Sport Business Research Network, 2011). Not surprisingly, an industry of that scale and geographic footprint has come under great pressure regarding its social and environmental impact (Greenpeace International, 2011).

In response to these pressures within the footwear and the broader apparel industry, many companies are active in publishing reports on their products' environmental performance and corporate social responsibility. Collaborative efforts within the sector have also begun to emerge. An industry consortium, driven by the Outdoor Industry Association and the Sustainable Apparel Coalition, is developing an Eco Index assessment tool that defines shared guidelines to help companies measure and evaluate the environmental impact of their products (Choinard et al., 2011; Zeller, 2011). One reason that companies are partnering on this issue is the inherent complexity in measuring and improving social and environmental performance. The supply chain is geographically distributed and market concentration is low as the top players in the sector account for less than 10% of total industry revenue (IBISWorld, 2010). Due to the diluted nature of brand owner influence on sizeable, consolidated upstream manufacturers within the apparel sector, the ability to impact and direct the actions of suppliers remains challenging (Locke and Romis, 2010; Plambeck et al., 2012; Zhu et al., 2011).

One element of environmental performance reporting includes measurement of the greenhouse gas emissions over a product's life cycle, which, even taken on its own, can be a complex process. This study documented the process of assessing the so-called carbon footprint of a common footwear product – one pair of running shoes. The first objectives were to carry out a benchmarking exercise in order to understand the lifecycle greenhouse gas emissions of an existing shoe design, including the uncertainty associated with these calculations, and thereby contribute to carbon footprinting methodology. This contribution helps shoe designers understand the impact of the products they are designing, as well as identify and evaluate potential improvements in future designs. As will be shown below, this case was of particular interest because, unlike most reported in the literature, the burden from manufacturing was found to be the dominant life cycle phase. This paper postulates some of the characteristics of a product that lead to manufacturing dominance in the resulting footprint, as well as discusses the potential strategies for reducing the impact of products without use phase energy consumption.

Often in product life cycle assessment (LCA) one or two of the life cycle phases drive the total impact (Ashby, 2009). Because full assessment is time consuming and complex, such phase dominance has been used to qualitatively streamline LCA efforts (Kaebernick et al., 2003). Particularly in the conceptual or early phase of product design, intuiting a particular product's impact before executing a complete analysis (or before all

information about a product is available) enables quick evaluation of product environmental performance. Beyond this dominance analysis, previous authors have recommended focusing instead on decision maker analysis to help support specific actors in prioritizing action, particularly in the case of manufacturing (Löfgren et al., 2011). For the purposes of this study, understanding the drivers of dominance in the life cycle points to areas where efforts should focus when developing mitigation strategies.

In order to systematize this phase dominance streamlining approach, efforts have been made to group products by characteristics and environmental performance to identify common environmental behavior of product groups. Through this categorization, several authors have identified the raw materials production phase (hereafter referred to more simply as materials phase) and/or the use phase as most typically dominant within the life cycle (Hanssen, 1999; Kaebernick and Soriano, 2000; Sousa and Wallace, 2006). Sousa performed an empirical study building on the work of others to classify products as material and use phase dominant products by product characteristics (Sousa, 2002). This classification can be summarized in three types:

- a) Products with (internal) power consumption during use, including home appliances and, vehicles (family cars, aircraft, etc.), among others.
- b) Products with (external) power consumption, including products that require a particular power consumption activity during use such as washing, refrigerating, and heating.
- c) Products with no (or negligible) power consumption during use such as furniture, paper/plastic bags, coffee filters, etc.

In general, it is straightforward to recognize when a product's burden will be focused in the use phase, based on whether the product consumes power during use. The degree of use phase dominance is dictated by its lifetime and energy intensity during use. The relative importance of materials (as opposed to manufacturing) is generally less obvious, but derives directly from broad trends in energy requirements. Examining the embodied energy of materials, or energy to produce a workable unit mass of raw material, in contrast to the typical manufacturing processes reveals why the materials phase generally dominates the life cycle for non-power using products. The embodied energy of materials illustrated in (Ashby, 2009) clusters by materials type (i.e., metals, polymers, ceramics, and hybrids) and ranges from $10 - 10^3$ MJ/kg (excluding precious metals that are in the order of $10^3 - 10^5$ MJ/kg; below 10 MJ/kg are cement and concrete, which do not typically undergo additional processing). Compare this distribution to the expected range for common manufacturing processes, which vary from 1 to 50 MJ/kg (Gutowski et al., 2009). Therefore, the upper bound of manufacturing energy requirement is typically at or below the lower bound of embodied energy for materials. For example, in the case of plastics, the embodied energy of different types of polymers³ (Smil, 2008) is often one order of magnitude

³ The embodied energy of plastics, excluding PVC is between 75 – 120 MJ/kg

higher than the energy requirements for injection molding of polymers⁴ (Thiriez, 2006). In the case of aluminum and steel, the embodied energy is 80 to 300⁵ times larger than the overall energy requirements for machining aluminum and 30 times higher for steel. Nevertheless, as the case presented here demonstrates there are cases where these trends can be reversed. As will be discussed later, reliably identifying these cases is valuable to minimize analytical burden and avoid overlooked opportunities for improvement.

The first section of this paper provides an empirical carbon footprint analysis for the apparel and footwear industry, providing details around the overall methodology and documenting the approach to relevant uncertainty calculations. Beyond this case study, section 5 of the document explores the drivers of dominance among life cycle phases of a product that, in turn, point to potentially high leverage mitigation strategies. This may help practitioners develop a sense of the potential “hot spots” of particular products before performing a complete carbon footprinting analysis. Identifying which phases may be significant can inform where effort should be directed in resource-intensive, detailed data collection for LCA. For example, a practitioner who is relying primarily on bill of materials information for a product LCA (rather than quantifying the manufacturing burden) may underestimate life cycle burden and preclude identifying truly high impact mitigation strategies.

2. Case Description: Materials and Methods

There has been effort to standardize methodologies for quantitative evaluation of environmental impact of products or processes. Proposed standards or specifications include those from the British Standards Institute (offering the PAS 2050 specification) (British Standards Institute, 2008), the World Resources Institute/World Business Council on Sustainable Development Greenhouse Gas Protocol (WRI and WBCSD, 2004) and the International Standards Organization among others (International Organization for Standardization, 2006b). The ISO has developed a standard methodology for LCA as part of its ISO 14000 environmental management series. The ISO 14040 standard outlines four main steps in an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. This study will adhere to the ISO standard to assess the life cycle impact of running shoes.

A few companies and reports in the academic literature have described carbon footprint results for apparel. Product assessments have emphasized the high impact of the materials processing and manufacturing phase, accounting for upwards of 90% of the burden in synthetic running shoes (Nike, 2010; PUMA, 2010). Milà et al. (1998) applied LCA to identify the high-impact life cycle phases of women’s leather shoes. These shoes are quite different from synthetic athletic shoes, due to the particularly high impact of cattle raising and leather processing. Companies have also looked into the footprint of

⁴ Specific energy consumption values for hydraulic, hybrid and all-electric injection molding machines are 19.0, 13.2 and 12.6 MJ/kg, respectively

⁵ Energy difference between virgin and recycled aluminum

leather shoes reporting greater than 90% of the burden arising from materials production, particularly from cattle or pig processing (Barling, 2008). Finally, Woolridge et al. (2006) and Staikos et al. (2007) explored alternative end-of-life treatments for textiles and footwear.

2.1 Goal and scope definition

This first part of this study evaluated the life cycle greenhouse gas emissions (GHG) associated with a specific model of running shoes, and investigates the important drivers behind this GHG impact. The study examined a pair of size 9 men's ASICS GEL - KAYANO 17 shoes, which were manufactured in year 2010 by a major contract manufacturer in China.

First, the impact of raw material extraction and processing was incorporated for all materials in the shoe, production scrap, as well as shoe packaging materials (though not the raw materials' packaging). Secondly, manufacturing and assembly of the product was considered, which encompasses the impact associated with the use of factory equipment in China, but does not involve the manufacturing and transport of the equipment to the factory (as this is assumed to be a small part of the burden for this industry (Frischknecht et al., 2007)). Further, the use of the product was included, namely the impact associated with washing the shoes. The impact of producing detergent to wash the shoes, however, was not included based on previous work indicating the small contribution to overall burden (Cullen and Allwood, 2009). Finally, end-of-life disposition and transportation between the life cycle phases was integrated in the analysis.

2.2 Inventory data collection

Several sets of data were required in order to estimate the GHG impact associated with the shoes. Information was obtained on material use, including the material scrap generated during production, as well as a detailed breakdown of material use for all shoe components, including packaging. Information was gathered on the location of each material or part supplier. Detail was assembled around the processes and general processing parameters used to manufacture and assemble the shoes. For the manufacturing phase, GHG emissions are known to arise primarily from fuel combustion and use of electricity to power equipment and machines, therefore information on fuel and electricity use was collected for each factory building involved in producing the specific shoe model. Finally, transportation data for the finished goods was gathered, including transportation mode, shipment volumes and distance.

For the use phase, the recommended washing instructions for shoes by the company is to use a shoe cleaner or to hand wash with cold water and mild detergent, followed by an air dry. It was assumed that most shoe users do not wash their shoes more than three times over the lifetime of the product.

Assumptions were made to consider the impact of the end of life phase. Based on statistics on U.S. municipal solid waste disposal (United States Environmental Protection Agency, 2008), it is assumed that, at the end of their useful lives, 80% of the shoes sold

are eventually landfilled, and the remaining shoes are incinerated. None of the shoes are recycled, so there is no material recovery.

For the processing of raw materials, the global warming potential (GWP) impact data in terms of kilograms of CO₂-equivalent emitted per kilogram of material processed was obtained from the ecoinvent 2.2 database (Frischknecht et al., 2007; Frischknecht and Rebitzer, 2005).

2.3 Impact assessment

The Global Warming Potential (GWP) impact was determined according to gaseous emissions' potential to contribute to global warming over a 100-year period, based on values published in 2007 by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 2007). The impacts for all gaseous emissions are evaluated relative to carbon dioxide. Impact values for GWP were reported in terms of an equivalent mass of carbon dioxide (kg CO₂-equivalent).

3. Uncertainty Calculation

While the calculation methods for GWP evaluation are described elsewhere, such as in PAS2050 (British Standards Institute, 2008), this section provides more detail on the method employed to estimate the uncertainty in these calculations. A thorough investigation of uncertainty was not the focus of this work; however, providing a description of the modeling approach adds an example of quantitative uncertainty evaluation to the LCA literature.

Within LCA literature, uncertainty is divided into two broad classes: measurement and complex system modeling (Williams et al., 2009). Measurement uncertainty refers to the precision or indeterminate error that is generated by a spread of measurement values of a quantity. This is also called parameter uncertainty, as these observed values (input data) in a model are inherently variable and random (Huijbregts et al., 2001). Complex system modeling refers to the systematic error generated in the modeling frameworks developed to estimate the LCI impact results and the actual emissions type. The difference in scenarios (normative choices) and models (mathematical relationships) used for the construction of these reference models that estimate impacts are the main components of source of variability for impact type (Lloyd and Ries, 2007). Therefore, data collected on the *quantity* of material and energy used in the production of the shoe, as well as the GWP impact associated with the *type* of material and energy source contain uncertainty. Data uncertainty was incorporated in quantity and type by establishing appropriate ranges and distributional information for the point values provided by the product designers and manufacturers. To calculate the total impact and its associated uncertainty, Monte Carlo statistical simulations were performed to aggregate the uncertainty associated with quantity and type. This approach towards incorporating uncertainty has been used by other LCA practitioners (Lo et al., 2005; Maurice et al., 2000; Sonnemann et al., 2003).

In terms of material quantity, a uniformly distributed 20% error within the scrap loss was assumed to account for the ordinary variation of the amounts of raw material used in production compared with the amount incorporated in the shoe (e.g., mass of pelletized polymers into mixing machines to process the materials into the shoe soles or the mass of injected material into the molds). For instance, if the reported mass of polyurethane entering the production process for a particular part was 100 grams and its reported mass in the shoe is 60 grams, the resulting scrap loss is 40%. Thus, the polyurethane scrap loss used in the analyses is 30%-50% (i.e., 20% error in the scrap loss).

Uncertainty in the material type was incorporated by estimating a surrogate impact from the ecoinvent database based on a categorization of the key parts by material family and deriving the uncertainty from the range of materials within the relevant category. For example, the GWP impact of nylon in the upper part of the shoe was modeled by sampling with equal probability from the twelve individual database inventories of nylon-related processes within ecoinvent. In addition, a middle range of uncertainty was estimated from the pedigree matrix for the individual entries (Frischknecht et al., 2007). This approach to materials type specification will be described in greater detail in a forthcoming publication by several of the authors of this work.

The variation of monthly manufacturing production volumes and utility use determined the uncertainty around the production quantity parameters, which includes both the electricity and coal used in manufacturing. Lognormal distributions were assumed for both the electricity and coal quantity with the average and standard deviation was derived from six months of data. The variation in electricity GWP impact is a function of grid fuel mix; the emissions factor was assumed to be a lognormal distribution with a mean of 0.88 kg CO₂-eq/kWh and a standard deviation of 0.21 kg CO₂-eq/kWh based on the location and temporal variation in the Chinese electric power generation grid mix (China-Electricity-Council, 2010). Coal was used for heating equipment in manufacturing. The average emissions associated with the use of coal is 2.0 kg CO₂/kg of coal combusted (see section 4.3 for further explanation). The uncertainty in coal combustion impact is a function of coal type. China's coal resources include most coal types, but mainly lignite, sub-bituminous, and bituminous varieties, accounting for about 13%, 43%, and 28% respectively of accumulated proven coal resources (Sun, 2010). These ratios and the energy content of each coal type enabled the approximation of 0.34 kg CO₂-eq/kg of coal combusted for the standard deviation on the lognormally distributed emissions factor.

4. Case Results

4.1 Total life cycle impact

Based on the data furnished by the shoe manufacturer, the total GHG emissions over the shoes' life cycle are estimated at 14 ± 2.7 kg CO₂-eq (coefficient of variation = 20%). This includes emissions associated with the scrap material lost during the manufacturing phase. For comparison, driving 100 km in a passenger vehicle produces about 18 kg CO₂-eq and a person emits the equivalent amount of carbon dioxide equivalents by using a 100-watt light bulb for a week. Figure 1 shows a breakdown of the total GWP impact by life cycle phase. The material processing and manufacturing phases of the product's life cycle dominate its life cycle greenhouse gas emissions, accounting for 97% of total emissions. The manufacturing burden is over twice that of the materials burden. The impact of each phase will now be examined separately in detail.

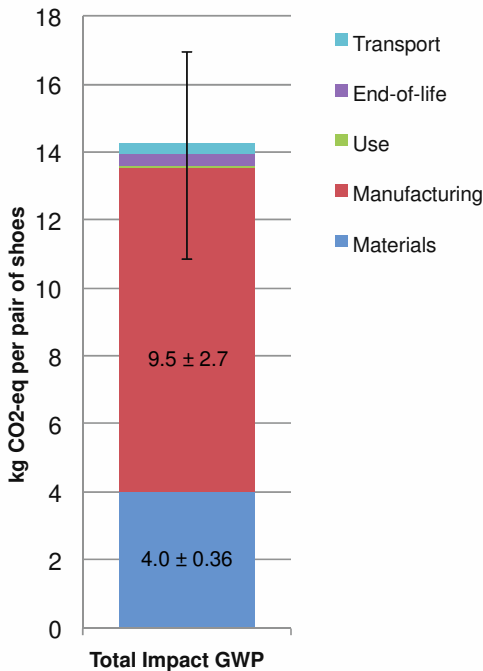


Figure 1. Breakdown of total GWP impact of running shoes by life cycle phase

4.2 Material extraction and processing

There were 26 distinct materials used to make the shoe, including pulp used in the shoe's packaging. The functional unit has three main components: the upper, the sole (together weighing 674 g), and the packaging that the shoes are sold in (178 g). The upper is the part of shoe that covers the sides and top of the user's foot. The sole can be further decomposed to several parts – the outsole, midsole, trussic, gel, and sock lining.

A breakdown of the shoes' mass by part and by material is illustrated in Figure 2. Pulp in the packaging, polyurethane, and polyester use in the shoes' upper, olefin copolymer in the midsole, and diene rubber in the outsole made up a majority (74%) of the shoes' mass.

By multiplying the quantity of materials with their respective emissions factors by type as described above, the material processing phase of the shoes was determined to emit 4.0 ± 0.36 kg CO₂-eq ($\pm 9\%$) of greenhouse gases. Figure 3 shows the breakdown of the shoes' GWP Impact, again by part as well as by material, for the mass of materials that are embodied in the shoes only (excluding scrap). Several insights can be gained from this figure. Firstly, the shoes' upper makes up only 23% of the shoes' mass, but is responsible for 41% of the shoes' emissions. Secondly, 57% of the material emissions arise from the use of polyester and polyurethane alone. This indicates that shoe designers should focus on upper and sock lining materials, specifically polyester and polyurethane, in order to reduce the materials impact.

Finally, it was noted that the emissions attributed to scrap material are about a third of the total materials processing emissions (see Figure 4). Material scrap loss is the difference between the amount of material used during the production of the shoes and the amount of material that ends up within the shoes. Material scrap loss during production is thus significant and indicates potential for both cost and emissions savings. For example, scrap loss in the total use of polyurethane to produce the shoes was 50%.

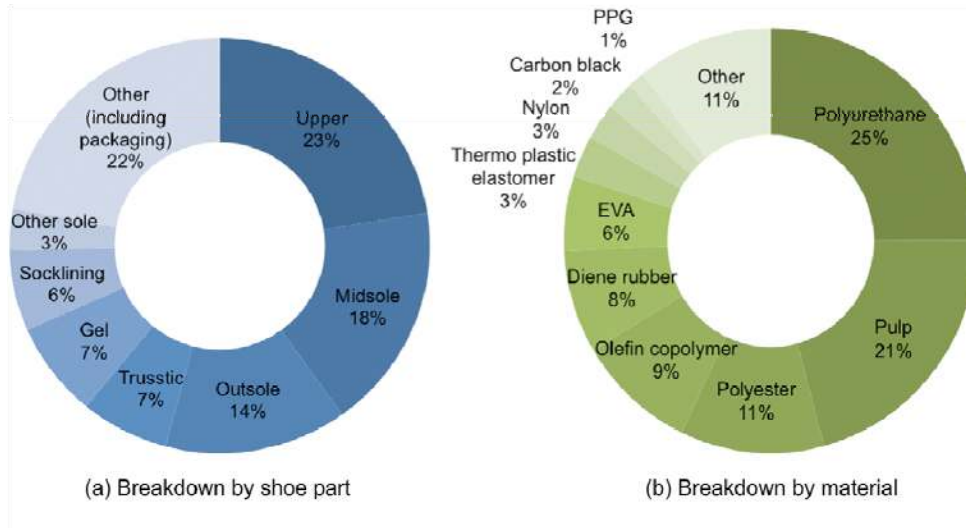


Figure 2. Mass of a pair of running shoes, by percent, including packaging (total around 850 grams) including a) breakdown by part and b) breakdown by material

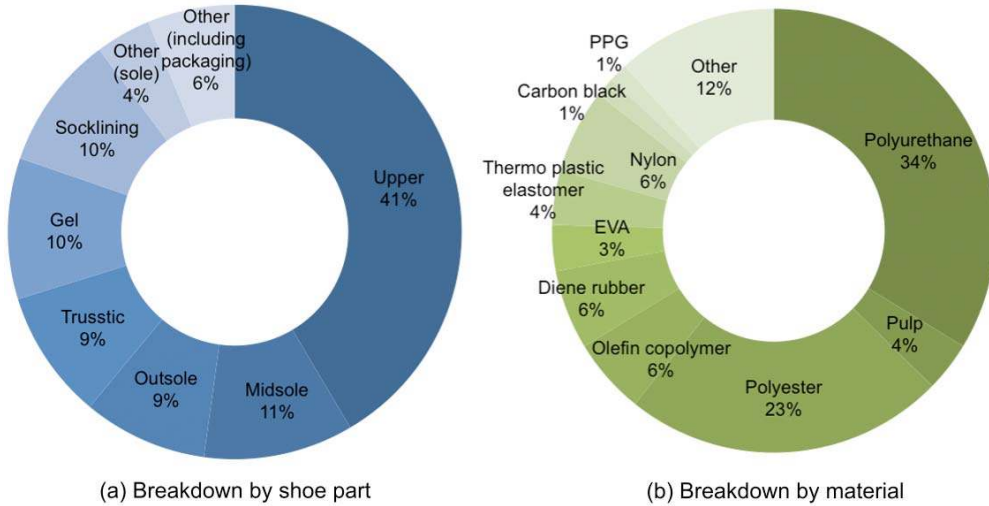


Figure 3. GWP (kg CO₂-eq.) impact of materials by percent within a pair of running shoes including a) breakdown by part and b) breakdown by material

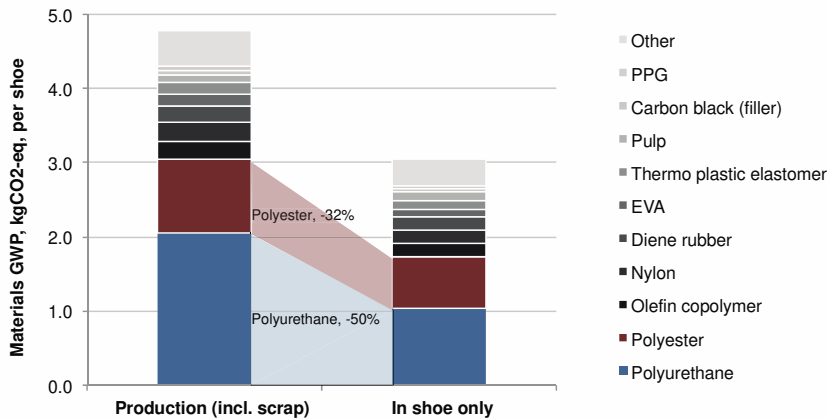


Figure 4. GWP (kg CO₂-eq.) impact of materials due to scrap loss compared with materials in shoe only, per pair of running shoes

4.3 Manufacturing

There are 360 process steps involved in the manufacturing and assembly of running shoes (see Figure 5). Manufacturing shoes is labor-intensive and most of the processing steps involve cutting and stitching together the 53 parts in the shoes' upper. The mid- and out-soles are pressed, while the trusstic is injection molded. The pressed parts have to be buffed and the shoes are assembled (glued and pressed). Most of these steps are performed either by hand or by workers operating individual machines.

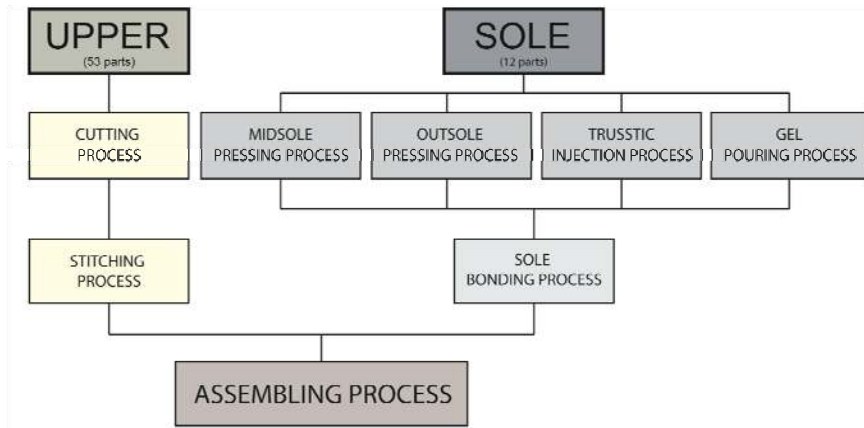


Figure 5. Processing stages in producing running shoes

The manufacturing of the shoes is contracted to a large footwear manufacturer based in China. Data on the amount of resources consumed by and emissions from each factory building involved in the shoe production were collected from the manufacturer over the production period of August 2010-January 2011, during which time 3.6 million pairs of shoes were produced. This included data on electricity use, fuel use, water use, and solid waste emissions. Data on air and water emissions were not available. Data on the number of parts/shoes produced during this 6-month period were also collected. Electricity use was the greatest in the Assembly and Midsole buildings, with a total of 23 GWh over all buildings. Coal was reported to be used in the Outsole and Midsole buildings for heating purposes as part of the manufacturing process.

GHG emissions from manufacturing are expected to arise from three sources: electricity use, fuel combustion, and waste disposal. The data on water use was not utilized in consideration of the GWP impact. Based on this facility-level data, the emission from manufacturing activity was estimated at 9.5 ± 2.7 (coefficient of variation = 28%) kg CO₂-eq per pair of shoes produced, representing 68% of the total burden. A breakdown of this impact between the three sources is shown in Figure 6. The effect of waste disposal is minimal, while the burden is roughly equally attributed to electricity use and the combustion of coal.

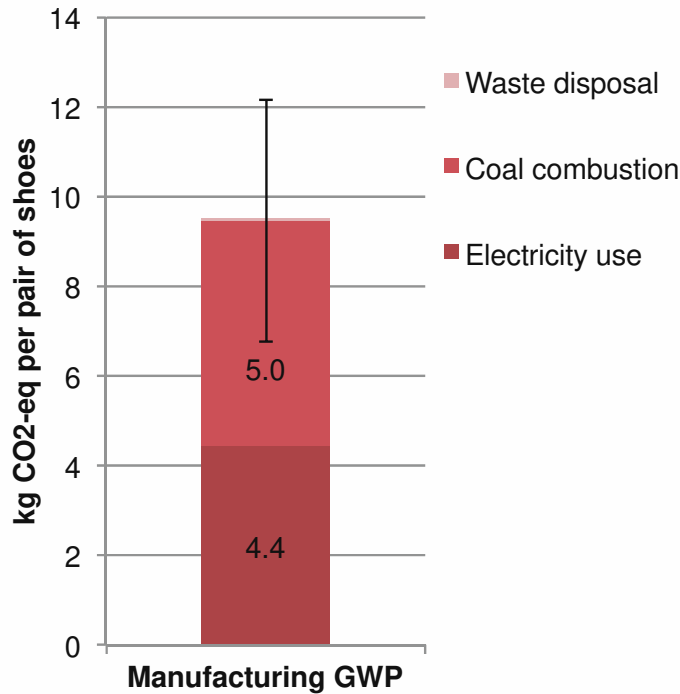


Figure 6. Manufacturing GWP (kg CO₂-eq.) impact, per pair of running shoes

It has been assumed that the emissions factor associated with the Chinese electricity grid is 0.88 kg CO₂/kWh of electricity distributed in the Guangdong province (Chinese National Development and Reform Commission, 2009). Uncertainty was incorporated as the variation in electricity GWP impact as a function of grid fuel mix (see section 3 for further explanation). The emissions factor for coal combustion in an industrial setting is 94 kg CO₂/mmBTU (United States Environmental Protection Agency, 2008), and the average heating value of Chinese coal is 23 MJ/kg (Sun, 2010), so the emissions associated with the use of coal is 2.0 kg CO₂/kg of coal combusted. The uncertainty was incorporated in coal combustion impact as a function of coal type. For the disposal of mixed plastics in a sanitary landfill,ecoinvent 2.2 estimates the impact at 0.09 kg CO₂-eq/kg waste disposed. For waste that is sent to a municipal incinerator, the impact is greater at 2.4 kg CO₂-eq/kg. However, in China, it is estimated that only 4% of solid waste that are disposed of ends up being incinerated, while the rest are landfilled (Huang et al., 2006).

4.4 Use

It was assumed that the GWP impact over the shoes' use phase will arise only from the washing of the shoes, as there is no impact from wearing the shoes. It was assumed that consumers will follow the company's recommendation to hand wash their shoes with cold water and a mild detergent, followed by an air dry. So emissions will only arise from the treatment of wastewater generated from washing shoes. Not including the life cycle emissions of the detergent, and assuming 90 liters of water is used over the lifespan of

the shoe to wash the shoes, the magnitude of treating this volume of wastewater was only 0.03 kg CO₂-eq.

4.5 Transportation/logistics

Data was also collected to estimate the impact of transporting materials or goods in between the shoes' life cycle phases. For transportation of raw materials or parts to the manufacturing facility, supplier locations (by country) were obtained. Combining this with the known amount of materials used in shoe production, as well as emissions factors for transport via freight ship (0.011 kg CO₂-eq/ton-km) and average truck (0.21 kg CO₂-eq/ton-km) obtained from the ecoinvent 2.2 database, the GWP impact of transporting raw materials is estimated at 0.034 kg CO₂-eq/pair of shoes.

For transportation of finished shoes, the shipment volumes of shoes to various markets and their destination ports, as well as locations of first distribution centers, were collected over the period of August 2009 to August 2010. This was used to estimate the shipment volume-weighted average impact of transporting finished shoes. Given that a pair of shoes in their packaging weighs 852 g, the impact of this transportation leg turns out to be 0.24 kg CO₂-eq/pair of shoes. Note that this figure varies widely from 0.092 to 1.0 kg CO₂-eq/pair of shoes, depending on the proximity of the market to the manufacturing facility. The lowest figure is for a pair of shoes shipped from China to Hong Kong. The highest figure is for a pair of shoes shipped from the same manufacturing facility to the Quebec province in Canada. It was assumed that no air transportation is used.

Adding the emissions associated with transporting production waste and shoes at end-of-life to the landfill/incinerator, the total emissions associated with transportation phase for an average pair of running shoes was 0.30 kg CO₂-eq, which makes up only 2% of the shoe's total impact. So the impact of transportation was expected to be trivial over the shoes' life cycle. If the highest figure for the transport of finished shoes was used (that is, considering a pair of shoes shipped to Quebec, Canada rather than the average pair of shoes shipped), this fraction increases to 7%. This is not insignificant, but still small compared to the material processing and manufacturing phases. More details on the transportation phase are available in the Appendix.

4.6 End-of-life treatment

Emissions associated with the end-of-life treatment of the running shoes are also small. As mentioned, it has been assumed that, at the end of their useful lives, 80% of the shoes are landfilled, while the remaining shoes are incinerated. This is based on the state of non-recyclable municipal solid waste treatment in the U.S. The end-of-life emissions were 0.37 kg CO₂-eq, or only 3% of the total life cycle impact.

5. Discussion

Because raw materials can be a primary driver of carbon impact, practitioners rely heavily on the bill of materials to approximate production impact to lower the data collection burden of LCA. Previous work on product attribute-based categorization and

the order of magnitude analysis described in the introduction above support this approach to streamlining LCA. However, where the manufacturing contributes to a significant portion of the overall burden this practice would underestimate the total carbon footprint and overlook high leverage mitigation strategies. Furthermore, scrap generated in production may be very significant and would misjudge the real impact if omitted, because of focus on just materials in the final product (Löfgren et al., 2011). It is therefore useful to hypothesize characteristics of a system when manufacturing is expected to be a major contributor and what drives this contribution.

One challenge in identifying such situations is in drawing distinct boundaries between materials and manufacturing in cases when the structure of the supply chain blurs the boundaries between the two phases. For example, in the case of electronic-containing products, it is complex to define these boundaries, as the production of components often combines both phases (e.g., metal deposition and substrate etching to produce an integrated circuit). Other industries, such as paper production (Lopes et al., 2003) or cement manufacture, are challenging to divide by phase because raw material transformation and “product” manufacturing happen at the same facility. In practice, where these boundaries are not distinct, the materials and manufacturing contribution can be accounted for jointly and the limitations of depending on the bill of materials are not as significant.

For cases where such a distinction does exist, this section explores two potential reasons for the importance of manufacturing in the overall impact of this product: the source of energy employed at the facility and the form of manufacturing (coupled with the characteristics of the material being manufactured).

Source of energy

An important driver for manufacturing as a major contributor is the source of energy used in manufacturing or the fuel mix for electricity available at the facility. In this particular study, results showed that not only is the electricity in China highly derived from coal (which leads to a high grid emissions factor), but also, half of the emissions in manufacturing derived from the direct use of coal for heat required in production.

In order to examine the breakdown of impact independently of the GWP-intensity of the energy source, the burden in terms of cumulative energy demand (CED) per pair of shoes was calculated (Figure 7). The fraction of the energy used in manufacturing is equally attributed to the use of electricity and the combustion of coal, and is still on the order of the materials impact. While recalculating the product burden based on energy explains some of why the GWP-intensity for manufacturing is high as shown in Figure 1, the burden is still on the order of material; therefore materials non-dominance still requires some exploration.

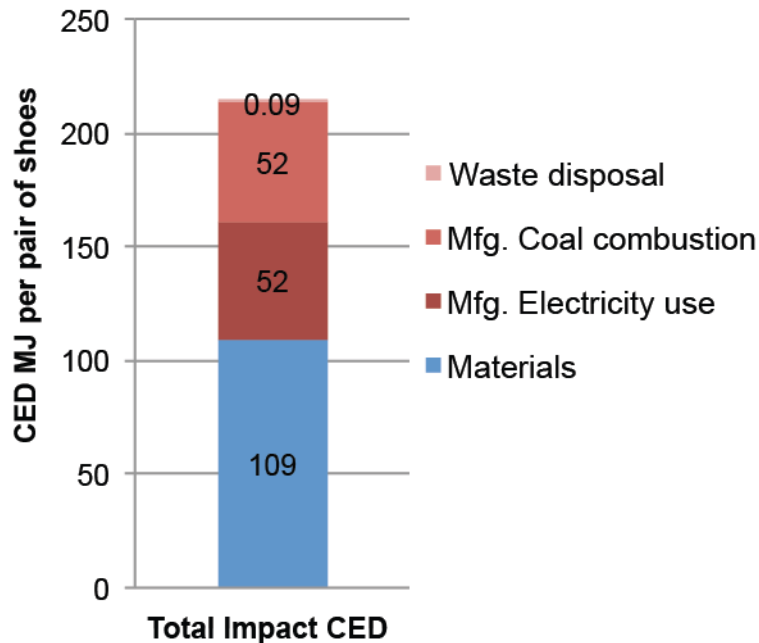


Figure 7. Cumulative Energy Demand (CED) of running shoes by life cycle phase

Form of manufacturing

Another way that manufacturing can provide an appreciable portion of the life cycle burden is through the type of manufacturing required in production. For example, products containing electronics can be manufacturing energy intense (e.g., personal computers (Deng et al., 2011; Williams, 2004) and mobile phones (Yu et al., 2010)). Energy intensity is significantly increased with micro/nano processes ranging from 10^4 - 10^9 MJ/kg of processed material (Gutowski et al., 2009). This suggests that one driver may be the complex nature of the manufacturing processes and the magnitude of the area over which the processes are performed.

While running shoes do not require anywhere near the process complexity seen in electronics, the required manufacturing processes do occur on the small, light components. As an example, in the case of running shoes, one of the main process contributors was the injection molding of several pieces of the sole. In order to investigate this hypothesis, the power consumption, cycle time, and amount of material processed for the specific injection molding machines used by the upstream footwear manufacturer were collected, resulting in 19 – 29 MJ/kg of polymer processed (excluding any auxiliary equipment or the efficiency of the electric grid). An empirical environmental study of injection molding concludes that the average values for hydraulic, hybrid, and all-electric machines are 1.4 - 3.4 MJ/kg of polymer processed (Thiriez, 2006).

A direct comparison of these two outcomes suggests that the energy magnitude of the processes in shoe manufacturing may individually contribute to a greater percentage of

the total burden. Similar relationships were observed for foaming machines, as well as some of the heating processes. It is noted that a much more complete quantitative analysis should be conducted for several additional steps within the process in order to draw generalized conclusions. The above observations would suggest that manufacturing may be significant when occurring in areas with carbon intensive energy sources and when the product involves many small light components – even if produced using conventional processes.

5.1 Emissions reduction mitigation strategies

By understanding the drivers of GWP burden within a product, it is possible to identify high leverage approaches to mitigate these impacts. The field of industrial ecology proposes implementation strategies toward improving environmental impact, including substitution, dematerialization, and waste mining. Several guidelines for ecodesign have also been proposed including 1) choice of materials and components towards recyclability, durability, reusability and low toxicity, 2) renewable energy use, 3) reduction in energy or materials intensity and 4) waste minimization (Borchardt et al., 2011; Niinimäki and Hassi, 2011). If product LCA or carbon footprinting results emphasize primarily the raw materials phase, reduction efforts might focus on substitution of the product's materials, where possible, for recycled or even bio-derived materials. Use of more recycled materials enables some GWP mitigation in the case of the product explored here, but finding ways to couple beneficial material use with streamlined manufacturing processes has the potential to create significant emission reductions. This section outlines potential mitigation strategies that focus on manufacturing in terms of two major categories: parts consolidation and process efficiency.

With over 65 parts in the shoe, many of which require labor-intensive activities like stitching or cutting to assemble, opportunities were explored where components of the same material could be consolidated in order to eliminate steps in the manufacturing process. Two adjacent parts of the upper shoe were identified that can be combined to achieve two potential improvements. Firstly, the amount of material lost to scrap would be reduced, thereby enabling the purchase of less material. Secondly, the combination of parts eliminates three cutting and welding process steps, reducing the electricity burden to operate the machines.

In terms of design, alternative strategies for including aesthetic features not related to performance of the shoe were assessed. For example, there are opportunities where design features could be printed onto the base fabric rather than affixing the features to the shoe through cut and weld processes. This change has the dual benefit of eliminating material and avoiding the welding and cutting process steps. The most significant savings arise from the avoided electricity burden of the cutting and welding machines, but the reduction in materials use also makes a contribution. Further, opportunities were identified where adjacent components of different colors could be combined to be the same color. This small change eliminates cutting process steps and

reduces the operation time of the pressing machine without impacting product performance.

Some processes were identified where machinery could be used more efficiently. In each case, there was downtime between production cycles where the machinery was left to idle (consuming energy) while the next batch of components was being prepared. By modifying the procedure such that while a batch is in the machine, staff could be staging the next set of components, the machinery could remain in continuous use. In all cases, a cost-benefit analysis would be required to fully understand the economic benefits of potential strategies.

The paragraphs above described some general strategies for mitigation that were explored by this research after the baseline footprint was determined. Figure 8 below shows a rank ordered list of design, materials and process changes by the potential magnitude of reduction from the baseline footprint described in the case study results. These percentages were determined based on the assumed embodied energy change, changes in material mass, and assumptions around energy savings in production (by looking at individual machine impact). The latter two quantities were provided through discussions with the brand owner and manufacturing partner. While material substitution for lighter weight, recycled, or bio-derived materials does provide impact reduction, the greatest GHG emissions savings can be found in the strategies that involve parts consolidation. As discussed above, this is because of the dematerialization as well as process efficiency improvements, highlighting the importance of targeting manufacturing aspects. It is noted that the rank order of these results depends on the particular mass of components under consideration.

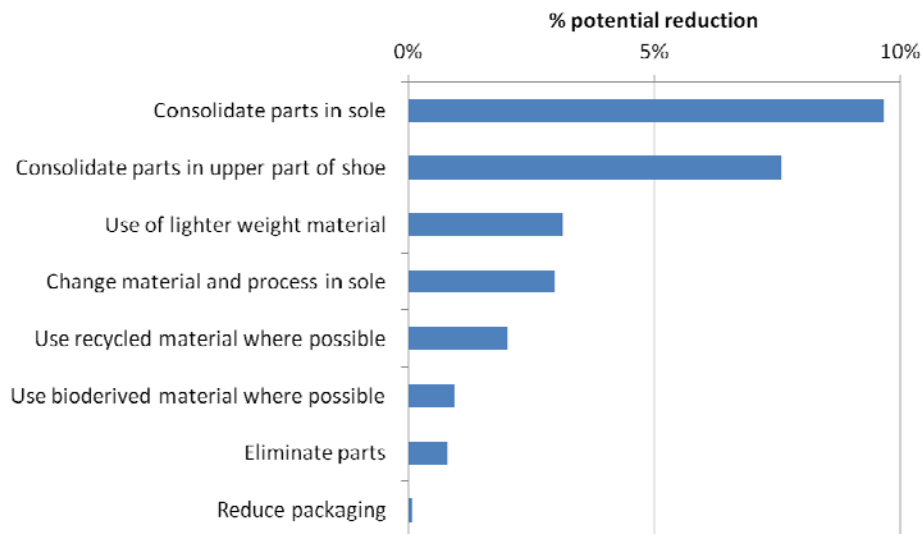


Figure 8. Rank ordered list of mitigation strategies by percent potential reduction from the baseline footprint

6. Conclusions

One purpose of this study was to determine the carbon footprint, or life cycle GWP, of a pair of running shoes and to suggest strategies to reduce the product's impact. The analysis was also used to investigate the characteristics of products that show a high manufacturing phase burden. The carbon footprint results indicated that the impact was 14 ± 2.7 kg CO₂-equivalent over the shoes' lifespan, from cradle to grave. There were negligible emissions expected over the shoes' use phase, and the transportation and end-of-life phases only contributed nominally to the shoes' overall impact. By carrying out this study, GWP hotspots, or materials/processes of particularly high impact, were identified. It was determined that most of the emissions were released during shoes' material processing (29%) and manufacturing phase (68%).

Using the hotspots as a guide, a number of mitigation strategies within the materials and manufacturing phases were considered that would not affect the product's performance. In the material processing phase, use of polyester and polyurethane in the shoes' upper was found to contribute to almost 60% of emissions; substituting a less carbon-intensive material, such as a recycled material, could greatly reduce the impact. Further, consolidating similar adjacent parts could eliminate production steps and minimize scrap loss. Also, shifting to printing design elements onto the shoe rather than affixing additional material can save energy and material. In terms of the manufacturing phase, finding cleaner alternatives for heating, pursuing energy-efficiency improvements related to the sole production and assembly processes, and reducing machinery idle time would help to lower the GWP of the product.

Gaining an understanding of product types that may trend towards a higher impact in the manufacturing phase could help to cue practitioners when to look beyond the bill of materials when quantifying life cycle impacts and developing mitigation strategies. This analysis pointed to two factors that appear to drive an increased energy burden in the manufacturing phase of a product's life cycle. The form of manufacturing can lead to a higher carbon footprint, particularly when a product involves many small, light components – even if produced using conventional processes. The source of energy for the manufacturing site can contribute significantly to the impact, especially when production occurs in areas with carbon intensive energy sources.

7. Appendices

There are several materials used in the shoes that are not available in the ecoinvent 2.2 life cycle inventory (LCI) database. In these cases, the closest match was used, and these substitutes are listed in **Table 1**. The impact of these materials on the total GWP impact is noted to be small.

Material in shoe	Substitute material referenced in ecoinvent for LCI data	Resulting GWP impact, kg CO ₂ -eq	% of total GWP impact
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Aluminum coated glass beads (in logo)	Glass fiber	0.0012	0.024%
di- α -cumyl peroxide (curing agent)	Hydrogen peroxide	0.0019	0.038%
Magnesium carbonate (filler)	Magnesium sulfate	0.0039	0.078%
Azodicarbonamide (blowing agent)	N,N-dimethylformamide	0.027	0.54%
N,N'-dinitroso pentamethylene (blowing agent)	Methylamine	0.015	0.30%
Chemicals (in outsole)	Acrylonitrile butadiene styrene (ABS)	0.022	0.45%
Total:		0.071	1.4%

Table 1. Closest matches for materials in shoe that are not available in theecoinvent database

Other assumptions were made on the transportation distances as well as mode for the other transportation legs, and all transportation legs accounted for are summarized in **Table 2** below. For example, it was assumed that waste generated from the manufacturing facility in China is transported over a distance of 100 km by lorry to the landfill or incinerator.

Product	Origin	Destination	Distance	Mode	Emissions, kg CO ₂ -eq
Raw materials	Various	China	Various	Various	0.03
Production waste	China	Landfill / incinerator	100 km*	Freight lorry	0.01
Finished shoes	China	1 st distribution center	Various	Various	0.15 (average)
Finished shoes	Distribution center	Retailer	500 km*	Freight lorry	0.09
Retired shoes	Customer	Landfill / incinerator	100 km*	Freight lorry	0.01
Total:					0.30

Table 2. Assumptions made (*) and resulting emissions for the transportation phase of shoes

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