ENVIRONMENTAL COMPARISON OF MICHELIN TWEEL™ AND PNEUMATIC TIRE USING LIFE CYCLE ANALYSIS

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Austin Cobert

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Environmental Comparison of Michelin Tweel™ and Pneumatic Tire Using Life Cycle Analysis

Approved By:

Dr. Bert Bras, Advisor
Mechanical Engineering
Georgia Institute of Technology

Dr. Jonathan Colton
Mechanical Engineering
Georgia Institute of Technology

Dr. John Muzzy
Chemical and Biological Engineering
Georgia Institute of Technology

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Chapter 1. Introduction

1.1 Background and motivation

Passenger car usage and fuel consumption have risen consistently since the invention of the automobile, and with the ever-growing population and increased city sizes it is difficult to find a peak to this upward trend. U.S. automobiles consume over 9 million barrels of oil per day (390 million gallons/day), which is 70% of the crude oil consumed throughout the country.[1] Unleaded gasoline has 8.87 kg of CO_2 per gallon, so daily automobile carbon dioxide emissions surpass 3 million metric tons.[2] People have become more aware of the effects of such carbon emissions, but there is a lot more to automobile usage than meets the eye. All the materials and energy that are used to make a car need to be considered, along with all the other gasoline emissions such as sulfur dioxide and nitrogen oxides. More efficient engines and more aerodynamic and environmentally friendly cars that will consume less gasoline on an average day have begun to be developed, but gasoline usage continues to rise.

It is now important to consider every part of a vehicle to determine from where environmental benefits can arise. The U.S. government has set a goal of an increased average fuel economy to 35 mpg by the year 2020, and the only way to make that happen is to make every part of the vehicle more fuel efficient, from the driveline to the tires.[3] Figure 1.1 shows where all the energy from gasoline is used during highway driving.

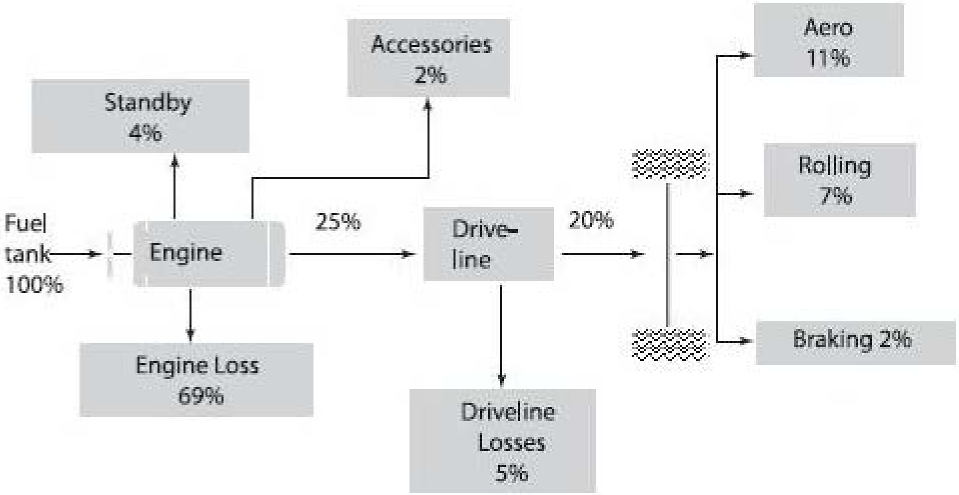

Figure 1.1. Energy flow for average passenger car, highway driving [4]

Obviously engine losses are a very important energy sink in this energy flow, but it can be seen that aerodynamics and rolling resistance are also very important in reducing a vehicle's fuel consumption. Specifically, this report will focus on the overall environmental effects of tires, and it will consider everything from the fuel consumption described above to the possible recycling or reuse at the end of a tire's life.

1.2 The Problem

1.2.1 Michelin's Tweel™

Recently Michelin has been developing a new airless, integrated tire and wheel combination called the Tweel™. The Tweel™ (the name is a contraction of "tire" and "wheel") is an airless one-piece wheel-and-tire combination with a rubber tread bonded to a deformable wheel hub with polyurethane spokes as shown in Figure 1.2.

Figure 1.2. Michelin's Tweel™ [5]

The Tweel™ promises performance levels beyond those possible with conventional pneumatic technology because of its shear band design, added suspension, and decreased rolling resistance. It delivers pneumatic-like load-carrying capacity, ride comfort, and as it has no pressurized air cavity, it cannot be punctured. Eventually it may be able to outperform conventional tires since it can be designed to have high lateral strength for better handling without a loss in comfort.

However, many questions remain as to what kind of environmental impact this radical new design will have. Currently there are environmental issues all throughout a tire's lifespan from rubber manufacturing emissions to tire disposal, and the rapidly growing method to evaluate all of these points is Life Cycle Analysis (LCA). LCA is the essential tool required by businesses in order to understand the total environmental impact of their products – cradle-to-grave. By considering the entire life cycle of a Tweel™ from manufacturing, through use and disposal, and comparing it to knowledge of current tires, an accurate assessment of the entire environmental impact of the Tweel™ will be made in this thesis.

1.2.2 Rolling Resistance

The main environmental advantage to the Tweel™ is its very low rolling resistance, or the constant force required to roll a wheel at a constant speed under a certain vertical load. This property, which exists in any tire, is a result of the way rubber interacts with a hard road surface. Under the vertical load, a rubber tire deforms in order to support the entire weight of a vehicle. This allows for the traction, cornering, and comfort that is expected from a tire, but it requires a certain energy expense as a tire repeatedly deforms and recovers during its rotation.

As shown in Figure 1.1 above, the amount of fuel consumed by a vehicle is affected by the efficiency of the vehicle in converting the chemical energy in motor fuel into mechanical energy and transmitting it to the axles to drive the wheels.[6] Most of the energy available in the fuel tank is lost in converting heat into mechanical work in the engine, but about 20% of the energy from the fuel makes it to the tires, and a significant percentage of this is used to overcome the rolling resistance. Most of this rolling resistance energy loss stems from the viscoelastic behavior of rubber materials. Some of the energy required to deform rubber is stored as elastic energy and is completely recovered when it is returned to its original shape, but some is converted to heat and lost due to rubber's partially viscous behavior. This energy loss under a load and unload cycle is called hysteresis.

The more a tire at a given pressure is loaded, the more it deforms, leading to an increase in hysteresis with wheel load. This relationship between rolling resistance and deflection due to load is approximately linear, so increasing the load on a tire results in a near-proportional increase in total rolling resistance. This linear relationship allows rolling resistance to be expressed as a coefficient called the Rolling Resistance Coefficient (RRC), which is traditionally expressed in units of kg/ton. For most passenger tires sold in the U.S., the coefficient of a new tire falls between 0.007 and 0.014, which means under a load of 1,000 kg, a constant horizontal force of 7 to 14 kg is required to maintain the vehicle's speed. The exact reasons for the Tweel™ having a lower rolling resistance than these average tires is confidential until the Tweel™ is completed, but the estimated rolling resistance coefficient is available and will be discussed later.

1.2.3 Product design issues

Since the Tweel™ is currently still in the research phase and is not currently manufactured and used, there are uncertainties with respect to end-of-life scenarios and rolling resistance estimates that will affect the LCA. Thus, it will be important to consider a range of options to determine which one will have the most environmental benefits while still keeping the strengths of the Tweel™ design intact. Most of the material composition of the Tweel™ is known and documented, but there are still uncertainties about tread wear and recycling options that need to be examined by considering a range of possible environmental impacts. For example, will it be more environmentally friendly to recycle Tweels™ or burn them as fuel? Or is it even possible to recycle them? These questions will be examined with the help of life cycle analysis tools.

1.2.4 Baseline comparison tire

It is necessary to analyze the overall environmental impact of all new products, especially ones that are responsible for as much fuel as Americans automobiles consume, but as will be discussed in more detail later, LCA is a tool that is best used on a simply relative scale. It is simple to demand decreased CO_2 emissions, but when considering the entire life cycle of a product, is it beneficial overall to develop a product that involves harmful chemicals in the production process to save energy while it is being used? In order to answer this question accurately, a system to compare a large range of environmental effects on a single scale is required, but it is also necessary to compare the new product to the product it is replacing in order to observe if the entire life cycle has been improved.

In this report, the baseline tire that will be considered for this comparison will be representative of the most fuel efficient, lowest rolling resistance tire on the market today so that it will be possible to accurately state whether or not the Tweel™ will be the most environmentally friendly tire on the market when it is released. The tire chosen for this comparison is a P205/45R17 passenger tire used as an OEM on a BMW Mini Cooper. Further specifications on this tire will be supplied later in the report.

1.2.5 Geographical Boundary

Vehicle use differs across the world, but for the purposes of this report only U.S. data and emissions will be used when appropriate. In the case of some of the raw materials needed to produce a tire, the inventory data of required inputs and outputs will come from the country where the material is produced, and then the environmental costs of transporting that material to the U.S. will be added on. For example, natural rubber is almost entirely produced in southeast Asia, so it would be inaccurate to assume it is produced in the U.S. to ignore the transportation emissions. For the majority of the analysis however, American standards and values will be used. The life cycle model will consider a tire and Tweel™ made in the U.S., driven by an average American, and disposed of by ratios corresponding to American recycling plants.

Two very important differences arise between an American tire and a European tire. The average driving distance and tire use varies drastically between countries, but more importantly, the energy mix supplied by power plants in the U.S. is very different from that of a European country. The U.S. gets a larger percentage of its electricity from coal plants instead of wind and water power like some European countries, which directly affects the environmental impact of tire production that takes a large amount of electricity.[7] So, for these reasons it is important to distinguish that this is a U.S. analysis. Thus, all estimates will only be valid for American tires, so conclusions about the environmental effects of European tires should be made with caution.

Chapter 2. Research Background

2.1 Introduction to life cycle analysis (LCA)

According to the life cycle analysis (LCA) standard ISO 14040, LCA is defined as "a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle."[8] LCA is a technique for assessing all of the environmental aspects associated with a product from "cradle-to-grave", or from a product's manufacturing stage through its life, and into its disposal route. This environmental assessment tool is critical to the foundation of this report and will be used extensively to compare the Tweel™ to a standard pneumatic, or air-filled, tire by adhering to the standards ISO 14040, 14041, 14042, 14043, 14044.

These standards outline a basic four step process to complete a life cycle analysis consisting of a goal and scope, inventory analysis, impact assessment, and interpretation that are described as follows: [8, 9]

1. Goal and Scope – This phase has already been discussed a little, but not in a sufficient manner to satisfy the ISO standards. The goal and scope phase identifies the LCA's purpose and determines the boundaries of the assessment by defining exactly why and how the study will be performed. The object of study is described in terms of a "functional unit" that defines a reference unit to help quantify the overall impact of the product.[10]
2. Inventory – This is the phase in which all the data is collected that models the product system. This encompasses all data related to environmental (e.g., CO_2 emissions) and technical (e.g., intermediate chemicals) quantities for all relevant unit processes

within the boundaries defined in the "goal and scope" phase. The results of the inventory is an LCI (life cycle inventory) that provides information about all inputs and outputs in the form of elementary flow to and from the environment throughout all stages of the functional unit's life.

3. Impact Assessment – The life cycle inventory contains all the information necessary to analyze the environmental impact of a product, but the impact assessment phase evaluates each elementary input and output flow so that they can be compared on a uniform scale. The inventory results are therefore grouped into a number of impact categories such as climate change, ecotoxicity, and depletion of fossil fuels. These impact categories can then be normalized and weighted to get a better understanding of the relative meaning of each category and an overall environmental score for the entire life cycle.
4. Interpretation – To validate the results of the impact assessment, in this stage the results are interpreted in relation to the original goals and scope of the study. A number of procedures can be used to check the validity of the conclusions of the study including uncertainty analysis, sensitivity analysis, consistency checks, and varying impact assessment methods.

This approach simplifies a complicated set of environmental inputs and outputs into four steps that are all interrelated as shown in Figure 2.1. There is a logical progression from steps 1 through 4, but changes to any step throughout the analysis will have effects through other stages, so this becomes somewhat of an iterative process until a valid scope is defined that leads to an impact assessment that can be verified with confidence. The analysis in this report will be performed using this rough outline with a consistent goal to compare Michelin's Tweel™ to a current pneumatic radial tire.

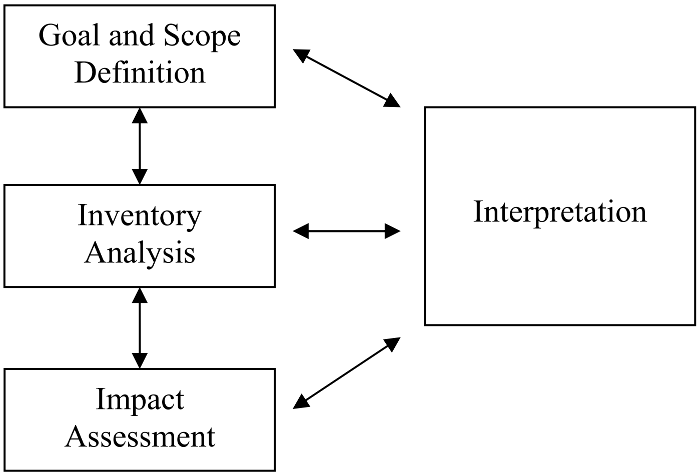

Figure 2.1. Interdependence of LCA phases

2.2 SimaPro

The computer program used to compile and interpret every aspect of a wheel's life cycle in this report is SimaPro (System for Integrated Environmental Assessment of Products) version 7.1 developed by PRé Consultants. Due to the large amount of input and output inventory data through an entire life cycle of a product, SimaPro is necessary to ensure a complete and reliable comparison of every effect. It features a user interface that allows the environmental inventory of any product or process to be modeled by specifying inputs (resources, fuels, electricity) and outputs (emissions to air, water, and soil, etc.) while ensuring the ISO LCA guidelines are followed. Each component of every phase of a product's life can be modeled separately and then combined to form a complete model of the entire life cycle. These components, such as raw materials production or disposal routes, can either be developed as new data sets by the user or existing pre-packaged databases that contain detailed environmental inventory data for thousands of products and processes across the world can be used. These databases (BUWAL, IDEMAT, Franklin USA, etc.) are developed by environmental professionals and are peer reviewed to assure confident data sets describing any potential environmental impact of a process, but each data set is usually geographically specific and may differ if the process is being modeled in a different country.

Not only does SimaPro offer pre-packaged databases describing a wide range of processes, but it also offers several different tools to analyze the environmental impact of the inventory data (step 4 of the general LCA process defined in section 2.1). Data describing the energy requirements and airborne emissions are necessary to the LCA process, but the most helpful trait of SimaPro is its ability to organize all of this data, interpret it with a range of impact assessment methods, and then present the overall environmental effects in an organized manner. Most of the impact assessment methods that are supplied with SimaPro output overall environmental impact results on a uniform scale to help compare different stages of a life cycle, and SimaPro has the capability to present these results in clear graphical form for easy interpretation. For these reasons and its growing use throughout the entire field of life cycle analysis, SimaPro will be used in this report to greatly facilitate the analysis of a large amount of data.

2.3 Tire LCA literature review

2.3.1 Life Cycle Analyses

Before a proper Tweel™ life cycle analysis can be performed, it is first necessary to understand previous LCA's done in the same area. Many papers have been published on the topic of life cycle analysis for roughly the past 10 years while this environmental area of research has developed, specifically in the Journal of Life Cycle Assessment, that not only give insight into environmental impacts of rubber, polyurethane, and tires in general, but also help to understand the progress of life cycle assessment altogether. Guinée, et al, describe the progression of life cycle analysis over the past 15 years starting from a time when the major data source, the Swiss BUWAL Report [11], did not list CO_2 as a pollutant and global warming (climate change) as an impact.[12] Due to this rapid progress in environmental analysis techniques, it is very important to use recent data and impact categorization tools in order to compose a life cycle assessment valid in today's world. The current baseline LCA rules that will help ensure this quality are described in the ISO 14040ff series.[8, 9, 13] These ISO standards lay out the fundamental life cycle analysis process, but do not give precise advice about specific ways to implement the basic rules. For this reason, life cycle analysis is a fairly subjective tool that can produce quite different results depending on the methods chosen to produce the conclusions. Pears, for example, when looking at cement manufacturing plants, found a wide variation in energy efficiency, greenhouse output, and other environmental impacts due to the methods he chose to not only collect the data but also to assess the environmental impact of that data. Depending on the plant, the embodied energy varied between 3.3 and 8 GJ per ton of cement produced. This variation was then compounded when different impact assessment methods were chosen that weighed global warming potential and natural resource depletion differently.[14] Thus, due to the ever-changing field of life cycle analysis and the fairly vague rules that allow differing assessments of environmental effects, a comprehensive analysis that attempts to nullify some of these questions by offering multiple impact assessment methods is necessary for a complete environmental analysis of any product.

Specifically in the tire industry however, today tire manufacturers and raw material suppliers are continuously challenged to develop economically and environmentally sustainable products, and a lot of research has already been completed attempting to minimize the overall environmental impact of this industry by adhering to the ISO standards of life cycle assessment.

Tire manufacturers are faced with a fundamental dilemma when environmental factors are considered, so weighing the pros and cons of each in a consistent manner has drawn much attention. On one hand, the tire industry is urged to provide tires with steadily improved on-the-road performances (wet / dry traction for safety reasons, wear resistance for durability, and rolling resistance for fuel economy). On the other hand, the tire industry is willing to develop tires with minimal impact on the environment. For the most part, these two are mutually exclusive. An increase in comfort or traction usually results in increased environmental load. By applying LCA techniques, the tire industry is recording all ecological aspects of the interaction of a tire and the environment during the lifetime of the tire. This global approach is considering the added contributions of raw materials, as extraction of fossil and mineral materials, manufacturing of additives such as fillers, curing package, and silanes, the tire production in plants, and the tire use on the road until the end of its life so that confident conclusions can be made about product improvements that have different environmental effects.

According to the European Tire and Rubber Manufacturers Association, the major environmental impact throughout a car tread's life cycle consists in the tire use phase with carbon dioxide emission linked to the fuel consumption of the car, attributed to the rolling resistance.[15] This conclusion is agreed upon by several other sources including a brief overview done by Continental and an in-depth, detailed report from PRé Consultants titled *Life Cycle Assessment of an Average European Car Tire.*[16, 17] As shown in Table 2.1 from Continental's analysis and Figure 2.2 from PRé Consultants it is easy to see that the use phase of a tire's life cycle is the most environmentally harmful. This environmental load results from the rolling resistance described in section 1.2.2, and is the focus of most of today's tire manufacturers.[18] According to these studies, reducing the rolling resistance by a small percentage will have a noticeable impact on the overall environmental performance of the tire.

Table 2.1. Continental's Life Cycle Energy Balance in Liters of Petroleum[16]

Process	Energy Input (MJ)	Global Warming Potential (kg CO_2 equiv.)	Acidification (kg SO_2 equiv.)
Acquisition of raw materials	211	14	0.0718
Transport	16	1.5	0.0123
Production	104	7.3	0.0103
Use	7520	601	0.54

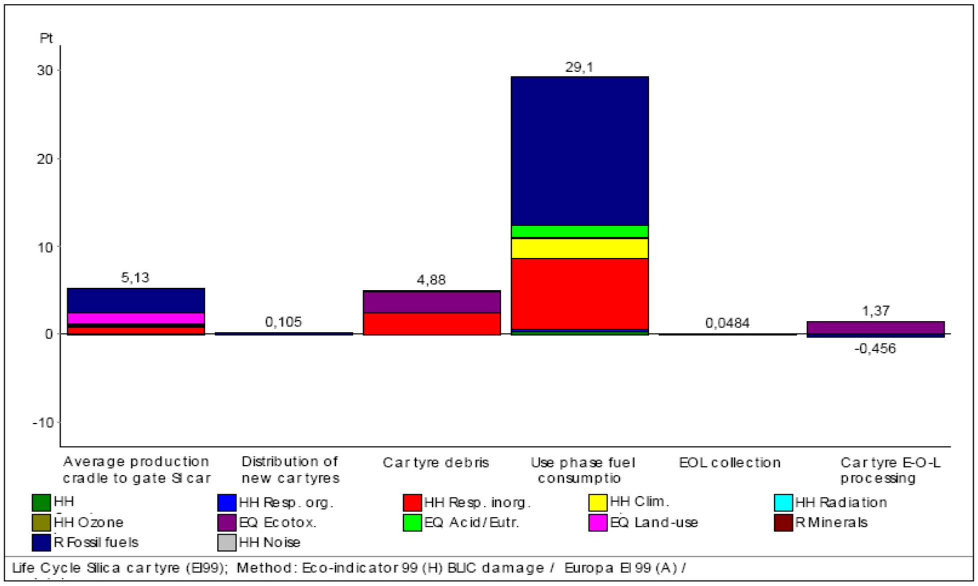

Figure 2.2. Life cycle analysis of European carbon black based tire life cycle [17]

The study performed by PRé Consultants assessed the overall environmental impact of an average European P185 car tire, and establishes a good foundation for an analysis done in the United States. U.S. tire manufacturers have been slower to adopt LCA techniques for product improvement, so there is minimal documentation of the differences between American and European tire production, but small differences between the European P185 tire and the fuel efficient P205 tire will be seen throughout this report. The most important differences between European tire LCA and this American version are the use mileage for an average tire and the end of life processing. Small differences occur in the material composition of the two tires and the production of these raw materials as will be seen in the inventory collection phase of this report, but the European tire producers used an average life of 40,000 km while the American average is over 40,000 miles. There are also obvious differences between the fuel use over the life cycle of a tire because the PRé study analyzed the environmental contributions of an average European tire, while the most fuel efficient American tire is used in this report to be able to state whether or not a Tweel™ would be the most environmentally friendly wheel if it was released today. The last major difference between this European analysis and this U.S. report is the end of life disposal route differences. As shown in Table 2.2, a much larger percentage of tires is landfilled in Europe instead of being incinerated for energy.

Table 2.2. European vs. American tire disposal routes [19]

	Material Reuse	Energy	Landfill
France	52%	35%	13%
U.K.	60%	20%	20%
European Average	35%	39%	26%
U.S.A.	34%	52%	14%

PE Product Engineering GmbH cooperated with the University of Stuttgart prior to the PRé study, but their LCA also focused solely on the environmental profiles of two different average European car tires – a silica-based and a carbon black-based tire.[20] In much the same way as the other European tire analyses they contacted European automobile producers and their suppliers to quantify the energy, raw materials, emissions, waste, and cost needed in every stage of a tire's life cycle, but most of the data found in these reports are not valid for an American tire production plant due to some of the differences in energy production, tire manufacturing, and tire use.[21] Even though there are no tire LCA reports published for American tires that cover an entire life span, there are still details available from every stage of a tire's life from raw materials to disposal, and this data will help to compare tire production and use between Europe and the United States. The key in this report will be to assemble all this American data spread across different industries into a clean, comprehensive report to fully understand not only the potential environmental impact of a Tweel™, but also that of a tire manufactured and used in the United States.

2.3.2 Raw materials

The environmental effects of the production of the raw materials needed to produce a tire or Tweel™ (rubber, polyurethane, carbon black, etc.) are documented in both the SimaPro databases and also some literature detailing the production methods of each material. Due to the differences in energy requirements and environmental emissions in different countries, the SimaPro databases should not be used as the only source of inventory data and will thus need aid from reports like the Encyclopedia of Chemical Processing and data from the International Rubber Research and Development Board (IRRDB).[22, 23] Several sources detail the production of both natural and synthetic rubber, but even reports that discuss the production of steel wires and sulfur are important.[24, 25] Each of these materials will be discussed in more detail in the inventory collection section of this report, but it is important to realize that sources beyond the packaged SimaPro databases are available for comparison and necessary for confidence in each raw material production process.

2.3.3 Gasoline emissions

Vehicle fuel economy has been the focus of intense discussion recently due to growing oil demands and increasing environmental consciousness, and tires play an often overlooked part in this problem. Tires are responsible for a noticeable percentage of a vehicle's fuel use because of the force required to overcome rolling resistance, but exactly how much of an effect this causes varies between different types of tires and has been under debate with some sources estimating a range of 5 to 20% of all fuel use.[6, 26, 27] Quantifying the specific amount of fuel use attributable to one tire or Tweel™ will be a key part of this LCA since the use phase has been documented as the most environmentally harmful stage of a tire's life, and such a large range of possible fuel use could have drastic effects on the overall environmental load of a tire or Tweel's™ life. Deciding on the precise amount of fuel use throughout a tire's life can be aided by the large number of rolling resistance coefficients (RRC) documented for a wide range of tires though, such as the data set assembled by the Transportation Research Board who compared over 200 tires of varying sizes and brands to try to understand the relationship between rolling resistance and tire size, tread quality, aspect ratio, etc.[28] Charts such as Figure 2.3 below from their report titled *Tires and Passenger Vehicle Fuel Economy* can help begin to develop a picture of the effects of tire rolling resistance on fuel use.

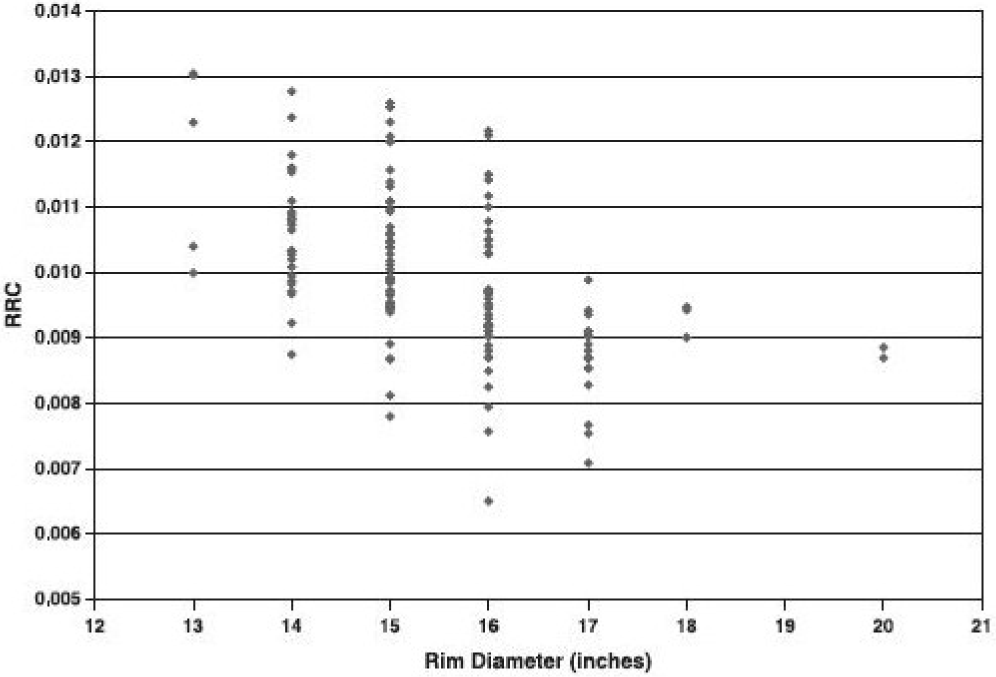

Figure 2.3. Rolling resistance coefficients sorted by rim diameter [28]

Although quantifying the amount of fuel used by a tire is under debate, the amount of overall fuel use by a vehicle and the corresponding tailpipe emissions are very well documented and easily agreed upon. Not only are national CAFE standards published enforcing a limit on the minimum fleet fuel economy [29], but details of gasoline emissions have also been closely monitored. Airborne emissions per gallon of gasoline are documented in several sources including reports from the Environmental Protection Agency and Energy Information Administration in which carbon dioxide, nitrogen oxides, and other potential environmentally damaging particles are quantified.[1, 30, 31] Each of these reports discusses the importance of minimizing the gasoline use and corresponding emissions from passenger vehicles, but the overall environmental effects require a broader life cycle approach.

2.3.4 End of life

There are several works about the impact of the increasing number of used tires in the waste stream, because excessive landfill use is the fastest growing environmental concern among the public.[32] As described by life cycle analysis efforts and shown in Figure 2.2, this may be an unrealistic concern compared to rolling resistance and gasoline use, but nonetheless it has sparked much progress and documentation in the literature about the impact of different disposal methods and their relative environmental impacts. Finding ways to reuse the growing 300 million tire landfill stockpiles has produced new innovations in rubber shredding and incineration out of necessity to reduce these excessive scrap tire numbers.[33] Figure 2.4 from the Rubber Manufcaturers Association describes the growing excess scrap tire production problem and the inability to utilize these stockpiles without resorting to landfilling.

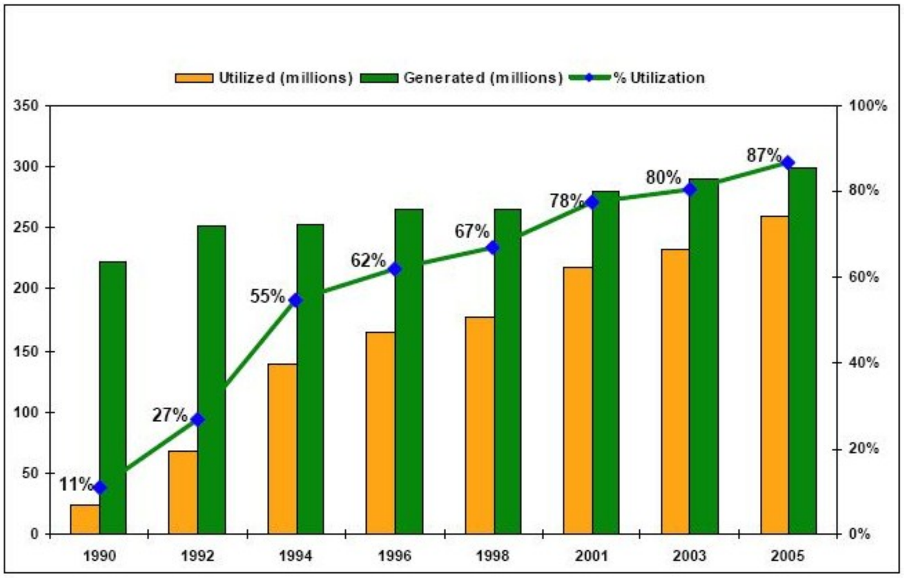

Figure 2.4. U.S. Scrap Tire Management Trends, 1990-2005 [34]

Morris concluded that for most recycling methods, recycling consumes less energy and imposes lower environmental burdens than disposal of solid waste via landfilling or incineration, even after accounting for energy that may be recovered from waste materials at either type of disposal facility.[35] However, due to the thermoset nature of rubber tires, markets simply do not exist to reuse hundreds of millions of pounds of shredded rubber. Research has been performed to find ways to reuse ground rubber in civil engineering, athletic and sport surface applications, rubber modified asphalt, etc., but currently only a relatively small percentage of rubber can be reused in this manner.[36] So, other methods of cleanly disposing of tires for beneficial means have had to be developed, and the best way to do this is by incineration.

One kg of tire rubber contains 36 MJ of energy (4 MJ more than the same mass of coal), so tire incineration has become a reliable method of disposing of large stockpiles of tires.[37] Not only does tire incineration produce a large amount of energy, but it also avoids the mining of coal or other energy production methods, so incineration has been shown to have an overall positive environmental effect.[38] However, as described by Reisman, the consequences of not cleanly and efficiently burning rubber can have serious environmental consequences.[37] Open tire fires that occur infrequently in landfills dispense large amounts of particulates, carbon monoxide, sulfur oxides, nitrogen oxides, and volatile organic compounds (VOCs) due to the incomplete combustion of whole tires in an uncontrolled environment, so the EPA has set strict emission standards on tire incineration plants to assure an environmentally beneficial process.[39] It has been well documented that rubber landfilling should be avoided whenever possible, so these standards and disposal methods are always being modified and updated to reflect the governmental environmental demands and the overall sustainability of the tire and rubber industries.

2.4 Literature review summary

All of these reports and standards give a good summary of the overall life cycle of a tire and its environmental impact in each stage of its life, but minimal knowledge is available on the environmental effects of Tweels™. A strong foundation has been set detailing each stage of a tire's life cycle from raw material production through various disposal routes, but the Tweel™ manufacturing process is constantly changing through its development stages, and since it is not in full production or use yet, it is impossible to compile an array of sources describing the environmental effects of Tweel™ use or disposal route percentages as is possible with tires. However, many of the literature sources that reference a particular stage of a tire's life cycle may be a helpful first step in analyzing the effects of Tweels™. The most current knowledge about the life cycles of both products will be compiled in this report through the help of SimaPro, literature sources, and Michelin processes and data in order to present an accurate environmental profile and corresponding environmental impacts of both products.

Chapter 3. Goal and Scope Definition

3.1 Goals of the study

As indicated in the introduction, this study intends to perform an environmental analysis of a Tweel™, but there are two main goals to this thesis. First, the main aim of the thesis is to present a detailed overview of the environmental profile of a low rolling resistance American car tire throughout its entire life cycle and compare its impact to that of a Michelin Tweel™. The environmental performance of these two tires is intended for external use by car tire users, environmental regulators, and suppliers by providing detailed information about the overall environmental effect of these two products so that external audiences can make their own judgments that meet their desires. Every part of the life cycle (production, transportation, use, and end of life) will be considered in order to present the most information possible so that consumers and suppliers will be able to make the most educated decision. Although a comparison with other products is not intended in the scope of this project, showing the relative contribution of a Tweel™ to a reference can enhance this information and help the external education. To help show someone the relative importance of the environmental load of tires and Tweels™, a reference impact will be set as the environmental load of the average European citizen. This will help to quantify the impact of the life of either product.

A specific comparison of end of life processes, such as land filling and energy recovery, will not only inform tire users of the most environmentally friendly way of disposing their used tires, but will also help to inform disposal companies about how to possibly improve their processes. It is important for tire consumers to understand the environmental impact of the products that they buy, but the second goal of this thesis, a product improvement goal that provides insight for Michelin for improvement of their Tweel™ design, is just as meaningful.

This goal is not directly part of an LCA, but an environmental comparison between a fuel efficient tire and a Tweel™ can show which stages of the life of a Tweel™ are most environmentally harmful, and can hypothetically show if a potential product improvement is beneficial to the environment. From this information, a prioritization of possible Tweel™ improvements can be developed to streamline the rest of the Tweel™ design process.

One issue that affects the project scope, however, is the confidentiality of some raw material production and tire manufacturing methods. Specific company techniques and processes are very important to a company in order to sustain their competitive advantage, so some of the collected data must remain confidential, and some data specific to a particular company may be impossible to obtain at all.[40] In the case of a confidentiality problem that limits the production knowledge of a particular process, a wider industry standard will be used that considers the average production process over a large number of companies. This will limit the precise results from an exact Tweel™ or P205/45R17 tire and may shift the results toward an average tire, but it will provide a good estimate for the actual environmental impact of each product. A more quantitative discussion of this effect will be discussed throughout the report when confidentiality issues arise.

3.2 Scope of the inventory phase

As discussed above, the main goal of this thesis is to compare the potential environmental impact of a Tweel™ to that of an environmentally friendly tire. Specifically, the functional unit of this analysis will be one P205/45R17 tire including its hub compared with what will potentially replace it – one Michelin Tweel™ and its hub. For this analysis, it is assumed that these functional units are produced, used, and disposed of in the United States. All of the energy considered will be assumed to come from the United States except in cases like natural rubber production where all the material is produced in Southeast Asia. The IDEMAT database has well documented energy mixes from every major area of the world but it is outdated by a few years and more recent energy mix percentages are available through the US Energy Information Agency. Both of these sources, which describe the percentages of American energy derived from coal, crude oil, etc., will be compared to assure an accurate energy environmental impact. The amount of gasoline use that can be attributed to one tire throughout its life will be considered as part of the material flow of the LCA. The analysis of these tires will be conducted under average American driving conditions – an average car is driven an average amount per year on average roads. As driving behavior and landscape characteristics varies across the country, national averages are used in the model to construct the most probable representative production and use of Tweels™. It will be important to note that environmental impacts will change with aggressive driving. Tire wear can increase as much as 300% with aggressive driving on rough, winding roads as compared to the average wear, but transforming this decrease in tire life to fuel use is problematic due to the difficulties in determining how much the fuel efficiency of a car declines with this increase in aggression.[17] Thus, only the average tire wear will be considered in order to match up with the national average fuel efficiency.

Rolling resistance also will change with poor tire care, but this aspect of the life cycle inventory will be ignored. The Transportation Research Board suggests that rolling resistance decreases about 1% with every 1 psi that a tire is underinflated.[28] Thus, if a tire is significantly underinflated, it will require more force to make it roll at a specific speed, causing an increase in the amount of fuel being used by the car. This fuel would then be directly attributable to the tire and thus would be included in the LCI. This effect may be offset by the reduction in the tire's life due to this usage without proper maintenance, but for the purposes of this thesis it will be assumed that tires always remain properly inflated as the exact quantity of underinflated tires on the road is impossible to determine.

The overall scope of the inventory data that will need to be determined is shown in Figure 3.1 below. Small variations will exist between the life cycle of a tire and a Tweel™, but the overall basic structure will remain the same.

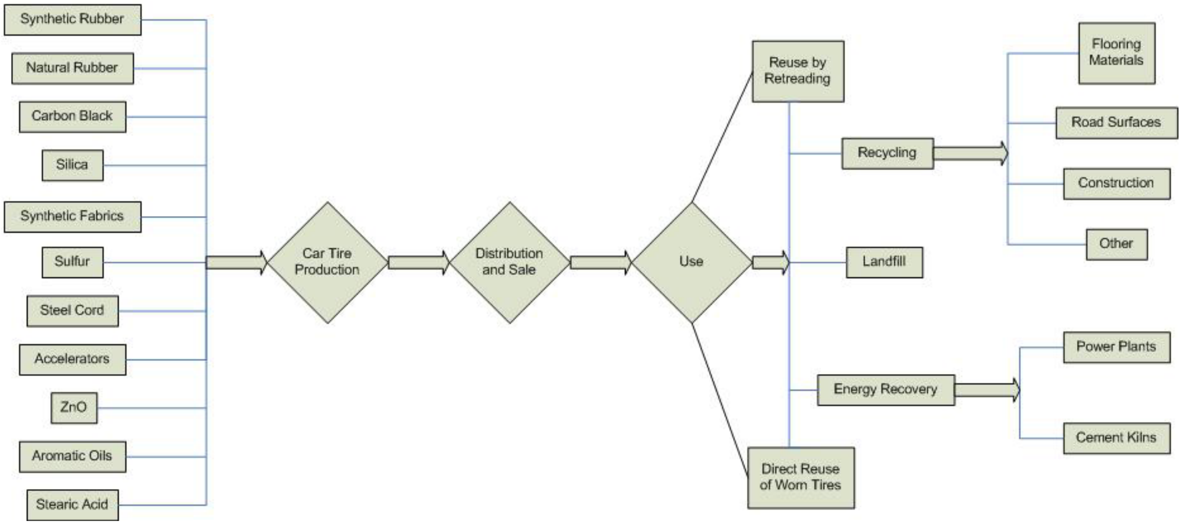

Figure 3.1. Flowchart of tire life cycle

In considering the entire life cycle of both a tire and a Tweel™, it will be necessary to construct an inventory of each of the blocks shown in Figure 3.1. All material inputs and outputs to the air, water, and land will be considered where appropriate and entered into the SimaPro program described earlier in order to analyze the results. The production phase of the life cycle will consider the production of the specific amounts of raw materials used in a tire or Tweel™ and then the process of transforming these raw materials into the final product that is place on a vehicle. The manufacturing of each tire will be discussed in more detail throughout the analysis, but it can be broken down into 3 steps: manufacturing of semi-finished products (tread, belts, sidewalls, etc.), tire building, and vulcanization. Manufacturing the semi-finished products will incorporate the use of the raw materials while tire building and vulcanization are mostly just energy inputs.

After the product assembly is considered, the distribution and use phases are added to the inventory. Tires are distributed to car manufacturing plants and to replacement tire shops, and traveling this distance in large trucks uses diesel fuel and expels the corresponding emissions while the tires are being transported. This same fuel usage is to be considered in the use phase (the time that a tire is being used on a car), but instead of diesel trucks, gasoline powered passenger cars will be considered. Other important aspects that need to be considered while a tire is being used is the environmental load of the tire wear and the emission of noise due to tire/road contact. Not only is wear important in determining the life of a tire, but the small parts of the tire tread that pile up on the side of roads and get washed away into water systems have very important environmental impacts. The noise on the other hand, is not so easy to consider. Currently there is no way to quantify the environmental effects of sound as can be done with carbon dioxide, but a qualitative analysis of noise will be useful as a side project.

To conclude the inventory data collection, four end-of-life disposal methods will be considered: land filling, incineration in cement kilns, incineration in power plants, and recovery through grinding. Current data for tires disposed of in the United States will provide appropriate numbers for the ratios of tires that are disposed of in each of these manners, but as Tweels™ are neither produced nor disposed of, this stage of the life cycle will be analyzed through a range of possible Tweel™ disposal routes. This uncertainty will make it difficult to draw any concrete conclusions about the overall environmental impact of Tweel™ disposal, but it will allow for product improvement information and tips about what needs to be done in the future to minimize the environmental impact of this end-of-life phase.

Typically the hub is left out of tire life cycle analysis due to its relative longevity compared to the life of the rubber, but it will be included in the analysis for both products in this thesis because of the way it is molded to the spokes of a Tweel™. Separating a Tweel™ from its hub is not as simple as the process for a tire because the polyurethane spokes of a Tweel™ are molded directly to the steel hub with a bond that is not easily broken, so for consistency the hub will be included in both life cycle analyses. Both products use a steel hub weighing roughly 4 kg, but the entire environmental impact of this large amount of steel should not be considered as part of one tire or Tweel™ life cycle because each hub lasts much longer than the rubber or polyurethane components of a tire or Tweel™ and can be used through roughly 4 tire life cycles.[41] For this reason, only ¼ of the environmental impact of the 4 kg hub from each product will be considered in this analysis. The entire life cycle of the steel hub will be considered from raw material production to casting to recycling, but it will be assumed that only 1 kg of steel is relevant to one life cycle due to the much longer use life compared to the rest of a tire or Tweel™.

3.3 Scope of the impact assessment

3.3.1 ISO Guidelines

Once the life cycle inventory data are collected, the wide range of inputs and outputs must be combined using a uniform scale that is able to compare the impact of say 1 kg of CO_2 emission to the air against 1 m^2 of land use. The general procedure for this process is described in the ISO 14042 document and is shown in Figure 3.2 below. This figure outlines a general procedure from constructing a wide range of possible impact categories that are consistent with the goal and scope of the thesis to selecting the impact categories that should be addressed and describing each of these categories so that they can be compared with each other using a uniform scale.

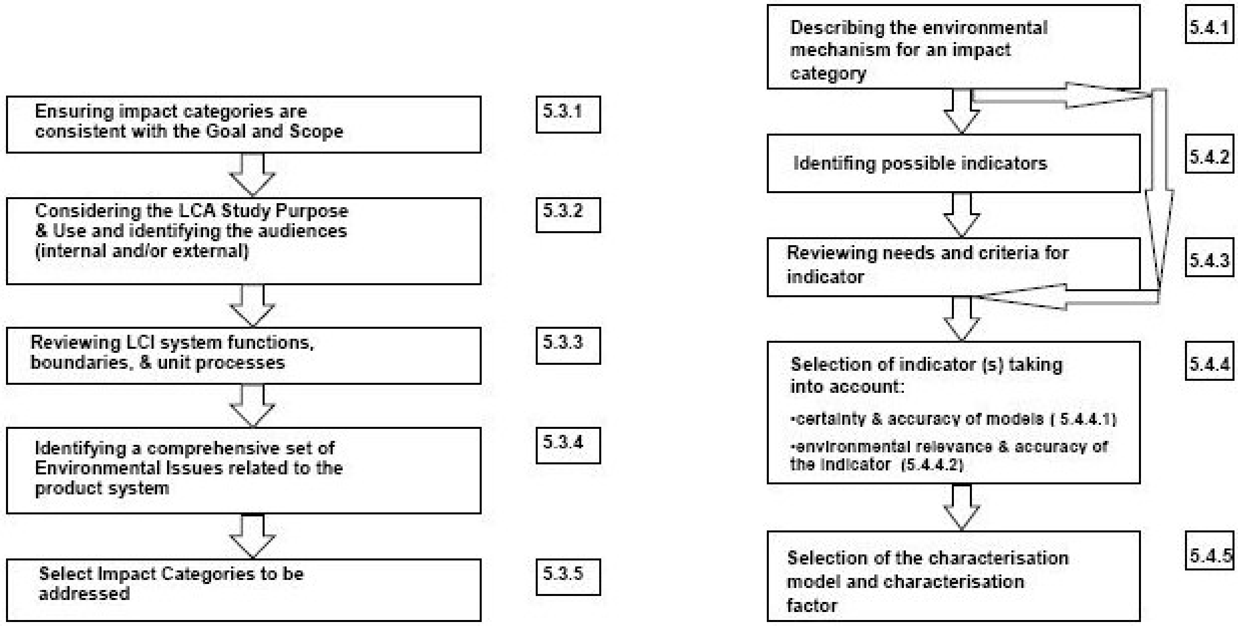

Figure 3.2. Schematic diagram for the selection of impact categories [13]

The ISO 14040 and 14046 documents provide a solid framework to assess the impact of the life cycle inventory, but their generalizations provide room for a variety of different impact assessment techniques. A number of different impact assessment methodologies are available to the LCA practitioner, and several of them are implemented in software commercially available on the market. For the purposes of this report, the EcoIndicator99 method will be the primary impact assessment tool used, but the EDIP2003 method will be used for validation to ensure that the results are not skewed simply because of the wrong choice of impact assessment methods. A fundamental difference between these two methods is that the EDIP method has a problem-oriented approach to impact assessment as opposed to the EcoIndicator method, which has a damage-oriented approach.[42] This means that whereas the EDIP method models the impacts between emissions and damages, EcoIndicator aims its assessment directly at the damages caused by the emissions. This difference in approach will give two very different views on the collected life cycle inventory, which will greatly contribute to the validity of the results if the two assessments agree on the relative environmental impacts of the Tweel™ compared to the tire.

3.3.2 EcoIndicator99

There are many ways to combine a wide range of environmental impacts associated with creating a product, but the process of weighing all these effects to develop with one concise score can be quite difficult. The first question to answer in this complicated method of combining all sorts of environmental impacts is to define what exactly the term "environment" means.[43] The EcoIndicator99 method breaks up this very broad term and all the impacts that couple it into three impact categories: Human Health, Ecosystem Quality, and Resources.[44] These three categories were determined to be sufficient to encapsulate the effects of most of the emissions and products, so it will be beneficial to understand each with greater detail. Of course this method can't be absolutely complete and can't capture all effects and all categories such as damage to cultural heritage but it is a good way to group effects for most products and processes.

The Human Health category includes the number and duration of diseases, and life years lost from environmental causes that result in premature death such as infectious diseases, cancer as a result of radiation, cancer due to ozone depletion, and respiratory diseases from airborne particles. There are a wide range of emissions that can damage human health in a number of ways, but, health damages from allergic reactions, noise, and odor cannot yet be modeled and are not included in this EcoIndicator. To aggregate all these different types of damage to human health that can be quantified into one number that can be compared to ecosystem quality and resources, a tool for comparative weighting of disabilities is needed. The EcoIndicator99 developers chose to use the DALY (Disability Adjusted Life Years) scale, which has been developed by Murray, et al [45], for the World Health Organization (WHO) and World Bank. This weighting scale lists many different disabilities on a scale between 0 and 1 (0 meaning perfectly healthy and 1 meaning death).

A quick example calculation with DALYs will attempt to clear up exactly how this human health weighting is performed. This example is taken from the EcoIndicator99 manual written by PRé, which is available for download at http://www.pre.nl/eco-indicator99/ei99-reports.htm.[46] First consider carcinogenic substances that cause a number of deaths each year. In the DALY health scale, death has a disability rating of 1. If a type of cancer is (on average) fatal ten years prior to the normal life expectancy, we would count ten lost life years for each case. This means that each case has a value of 10 DALYs. For comparison consider a smog period during a summer where many people have to be treated in hospitals for a number of days. This type of treatment in a hospital has a rating of 0.392 on the DALY scale. If the hospital treatment lasts 0.01 years on average (3.65 days) each case would be weighted 0.004 DALYs. In this way all diseases and harmful effects on human health can be combined into one measurement of DALYs, which can then be weighed against the other two impact categories in a method that will be described below.

Some of these Human Health factors overlap into the Ecosystem Quality category, but to avoid double counting things such as the greenhouse effect and ozone layer depletion, most of these are grouped in the Human Health category because this is most likely the most important piece for all of us. These could just as well be grouped in the Ecosystem Quality category, but that category is focused more on the effects on species diversity, especially for vascular plants and lower organisms. Some of these effects include ecotoxicity, acidification, eutrophication, and land use. An important difference between this Ecosystem Quality and Human Health is that even if we could determine all the complex damages inflicted upon the ecosystem, we are not really concerned with the individual organism, plant, or animal. Instead, the species diversity is used as an indicator for ecosystem quality. The EcoIndicator99 method expresses the ecosystem damage as a percentage of species that are threatened or that disappear from a given area during a certain time.[47]

Finally, the Damage to Resources category combines the effects on mineral resources and fossil fuels. The problem with determining how much impact that removing a certain amount of a mineral from the ground has on the environment is the uncertainty of the amount available. It is obvious that there is a limit on the human use of these resources and removing resources with a smaller availability will have a greater environmental impact, but to pin down these exact numbers would be rather arbitrary. Instead of considering Damage to Resources as a percentage of that resource available, the EcoIndicator99 method looks at the concentration of a resource as the main element of resource quality. Market forces will assure that the most concentrated, easily mine-able areas are depleted first, so Chapman and Roberts developed an assessment procedure for the seriousness of resource depletion, based on the energy needed to extract a mineral in relation to the concentration.[48] As more minerals are extracted, the energy requirements for future mining will increase. The unit of the Resources damage category is the "surplus energy" in MJ per kg extracted material that describes the increased energy needed to extract a kg of a mineral from a more difficult location in the future.

Now that all three impact categories are defined, the most difficult question must be answered: How does one weigh these categories against each other to be able to combine them into one score when they have completely different units and describe completely different effects? The answer that the EcoIndicator99 employed was to first normalize each category and then construct a panel of 365 members to determine a ranking and weighing procedure. They concluded that the damage to Human Health and damage to Ecosystem Quality should be weighed with equal importance while damages to Resources is considered about half as important.[46] Different people have different views on the correct way to weigh these categories against each other, but as shown in Figure 3.3 which was taken from the EcoIndicator99 manual, this 40/40/20 method of weighing is closest to the average, most agreed-upon ratio.

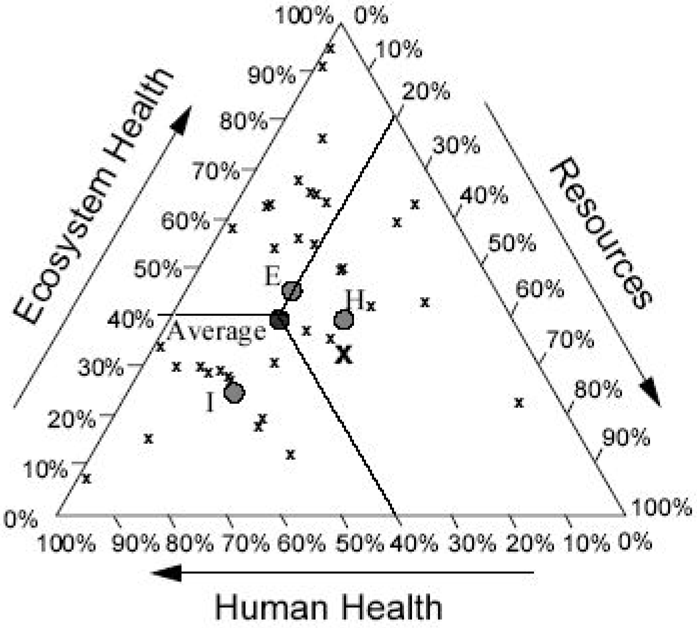

Figure 3.3. Weighing triangle to compare EcoIndicator99 impact categories[47]

In this weighing scheme, the normalized Ecosystem Quality score, for example, will be multiplied by 40% and combined with the other weighted impact categories to come to a final single score result called the environmental “indicator”, as described in Equation 3.1,

$$Pt = 0.4(EQ) + 0.4(HH) + 0.2(R) \tag{3.1}$$

where *EQ* is the normalized Ecosystem Quality score, *HH* is the normalized Human Health score, and *R* is the normalized Resources score. This gives a number that lies on a fairly arbitrary scale, but the EcoIndicator99 developers chose the scale in such a way that the value of 1000 Pts is representative of the yearly environmental load of one average European inhabitant.[47] This point scale can now be applied to any material or any process so that every possible input and output of a product can be combined to form one overall, generalized environmental impact score.

3.3.3 EDIP

The EDIP (Environmental Design of Industrial Products) method that will be used to verify the results of the EcoIndicator99 method follows the same framework set up by the ISO standards, but develops different impact categories with a different point of view. Whereas the EcoIndicator starts at the end and first identifies the areas of concern (damage categories) and then works backwards to determine what causes damage to these areas, the CML method works in a more linear fashion grouping inputs and emissions into impact categories directly without insight into future broader damage categories. Not only does this result in different impact groups, but it also requires a different method to weigh the non-dimensionalized versions of these groups to compare the impacts and obtain an overall environmental impact score.

There are too many CML impact categories to discuss in detail for the purposes of this thesis, but the main concepts are the same as the EcoIndicator groups. The weighting method on the other hand is quite different in that it uses a distance-to-target method to express scores in terms of Person Equivalents Targeted for a given year in the future (PET).[42] The goal of the weighting methods in both the EDIP and EcoIndicator is to reflect the society's view on which damages or potential impacts are of greatest importance, but both methods arrive at different ways of achieving this. This distance-to-target method examines the ratio between the actual impact potential and the political target level at some point in the future.[49] A contribution to the overall flow of a certain impact where the levels of contributors are far above the target level is thus given more weight than contributions to flows where the distance-to-target is smaller. So, rather than trying to discern the thoughts of the greater public from a group of a few hundred, the EDIP method considers well documented political targets and determines the importance of each impact category on the effect it will have on the overall environmental target of that group in the future.

Chapter 4. Inventory Analysis

In order to organize a large amount of inventory data throughout the entire life cycle of a tire and a Tweel™, five sub-categories will be created: production of raw materials, tire/Tweel™ manufacturing, distribution, use, and end-of-life. The production of raw materials and tire manufacturing categories will be combined later in the analysis to provide a better understanding of the overall environmental effects of the entire production process, but they will remain separated here.

All inventory data (energy inputs, emissions, etc.) will be derived from external sources whenever possible, but when limited data exist, the databases packaged with the SimaPro program will be used. Some of the databases used include BUWAL250, IDEMAT 2001, and EcoInvent. These databases are all peer reviewed and contain reliable information on a wide range of raw materials and processes. The only downfall of these SimaPro databases, however, is their lack of transparency. Limited citations are supplied, and it is very difficult to understand from where the inventory quantities are derived, so when at all possible these databases are not be used. When they are used though, an attempt to combine multiple databases will be tried to average out any errors or skewed data. Producing a material in one place can give different energy requirements and different emissions for example, so it is important to use data representative of national averages and to avoid trusting only one database representative of only one part of the world.

4.1 Production of raw materials

The production of a new tire is a fairly complicated process that involves many steps at a manufacturing plant, but before they can be considered, it must be understood how the necessary raw materials made it to the plant in the first place. Table 4.1 and Table 4.2 describe the material composition of both functional units (P205/45R17 and Tweel™) that will be analyzed throughout their life cycles. The details of the production processes of each of these raw materials are described in this section and all the LCI data quantifying the material inputs and emissions are provided in Appendix A.

Table 4.1. P295/45R17 tire material composition by weight [50]

	Carcass	**Tread**	**Total tire**	**Hub**
Raw material	**wt %**	**wt %**	**wt %**	**wt%**
Synthetic rubber	15.78	41.72	24.17	0
Natural rubber	24.56	3.53	18.21	0
Carbon Black	23.40	9.54	19.00	0
Silica	0.80	28.07	9.65	0
Sulfur	1.60	0.80	1.28	0
ZnO	1.83	0.91	1.58	0
Oil	4.02	10.64	6.12	0
Stearic Acid	0.87	1.47	0.96	0
Recycled rubber	0.60	0	0.50	0
Coated wires	17.2	0	11.4	0
Textile	7.0	0	4.7	0
Steel	0	0	0	100
Totals %	**100.0**	**100**	**100**	**100**
Weight (kg)	**7.25**	**2.75**	**10.0**	**4.0**

Table 4.2. Michelin Tweel™ material composition by weight [50]

	Shear band	**Tread**	**Spokes**	**Hub**	**Total Weight**
Raw material	**wt %**	**wt %**	**wt %**	**wt %**	**kg**
Synthetic rubber	0	41	0	0	1.15
Natural rubber	0	4	0	0	0.10
Carbon Black	0	10	0	0	0.26
Silica	0	28	0	0	0.77
Sulfur	0	1	0	0	0.02
ZnO	0	1	0	0	0.03
Oil	0	11	0	0	0.29
Stearic Acid	0	1	0	0	0.04
Recycled rubber	0	0	0	0	0
Coated wires	10	0	0	0	0.62
Textile	0	0	0	0	0
Polyurethane	90	0	100	0	8.44
Steel	0	0	0	100	4.00
Totals %	**100.0**	**100**	**100**	**100**	
Weight (kg)	**6.35**	**2.75**	**2.65**	**4**	**15.75**

4.1.1 Natural Rubber

Natural rubber (NR) products are made with an initial source of latex, a milky white liquid drained from rubber trees or *Hevea Brasiliensis.* These trees reach 20-30 meters in height and are able to produce commercial quantities of latex at about seven years of age and are used for about 20 years, but this lifespan can increase with proper latex extraction techniques. Rubber trees were originally only found in the Amazonian regions of Bolivia and Peru, but the beginning of the 20th century rubber tree farming moved to Southeast Asia, and the industry now uses approximately 9.5 million hectares of land.[23] Virtually no efficient, large scale rubber tree farms exist, so most natural rubber is produced on small family farms. Smallholders play a critical role by producing more than 85% of the world's total NR production. The average size of these uneconomic smallholdings in many countries is less than two hectares.[23] The small size of these farms has several negative impacts, both environmental and social. These smallholders are locked in poverty without the ability to noticeably improve and optimize their methods for obtaining latex, which results in inefficient land use. Rubber trees usually are not correctly spaced; so on average about 500 trees per hectare are planted with some spacing between rows less than 9 meters apart. This inefficient tree spacing yields less than ½ cup of latex per tree per day.[51] Thus, one tree produces about 6 to 10 kg of latex per year.

Ammonia is immediately added to the tapped latex in order to prevent early coagulation during transport. When the latex is ready to be processed, a dilute acid such as formic acid is added, and then the coagulated latex is kneaded and rolled to obtain the final consistency and to remove any waste water. Latex straight from a rubber tree contains between 25 and 40% natural rubber, so on average this transition from latex to natural rubber removes approximately 2/3 of the original weight. Combining the production of one tree and the density of trees on an average smallholder's farm yields an annual production of natural rubber between 1000 and 2000 kg/ha.[52] On average, one square meter produces about 0.15 kg of natural rubber every year. Thus, the production of 1 kg of natural rubber can be attributed to 7 m^2 of land annually.

The low income of these smallholders benefits the environmental efficiency of this latex production process in a small way in that mostly natural animal manure is used, but a lack of knowledge about proper crop rotation limits the productivity of the land used between the trees and yields low latex outputs. Because of the poor spacing between trees other crops, such as corn or other leafy vegetables, can only be planted among the rubber trees for the first 2 or 3 years.[53] Once the rubber trees grow tall enough, it is impossible to support other plants. So, because of this mild short term benefit, intercropping is not a common practice among smallholders and the minute amount of benefit from the small percentage of farms that take part in this practice can be ignored. Therefore, it can be assumed for the purposes of this environmental analysis that 100% of the land on these farms is dedicated to rubber production. Although the land used to produce latex is replaced with more trees that appear to have the same environmental effects as the original forest, this land use must be considered as an environmental impact because of the transition from natural forest to land with only one plant that eradicated all other plant life in the area.

Although these trees transform vibrant forests into a mono-cropped field, they still benefit the environment by converting carbon dioxide to oxygen through photosynthesis. As natural rubber is roughly 90% carbon, producing 1 kg of natural rubber results in a net intake of 0.9 kg of carbon from the atmosphere.[36] This carbon is separated from carbon dioxide, which has a carbon content by mass of 27%. Thus, to remove 0.9 kg of carbon from the atmosphere, an uptake of 3.3 kg of CO_2 is required and is modeled in this analysis as a negative emission to the air. This carbon uptake should counteract some of the energy costs and land use associated with the production of natural rubber, but the overall impact will be discussed in section 5.

After the life of a rubber tree is complete and no more latex can be drained, the tree is cut down and usually burned as cheap fuel. Some of this fuel is used to power the machines that process the latex liquid into natural rubber, but it is possible that it would be more environmentally friendly to use the wood to make furniture. Hevea wood is strong, flexible, and resistant to fungus, bacteria, and mold. Sources estimate that selling Hevea wood instead of burning it could add 30% to the economic value of each tree.[23] However, because of the inefficiencies associated with latex draining, many times the wood is very badly damaged and not suitable for furniture. If more smallholders improved their draining techniques and began using their wood for furniture, some of the land use associated with producing rubber could be diminished. The majority of the land would be allocated to the production of rubber, but some of the 7 m^2 used to produce 1 kg of natural rubber every year instead could be allocated to the production of furniture. This would be a benefit to both the tire and furniture industries because the tire industry would see less environmental impact and the furniture industry would not have to devote other unused land space to the production of trees whose only output is wood. For this analysis however that wood reuse scenario will be ignored due to the small percentage trees used for that purpose, but it is an important aspect to consider to improve the environmental effects of tire production.

4.1.2 Synthetic Rubber

Although there are several different kinds of synthetic rubber produced today, the vast majority of the market is dominated by styrene-butadiene rubber (SBR), especially in the tire industry. So, for this analysis it will be assumed that all synthetic rubber used in tires is SBR. Within the SBR category however there are two different production techniques: emulsion and solution polymerization.

Solution polymerization is a polymer chain building reaction that takes place in a solvent. The small monomers are dissolved in a hydrocarbon solvent, usually hexane or cyclohexane, and polymerized using a catalyst such as butyl lithium.[54] Polymers made in solution generally have more linear molecules, and they also have a narrower distribution of molecular weight. These characteristics allow the elastomer to flow more easily after production, and the ability to carefully monitor the concentration of monomers in the solution gives better control over the molecular weight and overall molecular structure of the polymer. However, because it can be difficult to remove solvent from the finished viscous polymer, solution polymerization is used less in the tire industry and more in industries that can use the solution form, such as adhesives and surface coatings.[55]

Emulsion polymerization is therefore used more in the tire industry because of its ease of production, but it inherently has less molecular structure control. Emulsion polymerization involves the formation of a stable emulsion of a monomer in water using a soap or detergent (e.g., sodium stearate) as the emulsifying agent and a water-soluble catalyst such as potassium persulfate. After the desired amount of polymerization is reached, the reaction is stopped by adding an inhibitor.[56] This produces the same type of liquid latex material that is produced from rubber trees. From this stage the synthetic rubber progresses through the same coagulation and drying process as natural rubber.

Because of this wide range of polymerization techniques, there is not much specific data on a general synthetic rubber production method. The only trustworthy source that contains a complete inventory of all the inputs and outputs of this process is the Franklin USA database (1998).[57] This database has been updated since 1998, and all of its data are peer reviewed and can be trusted to be quality, up-to-date information. This inventory of synthetic rubber is contained in SimaPro; it contains all materials and energy inputs as well as the emissions to air, water, and soil. Its energy grid and transportation are based on US data, so knowing the quality of this database qualifies it as a good source for all SBR inventory data for tires produced in the US. A quantitative comparison of this energy grid data with U.S. DoE Energy Information Administration data will be presented in section 4.2.3 to ensure an accurate energy profile.

4.1.3 Carbon Black

Carbon black is virtually pure elemental carbon in the form of fine particles or dust that are produced by the incomplete combustion of gaseous or liquid hydrocarbons under controlled conditions. It is produced by two simple and fairly similar production techniques: furnace black and thermal black.[58] The furnace black process uses heavy aromatic oils as its feedstock.

These oils are inserted into a furnace where temperature and pressure can be carefully monitored in order to atomize the feedstock. This atomized oil then is introduced into a hot gas stream where it vaporizes and then pyrolyzes into microscopic carbon particles. Pyrolysis is a similar process to charring but it does not involve reaction with oxygen. Pyrolysis results in carbon black with a carbon content greater than 97% whereas soot and black carbon contain less than 60% carbon.[59] So, this simple process requires only heat and oil, and it produces a relatively clean carbon product with only small traces of polycyclic aromatic hydrocarbons (PAHs) that cannot be extracted.

The thermal black process on the other hand uses natural gas as its feedstock material. This gas is injected into a refractory brick-lined furnace, and in the absence of air, the heat from the high melting point materials that line the furnace decomposes the natural gas into carbon black and hydrogen. This decomposed mixture is quickly cooled and the carbon black is filtered away from the hydrogen. The hydrogen gas is then burned to heat the furnace in an attempt to reduce energy costs. Again, this process is relatively simple, but its high production level uses a large amount of fossil fuels such as oil and natural gas.

Approximately 90% of carbon black is used in rubber applications, 9% as a pigment, and the remaining 1% as an essential ingredient in many applications.[60] So, because of this large carbon black demand by the tire industry and the overall preference for the furnace black process, about 95% of all carbon black produced is furnace black. It is uncertain whether the IDEMAT database takes this into account, but all the inventory data seem to match up with simple furnace black calculations, so this source can be trusted. Sources estimate that about 2000 cubic feet of gas and 2.5 liters of oil are needed to produce one pound of carbon black.[58] [59] These rough numbers are very comparable to the inventory in the IDEMAT database, which gives these numbers further validation and support. For that reason the IDEMAT inventory data are used in this thesis to analyze the impact of carbon black production for rubber use. The data describing the environmental emissions are supplied in Appendix A.

4.1.4 Silica

Silica, also known as silicon dioxide (SiO_2), is found naturally in the environment in several different sources including industrial sand and gravel, quartz crystal (a form of crystalline silica), special silica stone products, and Tripoli and is used in tires to improve rubber characteristics by increasing traction and reducing rolling resistance.[61] All of these silica production techniques are discussed in the U.S. Geological Survey (USGS) Minerals Yearbook. Included in these annual reports is an explanation of the production process of amorphous silica. Precipitated amorphous silica is the form most widely used in the tire industry because of its reinforcing characteristics. This precipitated silica is produced by two different methods: thermal and wet, but only the wet route produces the precipitated silica that is modeled in this analysis for use in tire treads and sidewalls.[22]

The first step in the production process is the raw materials storage that involves collecting an alkali metal silicate dissolved in water (e.g. waterglass or sodium silicate) and an acid, generally sulfuric acid. The process can be completed with hydrochloric acid or a different silicate, but these represent very small percentages of the precipitation process. To produce the waterglass, sand and soda ash are collected in a furnace heated to 1300 C.[62] The resulting solid then is dissolved in water to produce an aqueous solution of sodium silicate called waterglass. Waterglass and sulfuric acid are combined in neutral conditions, and the silica precipitates out of the mixture according to Equation 4.1

$$Na_2O \cdot nSiO_2 + H_2SO_4 \rightarrow n\ SiO_2 + Na_2SO_4 + H_2O \quad (n=2\text{-}4) \tag{4.1}$$

The precipitated silica then is continuously filtered through a belt or drum filter. After filtration, the silica is washed to remove salts that result from the acidic reactions, and then it is dried. Approximately 400 to 600 kg of water has to be evaporated for each 100 kg of final product, so this represents a considerable fraction of the total production costs.[63] The final energy intensive step is to mill the non-regular silica clumps into quantifiable sizes for use in different applications. A schematic overview of the entire precipitation process is shown below.

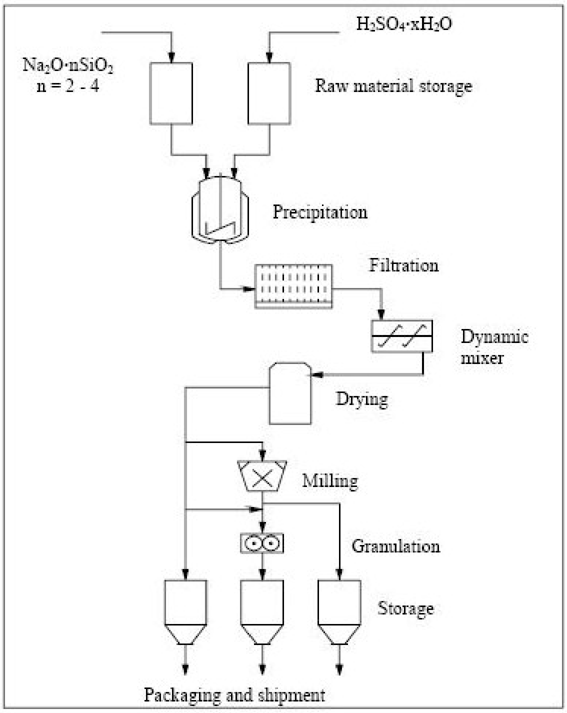

Figure 4.1. Silica production process schematic [62]

The basic process of producing 1 kg of silica involves the combination of 1.46 kg of sodium silicate and 445 g of sulfuric acid as presented in a report from the ECETOC.[62] Combining the rest of the processes shown in Figure 4.1 to get to the final desired product requires a total of 1.76 MJ of energy. As there are no other emissions in the production of this material, simply the required raw materials and energy use compose the environmental inventory for silica, which is assembled in Appendix A.

4.1.5 Sulfur

Sulfur is used in the tire industry to aid the vulcanization process while helping to maintain the rubber's desired flexibility and toughness characteristics. Until recently, a significant amount of the world's pure sulfur supply came from sulfur-bearing limestone deposits found in the gulf coast region of North America. By a process called the Frasch process, sulfur was released from depths of 500 to 3000 feet by superheated water that was pumped down under great pressure to melt the sulfur.[64] Air pressure then forces this sulfur to the surface where it is then cooled. This process of directly removing sulfur as a resource from the Earth is still performed but at a much slower rate.

Currently about 75% of the total elemental sulfur market is comprised of sulfur manufactured by the Claus process.[25] This process begins with hydrogen sulfide (H_2S), which is commonly found in natural gas and is also made at oil refineries, especially if the crude oil contains a lot of sulfur compounds. The environmental impacts of processing this crude oil or natural gas are contained in their respective process. The sulfur recovery process is treated separately and is not impacted by the energy requirements of oil or gas processing, but the amount of H_2S recovered is important.

The first step of the Claus process of transforming hydrogen sulfide into elemental sulfur is separating the H_2S from the host gas stream using amine extraction, which uses amines such as MEA (monoethanolamine) that have a natural affinity to H_2S, to remove it from the rest of the gases.[65] Once the gas has been separated, it is partially oxidized with air at high temperatures (1000-1400 C). A small amount of sulfur is formed, but some H_2S remains unreacted, and some SO_2 is made. The resulting H_2S is reacted with the SO_2 at lower temperatures (200-300 C) with the help of a catalyst.[66] Al_2O_3-supported metal oxides, cobalt and molybdenum oxides in particular, are used to catalyze this reduction reaction described below, provided the metals have been transferred into sulfides through a pre-treatment in H_2S/H_2.[67]

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \tag{4.2}$$

Even with these catalysts, the reaction does not go to completion, and some hydrogen sulfide is left untouched. So this process is repeated two or three times as shown in the schematic below, and the elemental sulfur is removed between each step. The trace amounts of H_2S remaining in the tail gas is recycled to the start of the process.

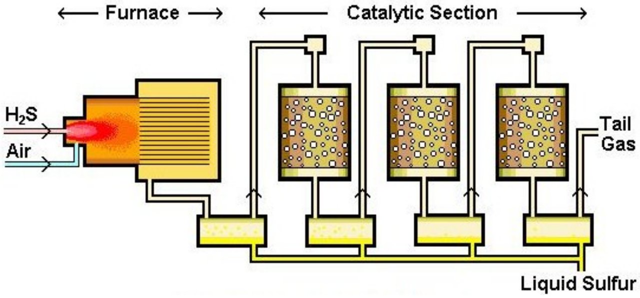

Figure 4.2. Sulfur Production by the Claus Process [66]

The process description above allows one to make some general estimations about raw material and energy requirements, but more reliable information can be found in the IDEMAT database. The rough input estimations compare quite well with the more detailed database values, so the IDEMAT database appears to be a good source for this sulfur production process. It appears that this inventory data does not account for the limestone deposit recovery method, but its Claus method seems accurate, so this source can be trusted.

4.1.6 Zinc Oxide

Almost all of the zinc oxide (ZnO) manufactured throughout the world is produced in two ways: the French process and the direct method. Both methods produce the same inorganic compound that usually appears as a white powder and is nearly insoluble in water. This fairly unreactive compound is used in small amounts to allow a quicker and more controllable rubber cure and is also used to protect the rubber from degrading due to fungus and UV light.

The French process is approximately four decades old and is the cheapest and most highly productive method to produce large quantities of ZnO, which makes it the main source of about 75% of manufactured zinc oxide. In the French process, molten zinc is vaporized at 1000-1400 °C and instantly oxidized in air into ZnO powder.[68] This newly created ZnO then is cooled in large cooling ducts and then transported to a machine that processes the random clumps of powder into a more uniform, smooth powder. The zinc vaporization stage of this process is very energy intensive. It takes roughly 200 liters of fuel oil with a calorific value of 9200 Cal/liter and 850 kg of raw zinc metal to produce 1000 kg of ZnO.[69] As this requires so much energy, the powder processing stage can be ignored because the energy requirements are so low and no other materials are input or released.

The American process on the other hand has been around for over 100 years and produces zinc oxide directly from oxidized ore. This process is slowly losing ground to the French process because of its mass production capability, but it still has its use to produce a product that has a little lower pH.[70] The zinc ore raw materials are reduced to the condition of coarse sand and mixed with powdered anthracite coal. This mixture is spread over perforated grate bars in a sealed furnace, and when the coal is ignited an air blast is forced through the perforations in the grate bars and the overlying zinc ore. The heat volatilizes the metallic zinc in the ore releasing metallic vapors that combine with air as in the French process. The vaporized zinc again transforms into a white ZnO powder and is cooled.

These fairly simple processes can be weighted with respect to the percentage of total worldwide production each process is responsible for (75% French process, 25% American process), but the main resource, raw zinc metal or zinc ore, is constantly changing. Pure zinc ore used to be the only raw material used in these processes, but again because of the economic concerns with optimizing the processes, more and more primary and secondary zinc is being recycled and reused. For the purposes of this study it can be estimated that a general zinc raw material contains 75% pure zinc and zinc ore and 25% primary and secondary zinc.[71] The data describing the materials needed to produce zinc oxide and the resulting production emissions are detailed in a report by the Chemical Substance Bureau of the Netherlands and supported by the tire life cycle analysis report from PRé Consultants.[17, 72] The processes are weighed together, and the inventory for the average production of 1 ton of zinc oxide is assembled in the appendix.

4.1.7 Aromatic Oil

Aromatic oils, also known as aromatic extracts or process oil, are highly viscous liquids that are used in the tire industry to improve the physical properties of natural and synthetic rubber to increase durability and flexibility. They are also used to aid processing of polymers during milling, mixing, and extruding by providing lubrication of the rubber molecules. Very large quantities are employed in tire manufacturing, greatly outweighing the quantity used in applications such as asphalt and seal coatings. They are also a key feedstock component and precursor for synthesis of hydrocarbons such as carbon black.[73]

Aromatics oils are produced as byproducts in the refining of crude oil into lubricating oil as described in Figure 4.3. Crude oil goes through two basic steps in a petroleum refinery: atmospheric and vacuum distillation. In atmospheric distillation, the crude oil is heated to 300°C and the more volatile components, e.g., gasoline and kerosene, are distilled off.[74] This leaves a residue that is further distilled under vacuum causing evaporation of the volatile liquids with the lowest boiling points. Due to the stable physical properties of aromatic oils, they do not boil off and remain as byproducts of the vacuum distillation process. The lubricating oil basestock (before the vacuum distillation process) must first be combined with a solvent such as furfural or phenol to ensure complete removal of the undesirable aromatic compounds from the lubricating oil.[74] After the distillation process, the solvent is stripped from the resulting aromatic extracts and reused for further distillation.

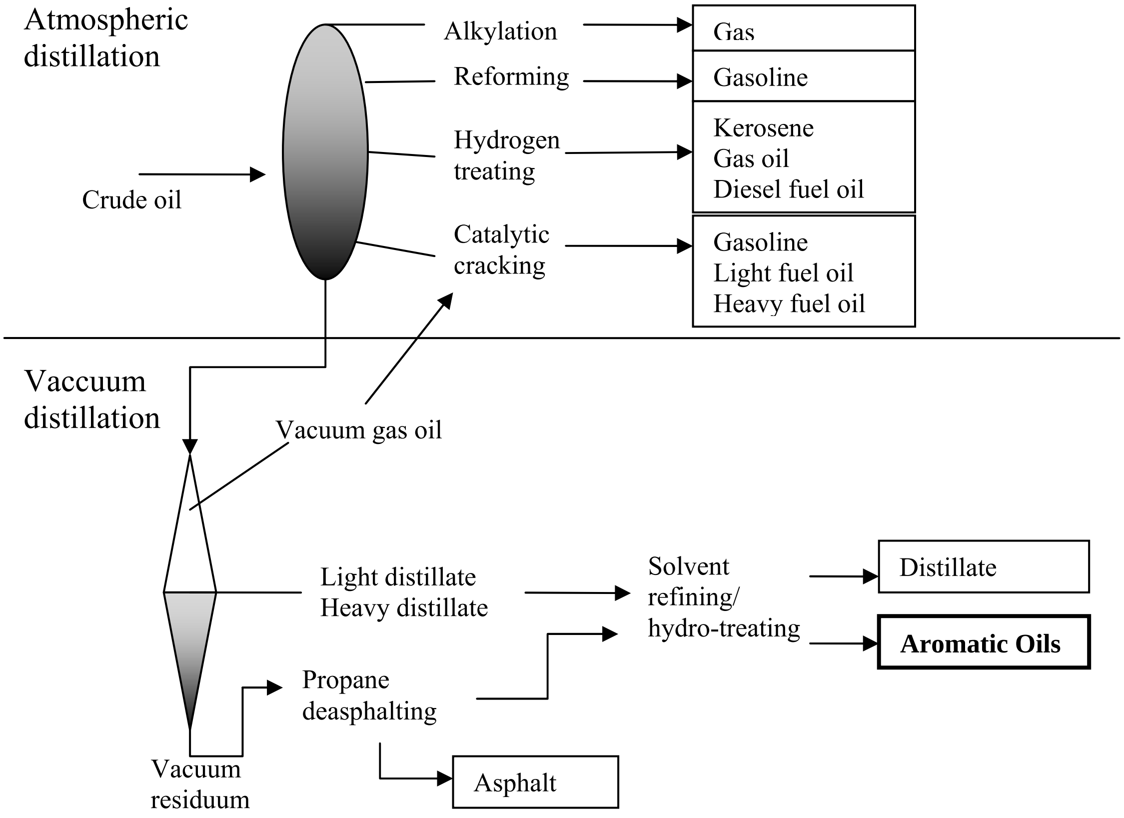

Figure 4.3. Processing plan for a petroleum refinery

So, to determine the share of the environmental impact of aromatic oils out of the entire range of crude oil processing, it is first necessary to ignore any impact of the atmospheric distillation process as that must be contributed to the effects of producing gasoline and kerosene.

This results in a simple process that has only two inputs: vacuum distillates from atmospheric distillation of crude oil and energy used to create a vacuum and process the extracts. The furfural or phenol solvent can be ignored because it is completely reused. Reliable inventory data for vacuum distillates are contained in the BUWAL database, and energy data are supplied by the American Petroleum Institute.[75] Both of these are combined to produce a full inventory of inputs and emissions from the aromatic oils production process, and this inventory is provided in the appendix.

4.1.8 Stearic Acid

Stearic acid is a saturated fatty acid that is used in the tire industry as a rubber softener that is produced from animal fat. The major fat used in the production of stearic acid, beef fat or tallow, is subjected to a process known as hydrolysis, which involves heating the fat in an alkaline solution (usually sodium hydroxide) to yield soaps.[76] These soaps are the sodium or potassium salts of fatty acids; pure acid is then obtained by removing these impurities through vacuum distillation.

This fatty acid soap solution is reduced to a pressure of about 35 mmHg and is heated to about 250°C.[77] When distilling tallow, the overhead products from the first distillation process are low-boiling impurities and small amounts of myristic acid. The remaining stock is pumped into a second stage where the pressure is reduced to 5 mmHg. A small amount of injected steam is necessary to minimize decomposition, and the overhead product distilled away from the tallow in this step is almost pure palmitic acid. The highest boiling fraction of the raw fatty acid soap is moved into a third step that again operates at 5 mmHg, and stearic acid is left as the only remaining substance.[77]

In order to understand the entire impact of producing stearic acid both the acquisition of the tallow and its processing must be analyzed. Producing tallow from cows or pigs is well documented in the EcoInvent database, but supporting material is difficult to find.[78] Very few sources exist that describe the details of this process, so this source will have to be trusted. It turns out that acquiring tallow contributes only a small percentage to the overall impact of stearic acid production however because of the high energy costs to distill the fat. The energy data for the vacuum distillation process are described in Wootthikanokkhan's paper on rubber mixing schemes.[79] Both the tallow acquisition and processing data are combined to give the overall raw material inputs and emissions for the stearic acid production process and this combined inventory is provided in the appendix.

4.1.9 Coated Wires

Thin steel wires are used in the tire industry to provide reinforcement so the rubber does not wear as quickly or fail catastrophically. However, because rubber does not bond well to plain steel it is necessary to coat the steel wires with brass or zinc. Zinc-coated wire is used for the bead and brass-coated wire is used for the belt wires. For both of these products, the first step is to cold draw piano wire to a diameter of about 2 mm.[80] Then a thin coating of 0.15 mm of zinc or brass is electro-deposited onto this steel wire and treated by a thermal diffusion process to ensure good bonding between the metals.[24] Further drawing of the wire then reduces the overall diameter of the wire to 1 mm with a zinc or brass coating of only 2 μm.[81] This process is the same for both coating materials, so for the environmental purposes of this analysis this can be modeled as one cohesive production process with a steel wire core a 50/50 mixture of brass and zinc coating, which is a rough estimate of the average wire composition used in several tire models.

The input and output inventory data for this coated wire production process begins with the very well documented cold drawing technique in the EcoInvent database. This inventory includes everything from the raw unalloyed steel to cooling water to transportation. Electroplating of zinc and brass are included in the IDEMAT database and its calculations that show that plating an area of 1 m^2 requires 0.035 kg of plating material and 9.8 MJ of electricity match very well with data from other sources.[81] The final drawing process of the coated wire can be modeled with the EcoInvent data again, and the complete inventory of all the inputs and emissions of the combination of these processes is provided in the appendix.

4.1.10 Textile

Textile cords are used in tires in conjunction with coated steel wires to provide strength and support and to increase the durability and mileage capabilities of rubber. Traditionally two types of textiles are used to reinforce a standard radial tire: nylon and polyester. Both fabric types are produced in nearly the same way from the raw fabric cord to weaving the fabric, but creating the nylon and polyester fibers differ somewhat. So, it is important to consider the fabrication inventory of both processes and average them to provide a consolidated impact score for all textiles included in the production of a tire.

Nylon is produced on when crude oil and natural gas are converted to plastic through a number of chemical processes. During the processing of the polyamide 6.6 materials into nylon fibers, lubricants are added in the form of spindle oil and antistatic agents.[82] Nylon production begins with polyamide 6.6 granules, which are heated and extruded into endless yarns called filament yarns. Then the yarns are split into very thin fibers called microfibers with the help of lubricants in the form of spindle oil and antistatic agents. The nylon microfibers are then woven into fabric and dipped in an adhesive coating to ensure the fibers stay intact.[83] It is assumed in this thesis that half of the textiles used in tire manufacturing is nylon while the other half is polyester. The EcoInvent database supplies a reliable inventory of the nylon production process while the polyester manufacturing is documented in the IDEMAT database.

4.1.11 Steel

Steel comprises the hubs of both tires and Tweels™, and since Tweels™ are manufactured directly onto a hub without a designed method to separate the steel from the polyurethane spokes, the hubs from both products must be considered as part of their life cycle analyses. Previous environmental analyses of tires have ignored the hub production because new tires can be easily mounted on old hubs, but this may not be that simple for Tweels™. So, an average steel production and casting process will be considered for both products assuming a 4 kg hub for both products.

Steel is manufactured by the chemical reduction of iron ore through a basic oxygen furnace (BOF) to produce high-tonnage steel or an electric arc furnace (EAF) to produce low-tonnage specialty steels. As the specific steel composition of tire rims vary, a worldwide average steel production process that considers both of these reduction methods from the IDEMAT database is used in this analysis. The World Bank Group wrote an article that describes some of the emissions of the steel production process, but the IDEMAT database is much more robust because it considers a wider range of emissions to both air and water.[84] The World Bank Group report is useful though to ensure the database inventory is accurate, but the IDEMAT database is much more thorough in its assessment of emissions with smaller concentrations such as sulfides and fluoranthene. Their report presents steel of 800 mg of particulate matter, 1500 mg of sulfur oxides, 1150 mg of nitrogen oxides, and 5 mg of flourides to produce 1 kg of steel along with several other emissions such as wastewater and lead. These emissions compare very well to the 888 mg of particulates, 1.6 g sulfur dioxide, 1.1 g nitrogen dioxide, and 8 mg of fluorides in the IDEMAT database, which gives confidence to the quality of the full IDEMAT database inventory that is presented in Appendix A.

4.1.12 Polyurethane

Several types of polyurethane exist today from solid elastomers to flexible foam for car seats. Only minimal data are available in SimaPro's databases, but as the manufacturing processes can vary greatly between different types of polyurethane, it is important to analyze the specific production process used by Michelin instead of finding data from other sources. Polyurethane makes up the spokes and the majority of the shear band in a Tweel™, and Michelin's process of molding this product is different from other major polyurethane producers. As described in Figure 4.4, the basic process involves the combination of a prepolymer (composed of two parts polyols and one part diisocyanate) with a curative. The curative only makes up 10% of the mass of the final polyurethane, but is very important in solidifying final molded product to the right properties. The reaction between these two components is an exothermic reaction, so although the prepolymer is held at 70 °C and the curative at 40 °C, no extra energy is required during the curing process.

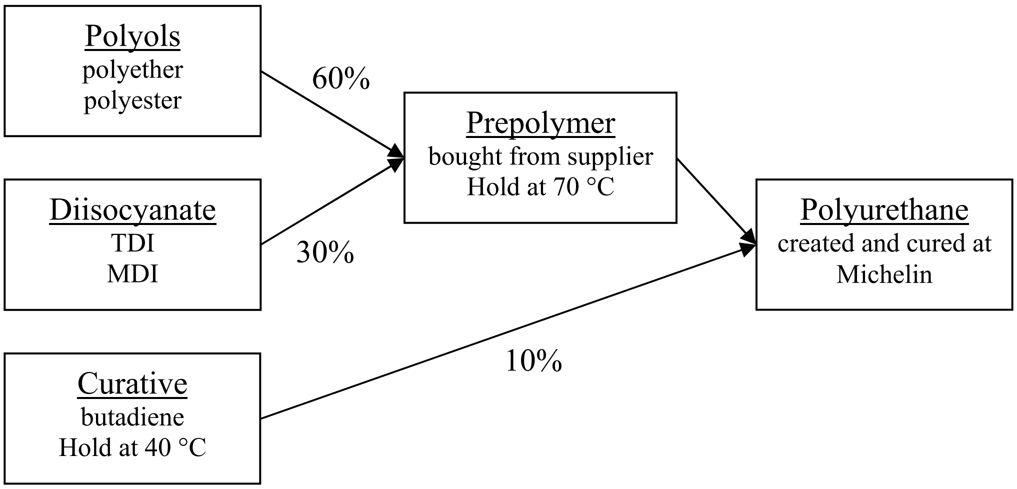

Figure 4.4. Polyurethane production process [85]

In this analysis it will be assumed that the energy required to heat the prepolymer and curative before they are poured together into the Tweel™ spoke mold is part of the environmental impact of the raw material production process. It could be considered as part of the manufacturing of a Tweel™, but instead this energy will be allocated to the polyurethane production in order to more accurately compare the total impacts of creating each raw material needed for a Tweel™. Assuming a room temperature of 20 °C, heating 0.9 kg of prepolymer (heat capacity 1200 J/kg-K) and 0.1 kg of curative (heat capacity 1100 J/kg-K) to produce 1 kg of polyurethane would require roughly 56 kJ of energy.[86] This energy is added to the manufacturing inventory of the prepolymer and curative that uses the required inputs and resulting emission outputs (which are documented in the IDEMAT database) to determine the overall environmental inventory to create 1 kg of polyurethane. This inventory is included in Appendix A, but for confidentiality reasons Michelin does not want the specifics of their prepolymer components revealed, so the table presented describes the production of each of these polyurethane components combined with the energy inventory to conceal details about each component.

4.2 Production of tires

4.2.1 Manufacturing of P205/45R17 tire

The tire construction process is a complicated one that involves several complex parts that are mated together. The general process of constructing a tire involves assembling the numerous components of a tire shown in Figure 4.5, and then vulcanizing these parts together to achieve the desired properties. The details of the production process of each tire manufacturer are difficult to find because of the confidentiality of their specific process, so for the purposes of this thesis, an average tire production process will be modeled. Combining this generic process with the specific material breakdown of a P205/45R17 tire described in section 4.1 will represent an average tire built anywhere across the country with the given specifications of a section width of 205 mm, aspect ratio of 45%, and a wheel rim diameter of 17 in. This generic and somewhat simplified tire production process is outlined in Figure 4.6. Each of these production stages has its own environmental inventory, but to simplify the presentation of these numbers, only a summation of all the processes into one tire manufacturing inventory is presented in Appendix A.

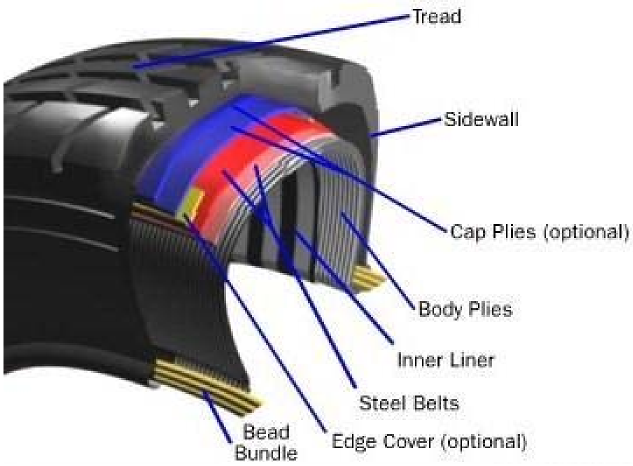

Figure 4.5. Tire component breakdown [28]

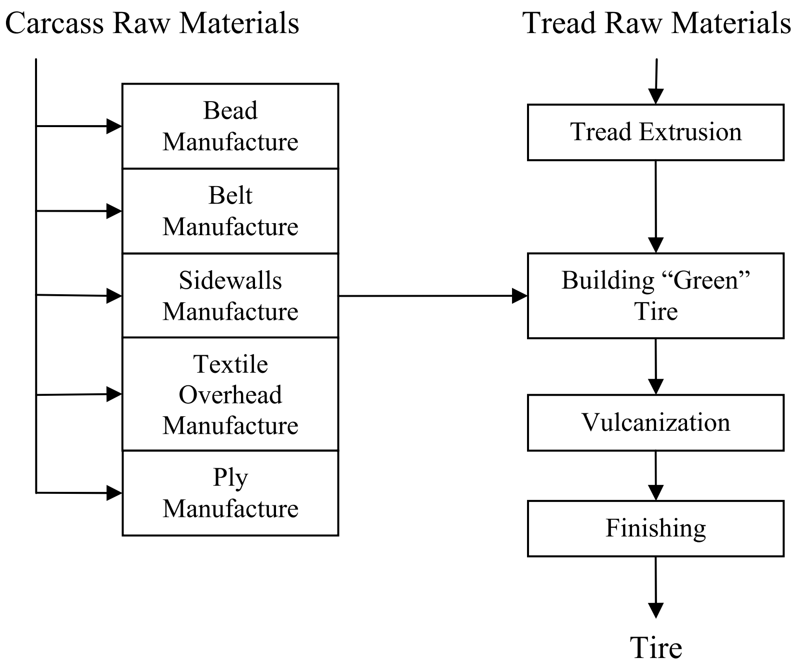

Figure 4.6. Generic tire production process [17]

The process begins with the mixing of basic rubbers with process oils, carbon black, accelerators and other additives. The environmental inventory of these basic ingredients has been described above, so simply considering the correct proportions described in Table 4.1 is all that is necessary to analyze the environmental impact of the raw materials entering the mixing process in the manufacturing plant. It is out of the scope of this thesis to consider the transport of most of the raw materials to the tire manufacturing facility due to the difficulty of modeling the distribution of raw materials from multiple production sites to multiple tire production sites across the country. As a result, it will be assumed that the raw materials are produced near the manufacturing plant so this transportation can be ignored. Thus, the only thing to consider in this mixing stage is the intense heat and pressure required in this process, the water required to cool the mixing so that vulcanization does not occur prematurely, and any emissions that result from these extreme conditions. Details for the required heat and pressure are not well-documented, so the only source available for the environmental inventory of this mixing process is the EcoInvent database. PRé Consultants documented the entire tire production process in their life cycle analysis of an average European tire, but due to some possible differences between European and American tire production, these values are only used as a comparison.[87]

This mixed rubber then takes all the different forms shown in Figure 4.5 – sidewalls, tread, liner, etc. Most of these sub-components are made by rolling the cooled rubber into the desired dimensions, but traditionally the tread is extruded. Rough assumptions about the energy requirements and necessary lubricants in these two rubber processing techniques are taken from J.L. White's book titled *Rubber Processing*.[88] Transporting these rubber components around the factory takes place on rollers, so minimal energy or ancillary materials are required; as a result this transportation can be ignored. So, modeling the assembly process of all the components of Figure 4.3 can be simplified to the rubber mixing process combined with the necessary lubricants and adhesives that secure the coated wires and textiles in place.

Once all the components are assembled, the "green" tire is cured or vulcanized to glue everything together and to achieve the final dimensions and rubber properties. This curing process takes place under conditions of roughly 350 degrees Fahrenheit with pressures around 350 psi for 15 minutes.[88] Details for the energy requirements of this curing process are modeled in Han's report titled *Dynamic Simulation of the Tire Curing Process*.[89] After the curing process is complete, the completed tires are inspected (which requires no extra environmental resources), and are sent out for distribution. Again, details of these intermediate steps are not listed here in order to simplify the inventory, but the inventory data from these small processes are combined and presented in Appendix A.

4.2.2 Manufacturing of Michelin Tweel™

Two problems limit the ability to present a complete environmental inventory of the Tweel™: Michelin's confidentiality and the incompleteness of the Tweel™ production process. Michelin does not want company information being presented to the public, so much of the Tweel™ production details analyzed in this report will be kept secret. But more importantly, the Tweel™ is not being mass produced yet, so there is only a theoretical knowledge of the process requirements and capabilities available. The manufacturing inventory will be as thorough as possible, though.

Tweels™ are produced in three steps: tread, hub, and polyurethane. In the first step, the tread is constructed by a similar method as the tire tread manufacturing process. The tread on a Tweel™ is exactly the same as a tire and is extruded in the same way, and it is mated to layers of belts in the same manner as tires. The process of rolling plies onto a drum to achieve the correct diameter currently is performed manually, but the same basic process that is performed on tires will be mimicked when the Tweel™ production is fully automated. In this fairly simple process, rectangular sheets of rubber and steel cord are rolled onto a steel drum, and the excess material from each sheet is removed. Once the desired base thickness is achieved in this matter, the extruded tread is rolled onto the top, and the entire assembly is vulcanized at 160°C degrees for 75 minutes. The second step is a very simple 4 kg steel hub casting that is well documented in several databases including BUWAL250.

In the third step, the hub and the tread are secured concentrically and polyurethane is poured into a spoke and shear band mold while the entire assembly spins so that the polyurethane will sufficiently fill the mold in the radial direction. The energy needed to spin the Tweel™ assembly and polyurethane mold for just 5 minutes while the polyurethane is poured is considered irrelevant compared to the large amount of energy required to heat and pressurize the ovens needed to cure the shear band and then solidify the entire assembly after the polyurethane is poured, so it can be ignored in this inventory. Before the pouring process occurs though, all the surfaces that contact the polyurethane are cleaned and covered with either an adhesive or a mold release for the shear band and spoke mold, respectively. The quantities of these additives were supplied by Michelin, and are listed in Table 4.3.

Table 4.3. Cleaning, adhesive, and release agents used during manufacturing of one 12 kg Tweel™

Additive	Mass (g)
Ethyl acetate	26.7
Adhesive	3.3
Chemlok 7701	30
Stoner M-804	250

As discussed in section 4.1.13, the polyurethane pre-polymers and curative are stored separately until they are heated and combined at this point in the manufacturing process, but this chemical process is considered part of the raw materials production in order to analyze which material is causing the most amount of environmental harm. The combination of the heated pre-polymers and curative could be considered in this Tweel™ manufacturing section, but in order to organize the impacts of the raw materials it is treated as part of the raw material production of polyurethane.

After the polyurethane is poured and the assembly is allowed to stop spinning, the entire Tweel™ (shear band, spokes, and hub) is placed into another oven. This final solidification cooking occurs at 100°C degrees for 4 hours so that the polyurethane solidification process is accelerated and to assure all the Tweel™ components are securely bonded together. To save some energy this solidification process could take place at room temperature, but it would take much longer to complete and during this time it would be susceptible to being bumped and permanently damaged, so this possible environmental benefit to save the energy required to heat and pressurize the oven is not a plausible option for Michelin. So, this energy must be considered along with all the other process inputs mentioned, and all of these are organized with the rest of the life cycle inventory in Appendix A.

4.2.3 Heating and Pressurizing Energy

In both of these manufacturing processes, the most important factor that affects the environmental impact of these processes is the energy required to heat and pressurize the ovens and molds used to cure rubber and solidify polyurethane. As stated in the section 3.2 in the scope of this project, the energy produced in the United States comes from a mix of coal, natural gas, nuclear power, etc. The details of this mix vary across the world, but the IDEMAT database does a good job of keeping updated records of these inputs and emissions for every country. However, their databases have not been updated in the past 5 years, while the U.S. DoE's Energy Information Administration (EIA) updates the United States' energy mix numbers every year.[90] The energy mix from both sources is displayed in Tables 4.4 and 4.5. The data from the IDEMAT database give the raw material inputs to produce 1 MJ and the corresponding emissions when they are converted into energy while the U.S. EIA only supplies the percentages of each energy production process.

Table 4.4. U.S. energy mix, inputs and emissions to produce 1 MJ, IDEMAT database [91]

Resources	Mass (kg)	Energy (MJ)
Coal, 29.3 MJ per kg, in ground	0.011	0.322
Oil, crude, 41 MJ per kg, in ground	0.0055	0.22
Gas, natural, 30.3 MJ per kg, in ground	0.0087	0.263
Energy, from hydro power		0.07
Energy, from uranium		0.103
Emissions to air		
Sulfur oxides	0.000227	
Nitrogen dioxide	0.000141	
Carbon monoxide	0.000009	
Carbon dioxide	0.0695	
Hydrocarbons, unspecified	0.000008	
Soot	0.000099	
Particulates, SPM	0.000013	

Table 4.5. DoE EIA energy mix, 2008 [90]

	Coal	Natural Gas	Crude Oil	Nuclear	Hydro
2008 Energy Production (Billion Btu)	23,855,916	21,150,164	10,519,487	8,455,236	2,452,073
Percentage of Total	36%	32%	15%	13%	3%

These tables differ slightly in that the U.S. has made a conscious effort over the past 20 years to reduce the energy dependence on crude oil while increasing the energy derived from nuclear power. The IDEMAT database is representative of data from around the year 2001, and in the time since then the U.S. has made more progress in reducing the percentage of crude oil used to create energy. According to these two tables, the percentage of energy from crude oil dropped from 22% to 15% in these 7 years, which closely matches the EIA's numbers which show a decrease from 20% to 15% from 2001 to 2008.[90] These differences are large enough to consider the IDEMAT database out of date for this constantly changing energy mix, so the American energy data used throughout this report will be representative of the EIA's numbers shown in Table 4.5. A comparison of the impact of these differences in energy percentages will be presented in the impact assessment method section (section 5) to compare the potential environmental impacts of various phases of each product's life cycle if either energy mix source is used.

The energy inputs for rubber curing ovens have been recorded and analyzed by tire manufacturers, and the average tire curing process requires about 1.1 kWh of energy for a tire weighing 10 kg, which means roughly 0.11 kWh of energy is needed to vulcanize 1 kg of rubber.[92] At the early stages of Tweel™ manufacturing, Michelin is using the same type of oven that is used to cure radial tires, so it is assumed in this analysis that the same energy will be required to cure 1 kg of rubber in a Tweel™ as 1 kg of tire rubber. The thickness of rubber in these two products varies slightly, but the curing temperature and time is close enough to assume the same energy requirements per kg of rubber. So, the required energy to cure the shear band in the Tweel™ is roughly (6.35 kg)*(0.11 kWh/kg), which equals 0.7 kWh. The energy required to heat, mix, and solidify the polyurethane is allocated to the raw material production of polyurethane, so this 0.7 kWh is all the energy that is needed in the Tweel™ manufacturing inventory.

4.3 Distribution

The transport of raw materials to the manufacturing plant was ignored in the production of both a tire and a Tweel™ due to its complexity and minimal impact as described in the PRé Consultants report, but it is important to analyze the required fuel expensed in distributing the final products to car dealerships and repair shops. The distribution of tires from the production site to the retail point has been recorded by Franklin USA, and it includes a mix of 28 and 16 ton trucks, delivery vans, and ships.[57] This database detailing the average environmental impact to transport 1 ton of material over 1 km in the United States is combined with an analysis done by Continental Tire North America which determined the average distance one tire must travel from its production site to its retail point.[16] These average distances are listed in the appendix.

4.4 Use Phase

4.4.1 Fuel Consumption

The first and most important part of the use phase of a tire, or the lifetime the tire is used on a car, is the amount of fuel it consumes. The amount of fuel consumed by a vehicle over a distance is affected by the overall efficiency of the vehicle in converting the chemical energy in motor fuel into mechanical energy and transmitting it to the axles to drive the wheels. However, not all of the fuel used by a car is used to drive the wheels, so only a certain percentage of the fuel used by a car should be allocated to the wheels and used in this analysis. Sources estimate that the rolling resistance of tires accounts for about 5 to 10% of the fuel used in a passenger vehicle, so only this percentage of fuel used over the entire life of the wheel should be included in this inventory.[27, 93] Rolling resistance is defined as the amount of force needed to roll a vertically loaded tire at a constant speed, and is represented in terms of a rolling resistance coefficient (RRC) in units of kg/ton (required thrust force/vertical load), which is constant for a given wheel under any vertical load. Wind resistance is not a factor here, simply the energy loss due to repeated loading and unloading of viscoelastic rubber.

Below are two tables of data supplied by Michelin that describe the effects of rolling resistance on fuel economy.

Table 4.6. Average fuel economy of passenger car fleets [94]

MODEL	**Total**	**Curb Weight (lbs)**	**City Economy (mpg)**	**HW Economy (mpg)**
CAMRY	4380631	3260	21	31
ACCORD	4327067	3400	21	31
CIVIC	3546835	2770	25	36
COROLLA	2995572	2820	26	35
TAURUS	2818465	3640	18	28
IMPALA	2338172	3680	18	29
ALTIMA	2280732	3130	23	31
MALIBU	2167215	3300	22	30
FOCUS	2070687	2588	24	33
Total	**26925376**			
Weighted Averages	**US (lbs, mpg)**	**3186**	**22.0**	**31.7**
	SI (kg, l/100km)	**1445**	**10.7**	**7.4**

Table 4.7. Fuel economy (L/100km) changes with increasing RRC

Drive Cycle	**RRC (kg/ton)**						
	3	**4**	**5.5**	**6**	**8**	**10**	**11.5**
FTP 75	9.98	10.08	10.24	10.29	10.49	10.70	10.85
HWFET	6.61	6.72	6.89	6.95	7.17	7.40	7.56
Combined	8.46	8.57	8.73	8.79	9.00	9.22	9.37
NEDC	10.47	10.58	10.73	10.79	11.00	11.21	11.36

Table 4.6 lists the top nine passenger vehicles on the road today and their average city and highway fuel economy. So, compiling a weighted average of these numbers gives the fuel economy of the average car on the road to be 10.7 L/100km in the city and 7.4 L/100km on the highway. These two average fuel economy values are imported into Table 4.7 under the rolling resistance coefficient of 10 kg/ton in their corresponding rows where FTP 75 labels city driving, and HWFET labels highway driving. The NEDC row is the European fuel efficiency at each RRC value, and is presented for comparison. The rolling resistance for a wide range of tires is supplied in the Transportation Research Board's report titled *Tires and Passenger Vehicle Fuel Economy*, which presents an average RRC of 10 kg/ton, so it is valid to assume that RRC as the coefficient of an average tire.[28] In that same report, it is stated that 55% of driving occurs on

urban roads while 45% is done on highways, so by taking 55% of 10.7 L/100km and combining that with 45% of 7.4 L/100km gives the 9.22 L/100km value shown in Table 4.7 under the RRC of 10.[28] Note that all of the vehicles listed in Table 4.6 run on gasoline, so this inventory assumes no diesel fuel use and 100% gasoline use. The rest of Table 4.7 was populated by Michelin using their own rolling resistance calculating methods with respect to this baseline average tire, and although the fuel economies with a RRC below 6 are purely theoretical, they are still relatively reliable. No standard deviation or uncertainty was supplied with this table, so it will be assumed that these calculations are accurate, although it is important to note that these values were derived from a theoretical formula and currently there are no tires with a low enough rolling resistance to check the very small RRC fuel economy values.

The main purpose of this report is to compare the theoretically lower rolling resistance Tweels™ to proven low rolling resistance tires. Concluding that a Tweel™ has lower environmental impact than an average tire would be only mildly useful to consumers looking to buy the most environmentally friendly wheel available. So, in this analysis a Tweel™ will be compared against a tire with the best rolling resistance characteristics on the market today. According to the Transportation Research Board's report this low end of the spectrum occurs at a rolling resistance of about 6 kg/ton.[28] Bridgestone's B381 tire has a rolling resistance of 6.2 kg/ton while Michelin's Symmetry tire is measured around 6.5 kg/ton.[95] Thus by the values supplied in Table 4.7, the combined fuel economy for the P205/45R17 tire analyzed in this report is 8.79 L/100km (26.8 mpg).

At this point it is necessary to point out that Michelin has a few different Tweel™ models in preparation, all of which have different theoretical rolling resistance coefficients. The "Thrust 1" Tweel™ is expected to have roughly 10% lower rolling resistance than a fuel efficient tire through the use of conventional tire materials and commercially available polyurethanes. The goal for the “Thrust 2” Tweel™ is around a 30% lower rolling resistance by using advanced polyurethanes or other elastomers, while the “Thrust 3” Tweel™ research target hopes to obtain a 50% reduction in rolling resistance by using meta-materials to replace the elastomers in the shear band. The research targets for these three Tweel™ models are to have rolling resistance coefficients of 5.5, 4, and 3 kg/ton respectively, but the 4 and 3 kg/ton RRCs are still very uncertain since the Thrust II and III Tweels™ are still early in development. Table 4.7 reports the overall fuel economy of the vehicle for each of these Tweels™ as 8.73, 8.57, and 8.46 L/100km. The confidence in these potential coefficients decreases with the more complex materials (Thrust II and III) because they are simply educated guesses of the expected performance of Tweel™ products that do not yet exist for testing, but those are the RRC values that will be assumed in this analysis. The differences in these materials are not known yet because these are only goals for the future development of the Tweel™, so the raw material production and Tweel™ manufacturing data are assumed to be the same for all three thrusts. This will require more work in the future, but as there are very limited data available at this point, it is impossible to create fully accurate manufacturing profiles of each Tweel™ thrust. The three Tweel™ thrusts will have the same production inventory for modeling purposes without full manufacturing profiles available, but the use phase will consume different amounts of fuel.

Table 4.7 can now be used to evaluate the amount of fuel used by the wheels by comparing the relative fuel savings from differing levels of rolling resistance. The key fact in the fuel economy table is that everything on the vehicle is held constant except the rolling resistance, so all fuel savings with a decreased RRC is a result of only the wheel. Comparing this knowledge between the average fuel consumption of a 6 kg/ton tire and 5.5 kg/ton Tweel™ having fuel economies of 8.79 and 8.73 L/100km respectively, shows that the 5.5 kg/ton Tweel™ is responsible for a fuel savings of 0.06 L/100km. The 5.5 kg/ton Tweel™ has a 10% lower rolling resistance than the tire, so the associated fuel use by the tire also should drop by roughly 10%. The only appropriate two numbers for the fuel use by each wheel that differ by both 10% and 0.06 L/100km are 0.60 and 0.54, so the reference tire is responsible for consuming 0.60 L of gasoline every 100 km. Equation 4.3 checks this value to assure that the tire's rolling resistance is responsible for between 5% and 10% of the total fuel used by a vehicle.

$$\frac{0.60\ \mathrm{L/100km}}{8.79\ \mathrm{L/100km}} = 0.068 = 6.8\% \tag{4.3}$$

So, according to the above calculations, the reference tire is responsible for 0.60L/100 km or 6.8% of the total fuel use of a vehicle, which falls within the documented range of rolling resistance fuel use. But, the Tweels™ use a smaller percentage due to their decreased rolling resistance, so simply taking 6.8% of the reported fuel economy for each Tweel™ will not work. Instead, the overall fuel savings must be subtracted from the 0.60 L/100km fuel use by the reference tire. For example, a RRC of 4 kg/ton decreases the vehicle fuel consumption from 8.79 to 8.57 L/100km, which means a Thrust 2 Tweel™ saves 0.22 L/100km. Thus, instead of being responsible for 0.60 L/100km, the Thrust 2 Tweel™ uses only 0.60 – 0.22 L/100km, or 0.38 L/100km. Each Tweel™ fuel consumption is calculated in this way and is listed in Table 4.8 in terms of L/km.

The fuel consumption units were converted to L/km because the last step of the process of determining the total amount of fuel used by one wheel is to multiply the fuel consumption rate by the average lifetime mileage of a tire. The average life of a tire is determined by finding the ratio of the number of vehicles in the United States to the national replacement tire sales.

This ratio (175 million/200 million = 0.88) suggest that a motorist can expect to purchase a replacement tire an average of every 0.88 years, or a complete set of four tires about every 3.5 years. (4 x 0.88 = 3.52).[28] Multiplying this by the average annual vehicle mileage of 12,000 miles, the total life of a tire is found to be roughly 42,000 miles (3.5 years x 12,000 miles/year).[30, 96] Multiplying the fuel consumption rate of a wheel by this lifetime mileage give the total fuel used by all four tires, so this final number must be divided by 4 to find the total fuel consumption by one tire over its life. In this analysis it is assumed that the Tweels™ have the same lifespan of 42,000 miles, but there is some evidence to suggest that a lower rolling resistance and different construction altogether may increase the life of a Tweel™. Data are limited on this topic and entirely theoretical, so that possible difference will be ignored in this thesis, but it may deserve some extra research in the future. A sample calculation for the total fuel consumed by the reference 6 kg/ton tire is shown in Equation 4.4

$$(0.006\ \mathrm{L/km})(42{,}000\ \mathrm{mi})\left(\frac{1.61\ \mathrm{km}}{\mathrm{mi}}\right)\left(\frac{1}{4}\right) = 101\ \mathrm{L} \tag{4.4}$$

Note that the total fuel use does match fairly well with the intended 10%, 30%, and 50% reductions in rolling resistance that Michelin is trying to achieve with these three Tweel™ models. The model isn't quite linear, but a 50% reduction in rolling resistance does correspond to roughly a 50% decrease in fuel consumption as expected.

Table 4.8. Total fuel use over lifetime of one tire or Tweel™

Wheel	Rolling Resistance (kg/ton)	Vehicle Fuel Economy (L/km)	Tire Fuel Consumption (L/km)	Total Fuel Use (L)
P205/45R17 Tire	6	0.0879	0.006	101
Tweel™ – Thrust 1	5.5	0.0873	0.0054	91
Tweel™ – Thrust 2	4	0.0857	0.0038	64
Tweel™ – Thrust 3	3	0.0846	0.0027	46

4.4.2 Gasoline Emissions

The amount of fuel used by a wheel throughout its life is important, but for a life cycle inventory the environmental effects of producing the gasoline and then the corresponding emissions when it is burned are also necessary to develop a full environmental profile of gasoline use. In the production of a tire, both the production of the raw materials and the processing of those materials once they reach the manufacturing plant are considered as part of the life cycle inventory. In the same way with the inventory of gasoline usage, not only do the emissions that come out of a tailpipe need to be considered, but producing the gasoline is just as important.

In considering the life cycle inventory of the gasoline used by a tire, the data detailing the production, storage, and transport of crude oil and gasoline are taken from three SimaPro databases: BUWAL250, IDEMAT, and Franklin USA.[57, 91, 97] Each of these define the refining of crude oil into gasoline, but they all obtain slightly different results most likely due to the differing geographical regions from where the data were taken. Each database can be trusted to give accurate data, but to be completely sure, all three databases are averaged together in the life cycle analysis to minimize any potential error in one database and to assure the best use phase inventory possible. To understand the potential range of environmental impacts if only one of the three databases is used, a comparison of each database will be presented in the impact assessment section, but for the overall life cycle effects an average of these sources describing the production of gasoline will be combined with tailpipe emissions once the gasoline is burned.

Those databases supply the complicated and rarely supplied details about the production and transport of gasoline, but the emissions that result after that gasoline is burned is well documented in several places, the most reliable of which is the EPA. The EPA supplies the emissions from 1 kg of burned gasoline, so in order to find how much of each compound is released into the air throughout the entire life of a tire these values are multiplied by the density of gasoline which varies slightly with temperature but is about 0.74 kg/L.[98] Both of these values are included in Table 4.9. The emissions per liter of gasoline are finally multiplied by the corresponding gasoline usage described in Table 4.8 to determine the overall gasoline emissions corresponding to each respective tire or Tweel™. Then, combining these emissions with the gasoline production inventory provided by the specified databases gives the overall inventory of the gasoline used in the use phase of each wheel.

Table 4.9. Emissions from combustion of gasoline [30]

Emissions to air	Mass (kg) / kg of gas	Mass (kg) / L of gas
Sulfur dioxide	0.000494	0.000366
Nitrogen oxides	0.022147	0.016389
Carbon dioxide	3.407155	2.521295
Carbon monoxide	0.098807	0.073117
VOC, volatile organic compounds	0.014140	0.010464
Soot	0.000239	0.000177
Dinitrogen monoxide	0.000681	0.000504

4.4.3 Tire Debris

An inherent environmental problem with tire use is the debris that results from tire wear. The tread on any rubber tire naturally wears away during normal use due to the frictional contact with road surfaces, and this debris can become airborne and cause respiratory problems, or it can accumulate on the ground or in water causing substances to leach into the environment as the rubber degrades. The problem with collecting the effects of this debris however is the difficulty in quantifying the rate of tread wear under a range of driving conditions and the total tread worn off when the tire reaches the end of its life. Typically a tire loses about 10-20% of its weight during its use phase, but this range is too large for any confident results in this thesis.[41]

So instead of using the total amount of material removed from differing tread depths, several sources will be used that have studied the specific rate of debris produced during a range of driving scenarios.[99-101] The most complete and reliable data on the tread wear throughout a tire's life are documented in PRé Consultant's *Life Cycle Assessment of an Average European Car Tyre*, where data were collected from several papers and tire manufacturers and were averaged to find an average tread wear rate of roughly 3 g/100km as shown in Table 4.10.[17] Using the average driving distance established above as 42,000 miles, the average amount of wear over a tire's lifetime results in 2 kg.

Table 4.10. Tread wear rate under differing driving conditions

Driving Condition	Wear Rate (g/100km)
Highway, Moderate Driving	0.5
Winding Road, Professional Driving	10
Median	3

It is not sufficient to simply model the effects of 2 kg of tire tread in the environment because tire debris occurs in a wide range of sizes, each of which has different environmental effects. Two main categories of tire debris are created here: particles small enough to remain airborne and large particles that remain on the ground. The particle size distribution of airborne particles of tire debris is very important because particles with a diameter smaller than 10 microns (PM_{10}) can penetrate the human lungs and cause respiratory effects, irrespective of their chemical composition.[102] Details about this distribution are difficult to obtain though because of the difficulty in distinguishing tire particles from other types of road dust. In most field studies the fraction of airborne particles that could be attributed to tire wear was less than 10%.[103, 104] Sources have tested tread wear in a laboratory setting to avoid this problem, but the difficulty in modeling a range of driving conditions decreases the validity of these studies.[41, 105] Not only is it difficult to recreate the complex range of wear rates during actual driving, but the smallest PM_{10} particles exhibit completely different settling characteristics in a calm laboratory as compared to the real environment with wind and rain.

Due to these uncertainties, the data collected by PRé Consultants in their European tire LCA are used in this analysis.[17] Their data collection technique is kept somewhat confidential, but the final life cycle inventory of an average tire's debris is provided. This inventory includes both airborne and soil deposited particles of both rubber and metal from the tire cords, and is used in this report for both the tire and Tweel™. The Tweel™ wear rate has not been studied yet, but it will be assumed to be the same as that of a standard European tire. This is a valid assumption due to the similarities in the tread between a tire and a Tweel™ considering that the tread wear accounts for over 90% of the rubber debris from a tire.[41] There may be some differences due to the greater contact patch between the tread and road because of the increased spoke deformation, but these effects have not been studied yet so they will be kept out of this analysis. The only change made to the inventory from the PRé report is a change from their average European driving distance of 40,000 km to 42,000 miles. This change results in a proportional increase in the tread debris over the life of a tire of roughly 1.6. As with the rest of the LCI, the tire debris inventory is organized in Appendix A.

4.4.4 Noise

Traffic noise resulting from tire to road contact typically averages around 75 dBA on the highway, and can be considered a type of environmental emission leading to adverse effects on a large percentage of the human population including hearing impairment, interference with speech communication leading to stress, sleep disturbance, and mental health effects.[106] However, noise effects are not considered yet as part of either the EcoIndicator or EDIP impact assessment method, so they will be left out of this analysis. Müller-Wenk developed a method for assessing the impact of Switzerland vehicle noise on human health aggregated in DALY (Disability Adjusted Life Years, as in the EcoIndicator99 method), but a comprehensive technique to compare these effects to more tangible effects from emissions to the atmosphere is under scrutiny and remains only a qualitative discussion point in life cycle assessments using EcoIndicator or EDIP. Müller-Wenk's method assesses the environmental damage of noise in the same manner as other emissions by four modules of fate analysis, exposure analysis, effect analysis, and damage analysis, but the assessment of health effects from sleep disturbance and annoyance however is still under debate because effects are not measurable and of a more psychological nature.[107] Evidence on cardiovascular disease caused by additional stress is measureable through hospital admissions and physiological changes, but due to the uncertainty of the noise level of a Tweel™ and the questions around the assessment of the effects of noise on human health, this will be left out of the life cycle analysis.[108] Preliminary tests hint that Tweels™ may produce a greater amount of road noise and thus a larger overall environmental impact, but these effects are too difficult to quantify at this point. If a better method of modeling the effects of noise is produced in the future, then this area could be updated to be a part of the environmental impact of tires on human health during the use phase.

4.5 End of Life

4.5.1 Processing Routes

During the past few years there has been substantial progress in the recycling of polymeric materials. Unfortunately, progress in the area of recycling thermosetting polymers such as rubbers has not been as successful because these materials, by definition, cannot be reformed once they have been "set" or crosslinked. Effort has been made to increase the effectiveness of recycled rubber, and markets now exist for over 80 percent of scrap tires – up from 17 percent in 1990.[30] States have played a major role in tackling the problem of almost 300 millions scrap tires in stockpiles in the U.S. by regulating the hauling, processing, and storage of scrap piles, and by working with industry to recycle and beneficially use scrap tires. In 2003, instead of sending used tires to landfills, 38 states banned whole tires from landfills, eleven banned all tires from landfills, seventeen allowed processed tires, and eight states had no restrictions. However, tire recycling benefits still remain limited due to the limited uses of thermoset materials. The Rubber Manufacturers Association documents the progress of the uses of used tires, and their data from 2005 are shown below in Figure 4.7. The four main processing techniques that are used in the United States are tire derived fuel (TDF), civil engineering uses, landfill, and ground rubber used in other products. Scrap tires are either incinerated and used as fuel, ground into crumb rubber, or thrown away intact. The rough energy requirements for these processes are described in Table 4.11, which shows that there is no perfect way to recycle scrap tires. Burning a tire produces less than 30% of the energy required to produce a new tire, crumb rubber requires a noticeable amount of energy but has limited uses, and landfilling occupies land space and breeds insects. Details of each major disposal route will be discussed below.

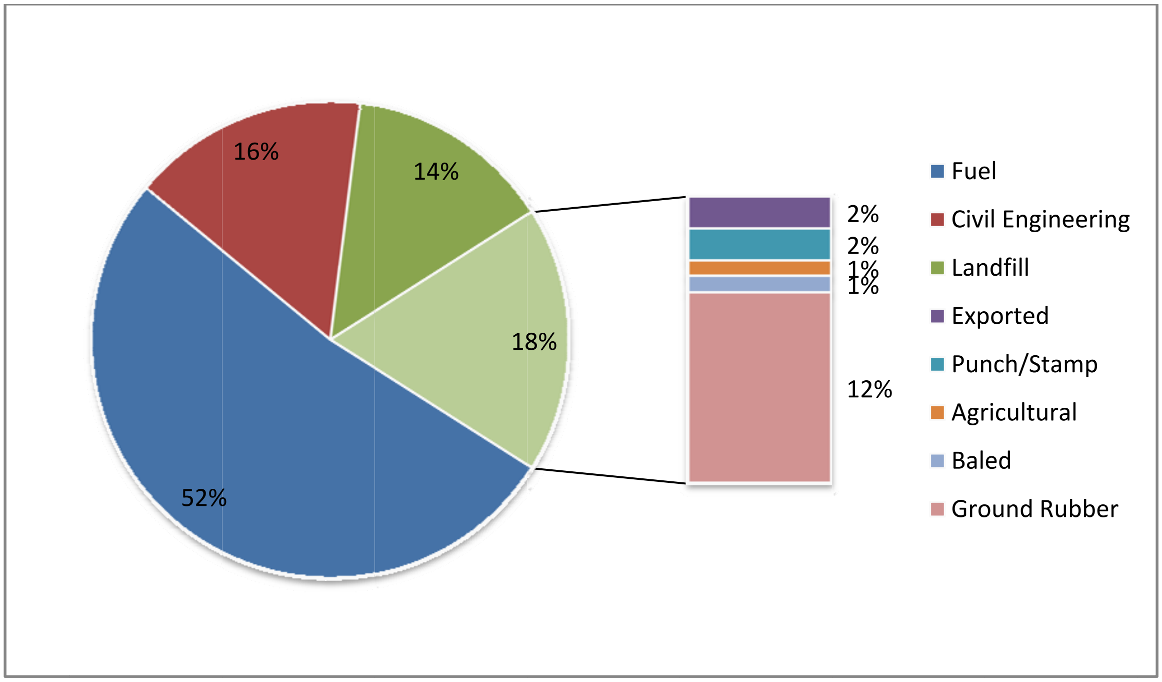

Figure 4.7. 2005 U.S. scrap tire disposition [34]

Table 4.11. General tire life energy requirements [19]

Energy needed to manufacture a tire	32.0	kWh/kg
Energy needed to produce tire rubber compound	25.0	kWh/kg
Thermal energy released when incinerating scrap tires	9.0	kWh/kg
Energy consumed in the process of grinding scrap tires into crumb rubber	1.2	kWh/kg

Tire recycling has always been well documented, but as Tweels™ are not even produced yet, let alone being recycled in mass quantities, it is difficult to assess the overall environmental impact of the end of life phase of a Tweel™. It appears that the shear band, spokes, and hub will all be able to be separated with a little bit of effort, but it is difficult to predict the demand for Tweel™ re-use. Preliminarily, the same percentages as shown in Figure 4.7 will be used for Tweel™ processing routes, but some of these routes will have different environmental impacts due to the large amount of polyurethane, so the demanded percentage of, say, ground Tweels™ may change. With each potential disposal route defined separately it will be helpful to compare each route to decide which is most environmentally friendly and which should be pursued by not only Michelin but also by recycling plants or landfills. A comparative analysis of these potential disposal routes will be compared in the impact assessment chapter (section 5), but first an understanding of each is necessary to produce a hypothetical inventory that is as close as possible to future Tweel™ end of life requirements.

4.5.2 Tire Recycling

The term "recycling" defines a group of tire disposal techniques that reuse tire materials in different applications as a substitute for producing new raw materials. According to the data in Figure 4.7, 18% of scrap tires are recycled by five methods: export, stamping, agricultural, baled, grinding. The first four methods are all less than 2% of the total and will be ignored due to their minimal impact on the overall end of life phase, but the grinding of used tires is a widely used process that must be considered. In this market, whole scrap tires are processed, removing the wire and textile to create ground rubber for sport surfaces and floors, asphalt, and molded or extruded consumer products by one of two processes: grinding at ambient temperature or cryogenic grinding.[34] Table 4.12 describes the markets for crumb rubber in 2001.

Table 4.12. Markets and applications for recycled tire rubber [19]

Application/Market	Million lbs.	Metric tons
Rubber Modified Asphalt (RMA)	292	132,727
Molded Products	307	139,545
Athletic Surfaces	141	64,091
Tires/Automotive	112	50,909
Devulcanized and Surface Modified Rubber	36	16,364
Plastic/Rubber Blends	38	17,273
Construction and Miscellaneous	70	31,273
Total	996	452,727

Prior to grinding to the mesh size specifications of these recycled rubber markets, the tire is cut up into relatively large pieces and then shredded into pieces less than ½ inch in size. Ambient grinding is carried out on a two-roll cracker-mill that has sharp edges to tear the rubber into small pieces. This general process can produce a wide range of rubber particle sizes as small as 80 mesh but usually involves the general activities of coarse crumb sizing, ultra fine sizing, metal separation, fiber separation, bagging, and weighing.[33] Cryogenic grinding, by comparison, first cools the coarsely shredded rubber pieces with liquid nitrogen until the rubber freezes. The frozen shreds are then passed through an impact mill such as a hammer or pin mill where is it shattered, pulverized, and ground into finer mesh grids. After the shattered pieces are dried, the fibers and metal pieces are separated, and the pieces are organized by various mesh sizes at which time they are bagged and ready to be reused in a number of applications described in Table 4.12.

PRé Consultants performed a rigorous study of four different tire recycling processes assuming that roughly 80% of the rubber is ground at ambient temperature while 20% is first cryogenically frozen.[17] Myhre and MacKillop support these percentages and the rough energy requirements of 1.2 kWh/kg, but fail to provide more details to add to the life cycle inventory of this process.[33] PRé assembled data from IFEU (Institut für Energie und Umweltforschung) and several tire manufacturers to provide full inventories of raw materials, energy consumption, emissions to air and water, and solid waste. Data for ambient grinding include mostly emissions of dust and use of electricity which seem to be the two most important parameters, while data for cryogenic grinding models the details of nitrogen and electricity. The most complete report on all types of rubber recycling, however, is presented by Corti and Lombardi in their work entitled *End Life Tyres: Alternative tire disposal processes compared by LCA*, but they fail to mention the large civil engineering category.[109] The PRé Consultants report describes the grinding of rubber into course pieces for civil engineering purposes, but the data describing rest of the rubber recycling scenarios are taken from the Corti and Lombardi report. Due to the slightly different size of the recycled rubber and the resultant use, the civil engineering category will be left separate from the other recycling methods even though it uses the same basic rubber grinding process as the more general recycled rubber category. Both are presented in different sections in Appendix A. The avoided product in this inventory is synthetic rubber because the production of 1 kg of recycled ground rubber enables the users of this rubber to avoid purchasing or producing 1 kg of new synthetic rubber. The avoided product category in each of the end of life inventories describes the product or raw material that does not need to be manufactured from scratch because the recycled product can be used in its place. These will produce an environmental benefit to counteract the impact from the energy requirements and other inputs or emissions.

The hub recycling impact through one tire life cycle includes only 25% of the hub mass because the steel can be used about four times as long as the rubber. For that reason, only 1 kg of recycled steel is considered in the life cycle of one tire. Recycled steel is documented in the BUWAL database and is combined with the recycling of rubber to give an overall tire recycling profile.

4.5.3 Tweel™ Recycling

As with all other potential Tweel™ end of life scenarios, Tweel™ recycling begins with separating the three main components: hub, polyurethane spokes and shear band, and rubber tread. This can either be done by roughly cutting the polyurethane away from the hub and the rubber tread leaving a small amount of polyurethane still attached to both, or they can all be separated by heating the entire assembly to a temperature of about 150 °C for 2 or 3 hours to allow the adhesives to break down and the polyurethane to relax and shrink away from the hub and tread. Obviously the second method is more energy intensive, but results in clean separation of each component without the need to use harmful cleaners to remove the excess polyurethane from the steel and rubber that was not able to be cut off. Because of this clean, easy separation, and the uncertainty of the methods necessary to completely clean the excess material that could not be cut off, the heating method of separation will be preferred by Michelin and will be the only method considered in this analysis. The energy required to maintain an oven at this temperature for 2 to 3 hours is documented in the Franklin USA database for a general oven, and since the size and characteristics of the oven needed for this component separation is not know, this database is the only option available. This oven inventory will be added to each disposal route as a prerequisite for processing.

Once the three components have been separated, each can be considered to follow their own disposal routes. The hub can go straight back to being reused in another Tweel™ an estimated four times following the same cleaning and adhesion method described in section 4.2.2, so only 25% of the steel hub's recycling impact will be included with one Tweel™. Due to the similarities between the Tweel™ shear band and the rubber in a tire, shear band recycling will be considered to be the same as tire rubber and will follow the same disposal route percentages as described in Figure 4.7. The processing of a Tweel™ shear band may be somewhat different than processing tire rubber, but because the details of these differences are unknown, the best option to provide a reliable analysis of the shear band disposal is to use the inventory for rubber disposal. As with tires, each disposal route (landfill, incineration, etc.) will be weighted together to give one overall environmental inventory.

This only leaves the polyurethane spokes, which are recycled in much the same way as rubber – shredding for reuse or incineration. As shown in Figure 4.8 however, polyurethane recycling occurs in much smaller percentages than rubber recycling. These percentages will probably change however because a 300 million Tweel™ stockpile has the potential to pressure polyurethane producers and others to use more recycled materials. For this reason, it will be important to analyze the environmental impact of each polyurethane disposal route so that qualitative observations can be made about the different options rather than using Figure 4.8 to weigh everything together into one inventory that may give misleading results.

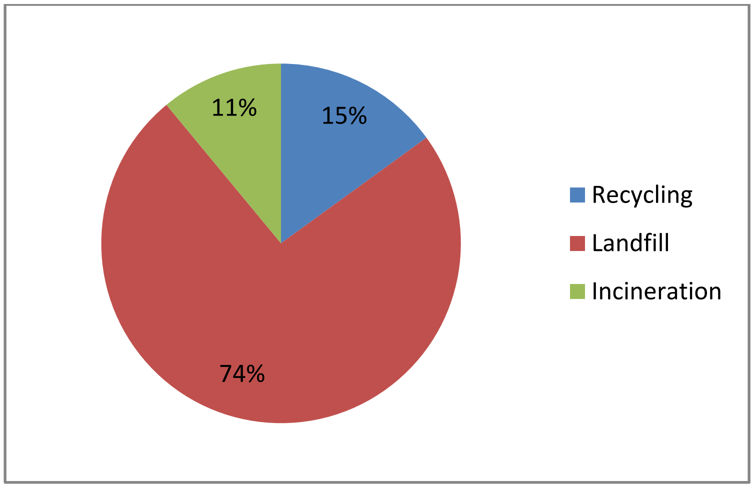

Figure 4.8. Polyurethane end of life disposal routes, North America. [110]

Recycled polyurethane must be shredded into much smaller granules than recycled rubber because usually it is reused by adding it to the liquid (polyol/polyether) reactant. Foam polyurethane can be recycled in several different ways including adhesive pressing, compression molding, and injection molding, but the more rigid, solid polyurethane used in Tweels™ must be ground into fine pellets.[111] Due to the thermoset nature of polyurethane, these finely grinded pieces do not melt and homogenously mix with the liquid reactant. Instead, the recycled material enhances the new polyurethane in a composite-like manner. For this reason, the energy requirement to grind polyurethane to these small sizes on the order of 0.2 mm is about twice that of rubber.[110] A rough outline of the energy requirements for polyurethane recycling is presented in Zevenhoven's report.[112] Due to the similarities between the two roll systems of grinding polyurethane and rubber, one can expect a proportional environmental impact between the two processes. The overall environmental inventory of Tweel™ recycling is assembled in Appendix A by combining the appropriate weight percentages seen in one Tweel™ of polyurethane and rubber recycling (9.0 kg polyurethane, 2.8 kg rubber tread, 1 kg steel hub).

4.5.4 Rubber Derived Fuel

Tires contain more than 90% organic materials and have a higher heat value than coal, so a widely used option to process discarded tires is to use them as fuel.[33] The market is generally called the tire derived fuel (TDF) market, but because both the processing of tires and Tweel™ shear bands will be analyzed in this report, that term will be generalized to rubber derived fuel. Environmental effects of rubber combustion can be grouped into uncontrolled and controlled sources. Uncontrolled sources are open tire fires which will not be considered in this analysis for reasons discussed in section 4.5.5, while controlled combustion sources include boilers and kilns specifically designed for the efficient combustion of solid fuel. These controlled atmospheres not only produce energy in the place of traditional coal or oil plants, but they are also able to control the quantity of air emissions. As shown in Table 4.13, the TDF market has consistently growed over the past 20 years, with the highest percentage of tires incinerated in cement kilns.

Table 4.13. Tire derived fuel per disposal route (in millions of tires) [34]

	1990	1992	1994	1996	1998	2001	2003	2005	2007
Cement Kilns	6	7	37	34	38	53	53	58	66
Pulp & Paper	13	14	27	26	20	19	26	39	42
Industrial Boilers		6	10	16	15	11	17	21	35
Utility Boilers	1	15	12	23	25	18	23.7	27	26
Tires-to-Energy	4.5	15	15	16	16	14	10	10	10
Total Fuel	24.5	57	101	115	114	115	129.7	155	179

In general there are two methods of using rubber as fuel – whole tires or incineration of pre-processed rubber. Some plants are established to burn whole tires, while some need pre-processing into rubber shreds in order to burn efficiently and meet EPA standards. These standards control the potentially hazardous act of burning rubber so that emissions are minimized. Sources indicate that properly designed existing solid fuel combustors can supplement their normal fuels (coal, wood, and various combinations of fuel) with 10 to 20% TDF and still satisfy environmental compliance emissions limits. Furthermore, results from a dedicated tires-to-energy (100% TDF) facility indicate that it is possible to have emissions much lower than produced by existing solid fuel-fired boilers when properly designed and the facility is controlled.[37] One or the other of these cases will be considered in this rubber derived fuel analysis because the number of devices that are not well-designed for scrap tire combustion is negligible. Air emissions from these types of devices are likely more similar to open tire fires in a landfill than large controlled burning facilities, but these devices will be ignored.

The air emissions from all the rubber derived fuel sources defined in Table 4.13 are described in a report from the EPA titled *Air Emissions from Scrap Tire Combustion* that considers source test data from 22 industrial facilities that use TDF are presented: 3 kilns (2 cement and 1 lime) and 19 boilers, all of which have some type of particulate control. Based on the results from a rotary kiln incinerator simulator, with the exception of zinc emissions, potential emissions from TDF are not expected to be very much different than other conventional fossil fuels, as long as combustion occurs in a well-designed, well-operated, and well-maintained combustion device.[37] As these efficient devices are all that will be considered in this analysis, it should be expected that the overall environmental impact of rubber derived fuel should be close to zero because the avoided product will have close to the same environmental impact, negating any overall effects. Table 4.14 illustrates the similarities between rubber and coal. Note that rubber derived fuel produces about 36 MJ/kg, whereas coal is only capable of producing 31 MJ/kg.

Table 4.14. Comparative Fuel Analysis by Weight [37]

Fuel	Composition (percent)							Heating Value	
	Carbon	Hydrogen	Oxygen	Nitrogen	Ash	Sulfur	Moisture	kJ/kg	Btu/lb
TDF	83.87	7.09	2.17	0.24	1.23	4.78	0.62	36,023	15,500
Coal	73.92	4.85	6.41	1.76	1.59	6.23	5.24	31,017	13,346

Depending on the design of the combustion device, a small amount of extra energy may be needed to process the rubber by dewiring and shredding, but some specially designed boilers and cement kilns have had their feed systems designed to accept whole tires. In either case, this processing energy is added to the air emissions in the EPA's report to give an overall inventory of each of the 22 facilities. Some of the facilities differ slightly from other traditional combustion plants, but it is important to make the distinction between burning rubber and burning coal or other raw materials. To complete the overall rubber derived fuel inventory for this analysis, a weighted average of the EPA data is used in correspondence with the disposal route percentages described in Table 4.13, and the results of this weighted average are listed in Appendix A. This inventory takes into account the energy required to process the rubber, the air emissions from the combustion process, and the avoided energy production from the U.S. average energy grid. As described in Table 4.14, the avoided energy production for 1 kg of rubber is 36 MJ, which is modeled as the average energy mix in the United States.

Due to the similarities between the rubber compounds, this inventory will be used for both tires and Tweel™ shear bands. Incinerating the polyurethane spokes from a Tweel™ however requires a different analysis. Polyurethane releases 25.6 MJ/kg when incinerated, so avoiding that energy production will be offset by roughly the same amount through the air emissions described in Zevenhoven's paper titled *Treatment and Disposal of Polyurethane Wastes*.[112] A much less comprehensive data set is available that compares several methods of incineration like what is available for rubber derived fuel, but Zevenhoven's source of emissions data is sufficient and will be combined with the rubber derived fuel data discussed above to complete the overall inventory for Tweel™ incineration.

4.5.5 Landfilling

Problems associated with scrap tire disposal have been widely documented and discussed in the media, and most people greatly fear the dangers of ever-growing piles of tires in landfills. These views of the general public are often times exaggerated due to emotional prejudice sparked by pictures of mounds of tires or out of control tire fires. Performing an objective, scientific analysis of tire landfilling is thus important to understand the real environmental effects beyond the pictures that spark fear. The three main environmental pressures from landfilling any substance are as follows:

1. Toxic substances and nutrients leaching into surface and ground water.
2. Contribution to the greenhouse effect by emission of methane.
3. Land use.

Tires also present the rare risk of tire fires. Tire fires are difficult to fight because tires represent a high-energy content hydrocarbon fuel and have 75% void space, which provides oxygen and a perfect source for a blaze that is difficult to extinguish, and due to their smoldering, low temperature pyrolytic nature, these fires are responsible for uncontrolled pollution by releasing toxic fumes.[113] As a tire fire is not common and not predictable however, it can only be treated as an accidental side effect; therefore no quantitative assessment will be included in the analysis.

Normal everyday use of landfills however, will be analyzed by considering both controlled and uncontrolled landfills. Landfill technology has attempted to improve two of the major environmental pressures listed above through the use of impermeable liners, the collection and treatment of leachates, and the collection of methane, but some small landfills remain uncontrolled.[114] Sources estimate the number of uncontrolled landfills in the United States to be about 25%.[35] This is from where most of the environmental impact of landfilling comes. As tires can be stacked on top of each other as high as necessary, each tire is only responsible for a small percentage of its area, which can be assumed to be roughly 10%. The overall diameter for both a tire and Tweel™ is roughly 0.3 m, so 10% of its circular area is only about 0.03 m^2. This area is obviously important because of the rate it can accumulate with 300 million scrap tires, but perhaps more important are the materials that may leach into the environment in the uncontrolled landfills. As tire fires are not being considered in this analysis, the only things to consider in controlled landfills are the land use and the energy required to control and treat the gaseous emissions and leached substances that are caught by the lining.

Both of these inventories are compared in Table 4.15. However, these are only simplified short term inventories that do not take into consideration the long-term degradation of rubber and metal. PRé Consultants analyzed the entire LCI of both controlled and uncontrolled landfills in a more detailed and more long term approach by creating a model based on a report from BUWAL 250 entitled *Life Cycle Inventories*.[17, 115] Their analysis assumes energy produced in Europe, but as the energy required to sort the scrap and to treat the emissions is only about 5 or 10%, this difference is acceptable. The overall environmental inventory for mixed landfilling, which assumes 25% uncontrolled landfills, is supplied in Appendix A.

Table 4.15. Environmental costs of landfilling

	Controlled Landfill	Uncontrolled Landfill
Land Use	0.03 m^2	0.03 m^2
Energy	2.5 kWh	0 kWh
Leached plastics	0 g	25 g
Leached metals	0 g	5 g
Methane	0 g	15 g

The same analysis is performed to model the landfilling of the tread of the Tweel™ due to its similarities to the rubber compound of a tire, but the polyurethane must be considered separately because it will have different environmental effects. The only reliable data that could be found that includes the entire inventory necessary for this LCA are in the BUWAL database. However, due to the lack of transparency or explanation about the origins of the data, it is unclear whether controlled or uncontrolled landfills were assumed. The general idea of polyurethane landfilling though is maintained, so it will suffice for the purposes of this analysis. These data are added to the tire landfill data with appropriate weights representative of the relative mass of the spokes with respect to the shear band.

4.5.6 Retreading

There are currently more than 1900 retreading facilities in the U.S. and Canada.[116] However, the number is shrinking because of decreased markets for passenger retreads due to the low prices of new tires and a declining trust in modified used tires. Truck tires often are retreaded three times before being discarded and thus the truck tire retreading business is increasing, but the difference between truck tires and passenger tires in this respect is great. Although passenger tires are retread in small percentages in Europe, passenger tires in the United States today rarely are retread, so the environmental effects or benefits of retreading tire will not be included in this analysis. Preliminary research reveals that Tweels™ may have higher incentives to be retread, and consumers may take this option more often due to a change in perception of the safety of retreading. This possibility is purely hypothetical at this point though, and no data have been gathered to support this opinion, so retreading is not considered an end of life option for either tires or Tweels™.

Chapter 5. Impact Assessment

5.1 Introduction and Overview

5.1.1. Impact Assessment Methods

The inventory collected through the process discussed in this thesis provides all the details concerning the inputs and outputs and potential environmental hazards, but assembling this information in an organized manner that allows comparisons to be made between different products or different emissions in a given life cycle phase requires more analysis that assesses the impacts of each portion of the life cycle inventory. It is a useful exercise to compare specific emissions such as CO_2 or nitrogen oxides throughout each phase of a product's life cycle, but in order to most accurately weigh the pros and cons of each phase, impact assessment methods that weight the environmental factors using a single, relative, uniform scale, such as EcoIndicator99 and EDIP, must be used. Both of these methods determine relative environmental impacts between 1 kg of methane vs. 1 kg of sulfur or any other compound listed in the life cycle inventory by assembling them into similar impact categories and then weighting the importance of each category against the others. As described in Table 5.1, the EcoIndicator method groups the 11 impact categories determined by its developers into three broader "damage categories" and then weights these human health, ecosystem quality, and resources categories using a 40/40/20 ratio. Table 5.2 lists the categories used by the EDIP method and its weights that describe the relative importance of each category. Although these methods differ slightly, the goal of both methods is to group together similar environmental effects and then compare the relative importance of each category against the others to be able to weight each category to present a single value that encompasses every environmental impact of a product or process. This value is presented in units of Pt, or EcoPoints, a relative scale that is determined by each impact assessment method's creators. One thousand EcoIndicator Pts is equivalent to the yearly environmental impact of the average European, but is not the same scale on which the EDIP method is presented With a life cycle as complicated as a tire that includes the large amount of raw materials, fuel use, and a variety of possible disposal routes, the use of these two methods to combine the environmental effects of each stage will facilitate the overall comparison between a conventional tire and a Tweel™.

Table 5.1. EcoIndicator impact categories

Damage Category	Impact Category	Weighting
Human Health	Carcinogenic effects on humans	40%
	Respiratory effects caused by organic substances	
	Respiratory effects caused by inorganic substances	
	Damage caused by climate change	
	Effects caused by ionizing radiation	
	Effects caused by ozone layer depletion	
Ecosystem Quality	Damage caused by ecotoxic effects	40%
	Damage caused by the combined effect of acidification and eutrophication	
	Damage caused by land occupation and land conversion	
Resources	Damages caused by extraction of minerals	20%
	Damages caused by extraction of fossil fuels	
Total		100%

Table 5.2. EDIP impact categories

Impact Category	Weighting
Global warming	1.3
Ozone depletion	23.0
Ozone formation from vegetation	1.2
Ozone formation from humans	1.2
Acidification	1.3
Terrestrial eutrophication	1.2
Aquatic eutrophication	1.2
Human toxicity from air pollution	2.8
Human toxicity from water pollution	2.5
Human toxicity from soil pollution	2.5
Hazardous waste	1.1
Slags/ashes	1.1
Bulk waste	1.1
Radioactive waste	1.1
Total	42.6

Both of these methods present the overall environmental impact of a product or process for useful comparison against other impacts, but some processes result in a negative environmental impact score, or an environmental benefit. When a tree consumes CO_2 from the atmosphere, for example, a negative climate change or global warming score will arise because of the benefit to this category instead of the negative impact that the assessment methods are designed to compare. Some processes will contain both categories that have an overall benefit to the environment (negative score) and impact categories with a negative environmental impact (positive score). In the graphs below that describe the overall impact of every life cycle phase, the environmental load of each impact category listed in Tables 5.1 and 5.2 are displayed to help determine which category contributes the most to the environmental impact. So, instead of directly subtracting the negative scores from the positive scores to give one overall assessment of each phase, one column (or environmental impact score) may present both a positive and a negative component from different categories. This will help to establish details about the most environmentally problematic categories. Once these observations have been made, it will be possible to combine the positive and negative values together into one environmental impact score.

5.1.2. U.S. Energy Impact

As energy is used in almost every phase of the life cycle of both of these products (except the burning of gasoline), it is important to model the environmental impact of producing energy in the U.S. before each phase is analyzed. As discussed previously, the two most reliable sources for the energy mix are the IDEMAT database and the DoE Energy Information Administration, but the percentages in the IDEMAT database are outdated and represent values closer to the American energy grid in 2001. The production process to create the raw materials of a tire or a Tweel™ have not changed much over the past 7 or 8 years, so a database that is a couple years old is acceptable for their purposes. Yet as the energy production (energy from crude oil in particular) has noticeably changed this decade, it is important to use up-to-date data.

The differences between Table 4.4 and Table 4.5 illustrate the recent attempt to reduce electricity production from crude oil and replace it with more domestic and environmentally friendly means of energy production. However, it is difficult to quantify this tradeoff in terms of an overall environmental effect without impact assessment methods that can weigh, say, a reduction in CO_2 emissions against an increased demand for the planet's natural resources. Figure 5.1 and Figure 5.2 (with corresponding tables that document the exact impact numbers) compare the overall environmental impact of the production of 1 MJ of energy according to both the IDEMAT database and the EIA percentages using the two impact assessment methods previously described.

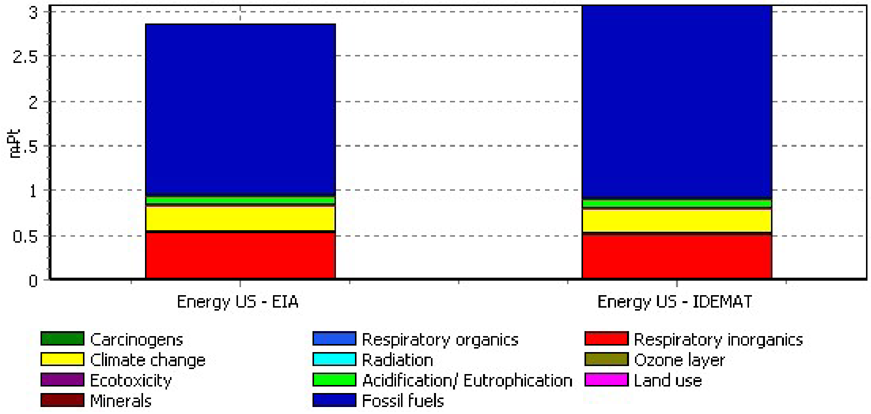

Figure 5.1. Environmental impact of producing 1 MJ of energy in U.S. (Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.3. Supplemental data for Figure 5.1

Impact category	Unit	Energy US - EIA	Energy US - IDEMAT
Carcinogens	mPt	0.000	0.000
Respiratory organics	mPt	0.000	0.000
Respiratory inorganics	mPt	0.524	0.512
Climate change	mPt	0.301	0.283
Radiation	mPt	0.000	0.000
Ozone layer	mPt	0.000	0.000
Ecotoxicity	mPt	0.000	0.000
Acidification/ Eutrophication	mPt	0.107	0.102
Land use	mPt	0.000	0.000
Minerals	mPt	0.000	0.000
Fossil fuels	mPt	1.920	2.172
Total	mPt	2.853	3.069

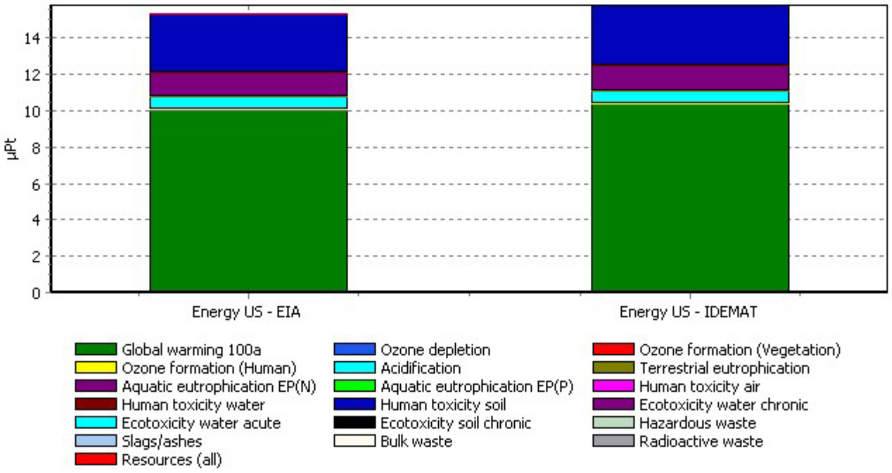

Figure 5.2. Environmental impact of producing 1 MJ of energy in U.S. (Method: EDIP 2003 V1.00 / Default / single score)

Table 5.4. Supplemental data for Figure 5.2

Impact category	Unit	Energy US - EIA	Energy US - IDEMAT
Global warming 100a	μPt	10.04	10.40
Ozone depletion	μPt	0.00	0.00
Ozone formation (Vegetation)	μPt	0.01	0.00
Ozone formation (Human)	μPt	0.01	0.00
Acidification	μPt	0.70	0.72
Terrestrial eutrophication	μPt	0.00	0.00
Aquatic eutrophication EP(N)	μPt	1.32	1.35
Aquatic eutrophication EP(P)	μPt	0.00	0.00
Human toxicity air	μPt	0.01	0.01
Human toxicity water	μPt	0.00	0.00
Human toxicity soil	μPt	3.26	3.33
Ecotoxicity water chronic	μPt	0.00	0.00
Ecotoxicity water acute	μPt	0.00	0.00
Ecotoxicity soil chronic	μPt	0.00	0.00
Hazardous waste	μPt	0.00	0.00
Slags/ashes	μPt	0.00	0.00
Bulk waste	μPt	0.00	0.00
Radioactive waste	μPt	0.00	0.00
Resources (all)	μPt	0.00	0.00
Total	μPt	15.34	15.82

Even though the two energy mixes differ by a substantial amount, the overall difference in the environmental load of producing energy between these two sources is only 7% according to the EcoIndicator method and 3% according to EDIP. These differences are small and will not be fully felt by the most environmentally significant life cycle phase, the use phase, because energy is only required to produce gasoline while the other half of the environmental impact, the emissions resulting from burned gasoline, requires no energy input, so either source may be acceptable for this analysis. However, these small differences may have noticeable impacts on the overall life cycle of a tire or Tweel™ because energy is used in the production of the raw materials, manufacturing, and most disposal routes, so the most recent data should be used to assure as much accuracy as possible. The EIA energy grid percentages and the corresponding impacts described above will be used to model the energy requirements throughout the impact analysis of each of the different phases of each product's life cycle and is signified in Appendix A as "Energy US I".

5.2 Production Phase

5.2.1 Production of Raw Materials

The environmental impact of producing 1 kg of each raw material used in either a tire or a Tweel™ is illustrated in Figure 5.3 and Figure 5.4 (again with corresponding tables that document the exact numbers presented in each graph). Figure 5.3 evaluates each raw material inventory through the use of the EcoIndicator99 method, whereas Figure 5.4 uses the EDIP method.

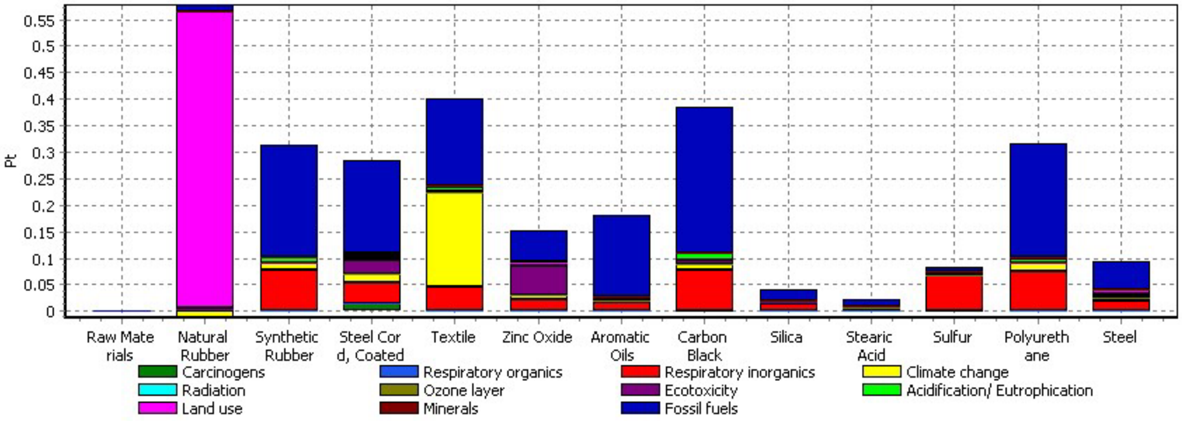

Figure 5.3. Impact of production of 1 kg of each raw material
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.5. Supplemental data for Figure 5.3

Impact category	Unit	Natural Rubber	Synthetic Rubber	Steel Cord, Coated	Textile	Zinc Oxide	Aromatic Oils	Carbon Black	Silica	Stearic Acid	Sulfur	Polyurethane	Steel	**Total**
Carcinogens	Pt	0.000	0.000	0.013	0.001	0.001	0.001	0.002	0.000	0.000	0.000	0.000	0.001	0.020
Respiratory organics	Pt	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
Respiratory inorganics	Pt	0.001	0.076	0.040	0.044	0.020	0.015	0.075	0.014	0.005	0.067	0.075	0.019	0.450
Climate change	Pt	-0.013	0.013	0.017	0.178	0.009	0.004	0.010	0.002	0.001	0.001	0.015	0.004	0.242
Radiation	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ozone layer	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ecotoxicity	Pt	0.000	0.001	0.025	0.004	0.057	0.004	0.007	0.000	0.001	0.001	0.001	0.004	0.105
Acidification/ Eutrophication	Pt	0.000	0.012	0.006	0.008	0.004	0.003	0.014	0.002	0.001	0.006	0.009	0.004	0.068
Land use	Pt	0.561	0.000	0.005	0.000	0.001	0.000	-0.002	0.000	0.000	0.000	0.001	0.007	0.573
Minerals	Pt	0.000	0.000	0.003	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.006
Fossil fuels	Pt	0.009	0.212	0.176	0.166	0.064	0.155	0.275	0.022	0.014	0.009	0.216	0.051	1.370
Total	Pt	0.559	0.314	0.285	0.402	0.156	0.182	0.382	0.041	0.023	0.083	0.317	0.093	2.837
Total	Pt	0.559	0.314	0.285	0.402	0.156	0.182	0.382	0.041	0.023	0.083	0.317	0.093	2.837

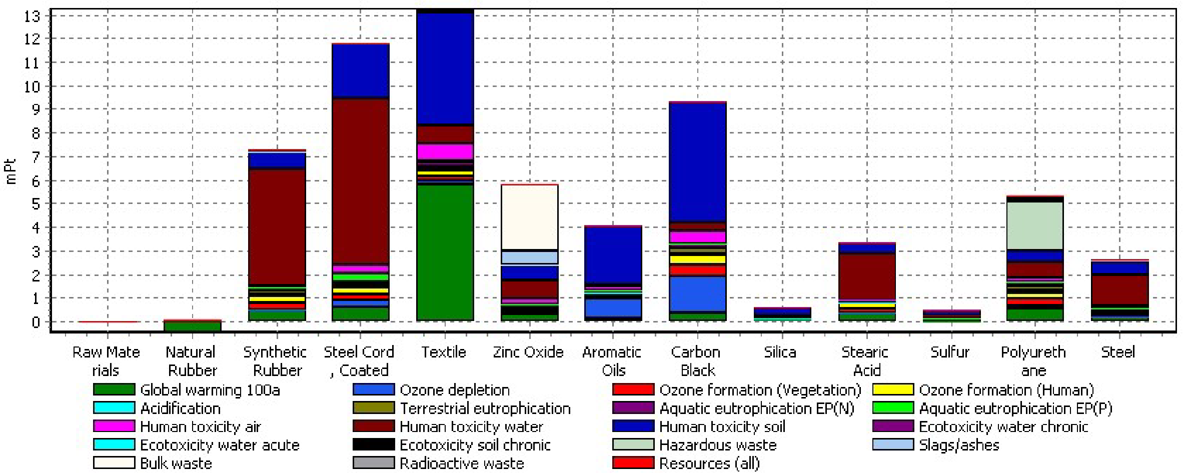

Figure 5.4. Impact of production of 1 kg of each raw material
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.6. Supplemental data for Figure 5.4

Impact category	Unit	Natural Rubber	Synthetic Rubber	Steel Cord, Coated	Textile	Zinc Oxide	Aromatic Oils	Carbon Black	Silica	Stearic Acid	Sulfur	Polyurethane	Steel	**Total**
Global warming 100a	mPt	-0.47	0.48	0.63	5.82	0.32	0.16	0.39	0.07	0.06	0.04	0.56	0.16	8.21
Ozone depletion	mPt	0.00	0.00	0.28	0.18	0.03	0.78	1.56	0.01	0.04	0.07	0.12	0.00	3.08
Ozone formation (Vegetation)	mPt	0.00	0.30	0.26	0.19	0.08	0.13	0.42	0.02	0.02	0.01	0.26	0.09	1.80
Ozone formation (Human)	mPt	0.00	0.30	0.27	0.19	0.08	0.14	0.43	0.02	0.02	0.01	0.25	0.09	1.80
Acidification	mPt	0.00	0.07	0.05	0.09	0.10	0.02	0.09	0.01	0.01	0.00	0.13	0.09	0.66
Terrestrial eutrophication	mPt	0.00	0.18	0.11	0.14	0.07	0.05	0.25	0.01	0.01	0.01	0.20	0.07	1.11
Aquatic eutrophication EP(N)	mPt	0.00	0.12	0.07	0.16	0.05	0.04	0.17	0.01	0.01	0.00	0.18	0.06	0.87
Aquatic eutrophication EP(P)	mPt	0.00	0.00	0.37	0.02	0.01	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.43
Human toxicity air	mPt	0.00	0.06	0.36	0.75	0.25	0.21	0.52	0.03	0.01	0.09	0.15	0.09	2.51
Human toxicity water	mPt	0.00	4.92	7.05	0.75	0.73	0.04	0.32	0.06	0.04	0.02	0.66	1.30	15.90
Human toxicity soil	mPt	0.05	0.74	2.30	4.82	0.68	2.52	5.15	0.33	0.13	0.23	0.52	0.59	18.05
Ecotoxicity water chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hazardous waste	mPt	0.00	0.00	0.00	0.07	0.03	0.00	0.00	0.00	0.00	0.00	2.07	0.06	2.22
Slags/ashes	mPt	0.00	0.00	0.00	0.06	0.58	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.74
Bulk waste	mPt	0.00	0.14	0.00	0.03	2.78	0.00	0.00	0.00	0.00	0.00	0.16	0.01	3.11
Radioactive waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	mPt	-0.40	7.32	11.75	13.27	5.78	4.09	9.31	0.58	0.36	0.48	5.35	2.61	60.50

Both of these figures evaluate the same inventory data described in section 4.1, but the environmental impact results are not exactly the same due to the differences in what each method stresses as more environmentally harmful. The EcoIndicator and EDIP methods are evaluated on different scales (EDIP synthetic rubber = 7.32 mPt from Table 5.6, EcoIndicator synthetic rubber = 314 mPt from Table 5.5), but the comparative impacts within each impact assessment method is the only practical information because of the arbitrary way in which the overall vertical scales were chosen. Taking this into account, both methods relatively agree that synthetic rubber, steel wire, carbon black, and polyurethane are the most harmful materials per kilogram for the environment, but there is a large discrepancy in the environmental load of the production of natural rubber. Even though the EcoIndicator impacts are determined by categories such as respiratory inorganics and fossil fuels, and EDIP uses different categories like human toxicity water and bulk waste, the relative impacts of most of the raw materials are relatively equal because most of the inputs and outputs from the environmental inventory are considered in the same manner but under a different category name. The one glaring difference however is the EcoIndicator's evaluation of land use. The EDIP method attributes an overall negative score (environmental benefit) to natural rubber due to the Hevea tree's carbon uptake and ability to be used as firewood when it can no longer produce rubber. The EcoIndicator though evaluates the 7 m^2 land area needed to produce 1 kg of natural rubber as more environmentally harmful than the entire synthetic rubber production process. Natural rubber production takes place on 9.5 million hectares of tropical land that usually thrives with life due to a wide variety of plant sources [23], so this land use should be recognized as an environmental impact, but quantifying this in an impact assessment method for general use is difficult and can easily be argued against by claiming that the land required to produce natural rubber is not being transformed from a forest to a concrete parking lot but is instead simply using a specific type of tree to replace the previous trees.

This debate about land use has legitimate arguments on both sides, so to quantify the impact of natural rubber in relation to synthetic rubber, the energy required to produce each is another helpful tool. Table 5.7 and Table 5.8 list the raw energy requirements to produce both natural rubber and synthetic rubber. It must be mentioned that this is a very simplified approach that does not include the land use and carbon uptake from natural rubber or the oil requirements for or production emissions from synthetic rubber, but this simple analysis can help to establish fundamental differences between the two production methods.

Table 5.7. Energy requirements in natural rubber production [117]

Process	Energy (MJ/kg)
Crepe preparation	0.32
Crumb drying	4.2
Transport from Malaysia	1.5
Total	6.02

Table 5.8. Energy used in synthetic rubber production [117]

Energy source	Energy (MJ/kg)
Electricity	13.67
Refined oil products	66.57
Natural gas	75.14
Byproduct fuel credit	-16.01
Net Total	139.37

As shown in Table 5.7 and Table 5.8, the production of synthetic rubber requires more than 20 times the amount of energy than natural rubber. Considering simply the amount of CO_2 emissions that result from this energy production (see Table 4.4), 1 kg of synthetic rubber is responsible for 9.6 kg of CO_2, whereas the energy to produce 1 kg of natural rubber only emits 0.4 kg, which results in a net CO_2 output of -2.9 kg when the carbon uptake of the Hevea trees is added. These fundamental differences outline the contrasting impacts seen in Figure 5.3 and Figure 5.4, which show that natural rubber is much less environmentally harmful as compared to the rest of the raw material production methods when land use is not considered. For this reason, a more in depth analysis of the effects of natural rubber land use and the changes in the land when Hevea trees are planted in mass quantities may be required to establish a reliable overall environmental impact of natural rubber. For the purposes of this thesis however, this conflict will just have to be qualitatively noticed in the differences between the impact assessment methods. It appears however that this is the only fundamental difference that causes large deviations between the results, as the rest of the raw material environmental impacts are relatively similar between the EcoIndicator and EDIP methods.

Now that an environmental impact profile has been established for each raw material production inventory, Figure 5.5 and Figure 5.6 consider weighted impact of the differing masses of raw materials required to assemble one tire. Figure 5.5 is an impact assessment using the EcoIndicator99 method, whereas Figure 5.6 uses the EDIP method. Both of these include 1.8 kg of natural rubber, 2.4 kg of synthetic rubber, etc. as described in Table 4.1.

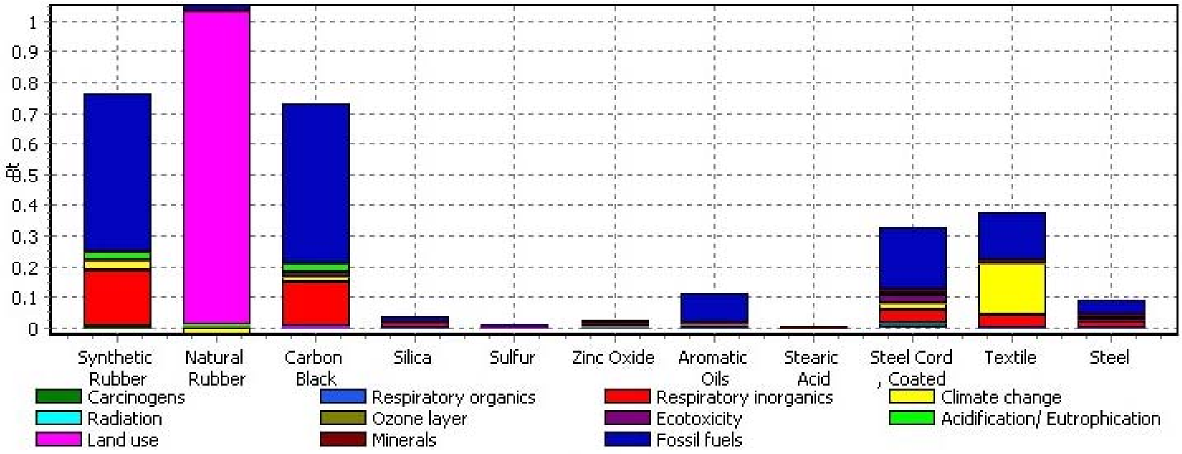

Figure 5.5. Weighted impact of raw materials used in one tire
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.9. Supplemental data for Figure 5.5

Impact category	Unit	Synthetic Rubber	Natural Rubber	Carbon Black	Silica	Sulfur	Zinc Oxide	Aromatic Oils	Stearic Acid	Steel Cord, Coated	Textile	Steel	**Total**
Carcinogens	Pt	0.001	0.000	0.003	0.000	0.000	0.000	0.001	0.000	0.015	0.001	0.001	0.022
Respiratory organics	Pt	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
Respiratory inorganics	Pt	0.184	0.002	0.143	0.014	0.009	0.003	0.009	0.000	0.045	0.041	0.019	0.470
Climate change	Pt	0.031	-0.023	0.019	0.002	0.000	0.001	0.002	0.000	0.019	0.167	0.004	0.224
Radiation	Pt	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ozone layer	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ecotoxicity	Pt	0.001	0.000	0.014	0.000	0.000	0.009	0.002	0.000	0.029	0.004	0.004	0.064
Acidification/ Eutrophication	Pt	0.029	0.000	0.026	0.002	0.001	0.001	0.002	0.000	0.007	0.008	0.004	0.079
Land use	Pt	0.000	1.021	-0.003	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.007	1.031
Minerals	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.002	0.005
Fossil fuels	Pt	0.513	0.017	0.522	0.022	0.001	0.010	0.095	0.001	0.201	0.156	0.051	1.588
Total	Pt	0.760	1.018	0.726	0.039	0.011	0.025	0.111	0.002	0.325	0.377	0.093	3.487

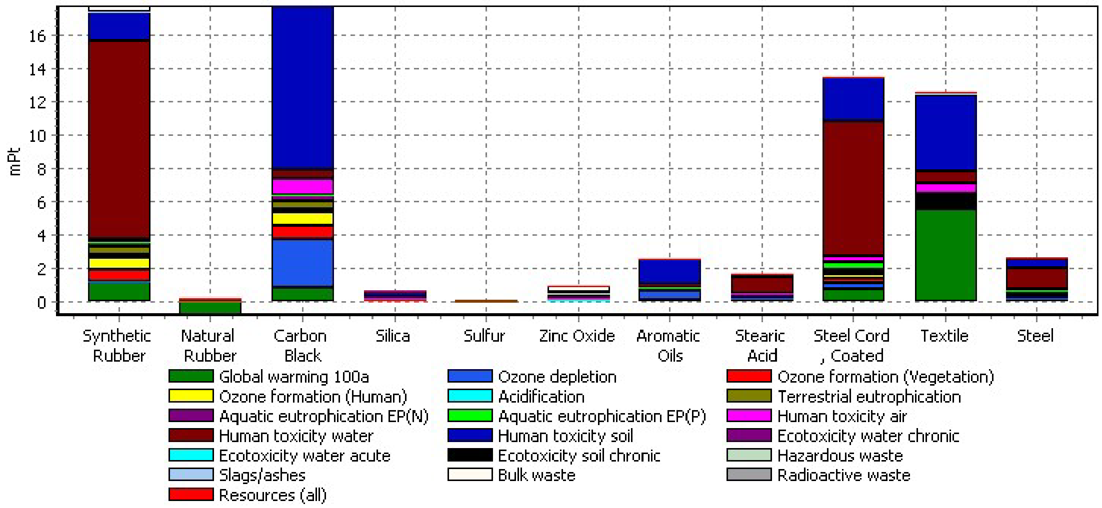

Figure 5.6. Weighted impact of raw materials used in one tire
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.10. Supplemental data for Figure 5.6

Impact category	Unit	Synthetic Rubber	Natural Rubber	Carbon Black	Silica	Sulfur	Zinc Oxide	Aromatic Oils	Stearic Acid	Steel Cord, Coated	Textile	Steel	**Total**
Global warming 100a	mPt	1.16	-0.85	0.74	0.07	0.00	0.05	0.10	0.01	0.72	5.47	0.16	7.62
Ozone depletion	mPt	0.00	0.00	2.96	0.01	0.01	0.00	0.48	0.00	0.32	0.17	0.00	3.96
Ozone formation (Vegetation)	mPt	0.72	0.00	0.80	0.02	0.00	0.01	0.08	0.00	0.30	0.18	0.09	2.22
Ozone formation (Human)	mPt	0.72	0.00	0.81	0.02	0.00	0.01	0.09	0.00	0.31	0.18	0.09	2.23
Acidification	mPt	0.16	0.01	0.18	0.01	0.00	0.02	0.01	0.00	0.06	0.08	0.09	0.61
Terrestrial eutrophication	mPt	0.45	0.00	0.48	0.01	0.00	0.01	0.03	0.00	0.13	0.13	0.07	1.31
Aquatic eutrophication EP(N)	mPt	0.30	0.01	0.32	0.01	0.00	0.01	0.02	0.00	0.08	0.15	0.06	0.95
Aquatic eutrophication EP(P)	mPt	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.42	0.02	0.00	0.48
Human toxicity air	mPt	0.15	0.01	0.98	0.03	0.01	0.04	0.13	0.00	0.41	0.70	0.09	2.55
Human toxicity water	mPt	11.90	0.00	0.61	0.06	0.00	0.12	0.02	0.00	8.04	0.71	1.30	22.77
Human toxicity soil	mPt	1.79	0.09	9.78	0.32	0.03	0.11	1.54	0.01	2.62	4.53	0.59	21.40
Ecotoxicity water chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hazardous waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.13
Slags/ashes	mPt	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.06	0.00	0.15
Bulk waste	mPt	0.33	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.03	0.01	0.81
Radioactive waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	mPt	17.69	-0.74	17.69	0.56	0.06	0.91	2.50	0.03	13.40	12.47	2.61	67.19

Again, correcting for the differences in the assessment of natural rubber production, Figure 5.5 and Figure 5.6 are very similar in that they both stress the environmental impacts of synthetic rubber, carbon black, coated wires, and textiles used in one tire. The rest of the raw materials have a much smaller relative environmental impact in some cases because only small amounts are used in the production of a tire (like sulfur and ZnO), while others have a smaller impact due to their environmentally safe production process as described in Figure 5.3 (e.g. silica). Similarly, Figure 5.7 and Figure 5.8 illustrate the weighted environmental impacts of each mass of raw material used in the production of one Tweel™ from Table 4.2, but in these figures almost the entire environmental load of Tweel™ raw materials is attributable to polyurethane because of the large amount needed relative to the 1.2 kg of rubber. As described in the inventory collection section of this report though, the energy needed to heat the prepolymers and curative before the polyurethane is mixed and poured into a Tweel™ mold and the energy needed to hold the mold at an elevated temperature while the polyurethane hardens is considered along with the production of the prepolymers themselves. This may falsely inflate the impact of the pure polyurethane raw materials, but these energy requirements are directly responsible for making polyurethane, so it has been considered part of the raw material production process. As with Figure 5.5 and Figure 5.6 that describe the impact of the tire raw materials, each of the impacts shown in Figure 5.7 and Figure 5.8 can be added together because they are presented on a uniform scale to assess the overall impact of the raw material production phase of one Tweel™. This overall assessment will be presented in section 5.2.3 below.

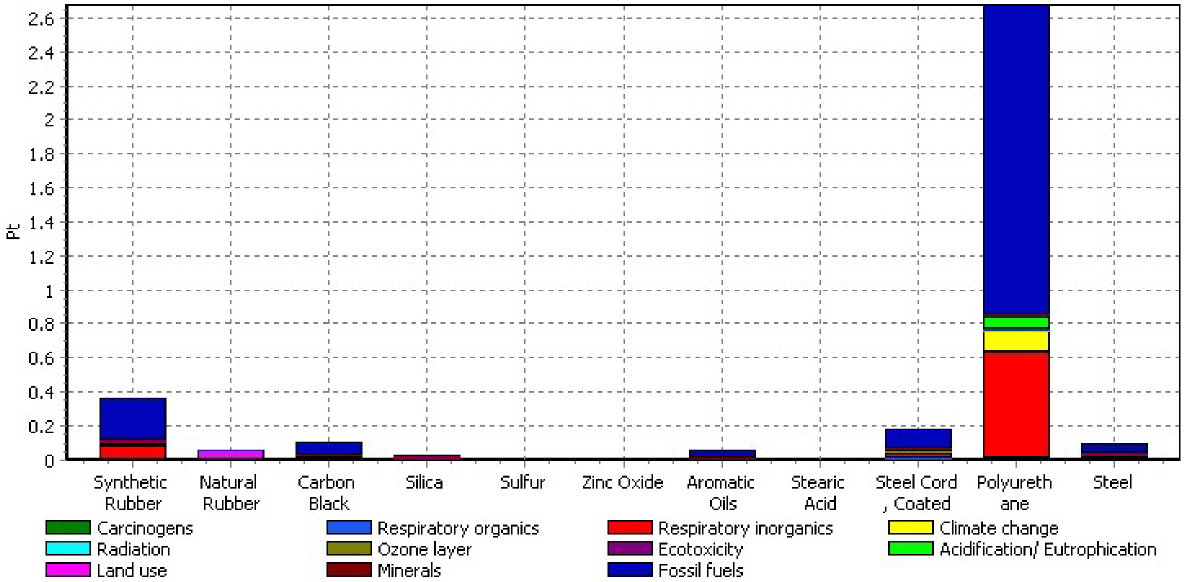

Figure 5.7. Weighted impact of raw materials used in one Tweel™
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.11. Supplemental data for Figure 5.7

Impact category	Unit	Synthetic Rubber	Natural Rubber	Carbon Black	Silica	Sulfur	Zinc Oxide	Aromatic Oils	Stearic Acid	Steel Cord, Coated	Polyurethane	Steel	**Total**
Carcinogens	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.002	0.001	0.013
Respiratory organics	Pt	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.003
Respiratory inorganics	Pt	0.088	0.000	0.020	0.011	0.001	0.000	0.004	0.000	0.025	0.629	0.019	0.798
Climate change	Pt	0.015	-0.001	0.003	0.001	0.000	0.000	0.001	0.000	0.010	0.128	0.004	0.162
Radiation	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ozone layer	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ecotoxicity	Pt	0.001	0.000	0.002	0.000	0.000	0.001	0.001	0.000	0.016	0.004	0.004	0.029
Acidification/ Eutrophication	Pt	0.014	0.000	0.004	0.001	0.000	0.000	0.001	0.000	0.004	0.075	0.004	0.103
Land use	Pt	0.000	0.054	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.008	0.007	0.072
Minerals	Pt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.002	0.004
Fossil fuels	Pt	0.244	0.001	0.072	0.017	0.000	0.002	0.045	0.001	0.109	1.826	0.051	2.368
Total	Pt	0.362	0.054	0.100	0.032	0.002	0.004	0.053	0.001	0.178	2.675	0.093	3.553

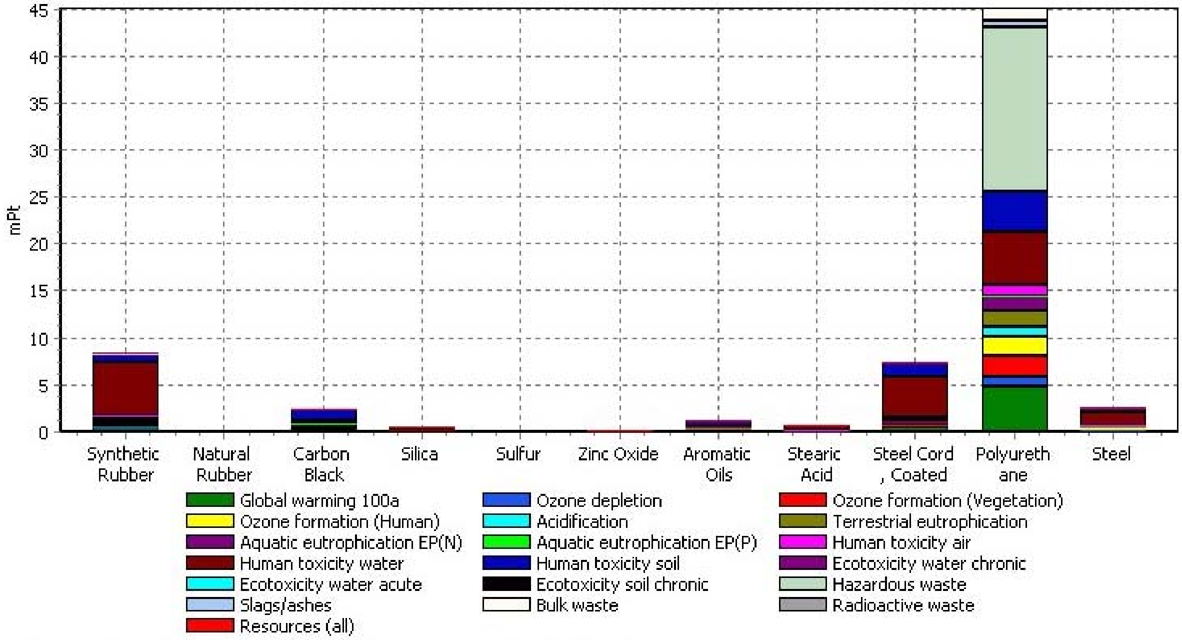

Figure 5.8. Weighted impact of raw materials used in one Tweel™
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.12. Supplemental data for Figure 5.8

Impact category	Unit	Synthetic Rubber	Natural Rubber	Carbon Black	Silica	Sulfur	Zinc Oxide	Aromatic Oils	Stearic Acid	Steel Cord, Coated	Polyurethane	Steel	**Total**
Global warming 100a	mPt	0.55	-0.05	0.10	0.06	0.00	0.01	0.05	0.00	0.39	4.76	0.16	6.04
Ozone depletion	mPt	0.00	0.00	0.41	0.01	0.00	0.00	0.23	0.00	0.17	1.00	0.00	1.83
Ozone formation (Vegetation)	mPt	0.34	0.00	0.11	0.02	0.00	0.00	0.04	0.00	0.16	2.19	0.09	2.96
Ozone formation (Human)	mPt	0.34	0.00	0.11	0.02	0.00	0.00	0.04	0.00	0.17	2.14	0.09	2.91
Acidification	mPt	0.08	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.03	1.11	0.09	1.35
Terrestrial eutrophication	mPt	0.21	0.00	0.07	0.01	0.00	0.00	0.02	0.00	0.07	1.68	0.07	2.13
Aquatic eutrophication EP(N)	mPt	0.14	0.00	0.04	0.01	0.00	0.00	0.01	0.00	0.05	1.49	0.06	1.80
Aquatic eutrophication EP(P)	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.24
Human toxicity air	mPt	0.07	0.00	0.14	0.02	0.00	0.01	0.06	0.00	0.22	1.23	0.09	1.84
Human toxicity water	mPt	5.66	0.00	0.08	0.05	0.00	0.02	0.01	0.00	4.39	5.57	1.30	17.09
Human toxicity soil	mPt	0.85	0.00	1.35	0.26	0.01	0.02	0.74	0.01	1.43	4.35	0.59	9.59
Ecotoxicity water chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hazardous waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.47	0.06	17.53
Slags/ashes	mPt	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.80	0.00	0.81
Bulk waste	mPt	0.16	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	1.34	0.01	1.57
Radioactive waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	mPt	8.42	-0.04	2.44	0.45	0.01	0.14	1.20	0.01	7.31	45.14	2.61	67.70

Figure 5.5 through Figure 5.8 assess the environmental impact of the production of the required amount of each raw material used to create both products, but the addition of the

impacts of each material together to give a profile of the impact of producing all the materials necessary for one tire or one Tweel™ returns surprisingly similar results between the two products. Table 5.13 describes the relative importance of each raw material in relation to the overall environmental impact of all the materials needed to produce both products, and there are two interesting results found. First of all, although the material breakdown differs greatly between the two products (Tweel's™ polyurethane production is 70% of the overall score compared to a tire's 0%) and a Tweel™ weighs 12 kg while a tire only weighs 10 kg (without considering the hub), both methods agree that producing all the raw materials necessary for a Tweel™ is almost exactly as environmentally harmful as the necessary tire materials. According to the EcoIndicator method, the Tweel's™ materials account for only 2% more environmental load as a Tweel's™ materials produce as environmental impact of 3.55 Pts compared to a tire's 3.49 Pts. The EDIP method supports this similarity with only a 1% difference (Tweel – 67.7 mPt vs. tire – 67.2 mPt). There is a second interesting point that there is a very clear similarity also between the scores for each product from both methods, but this will be discussed more later when the scales of each of the two impact assessment methods are compared against each other in the overall view of the life cycle. Since the two scales are relative to their own developed methods, a tire raw material's 3.49 Pt EcoIndicator score is difficult to compare to the EDIP's 67.7 mPt, but it will be seen that these two numbers agree quite well when the scales are compared against each other in section 6.

Table 5.13. Raw materials impact

	Tire - Eco		Tire - EDIP		Tweel - Eco		Tweel - EDIP	
Unit	Pt	%	mPt	%	Pt	%	mPt	%
Synthetic Rubber	0.760	21.8%	17.69	26.3%	0.362	10.2%	8.42	12.4%
Natural Rubber	1.018	29.2%	-0.74	-1.1%	0.054	1.5%	-0.04	-0.1%
Carbon Black	0.726	20.8%	17.69	26.3%	0.100	2.8%	2.44	3.6%
Silica	0.039	1.1%	0.56	0.8%	0.032	0.9%	0.45	0.7%
Sulfur	0.011	0.3%	0.06	0.1%	0.002	0.1%	0.01	0.0%
Zinc Oxide	0.025	0.7%	0.91	1.4%	0.004	0.1%	0.14	0.2%
Aromatic Oils	0.111	3.2%	2.50	3.7%	0.053	1.5%	1.20	1.8%
Stearic Acid	0.002	0.1%	0.03	0.1%	0.001	0.0%	0.01	0.0%
Steel Cord, Coated	0.325	9.3%	13.40	19.9%	0.178	5.0%	7.31	10.8%
Textile	0.377	10.8%	12.47	18.6%	0.000	0.0%	0.00	0.0%
Polyurethane	0.000	0.0%	0.00	0.0%	2.675	75.3%	45.14	66.7%
Steel	0.093	2.7%	2.61	3.9%	0.093	2.6%	2.61	3.9%
Total	3.487	100.0%	67.19	100.0%	3.553	100.0%	67.70	100.0%

The hub for both a tire and Tweel™ has lifespan of roughly 4 times that of the product which it supports, so only 25% of the environmental impact of the 4 kg steel hub is considered to impact the life cycle of one product.[41] Thus, only 1 kg of cast steel is considered in both the impact of the raw material production and manufacturing stages of the life cycle. Steel is used in the hub of both tires and Tweels™, so the same steel production impact scores are seen between both products.

5.2.2 Manufacturing

As discussed in the inventory collection, the production phase has been divided into two sections – raw material production and tire or Tweel™ manufacturing. The manufacturing step describes the environmental impact of the conversion of the raw materials into a tire or a Tweel™ and the final product. The environmental impacts of these manufacturing processes are shown in Figure 5.9.

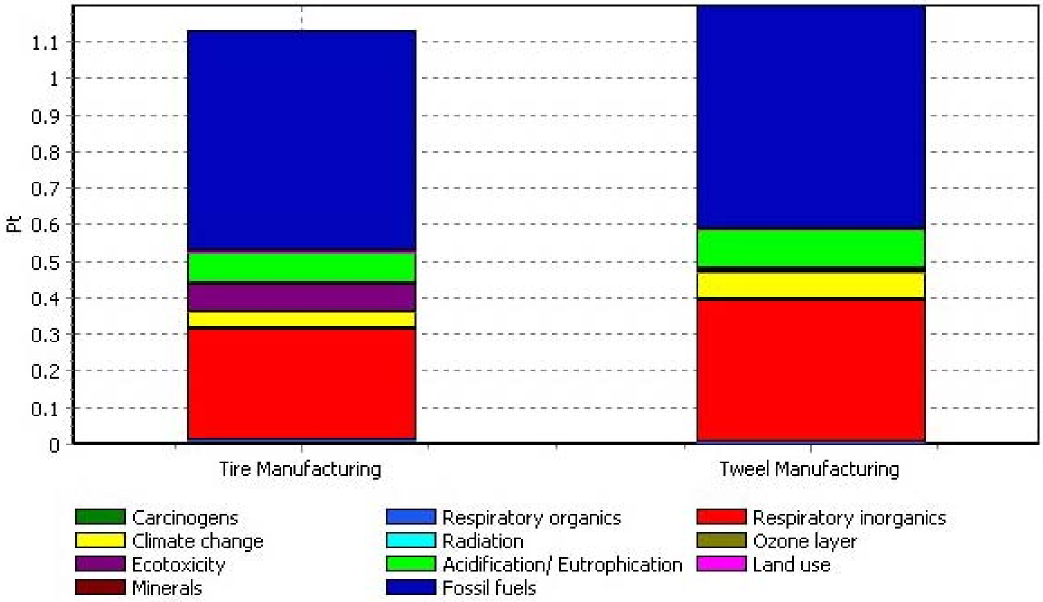

Figure 5.9. Manufacturing impacts of 10 kg tire and 12 kg Tweel™ (Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.14. Supplemental data for Figure 5.9

Impact category	Unit	Tire Manufacturing	Tweel Manufacturing
Carcinogens	Pt	0.009	0.003
Respiratory organics	Pt	0.001	0.002
Respiratory inorganics	Pt	0.303	0.392
Climate change	Pt	0.048	0.072
Radiation	Pt	0.000	0.000
Ozone layer	Pt	0.000	0.000
Ecotoxicity	Pt	0.075	0.008
Acidification/ Eutrophication	Pt	0.086	0.109
Land use	Pt	0.001	0.001
Minerals	Pt	0.002	0.000
Fossil fuels	Pt	0.603	0.612
Total	Pt	1.129	1.199

As expected due to the similarities in the manufacturing processes, the environmental impact of a 10 kg tire and a 12 kg Tweel™ (both with a 1 kg hub) are relatively equal. The EcoIndicator method scores the impact of the tire manufacturing process as 1.13 Pt, while the Tweel™ process is only rated 6% higher at 1.20 Pt. The manufacturing of the tread was modeled in the same way between both products and the overall energy requirement to manufacture a tire is 117 MJ and a Tweel™ requires roughly 100 MJ, while the energy to produce the raw materials necessary for either product is roughly 1100 MJ.[38] This 17% energy difference between the manufacturing processes is offset by the extra mold release and adhesives needed in the Tweel™ manufacturing process, resulting in a very minimal difference in environmental impact according to the EcoIndicator99 impact assessment method.

5.2.3 Overall Production Impact

Combining the production of all the required raw materials and the manufacturing inventory gives the overall production environmental impact shown in Figure 5.10 and Figure 5.11. As discussed in section 5.2.1, the total impact of the raw materials for each product is assembled by simply adding up the weighted impacts of the quantity of each material used to make a tire or a Tweel™ as described in Figure 5.5 through Figure 5.8. The addition of the impact of the manufacturing process on top of that gives the overall production impact labeled "Tire – production" and "Tweel™ – production" in Figure 5.10 and Figure 5.11 below.

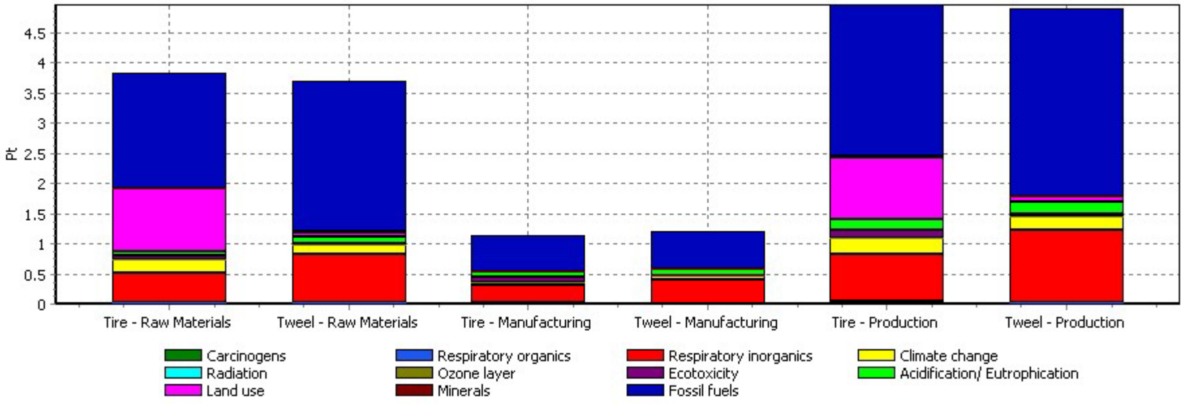

Figure 5.10. Overall tire and Tweel™ production impact (10 kg tire, 12 kg Tweel™, both with 1 kg hub)
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.15. Supplemental data for Figure 5.10

Impact category	Unit	Tire - Manufacturing	Tire - Production	Tire - Raw Materials	Tweel - Manufacturing	Tweel - Production	Tweel - Raw Materials
Carcinogens	Pt	0.009	0.032	0.022	0.003	0.016	0.013
Respiratory organics	Pt	0.001	0.004	0.003	0.002	0.004	0.003
Respiratory inorganics	Pt	0.303	0.780	0.477	0.392	1.193	0.801
Climate change	Pt	0.048	0.276	0.228	0.072	0.235	0.163
Radiation	Pt	0.000	0.001	0.001	0.000	0.000	0.000
Ozone layer	Pt	0.000	0.001	0.000	0.000	0.000	0.000
Ecotoxicity	Pt	0.075	0.139	0.064	0.008	0.038	0.030
Acidification/ Eutrophication	Pt	0.086	0.166	0.080	0.109	0.213	0.103
Land use	Pt	0.001	1.032	1.031	0.001	0.075	0.072
Minerals	Pt	0.002	0.007	0.005	0.000	0.004	0.004
Fossil fuels	Pt	0.603	2.519	1.915	0.612	3.116	2.505
Total	Pt	1.129	4.958	3.828	1.199	4.894	3.695

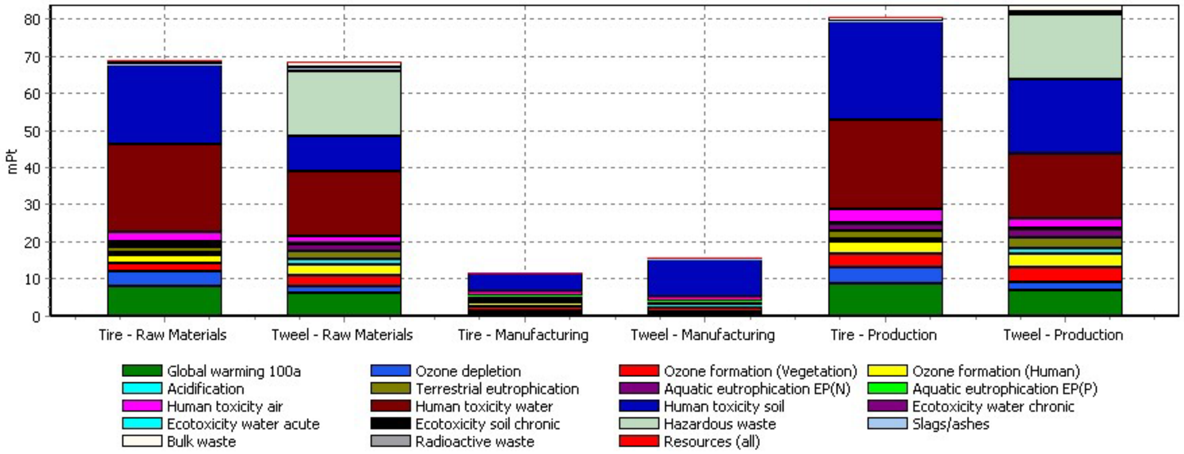

Figure 5.11. Overall tire and Tweel™ production impact (10 kg tire, 12 kg Tweel™, both with 1 kg hub)
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.16. Supplemental data for Figure 5.11

Impact category	Unit	Tire - Raw Materials	Tweel - Raw Materials	Tire - Manufacturing	Tweel - Manufacturing	Tire - Production	Tweel - Production
Global warming 100a	mPt	7.79	6.11	0.72	0.67	8.51	6.78
Ozone depletion	mPt	3.97	1.83	0.68	0.50	4.65	2.32
Ozone formation (Vegetation)	mPt	2.31	2.99	1.05	0.78	3.36	3.77
Ozone formation (Human)	mPt	2.33	2.95	1.01	0.75	3.34	3.70
Acidification	mPt	0.62	1.36	0.30	0.24	0.93	1.60
Terrestrial eutrophication	mPt	1.34	2.14	0.84	0.63	2.17	2.77
Aquatic eutrophication EP(N)	mPt	0.97	1.81	0.58	0.45	1.55	2.26
Aquatic eutrophication EP(P)	mPt	0.48	0.24	0.01	0.00	0.49	0.24
Human toxicity air	mPt	2.55	1.85	1.19	0.85	3.75	2.70
Human toxicity water	mPt	23.71	17.48	0.12	0.08	23.83	17.55
Human toxicity soil	mPt	21.61	9.68	5.03	10.33	26.64	19.99
Ecotoxicity water chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00	0.00	0.00	0.00
Hazardous waste	mPt	0.13	17.53	-0.05	0.00	0.08	17.53
Slags/ashes	mPt	0.15	0.81	-0.05	0.00	0.10	0.82
Bulk waste	mPt	0.81	1.57	0.11	0.10	0.92	1.69
Radioactive waste	mPt	0.00	0.00	0.00	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00	0.00	0.00	0.00
Total	mPt	68.76	68.35	11.55	15.39	80.31	83.71

Both of these figures above show a remarkable similarity between the overall environmental impact of tires and Tweels™ considering the great difference in raw materials and the increased overall weight of a Tweel™ from 10 kg to 12 kg. Again, it is difficult to compare the two methods because they are presented on different scales, but the 4% difference between the EDIP production impacts of 80.31 and 83.71 mPt only disagrees with the EcoIndiactor's 1% difference between 4.96 and 4.89 Pt by a small amount. The EDIP method attributes a slightly higher environmental impact to the Tweel™ production process because of the 'human toxicity soil' category in the manufacturing phase which is due to the mold release and adhesives necessary to mold the polyurethane. Similarities do exist though between both assessment methods. Both methods agree that producing all the raw materials has a much larger (about four times higher) impact on the environment than the actual tire or Tweel™ manufacturing, attributing between 75% and 80% of the total production impact to the raw material production. Again however, a similar difference arises as seen before due to the land use considered in the EcoIndicator method. The EcoIndicator method assesses the overall impact of both products as approximately equal, but the land use category accounts for 21% of the tire's production impact (1.03 of 4.96 points as shown in Table 5.17). If this category is ignored, then the impact of producing one tire would be approximately 20% lower than producing one Tweel™.

Table 5.17. Contribution of production phase EcoIndicator impact categories

Impact category	Tire - Production (Pt)	Tweel™ - Production (Pt)
Carcinogens	0.032	0.016
Respiratory organics	0.005	0.005
Respiratory inorganics	0.780	1.193
Climate change	0.276	0.235
Radiation	0.001	0.000
Ozone layer	0.001	0.000
Ecotoxicity	0.139	0.038
Acidification/ Eutrophication	0.166	0.213
Land use	1.032	0.075
Minerals	0.007	0.004
Fossil fuels	2.519	3.116
Total	**4.958**	**4.895**

Due to this uncertain land use impact again, it is useful to examine a few specific greenhouse gas emissions in order to assess the differences in the environmental impact of each product's production phase. Four of the major greenhouse gases, carbon dioxide, methane, nitrous oxide, and CFC-12, are listed in Table 5.18 along with the corresponding emissions for the overall production of either one tire or one Tweel™ due to both raw material production and product manufacturing.

Table 5.18. Greenhouse gas emissions

	CO_2 (kg)	Methane (g)	N_2O (g)	CFC-12 (μg)
Tire	42	158	2.51	2.44
Tweel™	58	180	0.75	0.83

These results are most useful when they are incorporated into an impact assessment method, but the raw data for each emission can also be useful to note that fabricating one Tweel™ produces 16 kg more CO_2 while avoiding less than half the N_2O and CFC-12 emissions as compared to a tire. It is difficult to quantify this tradeoff, but on an elementary level there are pros and cons to each production method, so the overall environmental impacts of both products roughly even out when all the factors are considered. Figure 5.10 and Figure 5.11 support this by assessing the overall production of both a tire and a Tweel™ as relatively equal. The small production differences between the 4.96 Pt tire score and the 4.89 Pt Tweel™ score from the EcoIndicator method (1%) and the 80.31 mPt tire production score and the 83.71 mPt Tweel™ score by the EDIP method (4%) show only minor differences between the entire production process of these two products, but it will be seen later whether these small differences effect the overall LCA. It may be argued that producing a Tweel™ is slightly more harmful to the environment due to any number of factors such as the large percentage of polyurethane, the ancillary products needed to mold the product, or the basic increase in mass, especially when the land use of the natural rubber used in tires is not taken into account, but as will be seen in the overall life cycle of each product, this difference is almost negligible compared to the impacts of the other life cycle stages.

5.3 Use Phase

The use phase of both a tire and a Tweel™ entails the gasoline use attributable to rolling resistance as described in Table 4.8 and the debris from both products' rubber treads. The gasoline tailpipe emissions are well documented by the EPA and described in Table 4.9, but there is a small amount of uncertainty in the environmental impact of producing gasoline before it is used by a vehicle. Three reliable databases describe the production of gasoline from oil refineries, but as shown in Figure 5.12 and Figure 5.13 below, they do not all agree on the environmental impact of producing enough fuel to roll a tire through its entire lifespan. Both figures describe the total environmental impact of both producing and burning (the resulting tailpipe emissions) 101 L of gasoline as defined by the BUWAL, IDEMAT, and Franklin databases separately. Then all three databases are equally averaged together to minimize the potential error of any one inventory data set, denoted by “Tire Fuel Use – Average”. This averaged fuel use impact is what will be used in the overall life cycle analysis, but an understanding of the variance is an important aspect of this very important phase.

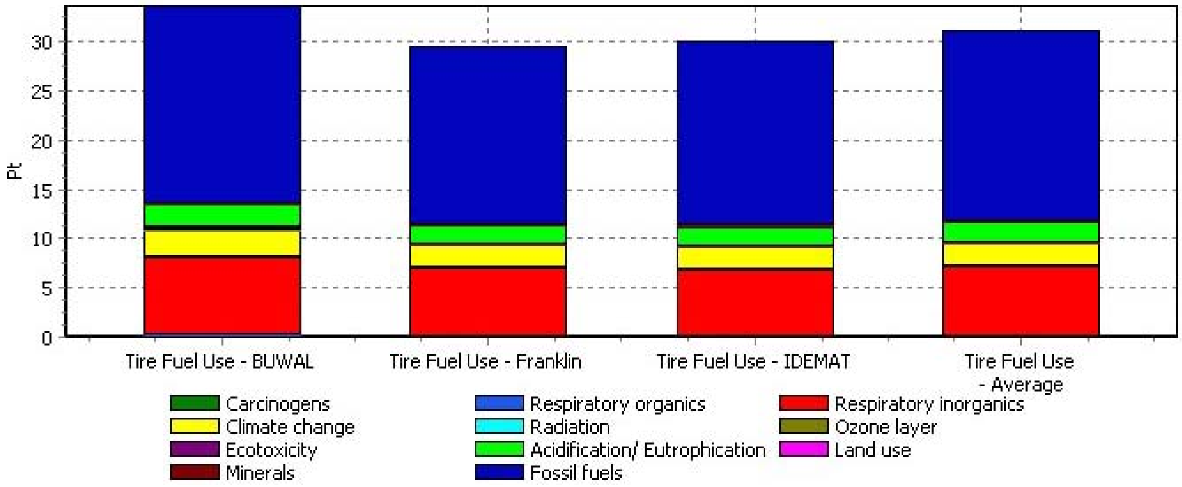

Figure 5.12. Fuel production and use variance, 101 L of gasoline
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.19. Supplemental data for Figure 5.12

Impact category	Unit	Tire Fuel Use - BUWAL	Tire Fuel Use - Franklin	Tire Fuel Use - IDEMAT	Tire Fuel Use - Average
Carcinogens	Pt	0.00	0.01	0.00	0.00
Respiratory organics	Pt	0.05	0.02	0.01	0.03
Respiratory inorganics	Pt	7.83	6.90	6.85	7.05
Climate change	Pt	2.71	2.42	2.29	2.36
Radiation	Pt	0.00	0.00	0.00	0.00
Ozone layer	Pt	0.01	0.00	0.00	0.00
Ecotoxicity	Pt	0.47	0.03	0.00	0.17
Acidification/ Eutrophication	Pt	2.20	2.00	2.06	2.12
Land use	Pt	0.00	0.00	0.07	0.03
Minerals	Pt	0.00	0.00	0.00	0.00
Fossil fuels	Pt	20.23	18.16	18.72	19.28
Total	Pt	33.66	29.58	29.99	30.88

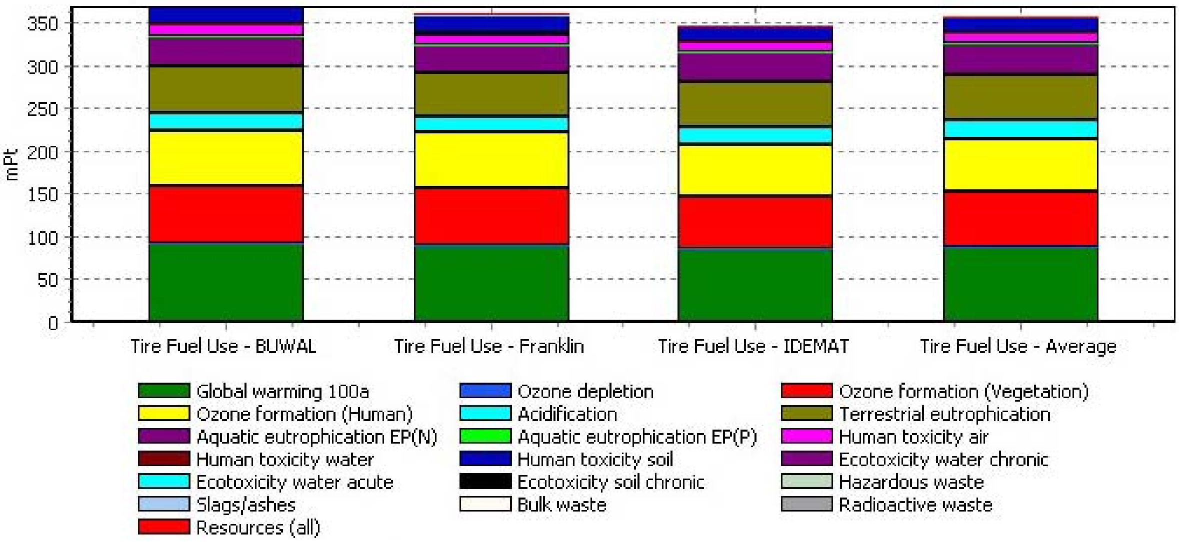

Figure 5.13. Fuel production and use variance, 101 L of gasoline
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.20. Supplemental data for Figure 5.13

Impact category	Unit	Tire Fuel Use - BUWAL	Tire Fuel Use - Franklin	Tire Fuel Use - IDEMAT	Tire Fuel Use - Average
Global warming 100a	mPt	91.8	89.8	84.6	87.2
Ozone depletion	mPt	0.0	0.1	0.0	0.0
Ozone formation (Vegetation)	mPt	67.4	67.0	63.0	64.9
Ozone formation (Human)	mPt	64.8	65.2	60.1	61.9
Acidification	mPt	20.6	18.6	21.0	21.6
Terrestrial eutrophication	mPt	54.6	50.7	52.9	54.5
Aquatic eutrophication EP(N)	mPt	36.1	33.5	35.0	34.9
Aquatic eutrophication EP(P)	mPt	0.0	0.1	0.0	0.0
Human toxicity air	mPt	12.7	12.2	11.4	11.7
Human toxicity water	mPt	0.8	2.3	0.0	1.0
Human toxicity soil	mPt	19.6	18.9	17.5	18.0
Ecotoxicity water chronic	mPt	0.0	0.0	0.0	0.0
Ecotoxicity water acute	mPt	0.0	0.0	0.0	0.0
Ecotoxicity soil chronic	mPt	0.0	0.0	0.0	0.0
Hazardous waste	mPt	0.0	0.0	0.0	0.0
Slags/ashes	mPt	0.0	0.0	0.0	0.0
Bulk waste	mPt	0.6	2.0	0.0	0.9
Radioactive waste	mPt	0.0	0.0	0.0	0.0
Resources (all)	mPt	0.0	0.0	0.0	0.0
Total	mPt	369.0	360.3	345.7	355.9

As shown in Figure 5.12 and Figure 5.13, there are slight differences in the overall impact of producing and burning enough gasoline to overcome a tire’s rolling resistance throughout its life, but combining all three database values into one impact gives a more reliable average fuel use impact. It is helpful though to consider a range of values that this single impact score can take from the average 30.88 Pts from the EcoIndicator method and 355.9 mPt from the

EDIP method. According to the EcoIndicator method, considering only one of the three database inventories could give an overall environmental impact value anywhere from 29.58 to 33.66 Pt (+9% or -4%). The EDIP method on the other hand gives a much smaller relative range of impacts from 345.7 to 369 mPt (+3% or -4%). Again, the average gasoline impact will be used throughout this report, but it will be examined in the life cycle analysis section 5.5 whether or not these 4% or 9% differences would have an impact on the overall life cycle comparison between a tire and a Tweel™.

As little is known about the wear characteristics of the Tweel™, it has been assumed that the tread wears at the same rate resulting in the same amount of particulates and emissions to the atmosphere. So, Figure 5.14 illustrates the impact of each product's fuel use (baseline tire, Thrust 1 Tweel™, Thrust 2 Tweel™, Thrust 3 Tweel™, respectively) alongside the impact of the rubber debris as a result of being driven 42,000 miles. The Thrust 1 Tweel™ is the only version of the Tweel™ being analyzed throughout its entire life cycle because it is the only version that has reliable production data. The other two versions are much more hypothetical at this point so they have not been included in the production phase analysis, but their fuel saving goals have been documented and the relative environmental benefit of this fuel savings is shown in Figure 5.14.

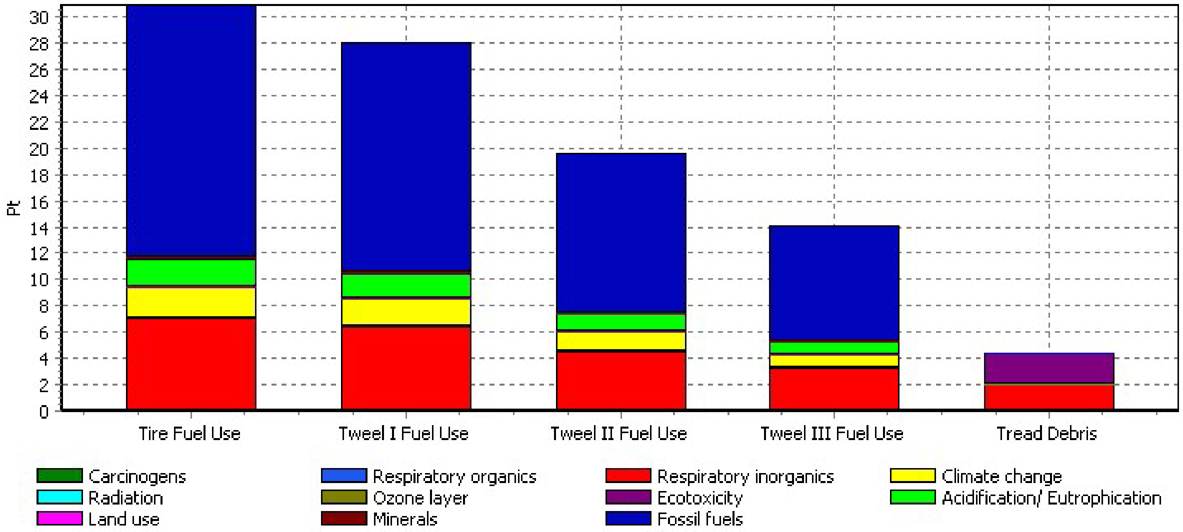

Figure 5.14. Use phase environmental impact comparison
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.21. Supplemental data for Figure 5.14

Impact category	Unit	Tire Fuel Use	Tweel I Fuel Use	Tweel II Fuel Use	Tweel III Fuel Use	Tread Debris
Carcinogens	Pt	0.00	0.00	0.00	0.00	0.01
Respiratory organics	Pt	0.01	0.01	0.02	0.02	0.00
Respiratory inorganics	Pt	7.05	6.37	4.49	3.21	1.97
Climate change	Pt	2.36	2.13	1.50	1.08	0.00
Radiation	Pt	0.00	0.00	0.00	0.00	0.00
Ozone layer	Pt	0.00	0.00	0.00	0.00	0.00
Ecotoxicity	Pt	0.00	0.00	0.00	0.00	2.44
Acidification/ Eutrophication	Pt	2.12	1.91	1.35	0.96	0.00
Land use	Pt	0.07	0.06	0.04	0.03	0.00
Minerals	Pt	0.00	0.00	0.00	0.00	0.00
Fossil fuels	Pt	19.28	17.46	12.23	8.78	0.00
Total	Pt	30.88	27.95	19.62	14.08	4.42

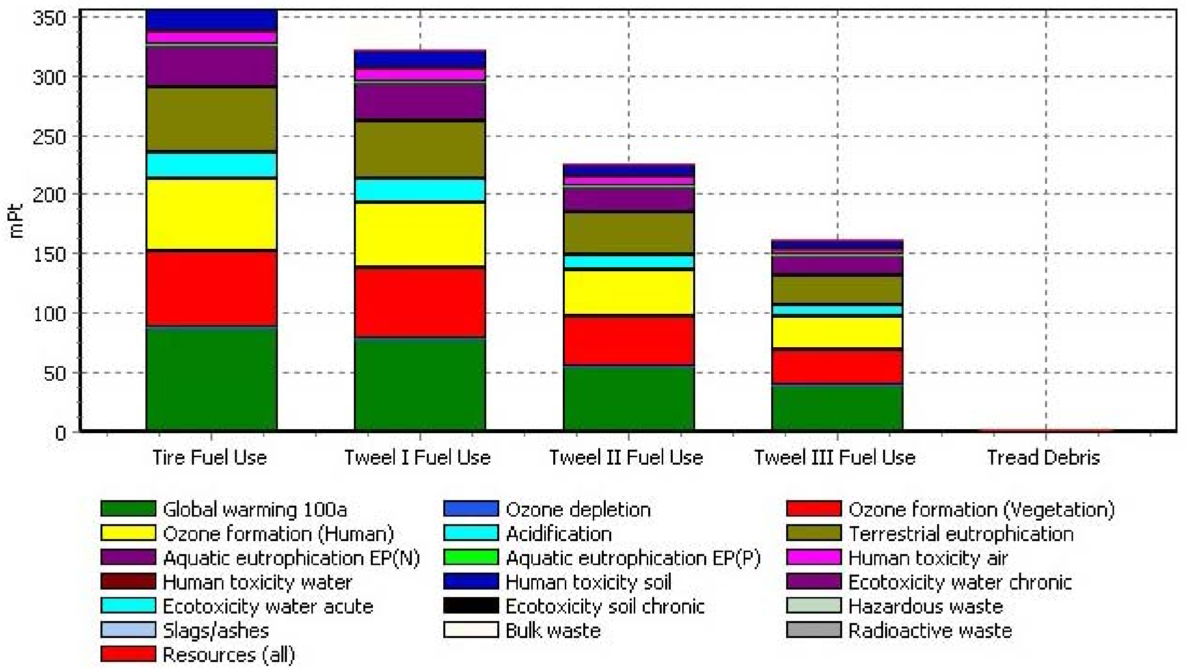

Figure 5.15. Use phase environmental impact comparison
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.22. Supplemental data for Figure 5.15

Impact category	Unit	Tire Fuel Use	Tweel I Fuel Use	Tweel II Fuel Use	Tweel III Fuel Use	Tread Debris
Global warming 100a	mPt	87.2	78.9	55.3	39.8	0.0
Ozone depletion	mPt	0.0	0.0	0.0	0.0	0.0
Ozone formation (Vegetation)	mPt	64.9	58.6	41.3	29.5	0.0
Ozone formation (Human)	mPt	61.9	56.0	39.4	28.2	0.0
Acidification	mPt	21.6	19.5	13.7	9.8	0.0
Terrestrial eutrophication	mPt	54.5	49.2	34.7	24.8	0.0
Aquatic eutrophication EP(N)	mPt	36.1	32.6	22.9	16.4	0.0
Aquatic eutrophication EP(P)	mPt	0.0	0.0	0.0	0.0	0.0
Human toxicity air	mPt	11.7	10.6	7.4	5.3	0.1
Human toxicity water	mPt	0.0	0.0	0.0	0.0	0.1
Human toxicity soil	mPt	18.0	16.4	11.5	8.2	1.0
Ecotoxicity water chronic	mPt	0.0	0.0	0.0	0.0	0.0
Ecotoxicity water acute	mPt	0.0	0.0	0.0	0.0	0.0
Ecotoxicity soil chronic	mPt	0.0	0.0	0.0	0.0	0.0
Hazardous waste	mPt	0.0	0.0	0.0	0.0	0.0
Slags/ashes	mPt	0.0	0.0	0.0	0.0	0.0
Bulk waste	mPt	0.0	0.0	0.0	0.0	0.0
Radioactive waste	mPt	0.0	0.0	0.0	0.0	0.0
Resources (all)	mPt	0.0	0.0	0.0	0.0	0.0
Total	mPt	355.9	321.8	226.2	162.2	1.3

As expected, the 10%, 30%, and 50% fuel savings from the three different Tweel™ versions result in a proportional decrease in the environmental impact from 30.9 to 28, 19.6, and

14.1 Pts on the EcoIndicator scale. Again the vertical Pt scale is fairly arbitrary, so the exact numbers do not represent much, but the relative impacts not only between the use phases of both products but also between the different life cycle phases are the important points to notice. As shown in the Figure 5.14 above, the relative impact of the rubber debris on the environment is only about 15% of the impact of the gasoline used by the low rolling resistance tire chosen for this analysis. So in designing a new tire or Tweel™ with the environmental impact of the use phase in mind, it is important to develop a product that has a minimal rolling resistance coefficient even if that correlates with a larger amount of rubber debris over its life, especially since the EDIP method values the importance of the tread debris much lower than the EcoIndicator method. This relationship between RRC and rubber wear is complicated and cannot be simply modeled, but hypothetically if a new tire is developed with 10% lower rolling resistance but 10% more rubber debris develops, an overall environmental savings of 8% would result due to the relative environmental importance of a tire's fuel use compared to its wear debris as shown in Figure 5.14. Both of these use phase components will be compared with the other phases of each product's life cycle in section 5.5 below to give an overall relative importance of this fuel use.

5.4 End of Life

Since the polyurethane can be separated from the rubber tread in a Tweel™ at the end of its life, this analysis will assume both materials will be disposed of separately, which simplifies the environmental assessment to a combination of rubber (whole tire and Tweel™ tread) and polyurethane treated separately. The national average disposal route percentages for both materials (Figure 4.5 and Figure 4.6) are analyzed individually and then combined in the appropriate weight percentages for both a tire and a Tweel™. Considering the rubber first, the tread separated from a Tweel™ by the heating method described in section 4.5.3 is assumed to have the same material properties and composition as rubber from a tire in order to group both rubber sources together for simplification and minimal Tweel™ recycling data purposes. The tread from a Tweel™ has no wires and thus will produce no scrap metal upon grinding, but all other properties are assumed to be equal. So, considering Tweel™ tread and tire rubber in the same disposal route categories, the environmental impacts of each are described in Figure 5.16 and Figure 5.17 by the EcoIndicator and EDIP methods respectively. Both figures describe the environmental impact of 1 kg of tire rubber or Tweel™ tread per disposal route.

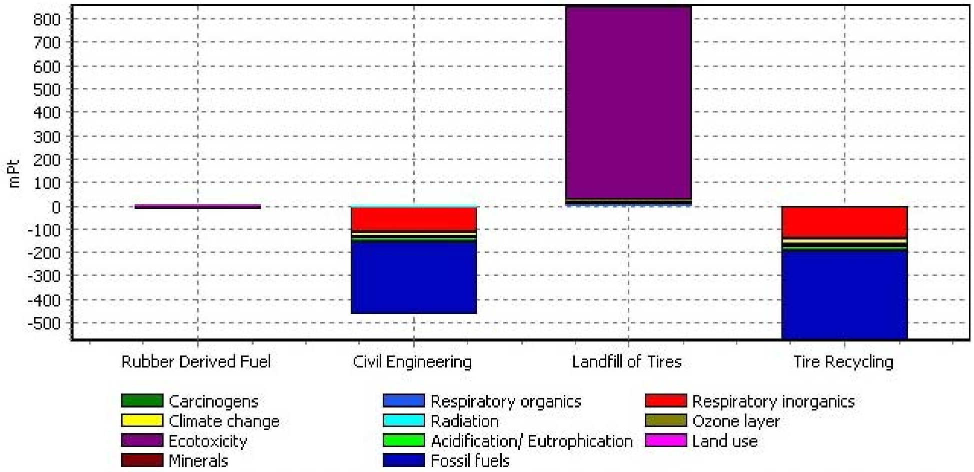

Figure 5.16. Environmental impact of 1 kg of rubber per disposal route (Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.23 Supplemental data for Figure 5.16

Impact category	Unit	Rubber Derived Fuel	Civil Engineering	Landfill of Tires	Tire Recycling
Carcinogens	mPt	-0.1	-0.4	0.4	-0.5
Respiratory organics	mPt	0.0	-0.9	0.0	-1.1
Respiratory inorganics	mPt	-2.2	-113.7	17.5	-138.1
Climate change	mPt	-0.7	-18.8	2.0	-29.1
Radiation	mPt	0.0	0.0	0.0	0.0
Ozone layer	mPt	0.0	0.0	0.0	0.0
Ecotoxicity	mPt	0.2	-0.9	832.7	-1.2
Acidification/ Eutrophication	mPt	0.1	-17.7	2.8	-21.6
Land use	mPt	0.1	0.0	0.0	0.0
Minerals	mPt	-0.2	0.0	0.0	0.0
Fossil fuels	mPt	-10.0	-316.3	2.7	-385.7
Total	mPt	-12.9	-468.7	858.1	-577.3

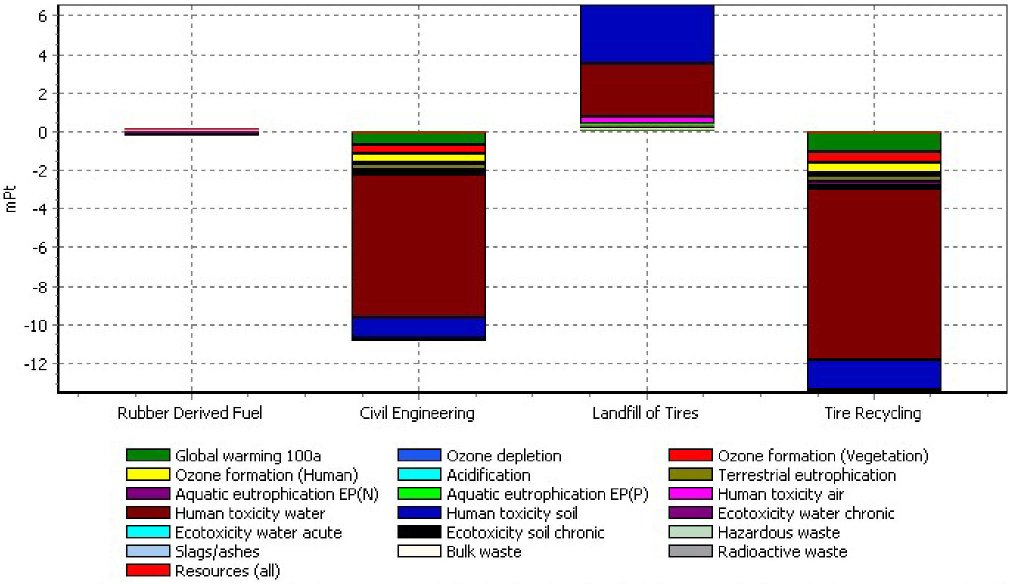

Figure 5.17. Environmental impact of 1 kg of rubber per disposal route (Method: EDIP 2003 V1.00 / Default / single score)

Table 5.24 Supplemental data for Figure 5.17

Impact category	Unit	Rubber Derived Fuel	Civil Engineering	Landfill of Tires	Tire Recycling
Global warming 100a	mPt	-0.03	-0.71	0.08	-1.07
Ozone depletion	mPt	0.01	0.00	0.01	-0.01
Ozone formation (Vegetation)	mPt	-0.02	-0.45	0.05	-0.54
Ozone formation (Human)	mPt	-0.02	-0.45	0.05	-0.54
Acidification	mPt	0.00	-0.10	0.13	-0.12
Terrestrial eutrophication	mPt	0.00	-0.28	0.01	-0.34
Aquatic eutrophication EP(N)	mPt	0.00	-0.18	0.03	-0.23
Aquatic eutrophication EP(P)	mPt	0.00	0.00	0.00	0.00
Human toxicity air	mPt	0.03	-0.10	0.44	-0.14
Human toxicity water	mPt	-0.02	-7.36	2.76	-8.87
Human toxicity soil	mPt	-0.14	-1.10	3.02	-1.50
Ecotoxicity water chronic	mPt	0.00	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00	0.00
Hazardous waste	mPt	0.00	0.00	0.00	0.00
Slags/ashes	mPt	0.00	0.00	0.00	-0.01
Bulk waste	mPt	0.10	-0.14	0.00	-0.17
Radioactive waste	mPt	0.00	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00	0.00
Total	mPt	-0.08	-10.87	6.57	-13.54

As agreed upon by most experts [35] and shown in the Figure 5.16 and 5.17, simply disposing of rubber from either a tire or Tweel™ tread into a landfill is by far the most environmentally harmful end of life option. According to the EcoIndicator method, landfilling 1 kg of rubber gives an environmental impact of 858 mPt while rubber derived fuel, civil engineering, and tire recycling all give environmental benefits (-13, -469, and -577 mPt respectively). Rubber landfilling should be avoided whenever possible, but as stated previously there is simply not a market available for the large amount waste rubber that results from old tires, so this may be difficult to achieve. It is apparent that the best way to dispose of rubber is to grind it and reuse it in civil engineering purposes or other applications. This requires minimal energy but avoids the production of rubber from scratch resulting in an overall benefit to the environment. The same tradeoff is seen with incinerating rubber for fuel, but the benefits of avoided energy production by other means does not quite outweigh the particulates and other emissions let into the air. In fact, according to the figures above, this is a fairly equal tradeoff resulting in a negligible net environmental impact. So, grinding rubber for recycling is preferred above incineration with landfilling as a last resort, but each disposal route will be weighed according to American averages and combined to give an overall picture of the rubber disposal industry today.

Before those rubber disposal routes are combined together though, the same analysis must be performed on polyurethane so that the overall impact of disposing both the rubber and polyurethane in a Tweel™ can be discussed. Figure 5.18 and Figure 5.19 show the environmental impact of 1 kg of polyurethane per disposal route in the same manner as the rubber disposal routes, and similar results are found.

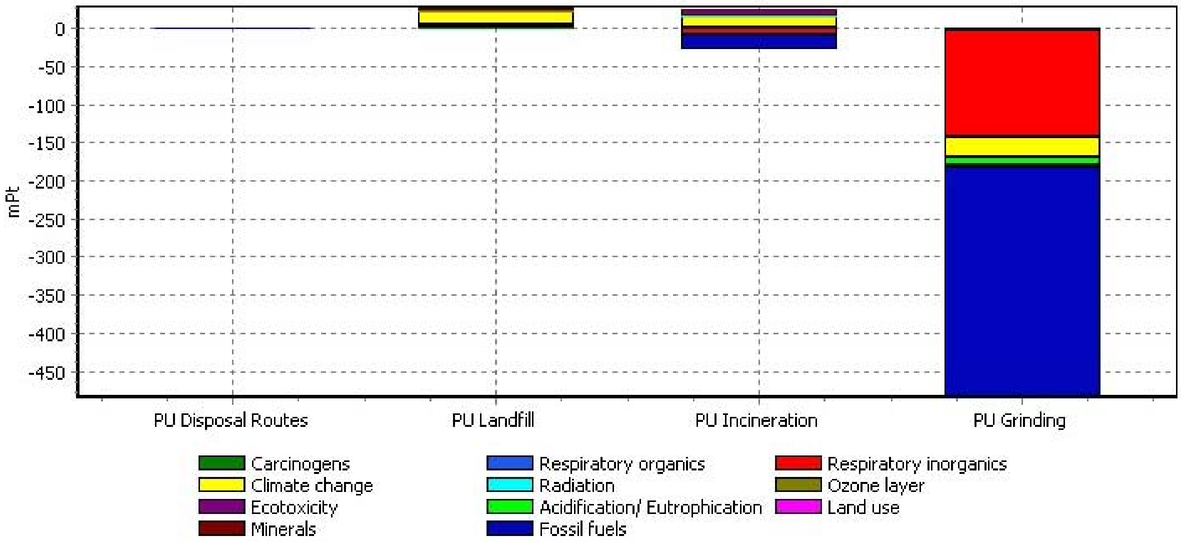

Figure 5.18. Environmental impact of 1 kg of polyurethane per disposal route (Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.25. Supplemental data for Figure 5.18

Impact category	Unit	PU Landfill	PU Incineration	PU Grinding
Carcinogens	mPt	1.3	1.6	-0.6
Respiratory organics	mPt	0.1	0.0	-0.4
Respiratory inorganics	mPt	4.2	-1.7	-142.2
Climate change	mPt	17.7	17.0	-26.4
Radiation	mPt	0.0	0.0	0.0
Ozone layer	mPt	0.0	0.0	0.0
Ecotoxicity	mPt	0.8	9.8	-0.6
Acidification/ Eutrophication	mPt	0.7	-0.1	-9.9
Land use	mPt	0.0	0.0	-1.1
Minerals	mPt	0.0	0.0	-0.1
Fossil fuels	mPt	4.0	-11.4	-302.6
Total	mPt	28.8	15.3	-483.9

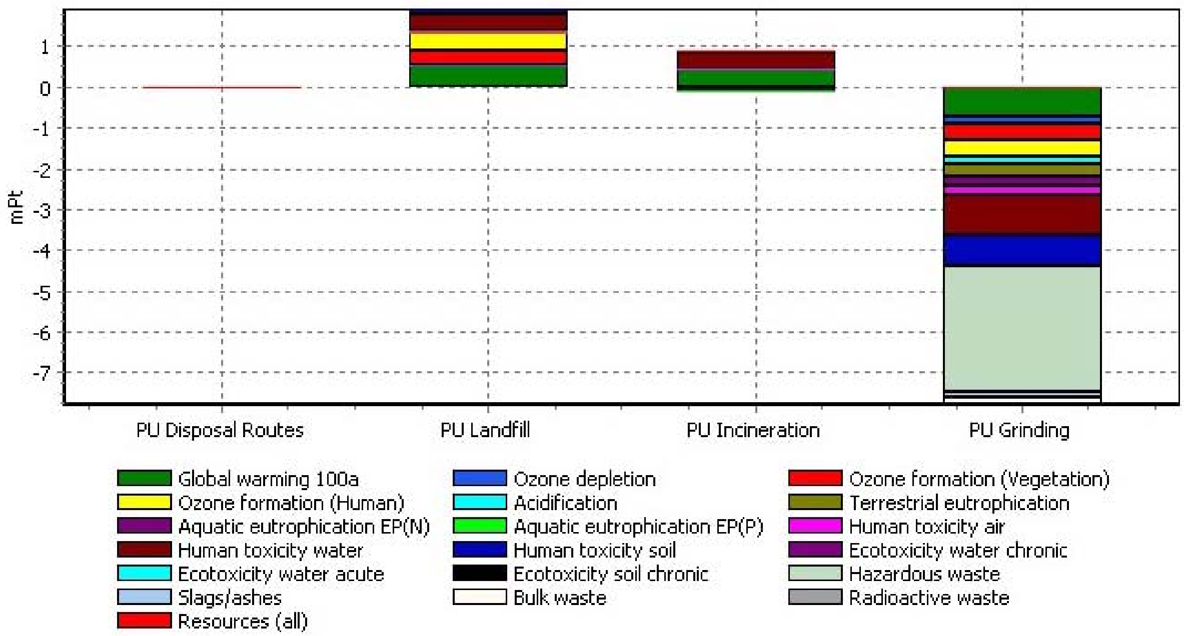

Figure 5.19. Environmental impact of 1 kg of polyurethane per disposal route (Method: EDIP 2003 V1.00 / Default / single score)

Table 5.26. Supplemental data for Figure 5.19

Impact category	Unit	PU Landfill	PU Incineration	PU Grinding
Global warming 100a	mPt	0.52	0.47	-0.74
Ozone depletion	mPt	0.02	0.00	-0.18
Ozone formation (Vegetation)	mPt	0.36	0.01	-0.39
Ozone formation (Human)	mPt	0.41	0.01	-0.38
Acidification	mPt	0.01	0.00	-0.19
Terrestrial eutrophication	mPt	0.02	0.01	-0.30
Aquatic eutrophication EP(N)	mPt	0.03	0.00	-0.25
Aquatic eutrophication EP(P)	mPt	0.00	0.00	0.00
Human toxicity air	mPt	0.01	0.05	-0.22
Human toxicity water	mPt	0.41	0.51	-0.99
Human toxicity soil	mPt	0.12	0.11	-0.74
Ecotoxicity water chronic	mPt	0.00	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00	0.00
Hazardous waste	mPt	0.00	0.00	-3.11
Slags/ashes	mPt	0.00	0.00	-0.14
Bulk waste	mPt	0.00	0.00	-0.16
Radioactive waste	mPt	0.00	0.00	0.00
Resources (all)	mPt	0.00	0.00	0.00
Total	mPt	1.91	1.18	-7.79

Clearly grinding polyurethane so that it can be reused as a composite-like filler for new plastic products or other purposes discussed previously is the most environmentally friendly option due to the minimal energy required to avoid the production of new polyurethane, similar to the benefits of tire recycling. The impact of incineration varies slightly between the two assessment methods, but the offset of risks and benefits results in an overall impact relatively close to zero as in the case of rubber incineration. Polyurethane incineration results in 2.5 kg of CO_2 emissions and 118 mg of CO while the net emissions for rubber when the avoided product is subtracted are 0.03 kg of CO_2 and 12 mg of CO. Thus, incinerating polyurethane is slightly more harmful to the environment, but both can be considered roughly a zero gain or zero loss process.

The only large difference between the disposing of rubber and that of polyurethane is the environmental effects of landfilling. According to Figure 5.18 and Figure 5.19, polyurethane landfilling is only slightly more harmful than incineration (29 mPt vs. 15 mPt on the EcoIndicator scale and 1.91 mPt vs. 1.18 mPt on the EDIP scale), but this is mostly likely because no data was available regarding polyurethane in uncontrolled landfills. Some polyurethane will end up in uncontrolled landfills without proper liners or gas emission controls, and these landfills will have much larger impacts on environmental categories like ecotoxicity in the EcoIndicator method and human toxicity in the EDIP method, but as no data are available on the frequency of this uncontrolled landfilling or on polyurethane's uncontrolled environmental effects, these have been left out of the analysis. It was estimated in this thesis that 25% of used tires are disposed of in uncontrolled landfills, but it is uncertain whether this will be the case for polyurethane disposal when large amounts of Tweel™ spokes need to be disposed. Due to this exemption, landfilling of polyurethane does not appear to be as much of an environmentally harmful option as with rubber, but more data may be needed to evaluate the possibility of disposing polyurethane into uncontrolled landfills and its corresponding environmental effects.

By combining both the material disposal methods (52% of rubber incinerated for fuel, 14% landfilled, etc.) and the material composition of both products (Tweel™ 77% polyurethane, etc.), an overall picture of the entire end of life processing of both a tire and a Tweel™ can be analyzed. These overall impacts of this end of life stage for both products are shown in Figure 5.20 and Figure 5.21 below.

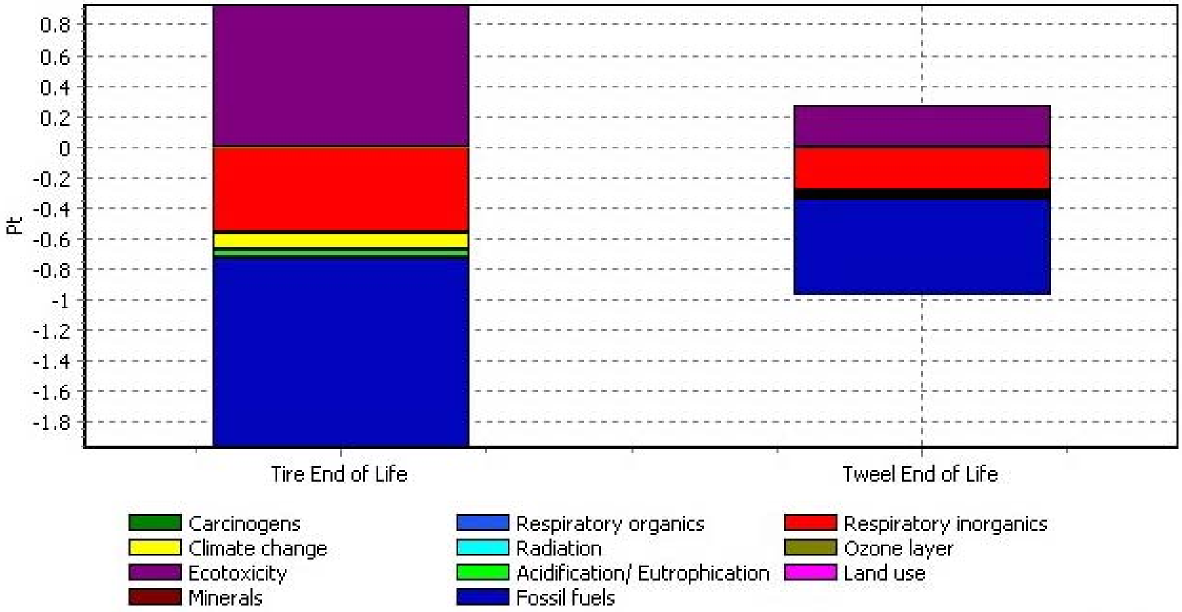

Figure 5.20. Tire and Tweel™ end of life overall impact - EcoIndicator (10 kg tire, 12 kg Tweel™, both with1 kg steel hub)
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.27. Supplemental data for Figure 5.20

Impact category	Unit	Tire End of Life	Tweel End of Life
Carcinogens	Pt	-0.002	0.002
Respiratory organics	Pt	-0.004	-0.002
Respiratory inorganics	Pt	-0.557	-0.286
Climate change	Pt	-0.111	-0.024
Radiation	Pt	0.000	0.000
Ozone layer	Pt	0.000	0.000
Ecotoxicity	Pt	0.931	0.274
Acidification/ Eutrophication	Pt	-0.050	-0.023
Land use	Pt	0.000	-0.001
Minerals	Pt	-0.001	0.000
Fossil fuels	Pt	-1.249	-0.639
Total	Pt	-1.043	-0.700

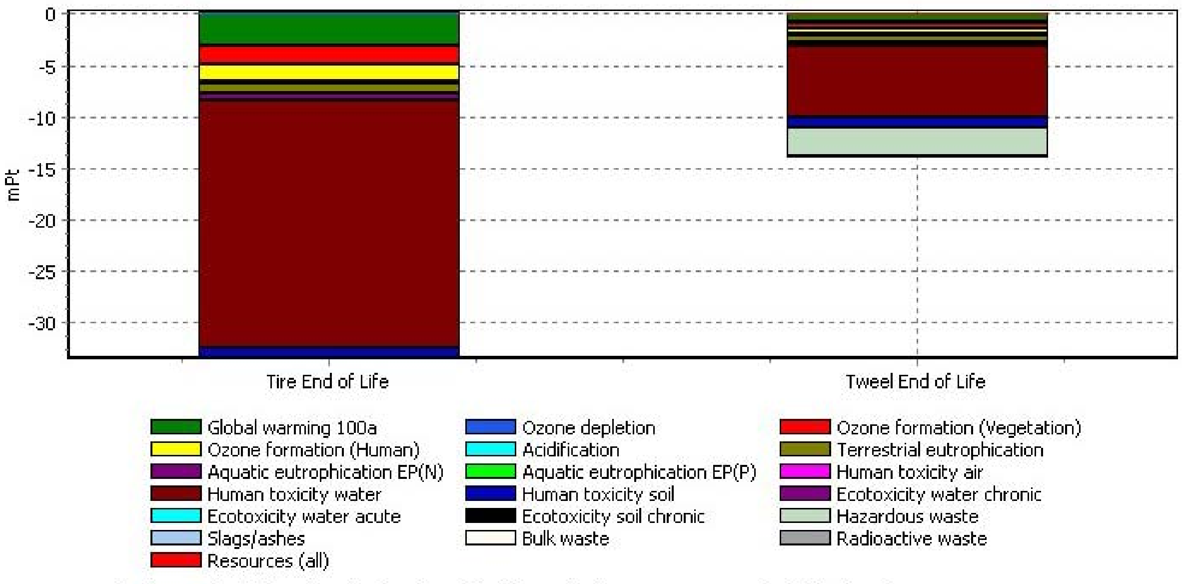

Figure 5.21. Tire and Tweel™ end of life overall impact
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.28. Supplemental data for Figure 5.21

Impact category	Unit	Tire End of Life	Tweel End of Life
Global warming 100a	mPt	-3.10	-0.66
Ozone depletion	mPt	0.03	-0.14
Ozone formation (Vegetation)	mPt	-1.72	-0.50
Ozone formation (Human)	mPt	-1.72	-0.46
Acidification	mPt	-0.21	-0.23
Terrestrial eutrophication	mPt	-1.03	-0.54
Aquatic eutrophication EP(N)	mPt	-0.64	-0.39
Aquatic eutrophication EP(P)	mPt	-0.03	-0.01
Human toxicity air	mPt	0.38	-0.03
Human toxicity water	mPt	-23.99	-6.89
Human toxicity soil	mPt	-0.95	-0.73
Ecotoxicity water chronic	mPt	0.00	0.00
Ecotoxicity water acute	mPt	0.00	0.00
Ecotoxicity soil chronic	mPt	0.00	0.00
Hazardous waste	mPt	0.00	-2.84
Slags/ashes	mPt	-0.01	-0.13
Bulk waste	mPt	0.00	-0.15
Radioactive waste	mPt	0.00	0.00
Resources (all)	mPt	0.00	0.00
Total	mPt	-32.99	-13.69

Due in part to the slight variation in landfill impacts between polyurethane and rubber and in part to the small percentage of polyurethane recycling in the United States today, the Tweel™ end of life scenario is shown to be slightly less environmentally beneficial. Also, extra energy is required to heat a Tweel™ enough to separate the polyurethane from the rubber tread even before any of the processing is performed, which will offset some of the benefits due to the recycling of both components. The EDIP method estimates that disposing of one Tweel™ (considering the national averages of both polyurethane and rubber disposal methods) is only about 45% as beneficial to the environment as a tire (-13.7 mPt score for Tweel™ end of life compared to -33.0 mPt for a tire). Combining the environmental benefits and impacts (positive and negative scores) shown by the EcoIndicator model however is not so easy to quantify. Figure 5.20 shows both a positive and negative environemntal impact because all the impact categories remain separated and not combined into one score. It can be argued that adding the 1.1 impact points from the tire's ecotoxicity category to the -1.8 points from the rest of the categories results in a net impact of -0.7 points for a tire and similarly -0.6 net points for a Tweel™, but this may be oversimplifying the scenario. Releasing 1 kg of CO_2 into the air through a process that avoids the need for a similar process that releases the same amount of CO_2 is easy to combine into a net zero environmental impact. However, if that same 1 kg of CO_2 is released while avoiding the introduction of a small amount lead into the water, that nullification is not as easily accepted. Hypothetically each category is weighed properly so that 1 point of ecotoxicity harm is negated by 1 point of fossil fuel benefit, but in this case it may be more helpful to leave the picture more complicated so that the conclusions remain that there are both positive and negative environmental effects instead of a score near zero if these positive and negative impact categories are added together. According to the EcoIndicator method, disposing of a Tweel™ has a lower ecotoxicity impact, but also a lower environmental benefit in fossil fuel savings and respiratory inorganics like dust, nitrogen oxides, and sulfur oxides. In either case it seems that recycling a tire is slightly more beneficial to the environment, but the overall scenario may be too complicated to summarize this entire life cycle stage into one number.

As stated previously in section 4.5.3 however, the overall results of the end of life phase used in the overall life cycle analyses of a Tweel™ as described in Figure 5.21 only considers the scenario in which the polyurethane spokes and shear band can be separated from the rubber tread. According to Michelin this will most likely be possible and desirable, but in the case of some unforeseen change in the bonding between the two components, it will be useful to compare the overall environmental effects of this stage if the polyurethane and rubber cannot be separated and must be processed together. In this case, grinding would most likely be impossible due to the difficulty of sorting small polyurethane and rubber pieces after the entire Tweel™ was shredded and the lack of a market that would be able to use such an unsorted mixture of materials with different properties. So, with grinding not an option, Figure 5.22 compares the established Tweel™ end of life environmental impact with a scenario in which the only Tweel™ disposal options are landfilling and incineration. All of the rubber and polyurethane that was shredded through the established grinding processes is instead incinerated.

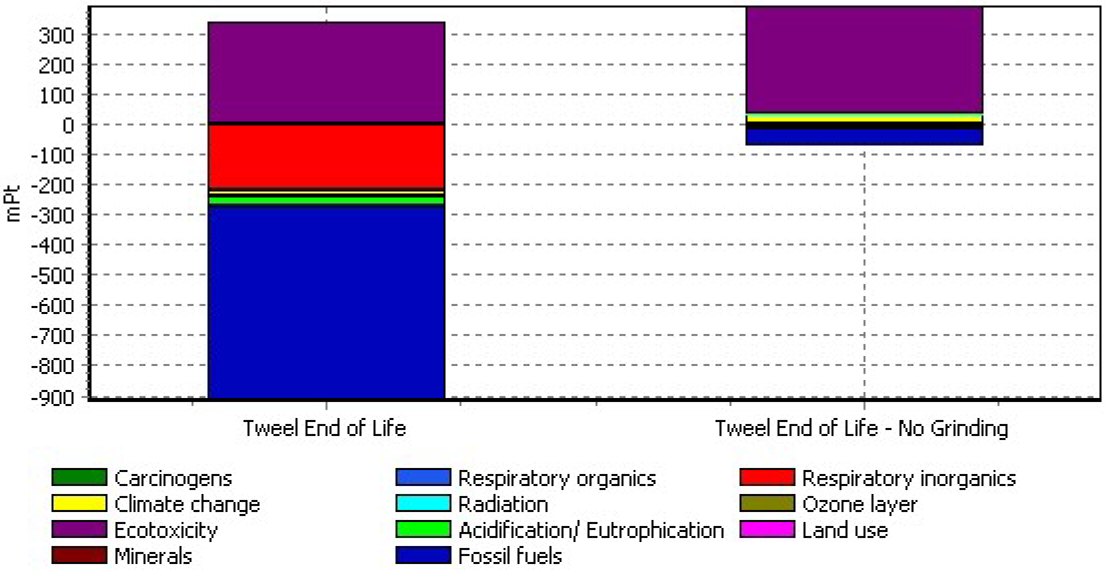

Figure 5.22. End of life comparison of one Tweel™ if polyurethane separation is not possible (Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.29. Supplemental data for Figure 5.22

Impact category	Unit	Tweel End of Life	Tweel End of Life - No Grinding
Carcinogens	mPt	1.6	4.6
Respiratory organics	mPt	-1.6	0.1
Respiratory inorganics	mPt	-286.3	2.4
Climate change	mPt	-24.0	51.7
Radiation	mPt	0.0	0.0
Ozone layer	mPt	0.0	0.0
Ecotoxicity	mPt	274.2	288.0
Acidification/ Eutrophication	mPt	-22.8	1.5
Land use	mPt	-1.0	0.1
Minerals	mPt	-0.4	-0.6
Fossil fuels	mPt	-639.2	-44.4
Total	mPt	-699.7	303.4

As shredding, the most environmentally beneficial method of disposing both components, has been deemed impossible in this scenario, this allows only landfilling and whole incineration of Tweels™, which results in a much higher environmental impact. According to the EcoIndicator method when all the positive and negative impact category scores are added together, avoiding the grinding option results in a 303 mPt environmental harm for one Tweel™ while the previously established end of life processing case where each component is isolated and treated separetely results in a -700 mPt environmental benefit. The Tweels™ are not reused in any sort of beneficial manner, so the negative environmental impact scores disappear and the only major impact left is the ecotoxicity resulting from landfills. Therefore, this scenario is undesirable. In order to maximize the end of life Tweel™ disposal impact on the environment, it is necessary to design a method to cleanly separate the polyurethane from the rubber so that they can be processed separately. It seems that this should not be a problem with the current Tweel™ model, so this will not be considered in the overall life cycle of the product, but it is a useful comparison for internal product improvement purposes.

5.5 Life Cycle Analysis

By combining all of the stages described above from "cradle to grave," a picture of the overall environmental effects of the entire life cycle can be assembled. This life cycle analysis presents the environmental impact of one tire or Tweel™ beyond simply the energy required to manufacture either, for example. Figure 5.23 and Figure 5.25 describe the relative environmental effects of each stage of a P205/45R17 tire's life cycle, while Figure 5.24 and Figure 5.26 illustrate the life cycle analysis for one Tweel™. The production phase combines the production of raw materials with the manufacturing of a tire or Tweel™, and similarly the end of life phase combines all the disposal routes as discussed in section 5.4. The use phase on the other hand is separated into the effects of tread wear and gasoline usage so that the most important aspect of each product's life cycle, the fuel use, can be accurately compared to both of the other main phases, production and disposal. The distribution phase assumes most of the raw materials are produced near the tire or Tweel™ manufacturing plants, but it illustrates the effect of transporting one product from the manufacturer to the retailer at the start of its life combined with the transportation from the retailer to the disposal site and the end of its life.

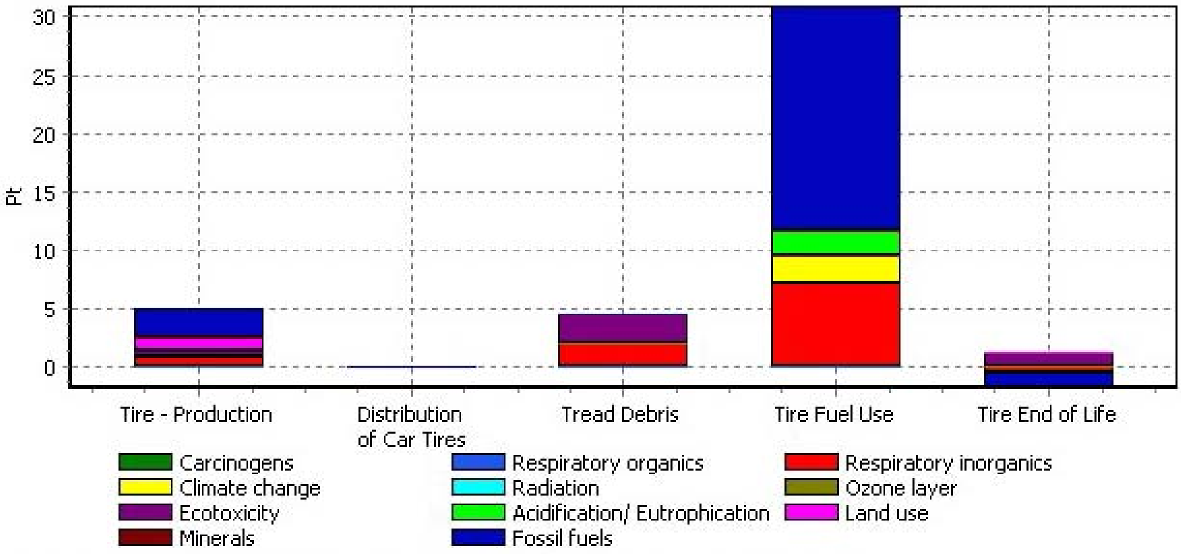

Figure 5.23. P205/45R17 Tire Life Cycle Analysis (10 kg tire w/ 1 kg steel hub)
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.30. Supplemental data for Figure 5.23

Impact category	Unit	Tire - Production	Distribution of Car Tires	Tread Debris	Tire Fuel Use	Tire End of Life	**Total**
Carcinogens	Pt	0.032	0.000	0.007	0.000	-0.001	0.038
Respiratory organics	Pt	0.004	0.000	0.000	0.011	-0.003	0.012
Respiratory inorganics	Pt	0.780	0.001	1.974	7.053	-0.417	9.391
Climate change	Pt	0.276	0.000	0.000	2.356	-0.083	2.549
Radiation	Pt	0.001	0.000	0.000	0.000	0.000	0.001
Ozone layer	Pt	0.001	0.000	0.000	0.000	0.000	0.001
Ecotoxicity	Pt	0.139	0.000	2.436	0.000	1.163	3.739
Acidification/ Eutrophication	Pt	0.166	0.000	0.000	2.117	-0.063	2.220
Land use	Pt	1.032	0.000	0.000	0.069	0.000	1.101
Minerals	Pt	0.007	0.000	0.000	0.001	-0.001	0.007
Fossil fuels	Pt	2.519	0.001	0.000	19.275	-1.249	20.546
Total	Pt	4.958	0.002	4.418	30.882	-0.655	39.605

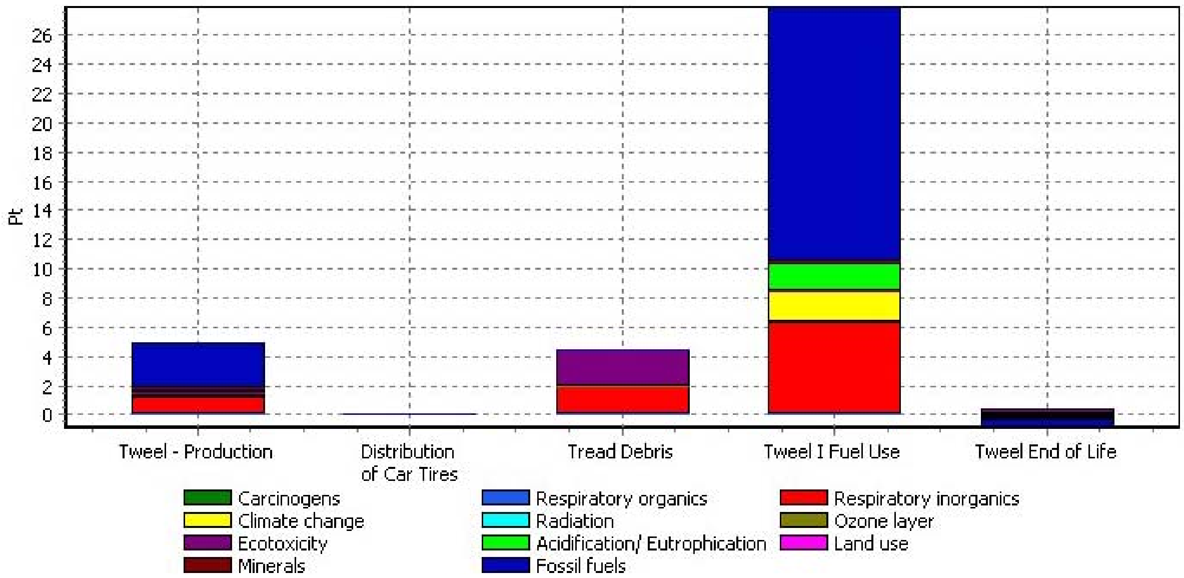

Figure 5.24. Tweel™ Life Cycle Analysis (12 kg Tweel™ with 1 kg steel hub)
(Method: EcoIndicator99(E) V2.05 / EuropeEI99E/E / single score)

Table 5.31. Supplemental data for Figure 5.24

Impact category	Unit	Tweel - Production	Distribution of Car Tires	Tread Debris	Tweel I Fuel Use	Tweel End of Life	**Total**
Carcinogens	Pt	0.016	0.000	0.007	0.000	0.001	0.024
Respiratory organics	Pt	0.004	0.000	0.000	0.010	-0.001	0.013
Respiratory inorganics	Pt	1.193	0.001	1.974	6.373	-0.215	9.326
Climate change	Pt	0.235	0.000	0.000	2.132	-0.018	2.349
Radiation	Pt	0.000	0.000	0.000	0.000	0.000	0.000
Ozone layer	Pt	0.000	0.000	0.000	0.000	0.000	0.000
Ecotoxicity	Pt	0.038	0.000	2.436	0.000	0.343	2.817
Acidification/ Eutrophication	Pt	0.213	0.000	0.000	1.912	-0.029	2.097
Land use	Pt	0.075	0.000	0.000	0.062	-0.001	0.136
Minerals	Pt	0.004	0.000	0.000	0.001	0.000	0.004
Fossil fuels	Pt	3.116	0.001	0.000	17.462	-0.639	19.939
Total	Pt	4.894	0.002	4.418	27.952	-0.559	36.707

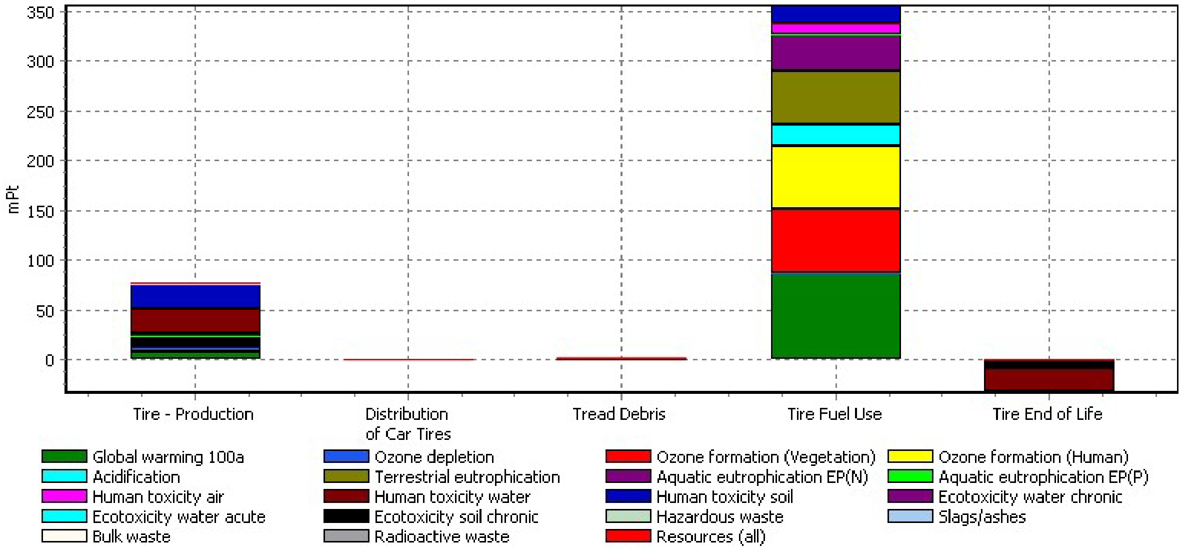

Figure 5.25. Tire Life Cycle Analysis
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.32. Supplemental data for Figure 5.25

Impact category	Unit	Tire - Production	Distribution of Car Tires	Tread Debris	Tire Fuel Use	Tire End of Life	**Total**
Global warming 100a	mPt	8.5	0.0	0.0	87.2	-3.1	92.6
Ozone depletion	mPt	4.7	0.0	0.0	0.0	0.0	4.7
Ozone formation (Vegetation)	mPt	3.4	0.0	0.0	64.9	-1.7	66.5
Ozone formation (Human)	mPt	3.3	0.0	0.0	61.9	-1.7	63.5
Acidification	mPt	0.9	0.0	0.0	21.6	-0.2	22.3
Terrestrial eutrophication	mPt	2.2	0.0	0.0	54.5	-1.0	55.7
Aquatic eutrophication EP(N)	mPt	1.5	0.0	0.0	36.1	-0.6	37.0
Aquatic eutrophication EP(P)	mPt	0.5	0.0	0.0	0.0	0.0	0.5
Human toxicity air	mPt	3.7	0.0	0.1	11.7	0.4	15.9
Human toxicity water	mPt	23.8	0.0	0.1	0.0	-24.0	0.0
Human toxicity soil	mPt	26.6	0.1	1.0	18.0	-0.9	44.9
Ecotoxicity water chronic	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Ecotoxicity water acute	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Ecotoxicity soil chronic	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Hazardous waste	mPt	0.1	0.0	0.0	0.0	0.0	0.1
Slags/ashes	mPt	0.1	0.0	0.0	0.0	0.0	0.1
Bulk waste	mPt	0.9	0.0	0.0	0.0	0.0	0.9
Radioactive waste	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Resources (all)	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Total	mPt	80.3	0.2	1.3	355.9	-33.0	404.7

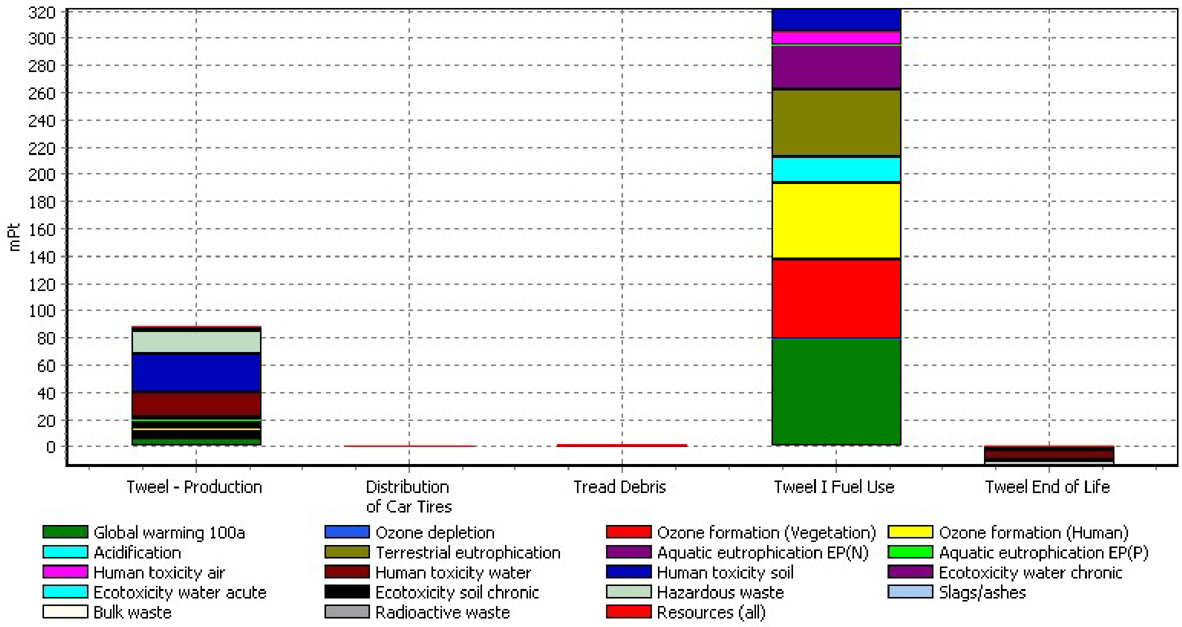

Figure 5.26. Tweel™ Life Cycle Analysis
(Method: EDIP 2003 V1.00 / Default / single score)

Table 5.33. Supplemental data for Figure 5.26

Impact category	Unit	Tweel - Production	Distribution of Car Tires	Tread Debris	Tweel I Fuel Use	Tweel End of Life	**Total**
Global warming 100a	mPt	6.8	0.0	0.0	78.9	-0.7	85.0
Ozone depletion	mPt	2.3	0.0	0.0	0.0	-0.1	2.2
Ozone formation (Vegetation)	mPt	3.8	0.0	0.0	58.6	-0.5	61.9
Ozone formation (Human)	mPt	3.7	0.0	0.0	56.0	-0.5	59.2
Acidification	mPt	1.6	0.0	0.0	19.5	-0.2	20.9
Terrestrial eutrophication	mPt	2.8	0.0	0.0	49.2	-0.5	51.5
Aquatic eutrophication EP(N)	mPt	2.3	0.0	0.0	32.6	-0.4	34.4
Aquatic eutrophication EP(P)	mPt	0.2	0.0	0.0	0.0	0.0	0.2
Human toxicity air	mPt	2.7	0.0	0.1	10.6	0.0	13.4
Human toxicity water	mPt	17.6	0.0	0.1	0.0	-6.9	10.8
Human toxicity soil	mPt	20.0	0.1	1.0	16.4	-0.7	36.8
Ecotoxicity water chronic	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Ecotoxicity water acute	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Ecotoxicity soil chronic	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Hazardous waste	mPt	17.5	0.0	0.0	0.0	-2.8	14.7
Slags/ashes	mPt	0.8	0.0	0.0	0.0	-0.1	0.7
Bulk waste	mPt	1.7	0.0	0.0	0.0	-0.1	1.6
Radioactive waste	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Resources (all)	mPt	0.0	0.0	0.0	0.0	0.0	0.0
Total	mPt	83.7	0.2	1.3	321.8	-13.7	393.3

Again, as both the EcoIndicator and EDIP assessment methods are presented on different vertical scales representing their unique method of weighing each impact category, direct comparisons between the two methods is impossible (33 Pt EcoIndicator fuel use phase is not 100 times more environmentally harmful than the 350 mPt EDIP fuel use phase). The relative impacts between each life cycle phase though are what are important. The first comparison that summarizes most of the details of the life cycle of both products is that the fuel consumed by rolling resistance is by far the most environmentally harmful portion of a wheel's life cycle. The overall effects of producing the necessary amount of gasoline and then burning it to overcome rolling resistance for 42,000 miles is 5 or 6 times that of the next most harmful phase, the production phase, according to both impact assessment methods. The EcoIndicator values the tire use phase over the next most important phase, the tire production, 30.88 Pt to 4.95 Pt, while the Tweel™ impacts in these two phases differs 570% between 27.95 Pt to 4.89 Pt. The EDIP method shows similar dominance by the use phase over any other phase quantifying the environmental impact of a tire as 450% more important than any other phase (356 mPt to 80 mPt) while the gap remains similar with a Tweel™ at a 380% difference between the 322 mPt use phase and the 84 mPt production phase. The two methods disagree on the relative environmental impact of the rubber debris, but the rest of the life cycle phases show remarkable similarity. The production of each product contributes less than 20% of the environmental impact of the use phase while the environmental benefits of the end of life impact either negate or slightly overcome the negative impact from emissions and energy use, and the effects of distributing one wheel compared to these other stages is negligible.

The benefit of portraying the effects of each stage of the life cycle on one uniform scale is that the slightly more harmful Tweel™ production and disposal phases can now be compared directly to its environmental savings as a result of the decreased fuel use due to its lower rolling resistance. It has been discussed in section 4.2.2 that the Tweel™ production process is slightly more environmentally harmful due to the effects of polyurethane and the additives like mold release needed to manufacture it along with the overall increased mass, and the disposal phase (although most of this analysis is hypothetical) will most likely be less beneficial because of the current state of polyurethane recycling. However, the two impact assessment methods allow these cons to be weighed against the pros of fuel savings in a manner that simply quantifing the CO_2 emissions cannot. It also allows the life cycle phases to be added together to provide an overall environmental score for every aspect of a Tweel™ so that one statement can be made that assesses whether it is better or worse overall than a conventional fuel efficient tire. The knowledge that producing a Tweel™ saves CO_2 tailpipe emissions while requiring more SO_2 emissions in the production phase as described in Table 5.34 is useful, but without the EcoIndicator and EDIP impact assessment methods it is very difficult to quantify this tradeoff as beneficial. Before the overall single score impacts are calculated to determine which product is more environmentally friendly overall though, some of the airborne emissions can provide details of the life cycle of these products and help to establish expected overall results.

Table 5.34. Selected emissions to air per life cycle phase

	Production	Distribution	Tread Debris	Fuel Use	End of Life	Total
CO2 - Tire (kg)	26.9	0.029	0	522	-15.8	533.1
CO2 - Tweel™ (kg)	53.2	0.035	0	472	-4.9	520.4
CO - Tire (oz)	4.95	0.008	0	519	-1.1	522.9
CO - Tweel™ (oz)	5.12	0.009	0	470	-0.4	474.7
N2O - Tire (g)	2.15	0.0009	0	101	-0.3	102.9
N2O - Tweel™ (g)	0.46	0.0011	0	91.8	-0.1	92.2
SO2 - Tire (g)	6.32	0	0.26	237	14.4	258.0
SO2 - Tweel™ (g)	51.7	0	0.26	215	-3.3	263.7

As described in Table 5.34, the fuel use is responsible for most of the major airborne emissions, which is a large contributing factor to the dominance of that phase in the overall life cycle impact. The CO_2 emissions for the fuel used by a tire are almost 20 times larger than the production of a tire and about 9 times higher for a Tweel™. In fact, every major tailpipe emission exhibits this same dominating trait that establishes the use phase as the most environmentally harmful phase. However, the overall importance of the fuel use was established as only contributing 5 or 6 times the amount of environmental load instead of the 100 times magnification of carbon monoxide. This dilution comes from the small range of different compounds expelled from a vehicle's tailpipe (see Table 4.9) as compared to the wide variety of inputs and outputs when all the raw material production processes are considered. All of these small emissions listed in Appendix A seem relatively harmless and many could be ignored in a simple comparison such as in Table 5.34, but they all contribute to the overall environmental impact, resulting in a slightly smaller relative importance of the fuel use phase on the environment from almost 20 times more harmful than the production process in terms of CO_2 emissions to the more conservative proportions shown in the single score impact figures. The CO_2 emissions in the use phase of a tire and Tweel™ total 522 kg and 472 kg, respectively, as compared to the production phase which only produces 26.9 kg and 53.2 kg of CO_2 respectively (1900% and 9% differences). These wide gaps are diluted by all the other small inputs and outputs in the production phase that cannot be organized into a simple table like Table 5.34, returning the overall importance of the fuel use phase over the production phase to 450% for a tire and 380% for a Tweel™.

The raw emissions life cycle totals can be helpful though to begin determining which product is more environmentally friendly overall. Summing up each of the emissions in Table 5.34 shows that a Tweel™ produces 13 kg less CO_2, 48 oz less CO, 10 g less N_2O, but 6 g more SO_2. These totals establish the Tweel™ as generally less harmful in terms of these emissions, but as with comparing the use phase to the production phase, the entire collected inventory must be considered to determine which product has a smaller environmental load most accurately.

Table 5.35 and Table 5.36 list the environmental impact scores from Figure 5.23 through Figure 5.26 interpreted by both the EcoIndicator and EDIP assessment methods.

Table 5.35. Total environmental impact over entire life cycle – EcoIndicator (Pt)

	Production	Distribution	Tread Debris	Fuel Use	End of Life	**Total**
Tire	5.06	0.00	4.59	30.88	-1.04	**39.49**
Tweel™	5.31	0.00	4.59	27.95	-0.72	**37.13**

Table 5.36. Total environmental impact over entire life cycle – EDIP (mPt)

	Production	Distribution	Tread Debris	Fuel Use	End of Life	**Total**
Tire	79.43	0.18	1.28	355.93	-32.99	**403.82**
Tweel™	87.76	0.18	1.28	321.82	-14.07	**396.96**

Again it can be seen that the use phase is the most environmentally harmful stage of the life cycle, but as all of the numbers in each table are on the same weighted scale, the impacts of all the stages can be summed up to give one single score representing the environmental impact of the entire life cycle of each product. According to the EcoIndicator method, a Tweel™ is 2.61 Pts less harmful to the environment than the most fuel efficient tire on the market today. So, even though its environmental load is slightly higher in the production phase, the 10% decrease in rolling resistance results in a 6% environmental savings overall. Similar results are found with the EDIP method even though it is presented on a different scale in which a Tweel™ is assessed as 6.86 mPts better than the tire, or an overall savings of roughly 2%. The EDIP method assesses the Tweel's™ production and end of life phases a little more harshly than the EcoIndicator method, but both agree that a Tweel™ is more environmentally friendly overall than the most fuel efficient conventional tire available when every phase of the life cycle is considered.

Although both of the chosen impact assessment methods have different weights and scales that result in overall impacts that slightly differ from each other, a simple comparison can be made between the importance of climate change or global warming since both methods contain this impact category. As shown in Table 5.37 below, the EDIP emphasizes its "global warming" category much higher than the EcoIndicator's "climate change" category by a spread of about 23% to only 6%. The EcoIndicator method stresses the use of fossil fuels and emissions that cause respiratory damage while global warming and ozone damage are much more important to the EDIP method. Even though differences such as these exist, the life cycle analyses of both impact assessment methods agree remarkably well with each other, supporting the important point that life cycle impacts of both products do not depend greatly on the choice of the impact assessment method.

Table 5.37. Climate change impact relative to overall LCA

	Unit	Tire - Production	Distribution of Car Tires	Tread Debris	Tire Fuel Use	Tire End of Life	Global warming total	LCA Total	**% of total impact**
Tire - Eco	Pt	0.28	0.00	0.00	2.36	-0.08	2.55	39.6	**6.4%**
Tire - EDIP	mPt	8.51	0.00	0.00	87.15	-3.10	92.56	404.7	**22.9%**
Tweel - Eco	Pt	0.24	0.00	0.00	2.13	-0.02	2.35	36.7	**6.4%**
Tweel - EDIP	mPt	6.78	0.00	0.00	78.85	-0.66	84.98	393.3	**21.6%**

Another important secondary aspect to these LCA figures is that a sensitivity analysis is necessary to ensure that the comparisons between the environmental effects of both of these products do not dramatically change with a different gasoline production database source because the most important phase of these life cycles is the use phase. As discussed in section 5.3, three different databases supply information on the production of gasoline (BUWAL, Franklin, and IDEMAT), but they differ by almost 10% and it is difficult to determine which is most closely representative of the real world production process. By performing the same life cycle analysis above with the sources that differ the most from the average data used in the primary LCAs from Figure 5.23 to Figure 5.26, a conclusion can be made as to the importance of choosing the correct database. Table 5.38 and Table 5.39 compare the overall LCA percentage improvement of a Tweel™ over a P205/45R17 fuel efficient tire with the average gasoline production process used in the primary LCAs and the two databases that give the highest and lowest environmental impact in each impact assessment method. As shown in Table 5.38, the EcoIndicator method shows a 6.2% and 5.9% improvement for the maximum and minimum database, respectively, as compared to the established 6.0% calculated above. Similarly, the EDIP method returns a 1.9% and 1.5% improvement with the maximum and minimum database inventories as compared to the average 1.7% discussed above. All of these differences bracket the average value calculated above, so as long as the gasoline production database choice is consistent throughout the analysis of both a tire and a Tweel™, it does not matter which database is chosen.

Table 5.38. LCA sensistivity with single fuel database – EcoIndicator

		Production	Distribution	Tread Debris	Fuel Use	End of Life	Total	Percentage Improvement
Tire	Average	5.06	0	4.59	30.88	-1.04	39.49	
	BUWAL	5.06	0	4.59	33.66	-1.04	42.27	
	Franklin	5.06	0	4.59	29.58	-1.04	38.19	
Tweel TM	Average	5.31	0	4.59	27.95	-0.72	37.13	6.0%
	BUWAL	5.31	0	4.59	30.46	-0.72	39.64	6.2%
	Franklin	5.31	0	4.59	26.77	-0.72	35.95	5.9%

Table 5.39. LCA sensitivity with single fuel database – EDIP

		Production	Distribution	Tread Debris	Fuel Use	End of Life	Total	Percentage Improvement
Tire	Average	79.43	0	1.28	355.9	-32.99	403.7	
	BUWAL	79.43	0	1.28	369.0	-32.99	416.7	
	IDEMAT	79.43	0	1.28	345.7	-32.99	393.4	
Tweel TM	Average	87.76	0	1.28	321.8	-14.07	396.8	1.7%
	BUWAL	87.76	0	1.28	333.6	-14.07	408.6	1.9%
	IDEMAT	87.76	0	1.28	312.6	-14.07	387.5	1.5%

These 6% and 2% improvements would be enhanced even further in favor of the Tweel™ if Thrusts II and III are considered as options resulting in a 30% or 50% lower rolling resistance than the baseline tire. As the materials and manufacturing methods are not yet known for these two products, they have been left out of the complete life cycle analysis, but initial estimates of the overall impacts of these products are possible assuming that every phase of their life cycles will be the same as the Thrust I Tweel™ analyzed above except for the fuel use. This is not a safe assumption, so these results are not as reliable as the scores for the tire and Thrust I Tweel™, but Table 5.40 is a good illustration of the possible benefits of reducing the rolling resistance by the estimated 30% and 50%. Assuming all else remains constant, a Thrust II Tweel™ with a 30% lower rolling resistance than the baseline tire will result in an overall environmental savings of 26%, while a Thrust III Tweel™ with a 50% lower rolling resistance will give an overall savings of 41%. Again these scores are purely hypothetical and are a result of assumptions about the same manufacturing and disposal processes that are most likely flawed, but this simple assessment gives a rough estimate of the potential environmental impacts of these two Tweel™ model in development.

Table 5.40. Thrust II and III Tweels™ single score environmental impacts – EcoIndicator

	Production	Distribution	Tread Debris	Fuel Use	End of Life	**Total**
Tire	5.06	0	4.59	30.88	-1.04	**39.5**
Tweel™ I	5.31	0	4.59	28.0	-0.72	**37.2**
Tweel™ II	5.31	0	4.59	19.6	-0.72	**28.8**
Tweel™ III	5.31	0	4.59	14.1	-0.72	**23.3**

Chapter 6. Discussion and Summary

6.1 Life Cycle Analysis

In concluding the goal and scope of this analysis it was found that a Tweel™ is more environmentally friendly than the most fuel efficient tire on the market today when the overall life cycles of both are considered due to its fuel savings. Both the EcoIndicator99 and EDIP assessment methods agree that producing and disposing of a Tweel™ contributes a slightly higher environmental load than the baseline tire, but benefits from the 10% fuel savings when it is used on a vehicle. Due to the much higher contribution from the use phase (5 times higher impact score, 10 times more carbon dioxide emissions, and 100 times more carbon monoxide), this fuel savings outweighs the environmental drawbacks of producing a large amount of polyurethane and the additives needed to mold it and adhere it to the hub and the rubber tread resulting in an overall environmental improvement if one replace tires with Tweels™. The numeric results from this analysis are presented in Table 5.35 and Table 5.36, and Figure 6.1 displays them in a graphical setting. Figure 6.1 graphs the single score environmental impacts of both a tire and a Tweel™ in each life cycle phase using both the EcoIndicator and EDIP assessment methods. As each method weighs its results on different scales, the figure plots each assessment method on a different scale and compares the two by setting the fuel use categories equal to each other. This does not mean that the EDIP rates the production phases of both products as more environmentally harmful though; this is an artifact due to the arbitrary scaling. If the different vertical scales were compared by equating the tire production phases, then the EDIP use phase would be presented as less environmentally harmful than that resulting from the EcoIndicator scale. So, instead of making direct comparisons between the scores between, say, the EcoIndicator and EDIP ratings of the tire production phase, Figure 6.1 illustrates the importance of the use phase and how the 10% benefit from the Tweel™ fuel savings outweighs the small drawback of the increased environmental load of the production and end of life phases. Although they disagree on the impact of the rubber debris, both impact assessment methods agree on this result alluded to by the difference in select air emissions described in Table 5.34. For simplification the positive and negative scores present simultaneously in the end of life phases have been added together to give one overall score. This removes some of the detail needed to describe the full end of life phase, but makes it more comparable to the other phases' single scores.

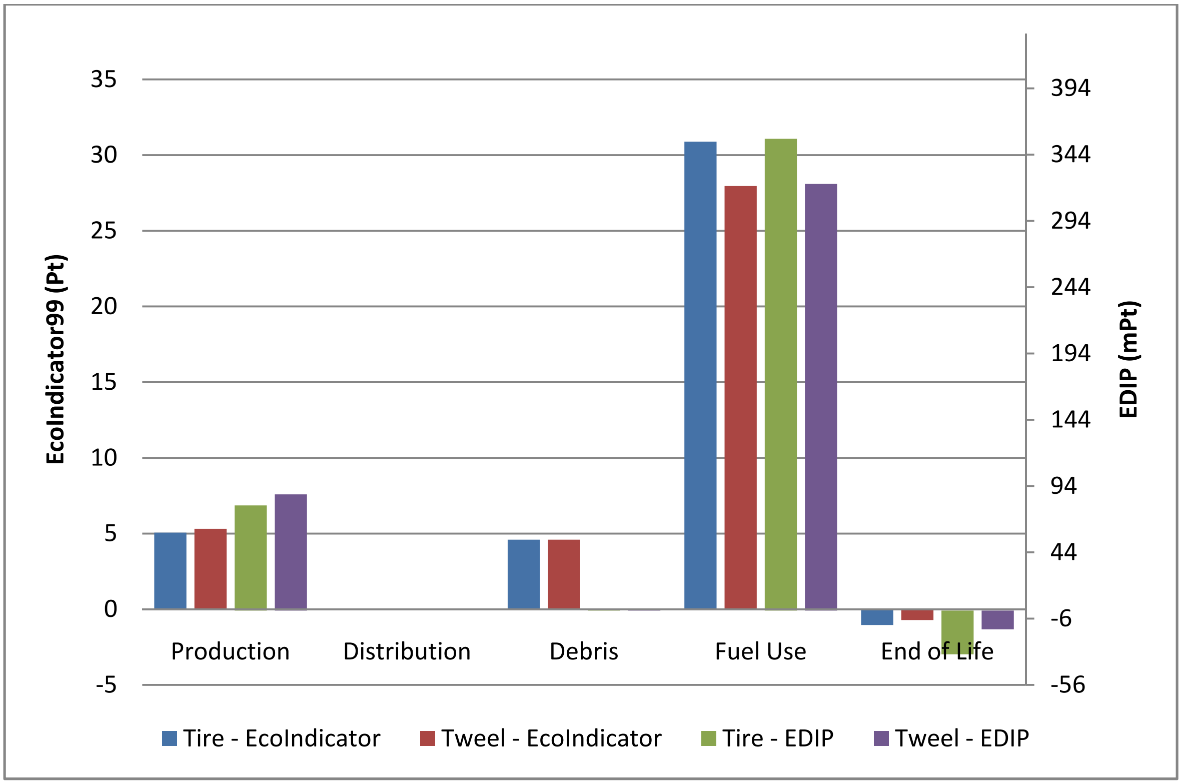

Figure 6.1. LCA Comparisons of P205/45R17 tire and Tweel™ on similar scale

As illustrated in the LCA comparison and discussed in section 5.5, the 10% lower Tweel™ rolling resistance results in a 2 to 6% overall environmental improvement depending on the assessment method chosen, but these results are based on a few assumptions. Most importantly, Tweels™ are currently not in mass production and changes are still being made to the design, so the production process may change slightly. Only minor changes are expected though; none of which would have a noticeable impact on the life cycle analysis. However, these changes might have a small impact on the expected 10% rolling resistance reduction that may impact the 42,000 mile lifespan. At this point there is no reason to expect a rolling resistance coefficient different than the expected 5.5 kg/ton, but the possibility exists that these estimates will differ from the actual performance of a Tweel™. So, it is very important to note that these results are representative only of the current knowledge of this product.

Also, the end of life phase of a Tweel™ contributes only about half the environmental benefit experienced by disposing of a tire, but this may improve if polyurethane landfilling gains as much publication as the dangers of whole tire landfilling. The Tweel™ end of life phase, although still beneficial to the environment when the avoided energy or polyurethane production is considered, has a large impact on decreasing the 10% fuel savings to only a 2 to 6% life cycle environmental savings. If the Tweel™ end of life stage was to have the same overall environmental effects as a tire's end of life, the overall environmental savings of a Tweel™ compared to a tire would rise to 7%. If millions of Tweel™ start piling up in landfills in the same way that tires have, a push to find better ways to incinerate and reuse polyurethane may develop, which could possibly reduce the 74% of polyurethane currently amassing in landfills. This may result in a more environmentally beneficial end of life phase, but this conjecture and only relative to the discussion on potential product improvements below in section 6.2. With the current knowledge available, the best estimate for the life cycle comparison of these two products is a 2 to 6% relative environmental savings with a Tweel™ as compared to a conventional fuel efficient tire with a rolling resistance of 6 kg/ton.

6.2 Product Improvements

Although not directly a part of the scope of this project, the environmental analysis of both products can influence the need for potential general product improvements in a purely environmental sense. It is impossible to determine the physical effects of reducing the rubber curing temperature which may result in product failures, but it is useful to notice with the help of this LCA that efforts to reduce tire rolling resistance should always be the top priority, even if that means a more environmentally harmful production process. Tire landfilling has always received the most environmental attention, but even this issue should not be addressed before the fuel consumed by a tire during its use. The use phase for these products has such a higher environmental importance than any other phase that even a small 10% improvement in rolling resistance can overcome an increase in the environmental load of both production and end of life phases. All other Tweel™ improvements, such as reducing the mass of polyurethane necessary to produce one or finding an easy way to disassemble the hub, tread, and spokes for disposal without the use of a large amount of energy, will benefit the environment, but if these result in an increased rolling resistance then they should not be implemented. As the use phase of a tire contributes at least five times the environmental load as any other phase, both tire producers and consumers need to be aware that any small change in rolling resistance can have a large effect on the overall environmental impact.

On a smaller scale though, it will be very important to also develop new ways to reuse polyurethane if millions of Tweels™ are produced in an effort to keep them out of landfills. Simply throwing away ¾ of the Tweel™ spokes due to a lack of demand for recycled polyurethane is unacceptable. Currently only a small percentage of polyurethane can be reused because it cannot be remolded into a different shape, so it must be shredded into fine particles and used as a composite filler material. Clearly the majority of used polyurethane cannot be reused in this way, but rubber had the same problem until research was performed to find ways of recycling large pieces of ground rubber in civil applications and other uses like sport surfaces. A similar development process must take place in the future to find a way to recycle the large amounts of polyurethane that will begin to pile up in landfills if Tweels™ are to be mass produced.

6.3 Future Work

Although this is a comprehensive analysis of every stage of the life cycle of both a tire and a Tweel™, it is only representative of the current knowledge available and thus requires more work in the future to update the LCA. The Tweel™ design may change in the next few years before it is mass produced and released for sale to the public, so it will be necessary to update this analysis with any changes to the production process or the use phase characteristics. The manufacturing profile probably will not change much, but two major studies need to be performed to ensure the use phase impact is accurate. In the analysis presented in this thesis, two assumptions were made that could affect the environmental impact of the Tweel™ use phase if more data is collected: (1) the rolling resistance coefficient does not degrade over the life of a tire and (2) a Tweel™ will last as long as a conventional tire (42,000 miles). Currently Michelin expects a Tweel™ to last the same length of time as a conventional tire due to the similar tread composition and thickness, but the larger contact area between the road and the tread due to the increased spoke deflection may cause a greater wear rate and thus a shorter life. Also, there is a small amount of data suggesting that a tire's rolling resistance will decrease throughout its life cycle due to tread wear instead of remaining constant throughout the use phase, but these data are currently insufficient to include in this analysis. One source estimates a 2/32 inch reduction in tread depth would lead to a 10% reduction in RRC, but it is also suggested that tire rubber becomes less elastic throughout its life and thus increases its rolling resistance.[28] Because of this complicated relationship, a more detailed study of the rolling resistance characteristics throughout the life of both a tire and Tweel™ can help update this LCA to accurately model these changing characteristics. Changes in rolling resistance also can affect the life of a tire, but another study must be performed to quantify this effect. It is currently uncertain whether a decrease in rolling resistance will affect the life of a tire or whether the potential changes in the tread depth throughout its life are enough to change the estimated life; so again more data must be collected on these secondary effects to be included in this LCA.

This LCA compared a fuel efficient tire and Michelin's first, or "Thrust I", Tweel™, but for a more comprehensive study of the Tweel™, the entire life cycle profiles of both Thrust II and III Tweels™ will be necessary to compare the 30% and 50% expected rolling resistance reductions against the other life cycle phases. The use phase fuel consumption of both of these future Tweel™ models was presented in section 5.3, but as neither the materials nor the manufacturing processes have been determined yet, it is impossible at this stage of the development process to complete a full life cycle analysis of either product. The same is true with Michelin's hope to develop a Tweel™ for use on trucks and larger vehicles, but until manufacturing and production profiles are available for these products, the environmental effects must remain a qualitative discussion of only the fuel savings. Due to the documented dominance of the fuel use in the overall life cycle analysis, it seems that a 30% or 50% decrease in rolling resistance would definitely benefit the environmental impact of a wheel, but producing the metamaterials necessary for these future upgrades to the Tweel™ may have unforeseen effects on the environment. So a Thrust II Tweel™ will probably be at least 20% more environmentally friendly as compared to a fuel efficient tire, but an accurate value is impossible to obtain before more information is known about the production of these products.

The final aspect of this analysis that was ignored but could have a small environmental effect is the noise produced from the tread to road contact. It has been suggested that Tweels™ will produce more road noise than a conventional tire, but due to the uncertainty of this claim and the difficulty of quantifying the human health effects of noise it was left out of this thesis. A future study may be helpful to quantify any increased road noise and its human health effects on hearing loss, sleep deprivation, stress, etc. It may be interesting to observe the potential effects, but relating them to issues such as ozone depletion or water acidification will encourage arguments similar to the land use issue that exist between the quantified natural rubber impacts resulting from the different assessment methods. All of the studies above were out of the scope of this thesis, but the addition of this knowledge to update the LCA comparison between a conventional tire and a Tweel™ may affect the predicted 2% to 6% Tweel™ environmental improvement.

Appendix A – Life Cycle Inventory

Appendix Table of Contents

RAW MATERIALS

SYNTHETIC RUBBER (1 kg)
Source – Franklin USA Database [57]

Resources		
Air	22.5	g
Baryte, in ground	-251	µg
Bauxite, in ground	1.15	g
Clay, bentonite, in ground	64.7	mg
Biomass	5.5	mg
Chromium ore, in ground	988	µg
Clay, unspecified, in ground	460	mg
Coal, 29.3 MJ per kg, in ground	161.36	g
Cobalt ore, in ground	-6.05	pg
Copper ore, in ground	-24.3	µg
Crude petroleum, natural gas etc., extracted for use	425	g
Oil, crude, 41 MJ per kg, in ground	658.46	g
Dolomite, in ground	8	mg
Energy, from hydro power	-971	J
Ferromanganese	500	µg
Fluorspar, in ground	2	mg
Gas, off-gas, oil production, in ground	-2.01	cm3
Gravel, in ground	2.5	mg
Gypsum, in ground	1.86	g
Iron ore, in ground	698	mg
Potassium chloride	65	mg
Lead ore, in ground	499	µg
Coal, brown (lignite)	9.779	g
Limestone, in ground	6.54	g
Manganese ore, in ground	-2.28	µg
Marl, in ground	-6.72	mg
Methane	-1.2	mg
Molybdenum ore, in ground	-2.32	pg
Gas, natural, 35 MJ per m3, in ground	-33.7	cm3
Gas, natural, 46.8 MJ per kg, in ground	899	g
Nickel ore, in ground	-8.77	µg
Nitrogen, in air	295	g
Olivine, in ground	6	mg
Oxygen, in air	140	mg
Palladium, in ground	-0.115	pg
Platinum, in ground	-0.254	pg
Rhenium, in ground	-0.061	pg
Rhodium, in ground	-0.0908	pg
Sodium chloride, in ground	7.36	mg
Salt, unspecified	2.95	g
Sand, unspecified, in ground	280	mg
Shale, in ground	19	mg
Silver, in ground	-122	ng
Sulfur, bonded	42	mg
Sulfur, in ground	100	mg
Tin ore, in ground	-67.9	ng
Uranium ore, 1.11 GJ per kg, in ground	-15	µg
Uranium, in ground	342	µg
Water, unspecified natural origin/kg	-32	g
Wood (16.9 MJ/kg)	60	g
Wood and wood waste, 9.5 MJ per kg	219	mg
Zeolite, in ground	-2.78	µg
Zinc ore, in ground	1000	µg
Land use II-III	48	mm2a
Land use III-IV	0.564	mm2a
Land use II-IV	1.1	mm2a
Land use IV-IV	0.00192	mm2a

Emissions to air		
Ethane, 1,1,1-trichloro-, HCFC-140	3.43	µg
Ethane, 1,2-dichloro-	-3.65	ng
Acetaldehyde	-331	ng
Acetic acid	-1.51	µg
Acetone	-329	ng
Acrolein	2.96	µg
Silver	57.7	ng
Aluminum	-10.5	µg
Aldehydes, unspecified	13.2	mg
Hydrocarbons, aliphatic, alkanes, unspecified	-3.06	µg
Hydrocarbons, aliphatic, alkenes, unspecified	-1.03	µg
Ammonia	1.56	mg
Arsenic	26.5	µg
Boron	-7.97	µg
Barium	-143	ng
Beryllium	2.27	µg
Benzaldehyde	-25.4	pg
Benzene	37.7	µg
Benzo(a)pyrene	-296	pg
Bromine	-514	ng
Butane	-4.43	µg
Butene	-70.6	ng
Calcium	-6.71	µg
Cadmium	29.9	µg

Chlorinated fluorocarbons, hard	500	µg
Ethane, hexafluoro-, HFC-116	-12.9	ng
Methane, tetrafluoro-, CFC-14	-103	ng
Phenol, chloro-	3.43	ng
Chlorine	8.01	mg
Carbon monoxide	5.24	g
Carbon dioxide	2.74	g
Carbon dioxide, fossil	2.8	kg
Carbon dioxide, biogenic	273	mg
Cobalt	28.2	µg
Chromium	44.3	µg
Carbon disulfide	500	µg
Copper	1.98	µg
Hydrocarbons, unspecified	14.6	g
Hydrocarbons, aromatic	23	mg
Hydrocarbons, chlorinated	500	µg
Cyanide compounds	-402	pg
Ethane, dichloro-	500	µg
Methane, dichloro-, HCC-30	12.6	µg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	17.7	pg
Particulates	1.4	g
Particulates, > 10 um	-1.08	mg
Ethane	-6.98	µg
Ethanol	-660	ng
Ethene	-392	ng
Benzene, ethyl-	1.77	µg
Ethyne	-12.2	ng
Fluorine	500	µg
Iron	-5.59	µg
Formaldehyde	3.52	mg
Hydrogen	500	mg
Hydrogen sulfide	499	µg
Sulfuric acid	500	µg
Methane, bromotrifluoro-, Halon 1301	-9.88	ng
Hydrogen chloride	47	mg
Heptane	-706	ng
Biphenyl, hexachloro-	280	ng
Hexane	-1.49	µg
Hydrogen fluoride	3.55	mg
Mercury	510	µg
Iodine	-248	ng
Potassium	-1.28	µg
Kerosene	75.4	µg
Lanthanum	-4.11	ng
Mercaptans, unspecified	500	µg
Metals, unspecified	7.11	mg
Methane	13.8	g
Methanol	-661	ng
Magnesium	-3.76	µg

Manganese	51.4	µg
Molybdenum	1.09	µg
Dinitrogen monoxide	2.32	mg
Sodium	-1.78	µg
Naphthalene	379	ng
Nickel	420	µg
N-Nitrodimethylamine	625	ng
Nitrogen dioxide	62.7	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	9.11	g
Nitrogen oxides	12.7	g
Oxygen	698	mg
Organic substances, unspecified	101	mg
Phosphorus	-123	ng
PAH, polycyclic aromatic hydrocarbons	500	µg
Particulates	484	mg
Lead	542	pg
Polychlorinated biphenyls	7.79	ng
Phenol, pentachloro-	592	pg
Pentane	-2.88	µg
Phenol	11.3	µg
Propane	-5.15	µg
Propene	-231	ng
Propionic acid	-25.5	ng
Platinum	-0.0146	pg
Antimony	53.27531	µg
Scandium	-1.55	ng
Selenium	30.1	µg
Silicates, unspecified	-26.7	µg
Tin	-3.58	ng
Sulfur dioxide	5.95	mg
Sulfur oxides	47.2	g
Strontium	-171	ng
Styrene	1.03	µg
Ethene, tetrachloro-	2.83	µg
Methane, tetrachloro-, CFC-10	5.13	µg
Thorium	-9.48	ng
Titanium	-462	ng
Thallium	-382	pg
Toluene	19.1	µg
Ethene, trichloro-	19.9	µg
Uranium	-4.13	ng
Vanadium	-2.55	µg
Ethene, chloro-	500	µg
VOC, volatile organic compounds	4.5	mg
water	3.69	g
Xylene	-4.4	µg
Zinc	10.4	µg
Zirconium	-230	pg

Heat, waste	-9.35	kJ
Radioactive species, unspecified	2.85	kBq

Emissions to water

Acidity, unspecified	20.5	mg
Acids, unspecified	6	mg
Silver	4.47	ng
Aluminum	14.7	mg
Hydrocarbons, aliphatic, alkanes, unspecified	-275	ng
Hydrocarbons, aliphatic, alkenes, unspecified	-25	ng
AOX, Adsorbable Organic Halogen as Cl	500	µg
Arsenic	499	µg
Boron	11.7	mg
Barium	-26.6	µg
Barite	-49	µg
Beryllium	2.12	ng
Benzene	-276	ng
BOD5, Biological Oxygen Demand	166	mg
Calcium, ion	13.1	mg
Calcium compounds, unspecified	-304	µg
Carbonate	65	mg
Cadmium	2.32	mg
Chlorate	500	µg
Benzene, chloro-	-0.00151	pg
Chromate	24.3	µg
Chloride	3.74	g
Chlorine	500	µg
Cobalt	-464	ng
COD, Chemical Oxygen Demand	1090	mg
Chromium	2.32	mg
Chromium VI	-701	pg
Crude oil	-170	ng
Cesium	-2.07	ng
Copper	499	µg
Hydrocarbons, unspecified	43.4	mg
Hydrocarbons, aromatic	-1.3	µg
Hydrocarbons, chlorinated	500	µg
Cyanide	503	µg
Detergent, oil	75	mg
Ethane, dichloro-	500	µg
Solved organics	23	mg
Solved solids	51.6	g
Solved substances	-115	µg
Benzene, ethyl-	-49.7	ng
Fluorine	500	µg
Iron	11.8	mg
Fluoride	300	µg
Formaldehyde	-16.1	pg
Glutaraldehyde	-6.04	ng
Hydrogen sulfide	-11.5	ng
Sulfuric acid	2.91	mg
Mercury	500	µg
Hypochlorous acid	-2.49	µg
Iodide	-207	ng
Solids, inorganic	1000	µg
Metallic ions, unspecified	15.5	mg
Potassium	1.91	mg
Metallic ions, unspecified	91.3	mg
Methane, dichloro-, HCC-30	-2.37	ng
Magnesium	269	µg
Manganese	6.76	mg
Molybdenum	12.5	µg
Sodium, ion	899	mg
Ammonia	566	µg
Ammonium, ion	4.5	mg
Nickel	500	µg
Nitrate	3.02	mg
Nitrite	2.5	mg
Nitrogen, total	-5.98	µg
Oils, unspecified	914	mg
Organic carbon	95	mg
Organic substances, unspecified	60.6	mg
Phosphorus pentoxide	2.5	mg
PAH, polycyclic aromatic hydrocarbons	-27	ng
Lead	499	µg
Phenol	8.5	mg
Phosphate	1.74	mg
Phosphorus, total	-502	pg
Sulfur	500	µg
Salts, unspecified	-780	µg
Antimony	50.6	ng
Selenium	-1.37	µg
Silicon	-1.16	ng
Tin	-3.72	ng
Sulfur trioxide	-121	ng
Strontium	-15.7	µg
Sulfate	2.12	g
Sulfate	32.1	mg
Sulfide	3.05	mg
Suspended solids, unspecified	1310	mg
Suspended substances, unspecified	-194	µg
Titanium	-16.1	µg
TOC, Total Organic Carbon	15	mg
Toluene	-250	ng
Tributyltin	-8.49	ng
Ethene, trichloro-	-312	pg
Vanadium	-1.22	µg

Tungsten	-2.92	ng
Xylene	-199	ng
Zinc	1370	µg
Radioactive species, unspecified	-12.1	Bq
Heat, waste	-187	J

Emissions to soil

Heat, waste	-8.94	J

Final waste flows

Waste, final, inert	32.8	g
Waste, nuclear, high active/m3	-0.00255	mm3
Waste, nuclear, low and medium active/m3	-0.151	mm3
Production waste	-20.6	mg
Slags	562	mg
Waste, solid	137	g

NATURAL RUBBER (1 kg)

Source – Rubber Manufacturers Association and PRé Consultants [17, 34]

Resources

Occupation, heterogeneous, agricultural	7	m2a
Roundup1	0.0058	kg
Ridomil	5.26E-05	kg
Validamycin	0.011	kg
Acids	0.0041	kg

Materials/fuels

Energy US I	1.6	MJ
Ammonia B250	0.003	kg
Sodium sulphate B250	0.0005	kg
Energy US I	0.596	MJ
Diesel	1.36	MJ

Emissions to air

Roundup	0.00058	kg
Ridomil	5.26E-06	kg
Carbon dioxide	-3.3	kg

Emissions to water

BOD5, Biological Oxygen Demand	11.7	g
COD, Chemical Oxygen Demand	17.9	g
Nitrogen, total	3.8	g

Emissions to soil

Roundup	0.0052	kg
Ridomil	0.000047	kg

CARBON BLACK (1 kg)

Source – IDEMAT Database [91]

Resources

Silver, in ground	294.5	µg
Baryte, in ground	434.3	mg
Bauxite, in ground	233.0	mg
Clay, bentonite, in ground	161.2	mg
Chromium ore, in ground	8.6	mg
Coal, 18 MJ per kg, in ground	159.4	g
Cobalt, in ground	7.2	ng
Copper ore, in ground	102.5	mg
Oil, crude, 41 MJ per kg, in ground	2.2	kg
Energy, unspecified	14.8	MJ
Energy, from hydro power	210.6	kJ
Land use II-III	69.5	cm2a
Land use II-IV	716.7	mm2a
Iron, 46% in ore, 25% in crude ore, in ground	1.7	g
Gravel, in ground	6.8	g
Lead ore, in ground	7.7	mg
Coal, brown (lignite)	29.5	g
Coal, brown (lignite)	142.6	g
Manganese ore, in ground	1.5	mg
Marl, in ground	3.0	g
Methane	756.8	mg
Molybdenum, in ground	122.1	ng
Gas, natural (0,8 kg/m3)	311.3	m3
Nickel ore, in ground	6.1	mg
Palladium, in ground	150.1	ng
Gas, petroleum, 35 MJ per m3, in ground	6.4	dm3
Platinum, in ground	168.7	ng
Energy, potential (in hydropower reservoir), converted	507.0	kJ
Energy, potential (in hydropower reservoir), converted	630.0	kJ
Rhenium, in ground	160.3	ng
Volume occupied, reservoir	0.0	m3y
Rhodium, in ground	159.4	ng

Salt, unspecified	103.5	mg
Sand, unspecified, in ground	749.3	mg
Tin ore, in ground	163.1	µg
Water, turbine use, unspecified natural origin	3.3	m3
Uranium ore, 1.11 GJ per kg, in ground	18.0	mg
Water, unspecified natural origin/kg	20.6	kg
Wood (16.9 MJ/kg)	1.8	g
Zinc ore, in ground	57.7	µg
Land use II-III	-361.6	cm2a
Land use III-IV	-380.3	mm2a
Land use II-IV	-561.1	mm2a
Land use IV-IV	-2.7	mm2a

Emissions to air

Acetaldehyde	213.4	µg
Acetic acid	1.0	mg
Acetone	212.5	µg
Acrolein	4.0	ng
Silver-110	4.0	µBq
Aluminum	7.1	mg
Aldehydes, unspecified	7.7	µg
Hydrocarbons, aliphatic, alkanes, unspecified	1.8	mg
Hydrocarbons, aliphatic, alkanes, unspecified	2.1	mg
Americium-241	74.6	µBq
Ammonia	2.5	mg
Argon-41	8.7	Bq
Arsenic	47.0	µg
Boron	5.4	mg
Barium	116.5	µg
Barium-140	15.6	µBq
Beryllium	1.2	µg
Benzaldehyde	1.4	ng
Benzene	38.6	mg
Benzo(a)pyrene	295.4	ng
Radioactive species, other beta emitters	499.6	nBq
Bromine	557.3	µg
Butane	8.1	mg
Butene	177.1	µg
Carbon-14	6.0	Bq
Ethane, hexafluoro-, HFC-116	2.5	µg
Calcium	8.5	mg
Cadmium	131.4	µg
Cerium-141	372.8	nBq
Cerium-144	792.2	µBq
Methane, tetrafluoro-, CFC-14	22.8	µg
Curium-242	0.4	nBq
Curium-244	3.6	nBq
Curium alpha	118.4	µBq
Carbon monoxide	1.8	g
Carbon dioxide	2.1	kg
Cobalt-57	6.9	nBq
Cobalt-58	113.7	µBq
Cobalt-60	168.7	µBq
Cobalt	103.5	µg
Chromium	68.2	µg
Chromium-51	14.1	µBq
Cesium-134	2.8	mBq
Cesium-137	5.5	mBq
Copper	194.8	µg
Hydrocarbons, aromatic	82.6	mg
Hydrocarbons, aromatic	29.2	ng
Hydrocarbons, aromatic	88.0	µg
Hydrocarbons, chlorinated	249.8	ng
Cyanide compounds	1.0	µg
Methane, dichlorofluoro-, HCFC-21	3.0	µg
Ethane, dichloro-	8.4	µg
Methane, dichloro-, HCC-30	369.1	ng
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	30.1	pg
Particulates	1.1	g
Particulates, < 10 um (mobile)	4.0	mg
Particulates, > 10 um (process)	213.4	mg
Particulates, < 10 um (stationary)	192.9	mg
Ethane	5.2	mg
Ethanol	425.9	µg
Ethene	760.5	µg
Benzene, ethyl-	772.6	µg
Ethyne	7.4	µg
Iron	5.2	mg
Iron-59	155.6	nBq
Formaldehyde	1.5	mg
Hydrogen sulfide	458.5	µg
Hydrogen-3, Tritium	61.9	Bq
Methane, bromotrifluoro-, Halon 1301	535.0	µg
Methane, chlorodifluoro-, HCFC-22	724.2	ng
Hydrogen chloride	116.5	mg
Helium	6.5	mg
Heptane	1.7	mg
Benzene, hexachloro-	470.7	pg
Hexane	3.5	mg
Hydrogen fluoride	14.4	mg
Mercury	51.5	µg
Iodine	251.6	µg
Iodine-129	21.2	mBq
Iodine-131	2.4	mBq
Iodine-133	1.3	mBq

Iodine-135	2.0	mBq
Potassium	1.2	mg
Potassium-40	11.2	mBq
Krypton-85	365.3	kBq
Krypton-85m	430.6	mBq
Krypton-87	192.9	mBq
Krypton-88	17.3	Bq
Krypton-89	135.1	mBq
Lanthanum	3.4	µg
Lanthanum-140	9.9	µBq
Radon-222	524.7	kBq
Metals, unspecified	37.9	mg
Methane	10.4	g
Methanol	432.4	µg
Magnesium	2.5	mg
Manganese	211.6	µg
Manganese-54	4.1	µBq
Molybdenum	42.9	µg
t-Butyl methyl ether	76.3	ng
Nitrogen	5.2	mg
Dinitrogen monoxide	54.9	mg
Sodium	2.4	mg
Niobium-95	716.7	nBq
Nickel	6.7	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	2.6	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	17.1	g
NMVOC, non-methane volatile organic compounds, unspecified origin	706.5	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	23.4	mg
Nitrogen oxides	9.0	g
Nitrogen oxides	7.1	g
Neptunium-237	3.9	nBq
Phosphorus	104.4	µg
Protactinium-234	2.4	mBq
PAH, polycyclic aromatic hydrocarbons	60.7	µg
PAH, polycyclic aromatic hydrocarbons	11.1	ng
PAH, polycyclic aromatic hydrocarbons	14.9	µg
Lead	654.3	µg
Lead-210	65.4	mBq
Benzene, pentachloro-	1.2	ng
Phenol, pentachloro-	202.2	pg
Pentane	10.4	mg

Phenol	680.4	ng
Promethium-147	2.0	mBq
Polonium-210	97.9	mBq
Propane	8.3	mg
Propene	394.2	µg
Propionic acid	13.8	µg
Platinum	3.9	ng
Plutonium-238	8.9	nBq
Plutonium-241	6.5	mBq
Plutonium-alpha	236.7	µBq
Methane, trichlorofluoro-, CFC-11	3.1	µg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	82.6	µg
Methane, dichlorodifluoro-, CFC-12	658.9	ng
Methane, chlorotrifluoro-, CFC-13	412.9	ng
Radium-226	84.3	mBq
Radium-228	5.5	mBq
Noble gases, radioactive, unspecified	517.3	mBq
Radon-220	517.3	mBq
Radon-222	5.7	kBq
Ruthenium-103	40.5	nBq
Ruthenium-106	23.7	mBq
Antimony	6.8	µg
Antimony-124	1.1	µBq
Antimony-125	139.8	nBq
Scandium	1.1	µg
Selenium	90.4	µg
Silicates, unspecified	26.3	mg
Tin	2.5	µg
Sulfur oxides	22.4	g
Sulfur oxides	14.1	g
Strontium	114.6	µg
Strontium-89	7.1	µBq
Strontium-90	3.9	mBq
Technetium-99	165.0	nBq
Tellurium-123m	17.8	µBq
Methane, tetrachloro-, CFC-10	2.0	µg
Thorium	2.2	µg
Thorium-228	4.6	mBq
Thorium-230	26.3	mBq
Thorium-232	2.9	mBq
Thorium-234	2.4	mBq
Titanium	321.5	µg
Thallium	820.2	ng
Toluene	1.5	mg
Chloroform	221.8	ng
Uranium	2.4	µg
Uranium-234	28.3	mBq
Uranium-235	1.4	mBq
Uranium-238	36.3	mBq

Uranium alpha	84.7	mBq
Vanadium	5.2	mg
Ethene, chloro-	1.4	µg
Heat, waste	11.8	MJ
Xenon-131m	893.8	mBq
Xenon-133	262.8	Bq
Xenon-133m	132.3	mBq
Xenon-135	44.9	Bq
Xenon-135m	4.4	Bq
Xenon-137	110.0	mBq
Xenon-138	1.2	Bq
Xylene	3.3	mg
Zinc	3.3	mg
Zinc-65	17.4	µBq
Zirconium	123.0	ng
Zirconium-95	260.0	nBq
Radioactive species, unspecified	730.7	kBq

Emissions to water

Ethane, 1,1,1-trichloro-, HCFC-140	720.4	pg
Acenaphthylene	40.9	µg
Acids, unspecified	43.4	µg
Silver	3.0	µg
Silver-110	27.2	mBq
Aluminum	262.8	mg
Hydrocarbons, aliphatic, alkanes, unspecified	76.8	µg
Hydrocarbons, aliphatic, alkanes, unspecified	589.6	µg
Radioactive species, alpha emitters	3.2	µBq
Americium-241	9.8	mBq
Ammonia, as N	7.7	mg
Solved substances, inorganic	39.8	g
AOX, Adsorbable Organic Halogen as Cl	318.7	µg
Arsenic	583.4	µg
Boron	437.1	µg
Barium	293.6	mg
Barium-140	48.8	µBq
Barite	86.6	mg
Beryllium	359.8	ng
Benzene	610.5	µg
Adipate, bis(2-ethylhexyl)-	387.7	pg
BOD5, Biological Oxygen Demand	6.8	mg
BOD5, Biological Oxygen Demand	704.6	µg
Carbon-14	495.8	mBq
Calcium, ion	370.0	mg
Cadmium	113.7	µg
Cadmium-109	282.4	nBq
Cerium-141	7.3	µBq
Cerium-144	224.6	mBq
Chloroform	2.6	µg
Chlorinated solvents, unspecified	184.5	ng
Benzene, chloro-	3.6	pg
Chloride	58.9	g
Curium alpha	13.0	mBq
Cobalt	736.3	ng
Cobalt-57	50.0	µBq
Cobalt-58	42.3	mBq
Cobalt-60	2.2	Bq
Cobalt	359.8	µg
COD, Chemical Oxygen Demand	228.3	mg
Chromium	3.5	mg
Chromium VI	369.1	ng
Chromium-51	1.1	mBq
Cesium	4.7	µg
Cesium-134	501.4	mBq
Cesium-136	261.9	nBq
Cesium-137	4.6	Bq
Copper	1.5	mg
Hydrocarbons, unspecified	62.6	µg
Hydrocarbons, aromatic	89.3	mg
Hydrocarbons, chlorinated	94.1	µg
Hydrocarbons, aromatic	273.1	µg
Hydrocarbons, aromatic	2.6	mg
Cyanide	341.1	µg
Phthalate, dibutyl-	4.1	ng
Ethane, dichloro-	4.3	µg
Phthalate, dimethyl-	26.0	ng
Solved substances	76.3	mg
DOC, Dissolved Organic Carbon	3.1	mg
Benzene, ethyl-	112.8	µg
Fluoride	1.2	mg
Oils, unspecified	86.1	mg
Fatty acids as C	23.8	mg
Iron	367.2	mg
Iron-59	864.9	nBq
VOC, volatile organic compounds, unspecified origin	1.6	mg
Formaldehyde	19.5	ng
Glutaraldehyde	10.7	µg
Hydrogen sulfide	7.2	µg
Hydrogen-3, Tritium	14.7	kBq
Ethane, hexachloro-	96.0	pg
Mercury	1.9	µg
Hypochlorous acid	1.6	mg
Iodide	468.8	µg
Iodine-129	1.4	Bq
Iodine-131	0.9	mBq
Iodine-133	223.7	µBq
Potassium	77.5	mg
Potassium-40	35.6	mBq

Kjeldahl-N	27.5	mg
Lanthanum-140	10.2	µBq
Metallic ions, unspecified	645.9	mg
Methane, dichloro-, HCC-30	39.8	µg
Magnesium	158.4	mg
Manganese	4.6	mg
Manganese-54	332.7	mBq
Molybdenum	675.7	µg
Molybdenum-99	3.4	µBq
t-Butyl methyl ether	6.6	ng
Nitrogen, total	7.7	mg
Nitrogen, organic bound	1.1	mg
Sodium, ion	1.7	g
Sodium-24	1.5	mBq
Niobium-95	27.7	µBq
Ammonium, ion	166.8	mg
Nickel	1.6	mg
Nitrate	60.8	mg
Nitrite	379.3	µg
Neptunium-237	626.3	µBq
Nitrogen, total	162.2	mg
Radioactive species, unspecified	21.2	µBq
Hypochlorite	1.6	mg
Oils, unspecified	2.8	g
Protactinium-234	43.8	mBq
PAH, polycyclic aromatic hydrocarbons	1.4	mg
PAH, polycyclic aromatic hydrocarbons	54.0	µg
Lead	1.7	mg
Lead-210	28.3	mBq
Phosphorus compounds, unspecified	2.8	µg
Phenols, unspecified	14.2	mg
Phosphate	17.6	mg
Polonium-210	28.3	mBq
Plutonium-241	1.0	Bq
Plutonium-alpha	39.1	mBq
Radium-224	233.9	mBq
Radium-226	180.8	Bq
Radium-228	468.8	mBq
Ruthenium	47.1	µg
Ruthenium-103	16.4	µBq
Ruthenium-106	2.4	Bq
Salts, unspecified	503.3	mg
Antimony	3.0	µg
Antimony-122	48.8	µBq
Antimony-124	7.0	mBq
Antimony-125	398.0	µBq
Selenium	932.0	µg
Silicon	103.5	µg
Tin	1.9	µg
Sulfur trioxide	162.2	µg
Strontium	30.5	mg
Strontium-89	110.0	µBq
Strontium-90	474.4	mBq
Sulfate	2.3	g
Sulfate	2.0	g
Sulfide	2.6	mg
Suspended substances, unspecified	6.2	g
Technetium-99	247.9	mBq
Technetium-99	23.0	µBq
Tellurium-123m	2.1	µBq
Tellurium-132	843.5	nBq
Ethene, tetrachloro-	11.4	ng
Methane, tetrachloro-, CFC-10	17.4	ng
Thorium-228	0.9	Bq
Thorium-230	6.8	Bq
Thorium-232	6.6	mBq
Thorium-234	44.2	mBq
Titanium	10.8	mg
TOC, Total Organic Carbon	1.1	g
Toluene	13.0	mg
Tributyltin	7.4	µg
Ethene, trichloro-	720.4	ng
Triethylene glycol	284.3	µg
Uranium-234	58.6	mBq
Uranium-235	87.2	mBq
Uranium-238	148.2	mBq
Uranium alpha	2.9	Bq
Undissolved substances	292.6	mg
Vanadium	1.0	mg
Ethene, chloro-	3.2	ng
Tungsten	8.5	µg
Heat, waste	915.2	kJ
Xylene	442.7	µg
Yttrium-90	5.6	µBq
Zinc	3.5	mg
Zinc-65	3.2	mBq
Zirconium-95	20.1	mBq
Radioactive species, unspecified	6.6	kBq

Emissions to soil

Aluminum	5.7	mg
Arsenic	2.3	µg
Carbon	17.7	mg
Calcium	22.8	mg
Cadmium	94.1	ng
Cobalt	127.7	ng
Chromium	28.6	µg
Copper	637.5	ng

Iron	11.5	mg
Mercury	17.9	ng
Manganese	228.3	µg
Nitrogen	5.3	µg
Nickel	1.0	µg
Oils, unspecified	4.1	mg
Oils, biogenic	21.9	µg
Phosphorus	293.6	µg

Lead	2.9	µg
Sulfur	3.4	mg
Heat, waste	25.8	kJ
Zinc	92.0	µg

Final waste flows

Waste, final, inert	57.2	mg

SILICA (1 kg)
Source – ECETOC [62]

Materials/fuels

Sodium silicate B250	1.46	kg
Sulphuric acid B250	445	g

Electricity/heat

Energy US I	1.76	MJ

SULFUR (1 kg)
Source – IDEMAT Database [91]

Resources

Rhodium, in ground	142.4	ng
Salt, unspecified	14.7	mg
Sand, unspecified, in ground	106.8	mg
Tin ore, in ground	112.1	µg
Water, turbine use, unspecified natural origin	23.2	dm3
Uranium ore, 1.11 GJ per kg, in ground	67.6	µg
Water, unspecified natural origin/kg	461.9	g
Wood (16.9 MJ/kg)	13.6	mg
Zinc ore, in ground	17.4	µg
Lead ore, in ground	185.1	µg
Coal, brown (lignite)	1.0	g
Manganese ore, in ground	85.1	µg
Marl, in ground	258.1	mg
Methane	7.9	mg
Molybdenum, in ground	108.6	ng
Gas, natural, 35 MJ per m3, in ground	144.2	cm3
Nickel ore, in ground	196.7	µg
Palladium, in ground	134.4	ng
Gas, petroleum, 35 MJ per m3, in ground	4.4	dm3
Platinum, in ground	151.3	ng
Energy, potential (in hydropower reservoir), converted	4.4	kJ
Rhenium, in ground	143.3	ng
Volume occupied, reservoir	96.1	cm3y
Silver, in ground	202.0	µg
Barite, 15% in crude ore, in ground	280.4	mg
Bauxite, in ground	3.0	mg
Clay, bentonite, in ground	22.3	mg

Chromium ore, in ground	309.7	µg
Coal, 18 MJ per kg, in ground	1.1	g
Cobalt, in ground	3.2	ng
Copper ore, in ground	1.2	mg
Oil, crude, 42.6 MJ per kg, in ground	64.1	g
Iron, 46% in ore, 25% in crude ore, in ground	311.5	mg
Gravel, in ground	446.8	mg
Land use II-III	-312.4	mm2a
Land use III-IV	-80.7	mm2a
Land use II-IV	-100.6	mm2a
Land use IV-IV	-1.1	mm2a
Land use II-III	-44.6	cm2a
Land use II-IV	-460.1	mm2a

Emissions to air

Acetaldehyde	3.9	µg
Acetic acid	16.2	µg
Acetone	3.9	µg
Acrolein	1.9	ng
Silver-110	27.9	nBq
Aluminum	56.4	µg
Aldehydes, unspecified	53.9	ng
Hydrocarbons, aliphatic, alkanes, unspecified	1.2	mg
Hydrocarbons, aliphatic, alkanes, unspecified	19.9	µg
Hydrocarbons, aliphatic, alkenes, unspecified	124.6	ng
Hydrocarbons, aliphatic, alkenes, unspecified	5.2	µg
Americium-241	520.7	nBq

Ammonia	14.7	µg
Argon-41	60.8	mBq
Arsenic	19.1	µg
Boron	38.2	µg
Barium	846.4	ng
Barium-140	109.5	nBq
Beryllium	9.2	ng
Benzaldehyde	659.5	pg
Benzene	496.6	µg
Benzo(a)pyrene	34.6	ng
Radioactive species, other beta emitters	3.5	nBq
Bromine	3.9	µg
Butane	4.9	mg
Butene	117.5	µg
Carbon-14	41.9	mBq
Ethane, hexafluoro-, HFC-116	32.9	ng
Calcium	235.0	µg
Cadmium	46.4	µg
Cerium-141	2.6	nBq
Cerium-144	5.5	µBq
Methane, tetrafluoro-, CFC-14	296.4	ng
Curium-242	0.0	nBq
Curium-244	0.0	nBq
Curium alpha	825.9	nBq
Carbon monoxide	38.1	mg
Carbon dioxide	202.0	g
Cobalt-57	0.0	nBq
Cobalt-58	793.9	nBq
Cobalt-60	1.2	µBq
Cobalt	46.9	µg
Chromium	23.9	µg
Chromium-51	97.9	nBq
Cesium-134	19.8	µBq
Cesium-137	38.2	µBq
Copper	71.8	µg
Hydrocarbons, aromatic	12.5	ng
Hydrocarbons, aromatic	3.0	µg
Cyanide compounds	94.3	ng
Methane, dichlorofluoro-, HCFC-21	591.0	ng
Ethane, dichloro-	97.9	ng
Methane, dichloro-, HCC-30	9.7	ng
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	1.2	pg
Particulates, < 10 um (mobile)	1.2	mg
Particulates, > 10 um (process)	4.8	mg
Particulates, < 10 um (stationary)	83.7	mg
Ethane	1.2	mg
Ethanol	7.7	µg
Ethene	302.6	µg
Benzene, ethyl-	119.3	µg
Ethyne	227.0	ng
Iron	291.0	µg
Iron-59	1.1	nBq
Formaldehyde	17.6	µg
Hydrogen sulfide	18.9	µg
Hydrogen-3, Tritium	431.7	mBq
Methane, bromotrifluoro-, Halon 1301	24.8	µg
Methane, chlorodifluoro-, HCFC-22	5.1	ng
Hydrogen chloride	2.7	mg
Helium	4.4	mg
Heptane	1.1	mg
Benzene, hexachloro-	4.0	pg
Hexane	2.4	mg
Hydrogen fluoride	287.5	µg
Mercury	3.2	µg
Iodine	1.8	µg
Iodine-129	148.6	µBq
Iodine-131	16.6	µBq
Iodine-133	9.3	µBq
Iodine-135	13.9	µBq
Potassium	60.1	µg
Potassium-40	79.7	µBq
Krypton-85	2.6	kBq
Krypton-85m	3.0	mBq
Krypton-87	1.4	mBq
Krypton-88	121.0	mBq
Krypton-89	1.0	mBq
Lanthanum	24.7	ng
Lanthanum-140	69.2	nBq
Radon-222	3.7	kBq
Methane	269.7	mg
Methanol	11.1	µg
Magnesium	19.5	µg
Manganese	14.7	µg
Manganese-54	28.4	nBq
Molybdenum	23.5	µg
t-Butyl methyl ether	34.2	ng
Nitrogen	41.6	µg
Dinitrogen monoxide	670.2	µg
Sodium	1.1	mg
Niobium-95	5.0	nBq
Nickel	0.9	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	405.0	µg
NMVOC, non-methane volatile organic compounds, unspecified origin	475.3	mg
NMVOC, non-methane volatile organic compounds, unspecified	17.6	mg

origin

Nitrogen oxides	418.3	mg
Neptunium-237	0.0	nBq
Phosphorus	2.8	µg
Protactinium-234	16.6	µBq
PAH, polycyclic aromatic hydrocarbons	3.1	ng
PAH, polycyclic aromatic hydrocarbons	305.3	ng
Lead	84.4	µg
Lead-210	463.7	µBq
Benzene, pentachloro-	10.9	pg
Phenol, pentachloro-	1.7	pg
Pentane	6.1	mg
Phenol	14.2	ng
Promethium-147	14.1	µBq
Polonium-210	696.0	µBq
Propane	4.8	mg
Propene	231.4	µg
Propionic acid	98.8	ng
Platinum	2.0	ng
Plutonium-238	0.1	nBq
Plutonium-241	45.5	µBq
Plutonium-alpha	1.7	µBq
Methane, trichlorofluoro-, CFC-11	21.4	ng
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	566.0	ng
Methane, dichlorodifluoro-, CFC-12	4.6	ng
Methane, chlorotrifluoro-, CFC-13	2.9	ng
Radium-226	591.0	µBq
Radium-228	39.1	µBq
Noble gases, radioactive, unspecified	3.6	mBq
Radon-220	3.7	mBq
Radon-222	40.4	Bq
Ruthenium-103	0.3	nBq
Ruthenium-106	165.5	µBq
Antimony	48.1	ng
Antimony-124	7.7	nBq
Antimony-125	1.0	nBq
Scandium	8.3	ng
Selenium	19.9	µg
Silicates, unspecified	190.5	µg
Tin	17.8	ng
Sulfur oxides	54.6	g
Strontium	844.6	ng
Strontium-89	49.7	nBq
Strontium-90	27.2	µBq
Technetium-99	1.2	nBq
Tellurium-123m	124.6	nBq
Methane, tetrachloro-, CFC-10	24.7	ng
Thorium	15.7	ng
Thorium-228	33.1	µBq
Thorium-230	184.2	µBq
Thorium-232	21.0	µBq
Thorium-234	16.6	µBq
Titanium	2.3	µg
Thallium	6.0	ng
Toluene	712.0	µg
Chloroform	2.6	ng
Uranium	17.4	ng
Uranium-234	198.5	µBq
Uranium-235	9.6	µBq
Uranium-238	255.4	µBq
Uranium alpha	592.7	µBq
Vanadium	3.8	mg
Ethene, chloro-	16.0	ng
Heat, waste	2.6	MJ
Xenon-131m	6.3	mBq
Xenon-133	1.8	Bq
Xenon-133m	0.9	mBq
Xenon-135	314.2	mBq
Xenon-135m	31.0	mBq
Xenon-137	769.0	µBq
Xenon-138	8.4	mBq
Xylene	480.6	µg
Zinc	71.4	µg
Zinc-65	121.9	nBq
Zirconium	4.6	ng
Zirconium-95	1.8	nBq

Emissions to water

Ethane, 1,1,1-trichloro-, HCFC-140	152.2	pg
Acenaphthylene	315.1	ng
Acids, unspecified	1.2	µg
Silver	1.9	µg
Silver-110	190.5	µBq
Aluminum	2.0	mg
Hydrocarbons, aliphatic, alkanes, unspecified	46.2	µg
Hydrocarbons, aliphatic, alkanes, unspecified	371.1	µg
Hydrocarbons, aliphatic, alkenes, unspecified	4.3	µg
Hydrocarbons, aliphatic, alkenes, unspecified	34.3	µg
Radioactive species, alpha emitters	22.6	nBq
Americium-241	68.5	µBq
Ammonia, as N	4.3	mg
AOX, Adsorbable Organic Halogen as Cl	12.6	µg
Arsenic	6.4	µg

Boron	110.4	µg
Barium	8.3	mg
Barium-140	343.5	nBq
Barite	55.5	mg
Beryllium	2.4	ng
Benzene	417.4	µg
Adipate, bis(2-ethylhexyl)-	5.6	pg
BOD5, Biological Oxygen Demand	390.7	µg
Carbon-14	3.5	mBq
Calcium, ion	126.4	mg
Cadmium	3.9	µg
Cadmium-109	2.0	nBq
Cerium-141	51.4	nBq
Cerium-144	1.6	mBq
Chloroform	30.8	ng
Chlorinated solvents, unspecified	34.5	ng
Benzene, chloro-	0.6	pg
Chloride	1.8	g
Curium alpha	90.8	µBq
Cobalt-57	352.4	nBq
Cobalt-58	298.2	µBq
Cobalt-60	15.1	mBq
Cobalt	3.5	µg
COD, Chemical Oxygen Demand	9.4	mg
Chromium	46.7	µg
Chromium VI	2.6	ng
Chromium-51	7.5	µBq
Cesium	3.2	µg
Cesium-134	3.5	mBq
Cesium-136	1.8	nBq
Cesium-137	32.3	mBq
Copper	15.1	µg
Hydrocarbons, unspecified	867.8	ng
Hydrocarbons, aromatic	186.0	µg
Hydrocarbons, aromatic	1.7	mg
Cyanide	14.5	µg
Phthalate, dibutyl-	31.9	pg
Ethane, dichloro-	50.5	ng
Phthalate, dimethyl-	200.3	pg
Solved substances	732.5	µg
DOC, Dissolved Organic Carbon	2.1	µg
Benzene, ethyl-	77.1	µg
Fluoride	407.6	µg
Oils, unspecified	58.8	mg
Fatty acids as C	16.3	mg
Iron	3.4	mg
Iron-59	6.1	nBq
VOC, volatile organic compounds, unspecified origin	1.1	mg
Formaldehyde	493.1	pg
Glutaraldehyde	6.9	µg

Hydrogen sulfide	424.5	ng
Hydrogen-3, Tritium	102.4	Bq
Ethane, hexachloro-	1.1	pg
Mercury	53.6	ng
Hypochlorous acid	11.0	µg
Iodide	321.3	µg
Iodine-129	9.9	mBq
Iodine-131	6.6	µBq
Iodine-133	1.6	µBq
Potassium	16.5	mg
Potassium-40	250.1	µBq
Lanthanum-140	71.2	nBq
Methane, dichloro-, HCC-30	25.5	µg
Magnesium	6.9	mg
Manganese	228.7	µg
Manganese-54	2.3	mBq
Molybdenum	8.6	µg
Molybdenum-99	24.0	nBq
t-Butyl methyl ether	2.8	ng
Nitrogen, total	5.7	mg
Nitrogen, organic bound	849.1	µg
Sodium, ion	1.1	g
Sodium-24	10.6	µBq
Niobium-95	194.9	nBq
Nickel	18.3	µg
Nitrate	2.2	mg
Nitrite	2.9	µg
Neptunium-237	4.4	µBq
Radioactive species, unspecified	148.6	nBq
Hypochlorite	11.0	µg
Protactinium-234	306.2	µBq
PAH, polycyclic aromatic hydrocarbons	4.6	µg
PAH, polycyclic aromatic hydrocarbons	37.1	µg
Lead	19.6	µg
Lead-210	199.4	µBq
Phosphorus compounds, unspecified	1.6	µg
Phenols, unspecified	411.2	µg
Phosphate	145.1	µg
Polonium-210	199.4	µBq
Plutonium-241	6.8	mBq
Plutonium-alpha	272.3	µBq
Radium-224	160.2	mBq
Radium-226	1.6	Bq
Radium-228	321.3	mBq
Ruthenium	32.1	µg
Ruthenium-103	114.8	nBq
Ruthenium-106	16.6	mBq
Salts, unspecified	3.6	mg

Antimony	36.6	ng
Antimony-122	343.5	nBq
Antimony-124	49.1	µBq
Antimony-125	2.8	µBq
Selenium	11.6	µg
Silicon	28.6	µg
Tin	13.2	ng
Sulfur trioxide	1.6	µg
Strontium	19.5	mg
Strontium-89	777.0	nBq
Strontium-90	3.3	mBq
Sulfate	78.3	mg
Sulfide	105.0	µg
Technetium-99	1.7	mBq
Technetium-99m	162.0	nBq
Tellurium-123m	14.5	nBq
Tellurium-132	5.9	nBq
Ethene, tetrachloro-	133.5	pg
Methane, tetrachloro-, CFC-10	202.9	pg
Thorium-228	642.6	mBq
Thorium-230	47.9	mBq
Thorium-232	46.6	µBq
Thorium-234	308.8	µBq
Titanium	105.0	µg
TOC, Total Organic Carbon	47.2	mg
Toluene	347.1	µg
Tributyltin	2.8	µg
Ethene, trichloro-	8.4	ng
Triethylene glycol	2.1	µg
Uranium-234	409.4	µBq
Uranium-235	609.7	µBq
Uranium-238	1.0	mBq
Uranium alpha	20.0	mBq
Undissolved substances	172.7	mg
Vanadium	11.9	µg
Ethene, chloro-	37.7	pg
Tungsten	61.1	ng
Heat, waste	769.9	kJ
Xylene	302.6	µg
Yttrium-90	39.7	nBq
Zinc	98.8	µg
Zinc-65	22.3	µBq
Zirconium-95	140.6	µBq

Emissions to soil

Aluminum	3.7	mg
Arsenic	1.5	µg
Carbon	11.4	mg
Calcium	14.7	mg
Cadmium	63.4	ng
Cobalt	87.5	ng
Chromium	18.4	µg
Copper	437.9	ng
Iron	7.4	mg
Mercury	12.0	ng
Manganese	146.9	µg
Nitrogen	3.4	µg
Nickel	656.8	ng
Oils, unspecified	2.8	mg
Oils, biogenic	213.6	ng
Phosphorus	187.8	µg
Lead	2.0	µg
Sulfur	2.2	mg
Zinc	59.6	µg
Heat, waste	216.3	J

ZINC OXIDE (1 ton)

Source – Chemical Substance Bureau of the Netherlands [72]

Materials/fuels

Zinc, Primary	0.284	ton
Zinc, Secondary	0.15	ton
Destillate Fuel Oil (DFO) FAL	14	l
Coal B300	49	kg
Natural gas B300	196	m3

Electricity/heat

Energy US I	167	kWh

Emissions to air

Particulates	265.3	g
Zinc	145.1	g
Lead	0.6	g
Sulfur oxides	94.7	g
Carbon monoxide	366.9	g
Nitrogen oxides	659.4	g
Methane	174.1	g
Carbon dioxide	684.2	kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	0.6	µg

Final waste flows

Residues	16.81	kg
Slags and ashes	160.08	kg
Slags and ashes	23.45	kg

AROMATIC OILS (1 kg)
Source – American Petroleum Institute [75]

Materials/fuels

Oil light B300	1	kg

Electricity/heat

Electricity from gas B250	0.25	MJ
Electricity from oil B250	1.9	MJ
Energy US I	0.03	MJ

STEARIC ACID (1 kg)
Source – EcoInvent Database and Wootthikanokkhan [78, 79]

Resources

Energy, potential (in hydropower reservoir), converted	534.9	kJ
Uranium ore, 1.11 GJ per kg, in ground	1.2	mg
Wood (16.9 MJ/kg)	297.3	mg

Materials/fuels

Coal B300	29.7	g
Crude oil I	57.8	g
Crude lignite	4.6	g
Energy US I	20.4	dm3

Emissions to air

Ammonia	419.2	µg
Benzene	821.5	µg
Cadmium	12.7	µg
Carbon monoxide	71.0	mg
Carbon dioxide	281.2	g
Hydrocarbons, aromatic	2.0	mg
Hydrocarbons, chlorinated	31.8	ng
Particulates	160.2	mg
Methane, bromotrifluoro-, Halon 1301	13.8	µg
Hydrogen chloride	15.0	mg
Hydrogen fluoride	1.6	mg
Mercury	3.3	µg
Metals, unspecified	9.2	mg
Methane	531.3	mg
Manganese	37.8	µg
Dinitrogen monoxide	4.7	mg
Nickel	1.0	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	468.1	mg
Nitrogen oxides	623.0	mg
PAH, polycyclic aromatic hydrocarbons	11.7	µg
Antimony	115.7	µg
Sulfur oxides	2.1	g
Zinc	95.2	µg
Radioactive species, unspecified	105910.0	Bq

Emissions to water

Aluminum	47.7	mg
Solved substances, inorganic	1.3	g
AOX, Adsorbable Organic Halogen as Cl	10.0	µg
Arsenic	97.9	µg
Barium	11.0	mg
BOD5, Biological Oxygen Demand	133.5	µg
Cadmium	5.6	µg
Chloride	1.9	g
COD, Chemical Oxygen Demand	2.4	mg
Chromium	501.1	µg
Copper	243.0	µg
Hydrocarbons, aromatic	2.5	mg
Hydrocarbons, chlorinated	2.8	µg
Cyanide	16.0	µg
DOC, Dissolved Organic Carbon	255.4	µg
Iron	20.6	mg
Mercury	147.7	ng
Kjeldahl-N	281.2	µg
Metallic ions, unspecified	22.6	mg
Ammonium, ion	3.2	mg
Nickel	216.3	µg
Nitrate	2.9	mg
Nitrogen, total	2.8	mg
Oils, unspecified	77.1	mg
PAH, polycyclic aromatic hydrocarbons	37.6	µg
Lead	262.6	µg
Phenols, unspecified	418.3	µg
Phosphate	2.9	mg
Sulfate	363.1	mg
Sulfide	92.6	µg
Suspended substances, unspecified	184.2	mg
TOC, Total Organic Carbon	39.6	mg
Toluene	344.4	µg

Zinc	503.7	µg
Radioactive species, unspecified	970.1	Bq

COATED WIRES (1 kg)
Source – EcoInvent and IDEMAT databases [78, 91]

Resources		
Additives	396.2	mg
Silver, in ground	427.5	µg
Air	-1502.3	mg
Baryte, in ground	15.9	mg
Baryte, in ground	656.6	mg
Bauxite, in ground	34.7	g
Clay, bentonite, in ground	15.2	g
Chromium ore, in ground	11.7	g
Coal etc., extracted for use	-87.5	g
Cobalt, in ground	61.1	ng
Cobalt ore, in ground	396.6	pg
Copper ore, in ground	142.1	mg
Energy, unspecified	10.1	kJ
Energy, from hydro power	61.5	kJ
Filler	175.8	mg
Land use II-III	104.8	cm2a
Land use II-IV	1081.9	mm2a
Gas, off-gas, oil production, in ground	127.4	cm3
Iron, 46% in ore, 25% in crude ore, in ground	3.5	lb
Iron ore, in ground	-72.6	g
Gravel, in ground	57.7	g
Lead ore, in ground	263.7	mg
Coal, brown (lignite)	38.3	g
Coal, brown (lignite)	137.7	g
Limestone, in ground	-6.5	g
Manganese ore, in ground	14.6	g
Marl, in ground	223.2	g
Methane	13.5	g
Molybdenum, in ground	34.1	pg
Molybdenum ore, in ground	166.1	pg
Nickel ore, in ground	10.4	mg
Palladium, in ground	20.0	ng
Gas, petroleum, 35 MJ per m3, in ground	9.1	dm3
Pitch, in ground	1.5	g
Platinum, in ground	22.8	ng
Energy, potential (in hydropower reservoir), converted	2.6	MJ
Energy, potential (in hydropower reservoir), converted	937.0	kJ
Rhenium, in ground	20.6	ng
Volume occupied, reservoir	0.0	m3y
Rhenium, in ground	5.1	pg
Rhodium, in ground	7.7	pg
Rhodium, in ground	21.3	ng
Sodium chloride, in ground	302.9	mg
Sand, unspecified, in ground	1.7	g
Sulfur dioxide, secondary	3.0	g
Tin ore, in ground	235.6	µg
Water, turbine use, unspecified natural origin	1291.5	gal*
Energy, unspecified	-93.2	kJ
Uranium ore, 1.11 GJ per kg, in ground	40.1	mg
Uranium, in ground	3.1	µg
Waste, from anode production	1.6	g
Water, unspecified natural origin/kg	31.5	kg
Water, unspecified natural origin/m3	677.3	mm3
Wood (16.9 MJ/kg)	16.5	g
Wood and wood waste, 9.5 MJ per kg	31.6	mg
Zeolite, in ground	176.2	µg
Zinc ore, in ground	4.2	g
Land use II-III	486.6	cm2a
Land use III-IV	36.0	mm2a
Land use II-IV	71.0	mm2a
Land use IV-IV	40.7	mm2a
Land use III-IV	49.2	cm2a
Land use II-IV	52.6	cm2a
	0.0	
Materials/fuels	0.0	
Coal mix D S	3.8	lb
Crude oil I	384.9	g
Natural gas B300	3.1	g
Natural gas FAL	160.4	dm3
	0.0	
Emissions to air	0.0	
Ethane, 1,2-dichloro-	823.0	ng
Acetaldehyde	303.3	µg
Acetic acid	1384.2	µg
Acetone	300.9	µg
Acrolein	67.3	ng
Silver-110	4.0	µBq
Aluminum	23.4	mg
Aldehydes, unspecified	2.1	mg
Hydrocarbons, aliphatic, alkanes, unspecified	193.6	µg
Hydrocarbons, aliphatic, alkanes, unspecified	2.6	mg
Hydrocarbons, aliphatic, alkanes,	2.1	mg

unspecified		
Hydrocarbons, aliphatic, alkenes, unspecified	65.4	µg
Hydrocarbons, aliphatic, alkenes, unspecified	2.4	µg
Hydrocarbons, aliphatic, alkenes, unspecified	1.6	mg
Americium-241	75.4	µBq
Ammonia	12.9	mg
Argon-41	8.8	Bq
Arsenic	288.0	µg
Boron	6.4	mg
Barium	283.3	µg
Barium-140	15.8	µBq
Beryllium	3.5	µg
Benzaldehyde	13.8	ng
Benzene	9.1	mg
Benzo(a)pyrene	143.3	µg
Radioactive species, unspecified	508.8	nBq
Bromine	748.4	µg
Butane	12.1	mg
Butene	345.7	pg
Carbon-14	6.1	Bq
Ethane, hexafluoro-, HFC-116	376.8	µg
Calcium	68.8	mg
Cadmium oxide	1.2	µg
Carbon black	-14.0	mg
Cadmium	552.9	µg
Cerium-141	375.8	nBq
Cerium-144	801.7	µBq
Methane, tetrafluoro-, CFC-14	3.4	mg
Ethane, hexafluoro-, HFC-116	1174.0	ng
Methane, tetrafluoro-, CFC-14	9.4	µg
Chlorine	8.9	µg
Curium-242	0.4	nBq
Curium-244	3.6	nBq
Curium alpha	120.2	µBq
Carbon monoxide	40.2	g
Carbon dioxide	7.6	lb
Carbon dioxide, fossil	141.3	g
Carbon dioxide, biogenic	35.2	mg
Cobalt-57	6.9	nBq
Cobalt-58	115.1	µBq
Cobalt-60	171.5	µBq
Cobalt	322.6	µg
Chromium	701.0	µg
Chromium-51	14.2	µBq
Cesium-134	2.9	mBq
Cesium-137	5.5	mBq
Copper	2.1	mg
Hydrocarbons, unspecified	-1402.0	mg

Hydrocarbons, unspecified	1.6	µg
Hydrocarbons, aromatic	8.1	mg
Hydrocarbons, aromatic	244.1	ng
Hydrocarbons, aromatic	159.9	µg
Hydrocarbons, chlorinated	764.6	ng
Cyanide compounds	455.0	µg
Methane, dichlorofluoro-, HCFC-21	37.4	µg
Ethane, dichloro-	11.0	µg
Methane, dichloro-, HCC-30	6.5	µg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.5	ng
Particulates	720.6	mg
Particulates, > 10 um	-399.7	mg
Particulates, SPM	-29.0	mg
Particulates, < 10 um (mobile)	88.8	mg
Particulates, > 10 um (process)	12.4	g
Particulates, < 10 um (stationary)	481.1	mg
Ethane	19.4	mg
Ethanol	604.0	µg
Ethene	24.6	mg
Benzene, ethyl-	961.7	µg
Ethyne	903.7	µg
Fluorine	-82.2	µg
Iron	104.6	mg
Iron-59	157.5	nBq
Fluoranthene	-26.0	µg
Formaldehyde	2.0	mg
Hydrogen sulfide	65.6	mg
Sulfuric acid	229.4	µg
Hydrogen-3, Tritium	62.5	Bq
Methane, bromotrifluoro-, Halon 1301	100.9	µg
Methane, chlorodifluoro-, HCFC-22	735.2	ng
Hydrogen chloride	244.7	mg
Helium	9.2	mg
Heptane	2.4	mg
Benzene, hexachloro-	512.5	pg
Hexane	5.1	mg
Hydrogen fluoride	38.5	mg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	0.0	pg
Mercury	144.1	µg
Iodine	301.9	µg
Iodine-129	21.6	mBq
Iodine-131	2.4	mBq
Iodine-133	1342.0	µBq
Iodine-135	2.0	mBq
Potassium	271.2	mg
Potassium-40	19.8	mBq
Kerosene	602.5	ng
Krypton-85	371.1	kBq

Krypton-85m	439.9	mBq
Krypton-87	196.1	mBq
Krypton-88	17.5	Bq
Krypton-89	137.7	mBq
Lanthanum	9.7	µg
Lanthanum-140	10.0	µBq
Radon-222	533.3	kBq
Metals, unspecified	38.1	mg
Methane	14.4	g
Methanol	707.6	µg
Magnesium	11.6	mg
Manganese	70.8	mg
Manganese-54	4.1	µBq
Molybdenum	49.7	µg
t-Butyl methyl ether	632.0	ng
Nitrogen	14.0	mg
Dinitrogen monoxide	28.8	mg
Sodium	3.6	mg
Naphthalene	40.8	ng
Niobium-95	727.0	nBq
Nickel	15.2	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	82.7	mg
N-Nitrodimethylamine	5.8	ng
NMVOC, non-methane volatile organic compounds, unspecified origin	2.1	g
NMVOC, non-methane volatile organic compounds, unspecified origin	1378.3	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	214.7	mg
Nitrogen oxides	288.9	mg
Nitrogen oxides	6.4	g
Neptunium-237	4.0	nBq
Organic substances, unspecified	1.8	mg
Phosphorus	322.0	µg
Protactinium-234	2.4	mBq
PAH, polycyclic aromatic hydrocarbons	55.9	µg
PAH, polycyclic aromatic hydrocarbons	155.4	ng
PAH, polycyclic aromatic hydrocarbons	856.3	µg
Particulates	14.8	mg
Lead	12.4	mg
Lead-210	97.0	mBq
Benzene, pentachloro-	1365.9	pg
Phenol, pentachloro-	220.6	pg
Pentane	15.2	mg
Phenol	8.4	µg
Promethium-147	2.0	mBq
Polonium-210	155.0	mBq
Propane	16.9	mg
Propene	2.1	mg
Propionic acid	24.5	µg
Platinum	31.1	ng
Plutonium-238	9.0	nBq
Plutonium-241	6.6	mBq
Plutonium-alpha	239.2	µBq
Methane, trichlorofluoro-, CFC-11	3.1	µg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	81.9	µg
Methane, dichlorodifluoro-, CFC-12	667.5	ng
Methane, chlorotrifluoro-, CFC-13	418.9	ng
Radium-226	93.2	mBq
Radium-228	9.8	mBq
Noble gases, radioactive, unspecified	526.3	mBq
Radon-220	688537.3	mBq
Radon-222	5.8	kBq
Ruthenium-103	41.1	nBq
Ruthenium-106	23.9	mBq
Antimony	49.4	µg
Antimony-124	1111.0	nBq
Antimony-125	141.2	nBq
Scandium	3.5	µg
Selenium	4.5	mg
Silicates, unspecified	47.6	mg
Tin	4.1	µg
Sulfur dioxide	170.5	mg
Sulfur oxides	149.7	mg
Sulfur oxides	15.2	g
Strontium	328.2	µg
Strontium-89	7.2	µBq
Strontium-90	4.0	mBq
Tar	2.5	mg
Technetium-99	168.0	nBq
Tellurium-123m	18.1	µBq
Ethene, tetrachloro-	26.9	ng
Methane, tetrachloro-, CFC-10	3.8	µg
Thorium	5.7	µg
Thorium-228	8.3	mBq
Thorium-230	26.6	mBq
Thorium-232	5.3	mBq
Thorium-234	2.4	mBq
Titanium	838.9	µg
Thallium	1.9	µg
Toluene	2.7	mg
Ethene, trichloro-	26.0	ng
Chloroform	289.8	ng

Uranium	4.9	µg
Uranium-234	28.7	mBq
Uranium-235	1388.7	µBq
Uranium-238	43.4	mBq
Uranium alpha	85.9	mBq
Unspecified emission	-11.3	mg
Vanadium	5.9	mg
Ethene, chloro-	2.3	µg
Heat, waste	26.6	MJ
Xenon-131m	904.4	mBq
Xenon-133	267.2	Bq
Xenon-133m	134.2	mBq
Xenon-135	45.5	Bq
Xenon-135m	4.5	Bq
Xenon-137	111.2	mBq
Xenon-138	1213.7	mBq
Xylene	4.7	mg
Zinc oxide	296.1	µg
Zinc	37.2	mg
Zinc-65	17.6	µBq
Zirconium	19.8	µg
Zirconium-95	262.6	nBq
Heat, waste	593.4	kJ
Radioactive species, unspecified	2634.3	kBq
	0.0	
Emissions to water	0.0	
Ethane, 1,1,1-trichloro-, HCFC-140	7.3	ng
Acenaphthylene	52.5	µg
Acidity, unspecified	3.7	µg
Acids, unspecified	5.0	mg
Silver	108.7	µg
Silver-110	27.7	mBq
Silver	2.8	g
Hydrocarbons, aliphatic, alkanes, unspecified	17.4	µg
Hydrocarbons, aliphatic, alkanes, unspecified	103.9	µg
Hydrocarbons, aliphatic, alkanes, unspecified	767.8	µg
Hydrocarbons, aliphatic, alkenes, unspecified	1581.5	ng
Hydrocarbons, aliphatic, alkenes, unspecified	9.6	µg
Hydrocarbons, aliphatic, alkenes, unspecified	70.9	µg
Radioactive species, alpha emitters	3.3	µBq
Americium-241	9.9	mBq
Ammonia, as N	39.0	mg
Solved substances, inorganic	4.9	g
AOX, Adsorbable Organic Halogen as Cl	60.8	µg
Arsenic	5.7	mg
Boron	2.4	mg
Barium	265.5	mg
Barium-140	49.8	µBq
Barite	134.0	mg
Beryllium	1003.5	ng
Benzene	897.6	µg
Adipate, bis(2-ethylhexyl)-	555.1	pg
BOD5, Biological Oxygen Demand	1.3	mg
BOD5, Biological Oxygen Demand	169.3	mg
Carbon-14	503.0	mBq
Calcium, ion	2.0	g
Calcium compounds, unspecified	19.2	mg
Cadmium	280.9	µg
Cadmium-109	288.2	nBq
Cerium-141	7.4	µBq
Cerium-144	227.6	mBq
Chloroform	3.4	µg
Chlorinated solvents, unspecified	173.8	µg
Benzene, chloro-	30.8	pg
Chromate	565.4	ng
Chloride	27.3	g
Chlorine	2.3	mg
Curium alpha	13.2	mBq
Cobalt	56.3	µg
Cobalt-57	51.1	µBq
Cobalt-58	43.2	mBq
Cobalt-60	2.2	Bq
Cobalt	5.1	mg
COD, Chemical Oxygen Demand	161.4	mg
Chromium	32.5	mg
Chromium, ion	62.3	ng
Chromium VI	684.9	ng
Chromium-51	1099.3	µBq
Crude oil	-100.0	µg
Cesium	6.8	µg
Cesium-134	508.7	mBq
Cesium-136	267.2	nBq
Cesium-137	4.7	Bq
Copper	2.0	g
Hydrocarbons, unspecified	3.1	mg
Hydrocarbons, aromatic	9.0	mg
Hydrocarbons, chlorinated	10.8	µg
Hydrocarbons, aromatic	819.6	µg
Hydrocarbons, aromatic	3.7	mg
Cyanide	6.6	mg
Phthalate, dibutyl-	5.3	ng
Ethane, dichloro-	6.1	µg
Phthalate, dimethyl-	33.5	ng
Solved organics	31.4	µg
Solved solids	202.1	mg

Solved substances	1043.6	mg
DOC, Dissolved Organic Carbon	2.2	mg
Benzene, ethyl-	3.2	µg
Benzene, ethyl-	159.2	µg
Fluoride	266.0	mg
Fluorine	-7.5	mg
Oils, unspecified	141.7	mg
Fatty acids as C	33.7	mg
Iron	9.1	g
Iron-59	882.2	nBq
VOC, volatile organic compounds, unspecified origin	2.3	mg
Fluoride	55.3	µg
Fluorine	77.9	ng
Formaldehyde	191.3	ng
Glutaraldehyde	16.5	µg
Hydrogen sulfide	2.0	mg
Sulfuric acid	39.9	µg
Hydrogen-3, Tritium	14.9	kBq
Ethane, hexachloro-	125.0	pg
Mercury	76.3	µg
Hypochlorous acid	1.8	mg
Iodide	678.1	µg
Iodine-129	1435.4	mBq
Iodine-131	953.4	µBq
Iodine-133	227.6	µBq
Potassium	799.0	mg
Potassium-40	41.5	mBq
Kjeldahl-N	1095.4	µg
Lanthanum-140	10.3	µBq
Metallic ions, unspecified	90.4	mg
Methane, dichloro-, HCC-30	60.0	µg
Magnesium	2.1	g
Manganese	53.4	mg
Manganese-54	336.9	mBq
Molybdenum	6.7	mg
Molybdenum-99	3.5	µBq
t-Butyl methyl ether	55.8	ng
Nitrogen, total	8.6	mg
Nitrogen, organic bound	945.1	µg
Sodium, ion	4.7	g
Sodium-24	1.5	mBq
Niobium-95	28.2	µBq
Ammonia	88.9	µg
Ammonium, ion	15.3	mg
Nickel	16.1	mg
Nitrate	27.2	mg
Nitrite	914.0	µg
Neptunium-237	634.8	µBq
Nitrogen, total	10.8	mg
Radioactive species, unspecified	21.5	µBq

Hypochlorite	1.6	mg
Oils, unspecified	279.4	mg
Organic substances, unspecified	491.3	µg
Protactinium-234	44.3	mBq
PAH, polycyclic aromatic hydrocarbons	371.9	µg
PAH, polycyclic aromatic hydrocarbons	76.8	µg
Lead	240.7	mg
Lead-210	33.1	mBq
Phosphorus compounds, unspecified	16.1	µg
Phenol	24.1	µg
Phenols, unspecified	10.6	mg
Phosphate	203.6	mg
Polonium-210	33.1	mBq
Phosphorus, total	31.8	ng
Plutonium-241	981.4	mBq
Plutonium-alpha	39.6	mBq
Radium-224	332.5	mBq
Radium-226	183.8	Bq
Radium-228	664.9	mBq
Ruthenium	66.9	µg
Ruthenium-103	16.7	µBq
Ruthenium-106	2.4	Bq
Sulfur	4.1	µg
Salts, unspecified	49.3	mg
Salts, unspecified	763.1	mg
Antimony	109.3	µg
Antimony-122	49.8	µBq
Antimony-124	7.1	mBq
Antimony-125	406.1	µBq
Selenium	12.8	mg
Silicon	169.4	µg
Tin	2.5	µg
Sulfur trioxide	202.6	µg
Strontium	71.3	mg
Strontium-89	112.7	µBq
Strontium-90	478.5	mBq
Sulfate	4.2	g
Sulfate	12.8	g
Sulfide	719.4	µg
Suspended solids, unspecified	34.5	mg
Suspended substances, unspecified	727.0	mg
Technetium-99	250.9	mBq
Technetium-99m	23.6	µBq
Tellurium-123m	2.1	µBq
Tellurium-132	861.2	nBq
Ethene, tetrachloro-	14.8	ng
Methane, tetrachloro-, CFC-10	22.8	ng

Thorium-228	1327.6	mBq
Thorium-230	6.9	Bq
Thorium-232	7.8	mBq
Thorium-234	44.8	mBq
Titanium	152.7	mg
Titanium dioxide	155.7	ng
TOC, Total Organic Carbon	402.3	mg
Toluene	2.0	mg
Tributyltin	128.9	µg
Ethene, trichloro-	1011.2	ng
Triethylene glycol	752.5	µg
Uranium-234	59.3	mBq
Uranium-235	88.3	mBq
Uranium-238	152.9	mBq
Uranium alpha	2.9	Bq
Undissolved substances	1007.4	mg
Emission, unspecified	9.7	mg
Vanadium	12.9	mg
Ethene, chloro-	4.2	ng
Tungsten	15.0	µg
Heat, waste	-38.0	kJ
Waste water/m3	4.4	cm3
Xylene	643.7	µg
Yttrium-90	5.8	µBq
Zinc	2.5	g
Zinc-65	3.3	mBq
Zirconium-95	20.3	mBq
Heat, waste	11.8	kJ
Radioactive species, unspecified	24.2	kBq
	0.0	
Emissions to soil	0.0	

Aluminum	8.6	mg
Arsenic	3.4	µg
Carbon	26.6	mg
Calcium	34.5	mg
Cadmium	265.1	ng
Cobalt	181.1	ng
Chromium	43.0	µg
Copper	904.5	ng
Iron	17.2	mg
Mercury	79.5	ng
Manganese	344.7	µg
Nitrogen	64.8	µg
Nickel	1355.5	ng
Oils, unspecified	6.1	mg
Oils, biogenic	229.8	µg
Phosphorus	750.8	µg
Lead	4.2	µg
Sulfur	5.2	mg
Heat, waste	28.4	kJ
Zinc	137.9	µg
Heat, waste	21.4	kJ
	0.0	
Final waste flows	0.0	
Chemical waste, unspecified	21.1	mg
Waste, final, inert	15.2	g
Waste, nuclear, high active/m3	0.2	mm3
Waste, nuclear, low and medium active/m3	10.2	mm3
Production waste	-32.1	g
Waste, solid	773.6	mg
Steel waste	2.6	g

TEXTILES (1 kg)
Source – EcoInvent and IDEMAT [78, 91]

Resources		
Silver, in ground	473.9	µg
Air	305.3	g
Artificial fertilizer	128.2	mg
Baryte, in ground	-19.8	mg
Baryte, in ground	664.6	mg
Bauxite, in ground	860.5	mg
Clay, bentonite, in ground	83.6	mg
Biomass	38.8	g
Chromium ore, in ground	1.5	mg
Other minerals, extracted for use	3.3	mg
Coal, 29.3 MJ per kg, in ground	494.8	g
Cobalt, in ground	8.6	ng
Cobalt ore, in ground	-522.3	pg
Copper ore, in ground	24.4	mg
Oil, crude, 41 MJ per kg, in ground	558.3	g

Dolomite, in ground	2.4	mg
Energy, unspecified	19.6	kJ
Energy, from coal	4.6	MJ
Energy, from hydro power	108.1	kJ
Energy, from hydrogen	395.9	kJ
Energy, from coal, brown	472.1	kJ
Energy, from gas, natural	16.6	MJ
Energy, from oil	8.0	MJ
Energy, from sulfur	28.3	kJ
Energy, from uranium	2.1	MJ
Energy, from wood	217.6	J
Energy, recovered	-1.0	MJ
Field latex	23.8	g
Land use II-III	105.8	cm2a
Land use II-IV	1088.2	mm2a
Fluorspar, in ground	435.1	µg

Gas, off-gas, oil production, in ground	-173.9	cm3
Gypsum, in ground	2.6	mg
Ilmenite, in ground	8.7	g
Iron, 46% in ore, 25% in crude ore, in ground	1196.7	mg
Iron ore, in ground	-4.7	g
Potassium chloride	15.5	mg
Gravel, in ground	3.5	g
Lead ore, in ground	3.5	mg
Coal, brown (lignite)	424.8	g
Coal, brown (lignite)	31.2	g
Limestone, in ground	26.1	g
Manganese ore, in ground	348.4	µg
Marl, in ground	630.2	mg
Methane	69.3	mg
Molybdenum, in ground	294.8	ng
Molybdenum ore, in ground	-199.8	pg
Sodium chloride, in ground	5.2	g
Gas, natural, 36.6 MJ per m3, in ground	1111.7	dm3
Gas, natural, 30.3 MJ per kg, in ground	205.8	mg
Nickel ore, in ground	1017.4	µg
Nitrogen, in air	39.2	g
Olivine, in ground	1.7	mg
Oxygen, in air	145.8	mg
Palladium, in ground	1.2	µg
Gas, petroleum, 35 MJ per m3, in ground	10.3	dm3
Platinum, in ground	1.4	µg
Energy, potential (in hydropower reservoir), converted	4.5	MJ
Energy, potential (in hydropower reservoir), converted	138.1	kJ
Water, process and cooling, unspecified natural origin	668.8	cm3
Rhenium, in ground	1.0	µg
Volume occupied, reservoir	0.0	m3y
Rhenium, in ground	-5.2	pg
Rhodium, in ground	-7.7	pg
Rhodium, in ground	1.3	µg
Sodium chloride, in ground	87.6	g
Rutile, in ground	184.9	mg
Sand, unspecified, in ground	486.5	mg
Sand and clay, unspecified, in ground	24.8	mg
Shale, in ground	7.2	mg
Silver, in ground	80.0	µg
Sulfur dioxide, secondary	117.8	g
Sodium dichromate, in ground	113.3	µg
Sulfur, bonded	1.6	g
Sulfur, in ground	3.0	g
Tin ore, in ground	257.1	µg
Water, turbine use, unspecified natural origin	727.7	dm3
Energy, unspecified	-8.6	kJ
Uranium ore, 1.11 GJ per kg, in ground	50.3	mg
Water, unspecified natural origin/kg	5.3	lb
Water, cooling, unspecified natural origin/kg	15.9	kg
Water, process, drinking	37.0	kg
Water, process, unspecified natural origin/kg	76.1	g
Water, cooling, salt, ocean	16.3	kg
Water, process, salt, ocean	104.4	g
Water, unspecified natural origin/m3	262.9	cm3
Water, cooling, well, in ground	4.8	g
Water, process, well, in ground	93.6	mg
Wood (16.9 MJ/kg)	214.2	g
Wood, feedstock	373.1	g
Wood and wood waste, 9.5 MJ per kg	1.9	mg
Zeolite, in ground	-240.8	µg
Zinc ore, in ground	5.5	mg
Land use II-III	-39.0	cm2a
Land use III-IV	-263.6	mm2a
Land use II-IV	-256.7	mm2a
Land use IV-IV	-35.0	mm2a

Emissions to air

Ethane, 1,1,1-trichloro-, HCFC-140	259.5	µg
Ethane, 1,2-dichloro-	-276.5	ng
1,4-Dioxane	217.6	µg
Acetaldehyde	4.4	mg
Acetic acid	374.3	µg
Acetone	92.2	µg
Acrolein	8.0	ng
Silver	3.2	µg
Silver-110	873.4	nBq
Aluminum	715.5	µg
Aldehydes, unspecified	551.3	mg
Hydrocarbons, aliphatic, alkanes, unspecified	-264.7	µg
Hydrocarbons, aliphatic, alkanes, unspecified	2.9	mg
Hydrocarbons, aliphatic, alkanes, unspecified	618.5	µg
Hydrocarbons, aliphatic, alkenes, unspecified	-89.4	µg
Hydrocarbons, aliphatic, alkenes, unspecified	500.3	ng

Hydrocarbons, aliphatic, alkenes, unspecified	159.0	µg
Americium-241	16.3	µBq
Ammonia	155.4	mg
Argon-41	1.9	Bq
Arsenic	41.8	µg
Boron	518.3	µg
Barium	13.3	µg
Barium-140	3.4	µBq
Beryllium	1.2	µg
Benzaldehyde	-0.4	ng
Benzene	67.3	mg
Benzo(a)pyrene	-6.1	ng
Radioactive species, other beta emitters	109.6	nBq
Bromine	77.8	µg
Butane	12.8	mg
Butene	279.9	µg
Carbon-14	1.3	Bq
Ethane, hexafluoro-, HFC-116	634.7	ng
Calcium	1.5	mg
Carbon black	-0.8	mg
Cadmium	135.0	µg
Cerium-141	81.6	nBq
Cerium-144	173.7	µBq
Methane, tetrafluoro-, CFC-14	5.7	µg
Chlorinated fluorocarbons, soft	21.8	µg
Ethane, hexafluoro-, HFC-116	-1090.6	ng
Methane, tetrafluoro-, CFC-14	-6.0	µg
Phenol, chloro-	259.5	ng
Chlorine	194.1	µg
Curium-242	0.1	nBq
Curium-244	0.8	nBq
Curium alpha	25.9	µBq
Carbon monoxide	5.9	g
Carbon dioxide	6.3	kg
Carbon dioxide, fossil	8.7	g
Carbon dioxide, biogenic	2.1	mg
Cobalt-57	1.5	nBq
Cobalt-58	24.9	µBq
Cobalt-60	37.1	µBq
Cobalt	97.6	µg
Chromium	481.1	µg
Chromium-51	3.1	µBq
Cesium-134	619.8	µBq
Cesium-137	1.2	mBq
Carbon disulfide	36.9	g
Copper	243.0	µg
Hydrocarbons, unspecified	1.7	g
Hydrocarbons, unspecified	69.4	mg
Hydrocarbons, aromatic	91.2	mg
Hydrocarbons, aromatic	50.0	ng
Hydrocarbons, aromatic	93.4	µg
Hydrocarbons, chlorinated	22.9	µg
Hydrocarbons, halogenated	202.4	ng
Hydrocarbons, unspecified	26.8	µg
Hydrocarbons, unspecified	17.2	µg
Cyanide compounds	429.6	ng
Methane, dichlorofluoro-, HCFC-21	4.5	µg
Ethane, dichloro-	2.9	µg
Methane, dichloro-, HCC-30	142.0	ng
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	125.9	pg
Biphenyl	775.1	µg
Particulates	3.5	g
Particulates, > 10 um	-124.1	mg
Particulates, SPM	2.2	g
Particulates, < 10 um (mobile)	8.1	mg
Particulates, > 10 um (process)	55.0	mg
Particulates, < 10 um (stationary)	133.1	mg
Esters, unspecified	3.8	mg
Ethane	2.9	mg
Ethanol	187.5	µg
Ethene	16.4	mg
Benzene, ethyl-	581.6	µg
Ethylene glycol	44.2	µg
Ethylene oxide	138.1	µg
Ethyne	1062.4	ng
Fluorine	17.2	µg
Iron	1011.3	µg
Iron-59	34.0	nBq
Fluoranthene	-1.4	µg
Formaldehyde	1.4	mg
Hydrogen	110.9	mg
Hydrogen sulfide	1.4	g
Sulfuric acid	21.8	µg
Hydrogen-3, Tritium	13.6	Bq
Methane, bromotrifluoro-, Halon 1301	120.2	µg
Methane, chlorodifluoro-, HCFC-22	159.2	ng
Hydrogen chloride	453.8	mg
Helium	10.4	mg
Heavy metals, unspecified	3.5	mg
Heptane	2.6	mg
Benzene, hexachloro-	116.3	pg
Biphenyl, hexachloro-	21.2	µg
Hexane	6.7	mg
Hydrogen fluoride	34.4	mg
Mercury	143.7	µg
Iodine	33.9	µg
Iodine-129	4.7	mBq
Iodine-131	516.9	µBq

Iodine-133	289.7	µBq
Iodine-135	434.1	µBq
Potassium	293.6	µg
Potassium-40	2.5	mBq
Kerosene	229.5	ng
Krypton-85	80.1	kBq
Krypton-85m	94.6	mBq
Krypton-87	42.4	mBq
Krypton-88	3.8	Bq
Krypton-89	29.7	mBq
Lanthanum	387.1	ng
Lanthanum-140	2.2	µBq
Radon-222	115.2	kBq
Mercaptans, unspecified	11.4	mg
Metals, unspecified	94.2	mg
Methane	17.5	g
Methanol	161.3	mg
Acetic acid, methyl ester	100.3	mg
Methyl formate	876.3	mg
Methyl mercaptan	1.6	µg
Magnesium	245.6	µg
Manganese	584.9	µg
Manganese-54	889.0	nBq
Molybdenum	81.8	µg
t-Butyl methyl ether	136.1	ng
Nitrogen	1.2	mg
Dinitrogen monoxide	3.3	g
Sodium	1568.5	µg
Naphthalene	2.6	ng
Niobium-95	157.2	nBq
Nickel	5.8	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	5.0	mg
N-Nitrodimethylamine	1.9	ng
Nitrogen dioxide	4.5	g
NMVOC, non-methane volatile organic compounds, unspecified origin	3.2	g
NMVOC, non-methane volatile organic compounds, unspecified origin	1120.8	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	19.6	mg
Nitrogen oxides	7.5	g
Nitrogen oxides	9.4	g
Neptunium-237	0.9	nBq
Oxygen	54.6	g
Mineral oil	178.8	mg
Organic substances, unspecified	48.5	mg
Phosphorus	23.6	µg

Protactinium-234	518.2	µBq
PAH, polycyclic aromatic hydrocarbons	387.5	µg
PAH, polycyclic aromatic hydrocarbons	24.2	ng
PAH, polycyclic aromatic hydrocarbons	4.0	µg
Particulates	12.3	mg
Lead	872.7	µg
Lead-210	14.4	mBq
Polychlorinated biphenyls	589.8	ng
Benzene, pentachloro-	310.0	pg
Phenol, pentachloro-	44.9	ng
Pentane	17.0	mg
Phenol	152.8	ng
Promethium-147	440.3	µBq
Polonium-210	21.5	mBq
Propane	13.3	mg
Propene	6.0	mg
Propionic acid	0.8	µg
Platinum	7.8	ng
Plutonium-238	1.9	nBq
Plutonium-241	1.4	mBq
Plutonium-alpha	51.8	µBq
Methane, trichlorofluoro-, CFC-11	671.1	ng
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	17.7	µg
Methane, dichlorodifluoro-, CFC-12	144.4	ng
Methane, chlorotrifluoro-, CFC-13	90.5	ng
Radium-226	18.5	mBq
Radium-228	1.2	mBq
Noble gases, radioactive, unspecified	113.5	mBq
Radon-220	113.6	mBq
Radon-222	1255.0	Bq
Ruthenium-103	8.9	nBq
Ruthenium-106	5.2	mBq
Sulfur, total reduced	666.3	mg
Antimony	12.1	µg
Antimony-124	240.5	nBq
Antimony-125	30.6	nBq
Scandium	113.6	ng
Selenium	33.2	µg
Silicates, unspecified	3.5	mg
Tin	235.1	ng
Sulfur hexafluoride	2.8	g
Sulfur oxides	6.4	g
Sulfur oxides	20.8	g
Strontium	10.6	µg
Strontium-89	1.6	µBq
Strontium-90	856.7	µBq

Styrene	77.8	µg
Technetium-99	36.3	nBq
Tellurium-123m	3.9	µBq
Ethene, tetrachloro-	8.8	ng
Methane, tetrachloro-, CFC-10	708.8	ng
Thorium	-344.4	ng
Thorium-228	1017.8	µBq
Thorium-230	5.8	mBq
Thorium-232	645.5	µBq
Thorium-234	518.2	µBq
Titanium	30.9	µg
Thallium	147.7	ng
Toluene	3.5	mg
Ethene, trichloro-	1.3	mg
Chloroform	75.5	ng
Uranium	175.5	ng
Uranium-234	6.2	mBq
Uranium-235	300.8	µBq
Uranium-238	8.0	mBq
Uranium alpha	18.6	mBq
Unspecified emission	-629.1	µg
Vanadium	5.2	mg
Ethene, chloro-	307.3	ng
Heat, waste	4.9	MJ
water	218.9	g
Xenon-131m	196.0	mBq
Xenon-133	57.7	Bq
Xenon-133m	29.0	mBq
Xenon-135	9.8	Bq
Xenon-135m	968.5	mBq
Xenon-137	24.1	mBq
Xenon-138	262.8	mBq
Xylene	1279.5	µg
Zinc	1.6	mg
Zinc-65	3.8	µBq
Zirconium	17.3	ng
Zirconium-95	57.0	nBq
Heat, waste	-808.7	kJ
Radioactive species, unspecified	4172.6	kBq

Emissions to water

Ethane, 1,1,1-trichloro-, HCFC-140	1157.6	pg
Acenaphthylene	9.7	µg
Acidity, unspecified	12.8	mg
Acids, unspecified	12.1	µg
Silver	4.8	µg
Silver-110	6.0	mBq
Aluminum	803.6	mg
Hydrocarbons, aliphatic, alkanes, unspecified	-23.8	µg
Hydrocarbons, aliphatic, alkanes, unspecified	109.3	µg
Hydrocarbons, aliphatic, alkanes, unspecified	872.4	µg
Hydrocarbons, aliphatic, alkenes, unspecified	-2.2	µg
Hydrocarbons, aliphatic, alkenes, unspecified	10.1	µg
Hydrocarbons, aliphatic, alkenes, unspecified	80.5	µg
Radioactive species, alpha emitters	708.4	nBq
Americium-241	2.1	mBq
Ammonia, as N	11.3	mg
Solved substances, inorganic	8.9	g
AOX, Adsorbable Organic Halogen as Cl	113.4	mg
Arsenic	1612.2	µg
Boron	361.1	µg
Barium	113.9	mg
Barium-140	10.7	µBq
Barite	127.7	mg
Beryllium	159.8	ng
Benzene	1.4	mg
Adipate, bis(2-ethylhexyl)-	138.8	pg
BOD5, Biological Oxygen Demand	116.9	g
BOD5, Biological Oxygen Demand	3.7	mg
Carbon-14	108.7	mBq
Calcium, ion	390.5	mg
Calcium compounds, unspecified	-26.3	mg
Carbonate	26.1	mg
Cadmium	73.2	µg
Cadmium-109	61.9	nBq
Cerium-141	1.6	µBq
Cerium-144	49.2	mBq
Chloroform	897.8	ng
Chlorinated solvents, unspecified	486.7	ng
Benzene, chloro-	10.7	ng
Chromate	36.2	ng
Chloride	21.8	g
Chlorine	831.1	mg
Curium alpha	2.9	mBq
Cobalt	-43.1	µg
Cobalt-57	11.0	µBq
Cobalt-58	9.3	mBq
Cobalt-60	475.5	mBq
Cobalt	81.5	µg
COD, Chemical Oxygen Demand	3.7	lb
Chromium	8.4	mg
Chromium, ion	22.0	µg
Chromium VI	64.3	µg
Chromium-51	235.8	µBq
Crude oil	-26.3	µg

Cesium	7.4	µg
Cesium-134	109.9	mBq
Cesium-136	57.5	nBq
Cesium-137	1011.0	mBq
Copper	6.2	mg
Hydrocarbons, unspecified	14.3	mg
Hydrocarbons, aromatic	13.8	mg
Hydrocarbons, chlorinated	47.8	µg
Hydrocarbons, aromatic	437.6	µg
Hydrocarbons, aromatic	4.1	mg
Cyanide	114.9	µg
Detergent, oil	17.2	mg
Phthalate, dibutyl-	976.8	pg
Ethane, dichloro-	1.3	µg
Phthalate, dimethyl-	6.1	ng
Solved organics	500.3	mg
Solved solids	1.3	g
Solved substances	268.1	mg
DOC, Dissolved Organic Carbon	158.5	mg
Benzene, ethyl-	-4.3	µg
Benzene, ethyl-	181.1	µg
Fluoride	1113.8	µg
Fluorine	-491.7	µg
Oils, unspecified	152.9	mg
Oils, unspecified	46.7	mg
Fatty acids as C	38.2	mg
Iron	1066.8	mg
Iron-59	189.8	nBq
VOC, volatile organic compounds, unspecified origin	2.6	mg
Fluoride	-71.0	µg
Fluorine	32.2	µg
Formaldehyde	4.8	ng
Glutaraldehyde	15.8	µg
Hydrogen sulfide	1.6	ng
Sulfuric acid	7.4	µg
Hydrogen-3, Tritium	3224.1	Bq
Ethane, hexachloro-	32.7	pg
Mercury	26.9	µg
Hypochlorous acid	129.1	µg
Iodide	737.0	µg
Iodine-129	311.0	mBq
Iodine-131	205.5	µBq
Iodine-133	49.1	µBq
Potassium	42.3	mg
Potassium-40	7.8	mBq
Kjeldahl-N	1.5	mg
Lanthanum-140	2.2	µBq
Metallic ions, unspecified	197.9	mg
Methanol	775.1	µg
Methane, dichloro-, HCC-30	60.5	µg

Magnesium	35.7	mg
Manganese	1017.5	µg
Manganese-54	73.0	mBq
Molybdenum	672.5	µg
Molybdenum-99	748.9	nBq
t-Butyl methyl ether	11.2	ng
Nitrogen, total	14.4	mg
Nitrogen, organic bound	2.2	mg
Sodium, ion	4.0	g
Sodium-24	330.3	µBq
Niobium-95	6.1	µBq
Ammonia	2.6	mg
Ammonium, ion	434.4	mg
Nickel	6.1	mg
Nitrate	6.6	g
Nitrite	83.6	µg
Neptunium-237	137.3	µBq
Nitrogen, total	50.2	mg
Radioactive species, unspecified	4.6	µBq
Hypochlorite	344.5	µg
Oils, unspecified	326.9	mg
Organic substances, unspecified	4.8	mg
Phosphorus pentoxide	163.2	mg
Protactinium-234	9.6	mBq
PAH, polycyclic aromatic hydrocarbons	178.1	µg
PAH, polycyclic aromatic hydrocarbons	87.2	µg
Lead	4.9	mg
Lead-210	6.2	mBq
Phosphorus compounds, unspecified	3.8	µg
Phenol	1.9	mg
Phenols, unspecified	2.8	mg
Phosphate	47.3	mg
Polonium-210	6.2	mBq
Phosphorus, total	-43.4	ng
Plutonium-241	212.6	mBq
Plutonium-alpha	8.6	mBq
Radium-224	377.8	mBq
Radium-226	40.3	Bq
Radium-228	754.8	mBq
Ruthenium	75.5	µg
Ruthenium-103	3.6	µBq
Ruthenium-106	518.2	mBq
Sulfur	16.2	µg
Salts, unspecified	-67.5	mg
Salts, unspecified	110.4	mg
Antimony	5.7	µg
Antimony-122	10.7	µBq
Antimony-124	1.5	mBq

Antimony-125	87.3	µBq
Selenium	98.1	µg
Silicon	79.7	µg
Tin	88.8	ng
Sulfur trioxide	30.2	µg
Strontium	44.9	mg
Strontium-89	24.2	µBq
Strontium-90	103.9	mBq
Sulfate	9.9	g
Sulfate	2.2	g
Sulfide	623.2	µg
Suspended solids, unspecified	683.9	mg
Suspended substances, unspecified	3.6	g
Technetium-99	54.4	mBq
Technetium-99m	5.1	µBq
Tellurium-123m	452.0	nBq
Tellurium-132	185.1	nBq
Ethene, tetrachloro-	3.9	ng
Methane, tetrachloro-, CFC-10	5.9	ng
Thorium-228	1.5	Bq
Thorium-230	1.5	Bq
Thorium-232	1.5	mBq
Thorium-234	9.7	mBq
Titanium	1.1	mg
Titanium dioxide	490.0	µg
TOC, Total Organic Carbon	1262.2	mg
Toluene	2.7	mg
Tributyltin	14.6	µg
Ethene, trichloro-	221.9	ng
Triethylene glycol	62.8	µg
Uranium-234	12.9	mBq
Uranium-235	19.1	mBq
Uranium-238	32.5	mBq
Uranium alpha	627.1	mBq
Undissolved substances	414.1	mg
Vanadium	508.1	µg
Ethene, chloro-	1.1	ng
Tungsten	1.6	µg
Heat, waste	614.3	kJ
Waste water/m3	3.7	dm3
Xylene	845.4	µg
Yttrium-90	1.2	µBq
Zinc	485.6	mg
Zinc-65	697.5	µBq
Zirconium-95	4.4	mBq
Heat, waste	-16.2	kJ
Radioactive species, unspecified	38.3	kBq
Emissions to soil		
Aluminum	8.7	mg
Arsenic	3.5	µg
Carbon	27.1	mg
Calcium	34.9	mg
Cadmium	153.5	ng
Cobalt	206.0	ng
Chromium	43.7	µg
Copper	1029.9	ng
Iron	17.5	mg
Mercury	28.3	ng
Manganese	349.3	µg
Nitrogen	8.0	µg
Nickel	1.5	µg
Oils, unspecified	6.5	mg
Oils, biogenic	5.2	µg
Phosphorus	445.9	µg
Lead	4.7	µg
Sulfur	5.2	mg
Heat, waste	6.6	kJ
Zinc	141.5	µg
Heat, waste	590.5	J
	0.0	
Final waste flows	0.0	
Calcium fluoride waste	446.7	ng
Chemical waste, unspecified	435.2	mg
Chemical waste, inert	892.0	mg
Chemical waste, regulated	500.4	mg
Construction waste	6.3	mg
Sludge	177.1	µg
Waste, final, inert	-6.1	g
Waste, nuclear, high active/m3	-0.2	mm3
Waste, unspecified	2.4	µg
Waste, industrial	17.4	g
Waste, nuclear, low and medium active/m3	-13.0	mm3
Waste, unspecified	87.7	µg
Metal waste	13.7	mg
Mineral waste	39.2	g
Mineral waste, from mining	8.0	g
Waste, unspecified	27.4	µg
Oil waste	511.0	mg
Oil separator sludge	24.0	mg
Packaging waste, plastic	41.3	mg
Production waste, not inert	-2.0	g
Slags	27.2	g
Slags and ashes	8.3	g
Waste, solid	226.0	mg
Steel waste	172.5	mg
Mineral waste, from mining	84.0	mg
Waste, unspecified	4.8	mg
Waste in bioactive landfill	3.9	g
Waste in incineration	108.4	mg

Waste in inert landfill	2.9	mg
Waste to recycling	80.5	mg

POLYURETHANE (1 kg)
Source – Michelin and IDEMAT [91, 118]

Resources

Air	185.8	g
Animal matter	3.8	ng
Baryte, in ground	784.3	mg
Bauxite, in ground	1.0	g
Biomass	111.2	g
Calcite, in ground	0.0	pg
Calcium sulfate, in ground	5.3	mg
Chromium, in ground	6.1	mg
Clay, bentonite, in ground	93.2	mg
Clay, unspecified, in ground	90.7	mg
Coal, 18 MJ per kg, in ground	2.4	g
Coal, 29.3 MJ per kg, in ground	107.0	g
Coal, brown, 10 MJ per kg, in ground	100.5	g
Coal, brown, 8 MJ per kg, in ground	2.1	g
Cobalt, in ground	5.6	ng
Copper, in ground	2.5	mg
Dolomite, in ground	256.9	mg
Energy, from biomass	984.1	kJ
Energy, from coal	4.9	MJ
Energy, from coal, brown	262.6	kJ
Energy, from gas, natural	22.4	MJ
Energy, from hydro power	334.9	kJ
Energy, from hydrogen	431.0	kJ
Energy, from oil	21.7	MJ
Energy, from peat	812.1	J
Energy, from sulfur	11.8	kJ
Energy, from uranium	976.3	kcal
Energy, from wood	3.6	kJ
Energy, geothermal	25.1	kJ
Energy, kinetic (in wind), converted	36.0	kJ
Energy, potential (in hydropower reservoir), converted	9.3	kJ
Energy, recovered	696.8	kJ
Energy, solar	524.9	J
Energy, unspecified	5.9	MJ
Feldspar, in ground	461.0	mg
Ferromanganese	753.7	µg
Fluorspar, in ground	17.2	mg
Gas, mine, off-gas, process, coal mining/kg	15.7	mg
Gas, natural, 30.3 MJ per kg, in ground	350.2	g
Gas, natural, 35 MJ per m3, in ground	427.2	cm3
Gas, off-gas, oil production, in ground	895.5	mm3
Gas, petroleum, 35 MJ per m3, in ground	476.0	cu.in
Granite, in ground	111.3	pg
Gravel, in ground	812.1	mg
Iron ore, in ground	183.1	mg
Iron, in ground	1.4	g
Land use II-III	634.0	mm2a
Land use II-III, sea floor	79.4	cm2a
Land use II-IV	179.0	mm2a
Land use II-IV, sea floor	819.0	mm2a
Land use III-IV	144.0	mm2a
Land use IV-IV	2.0	mm2a
Lead, in ground	2.2	mg
Limestone, in ground	345.4	g
Magnesium, in ground	6.6	µg
Manganese, in ground	156.6	µg
Marl, in ground	472.0	mg
Mercury, in ground	1.4	mg
Methane	1.7	mg
Molybdenum, in ground	295.0	ng
Nickel, in ground	383.7	µg
Nitrogen, in air	63.5	g
Occupation, arable	11.5	mm2a
Occupation, forest	0.0	mm2a
Occupation, industrial area	90.9	cm2a
Occupation, urban, continuously built	0.9	mm2a
Oil, crude, 41 MJ per kg, in ground	8.9	mg
Oil, crude, 42.6 MJ per kg, in ground	114.0	g
Oil, crude, 42.7 MJ per kg, in ground	184.1	g
Olivine, in ground	7.8	mg
Oxygen, in air	75.0	g
Palladium, in ground	328.0	ng
Phosphorus pentoxide	1.5	g
Platinum, in ground	369.0	ng
Potassium chloride	7.7	g
Rhenium, in ground	84.8	ng
Rhodium, in ground	348.0	ng
Rutile, in ground	1.5	µg
Sand, quartz, in ground	0.0	pg
Sand, unspecified, in ground	1.7	g
Shale, in ground	14.9	mg
Silver, in ground	359.1	µg

Sodium chloride, in ground	44.9	oz
Sodium nitrate	349.2	pg
Sulfur dioxide	23.2	g
Sulfur, bonded	7.7	µg
Sulfur, in ground	2.4	g
Talc, in ground	0.0	pg
Tin, in ground	199.0	µg
Transformation, to industrial area	50.8	mm2
Unspecified input	24.9	µg
Uranium ore, 1.11 GJ per kg, in ground	1.7	g
Uranium, 451 GJ per kg, in ground	1.6	µg
Uranium, 560 GJ per kg, in ground	142.0	µg
Volume occupied, reservoir	202.0	cm3y
Water, barrage	19.5	kg
Water, cooling, drinking	6.8	µg
Water, cooling, salt, ocean	9.3	kg
Water, cooling, surface	140.0	kg
Water, cooling, unspecified natural origin/kg	28.8	kg
Water, cooling, well, in ground	334.8	mg
Water, process, drinking	2.7	kg
Water, process, salt, ocean	413.8	g
Water, process, surface	25.6	kg
Water, process, unspecified natural origin/kg	4.7	kg
Water, process, well, in ground	10.2	g
Water, turbine use, unspecified natural origin	48.7	dm3
Water, unspecified natural origin/kg	209.3	lb
Wood, dry matter	27.3	mg
Wood, unspecified, standing/kg	2.5	mg
Zeolite, in ground	1.0	µg
Zinc, in ground	666.8	µg

Emissions to air

Acetaldehyde	7.5	µg
Acetic acid	32.1	µg
Acetone	7.4	µg
Acrolein	3.5	ng
Aldehydes, unspecified	35.6	µg
Aluminum	128.3	µg
Americium-241	1.1	µBq
Ammonia	171.9	mg
Antimony	104.7	ng
Antimony-124	16.1	nBq
Antimony-125	2.0	nBq
Argon-41	127.0	mBq
Arsenic	4.6	µg
Asbestos	972.0	pg
Barium	1.9	µg
Barium-140	229.0	nBq
Benzaldehyde	1.2	ng
Benzene	943.0	µg
Benzene, ethyl-	219.6	µg
Benzene, hexachloro-	8.2	pg
Benzene, pentachloro-	22.0	pg
Benzo(a)pyrene	63.1	ng
Beryllium	20.6	ng
Boron	80.9	µg
Bromine	8.7	µg
Butane	8.7	mg
Butene	209.0	µg
Cadmium	8.8	µg
Calcium	179.3	µg
Carbon-14	87.7	mBq
Carbon dioxide	118.4	oz
Carbon disulfide	1.1	mg
Carbon monoxide	3.3	g
Cerium-141	5.4	nBq
Cerium-144	11.6	µBq
Cesium-134	41.4	µBq
Cesium-137	79.9	µBq
Chlorinated fluorocarbons, soft	7.9	mg
Chlorine	233.5	mg
Chloroform	5.1	ng
Chromium	14.9	µg
Chromium-51	206.0	nBq
Coal dust	12.9	mg
Cobalt	9.7	µg
Cobalt-57	0.1	nBq
Cobalt-58	1.7	µBq
Cobalt-60	2.5	µBq
Copper	17.8	µg
Curium-242	0.0	nBq
Curium-244	0.1	nBq
Curium alpha	1.7	µBq
Cyanide	171.4	ng
Dinitrogen monoxide	17.6	mg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2.2	pg
Ethane	2.2	mg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	0.0	pg
Ethane, 1,2-dichloro-	1.5	µg
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	1.2	µg
Ethane, chloro-	2.4	µg
Ethane, dichloro-	193.0	ng
Ethane, hexafluoro-, HFC-116	67.3	ng
Ethanol	14.9	µg
Ethene	1.1	mg

Ethene, chloro-	32.9	ng
Ethyne	453.5	ng
Fluorine	31.8	µg
Formaldehyde	40.2	µg
Heat, waste	990.3	kJ
Heavy metals, unspecified	750.0	µg
Helium	7.9	mg
Heptane	2.1	mg
Hexane	4.3	mg
Hydrocarbons, aliphatic, alkanes, unspecified	2.3	mg
Hydrocarbons, aliphatic, alkenes, unspecified	11.8	µg
Hydrocarbons, aromatic	8.5	mg
Hydrocarbons, chlorinated	70.4	mg
Hydrocarbons, unspecified	7.9	g
Hydrogen	1.4	g
Hydrogen-3, Tritium	905.0	mBq
Hydrogen chloride	167.8	mg
Hydrogen cyanide	1.8	ng
Hydrogen fluoride	6.5	mg
Hydrogen sulfide	1.4	mg
Iodine	3.9	µg
Iodine-129	311.0	µBq
Iodine-131	34.6	µBq
Iodine-133	19.4	µBq
Iodine-135	29.0	µBq
Iron	165.3	µg
Iron-59	2.3	nBq
Krypton-85	5.4	kBq
Krypton-85m	6.4	mBq
Krypton-87	2.8	mBq
Krypton-88	253.0	mBq
Krypton-89	2.0	mBq
Lanthanum	55.9	ng
Lanthanum-140	145.0	nBq
Lead	21.8	µg
Lead-210	970.0	µBq
Magnesium	44.3	µg
Manganese	26.5	µg
Manganese-54	59.5	nBq
Mercaptans, unspecified	9.0	µg
Mercury	120.1	µg
Metals, unspecified	7.7	mg
Methane	16.6	g
Methane, bromotrifluoro-, Halon 1301	44.2	µg
Methane, chlorodifluoro-, HCFC-22	10.6	ng
Methane, chlorotrifluoro-, CFC-13	6.1	ng
Methane, dichloro-, HCC-30	63.2	µg
Methane, dichlorodifluoro-, CFC-12	9.7	ng
Methane, dichlorofluoro-, HCFC-21	1.1	µg
Methane, tetrachloro-, CFC-10	48.5	ng
Methane, tetrafluoro-, CFC-14	602.3	ng
Methane, trichlorofluoro-, CFC-11	44.9	ng
Methanol	20.9	µg
Molybdenum	5.0	µg
Neptunium-237	0.1	nBq
Nickel	224.4	µg
Niobium-95	10.5	nBq
Nitrogen	85.6	µg
Nitrogen dioxide	327.0	µg
Nitrogen oxides	13.0	g
NMVOC, non-methane volatile organic compounds, unspecified origin	858.6	mg
Noble gases, radioactive, unspecified	7.6	mBq
Organic substances, unspecified	535.4	mg
Oxygen	1.7	ng
PAH, polycyclic aromatic hydrocarbons	1.4	mg
Particulates, < 10 um	4.4	g
Particulates, < 10 um (mobile)	2.1	mg
Particulates, < 10 um (stationary)	27.3	mg
Particulates, > 10 um	855.0	µg
Particulates, > 10 um (process)	9.0	mg
Particulates, SPM	2.3	g
Pentane	10.9	mg
Phenol	29.1	ng
Phenol, pentachloro-	3.6	pg
Phosphorus	136.8	ng
Phosphorus, total	5.1	µg
Platinum	3.5	ng
Plutonium-238	0.1	nBq
Plutonium-241	95.1	µBq
Plutonium-alpha	3.5	µBq
Polonium-210	1.5	mBq
Potassium	110.9	µg
Potassium-40	167.0	µBq
Promethium-147	29.4	µBq
Propane	8.6	mg
Propene	802.4	µg
Propionic acid	303.5	ng
Protactinium-234	34.6	µBq
Radioactive species, other beta emitters	7.3	nBq
Radioactive species, unspecified	135.7	Bq
Radium-226	1.2	mBq
Radium-228	81.7	µBq
Radon-220	7.7	mBq
Radon-222	7.8	kBq

Ruthenium-103	0.6	nBq
Ruthenium-106	346.0	µBq
Scandium	19.2	ng
Selenium	6.1	µg
Selenium compounds	15.8	pg
Silicates, unspecified	18.9	µg
Silicon	396.7	µg
Silver	455.1	pg
Silver-110	58.6	nBq
Sodium	243.8	µg
Soot	1.0	mg
Strontium	1.9	µg
Strontium-89	104.0	nBq
Strontium-90	57.1	µBq
Styrene	2.0	µg
Sulfur dioxide	5.4	g
Sulfur oxides	8.4	g
Sulfuric acid	414.7	µg
t-Butyl methyl ether	60.8	ng
Technetium-99	2.4	nBq
Tellurium-123m	261.0	nBq
Thallium	13.0	ng
Thorium	43.4	ng
Thorium-228	69.1	µBq
Thorium-230	385.0	µBq
Thorium-232	43.9	µBq
Thorium-234	34.6	µBq
Tin	41.3	ng
Titanium	5.5	µg
Toluene	1.3	mg
Uranium	41.1	ng
Uranium-234	415.0	µBq
Uranium-235	20.1	µBq
Uranium-238	535.0	µBq
Uranium alpha	1.2	mBq
Vanadium	772.3	µg
VOC, volatile organic compounds	1.6	mg
Xenon-131m	13.1	mBq
Xenon-133	3.9	Bq
Xenon-133m	1.9	mBq
Xenon-135	657.0	mBq
Xenon-135m	64.9	mBq
Xenon-137	1.6	mBq
Xenon-138	17.6	mBq
Xylene	868.9	µg
Zinc	35.7	µg
Zinc-65	255.0	nBq
Zirconium	9.3	ng
Zirconium-95	3.8	nBq

Emissions to water

Acenaphthylene	650.0	ng
Acidity, unspecified	124.5	mg
Acids, unspecified	3.7	mg
Aluminum	4.9	mg
Americium-241	144.0	µBq
Ammonia, as N	9.4	mg
Ammonium, ion	4.2	mg
Antimony	77.0	ng
Antimony-122	719.0	nBq
Antimony-124	103.0	µBq
Antimony-125	5.9	µBq
AOX, Adsorbable Organic Halogen as Cl	19.1	mg
Arsenic, ion	13.6	µg
Barite	99.0	mg
Barium	14.8	mg
Barium-140	719.0	nBq
Benzene	744.2	µg
Benzene, chloro-	1.1	pg
Benzene, ethyl-	137.2	µg
Beryllium	5.0	ng
BOD5, Biological Oxygen Demand	509.5	mg
Boron	198.0	µg
Bromate	83.5	µg
Cadmium-109	4.1	nBq
Cadmium, ion	7.0	µg
Calcium compounds, unspecified	355.2	µg
Calcium, ion	91.8	g
Carbon-14	7.3	mBq
Carbonate	1.4	g
Cerium-141	107.0	nBq
Cerium-144	3.3	mBq
Cesium	5.7	µg
Cesium-134	7.4	mBq
Cesium-136	3.8	nBq
Cesium-137	67.7	mBq
Chlorate	78.3	mg
Chloride	719.3	g
Chlorinated solvents, unspecified	435.3	µg
Chlorine	642.7	µg
Chloroform	60.6	ng
Chromium	6.2	mg
Chromium-51	15.8	µBq
Chromium VI	6.4	ng
Chromium, ion	87.1	µg
Cobalt	7.8	µg
Cobalt-57	737.0	nBq
Cobalt-58	623.0	µBq
Cobalt-60	31.7	mBq
COD, Chemical Oxygen Demand	2.7	g

Copper, ion	109.5	µg
Crude oil	3.8	mg
Curium alpha	190.0	µBq
Cyanide	25.9	µg
Detergent, oil	20.2	mg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	145.1	pg
DOC, Dissolved Organic Carbon	145.1	mg
Ethane, 1,1-dichloro-	2.8	ng
Ethane, 1,1,1-trichloro-, HCFC-140	272.0	pg
Ethane, chloro-	33.8	ng
Ethane, dichloro-	100.5	ng
Ethane, hexachloro-	2.2	pg
Ethene, chloro-	74.3	pg
Ethene, tetrachloro-	262.0	pg
Ethene, trichloro-	16.7	ng
Fatty acids as C	28.9	mg
Fluoride	1.2	mg
Formaldehyde	958.7	pg
Glutaraldehyde	12.2	µg
Heat, waste	127.0	kJ
Hydrocarbons, aliphatic, alkanes, unspecified	743.2	µg
Hydrocarbons, aliphatic, alkenes, unspecified	68.6	µg
Hydrocarbons, aromatic	3.4	mg
Hydrocarbons, chlorinated	1.1	ng
Hydrocarbons, unspecified	65.9	mg
Hydrogen	3.2	mg
Hydrogen-3, Tritium	215.7	Bq
Hydrogen sulfide	809.3	ng
Hypochlorite	23.0	µg
Hypochlorous acid	24.5	µg
Iodide	571.2	µg
Iodine-129	20.8	mBq
Iodine-131	13.8	µBq
Iodine-133	3.3	µBq
Iron	6.9	mg
Iron-59	12.7	nBq
Iron, ion	6.4	mg
Lanthanum-140	149.0	nBq
Lead	42.3	µg
Lead-210	417.0	µBq
Magnesium	137.5	mg
Manganese	425.0	µg
Manganese-54	4.9	mBq
Mercury	20.8	µg
Metallic ions, unspecified	119.6	mg
Methane, dichloro-, HCC-30	45.5	µg
Methane, tetrachloro-, CFC-10	399.0	pg
Molybdenum	17.7	µg
Molybdenum-99	50.2	nBq
Neptunium-237	9.2	µBq
Nickel, ion	99.1	µg
Niobium-95	408.0	nBq
Nitrate	3.6	g
Nitrite	6.0	µg
Nitrogen, organic bound	2.0	mg
Nitrogen, total	1.3	g
Oils, unspecified	105.4	mg
Organic substances, unspecified	530.7	mg
PAH, polycyclic aromatic hydrocarbons	74.4	µg
Phenol	2.2	mg
Phenols, unspecified	708.0	µg
Phosphate	305.0	µg
Phosphorus compounds, unspecified	2.8	µg
Phosphorus, total	578.1	mg
Phthalate, dimethyl tere-	414.0	pg
Phthalate, dioctyl-	10.8	pg
Phthalate, p-dibutyl-	65.8	pg
Plutonium-241	14.2	mBq
Plutonium-alpha	571.0	µBq
Polonium-210	417.0	µBq
Potassium	29.5	mg
Potassium-40	524.0	µBq
Potassium, ion	104.8	mg
Protactinium-234	641.0	µBq
Radioactive species, unspecified	1.2	Bq
Radioactive species, alpha emitters	47.4	nBq
Radioactive species, from fission and activation	430.0	µBq
Radioactive species, Nuclides, unspecified	311.0	nBq
Radium-224	285.6	mBq
Radium-226	3.2	Bq
Radium-228	571.1	mBq
Ruthenium	57.1	µg
Ruthenium-103	241.0	nBq
Ruthenium-106	34.6	mBq
Salts, unspecified	7.5	mg
Selenium	24.5	µg
Silicon	51.1	µg
Silver	3.5	µg
Silver-110	399.0	µBq
Sodium-24	22.1	µBq
Sodium, ion	366.9	g
Solved organics	1.9	µg
Solved solids	5.2	g
Solved substances	1.6	mg
Strontium	34.7	mg

Strontium-89	1.6	µBq
Strontium-90	6.9	mBq
Sulfate	9.5	g
Sulfide	187.2	µg
Sulfur	1.7	µg
Sulfur trioxide	3.3	µg
Suspended solids, unspecified	32.9	g
Suspended substances, unspecified	2.0	g
t-Butyl methyl ether	5.0	ng
Technetium-99	3.6	mBq
Technetium-99m	339.0	nBq
Tellurium-123m	30.3	nBq
Tellurium-132	12.4	nBq
Thorium-228	1.1	Bq
Thorium-230	100.0	mBq
Thorium-232	97.6	µBq
Thorium-234	647.0	µBq
Tin, ion	32.4	ng
Titanium, ion	233.9	µg
TOC, Total Organic Carbon	675.1	mg
Toluene	617.7	µg
Tributyltin	5.0	µg
Triethylene glycol	4.4	µg
Tungsten	131.8	ng
Undissolved substances	306.5	mg
Uranium-234	857.0	µBq
Uranium-235	1.3	mBq
Uranium-238	2.2	mBq
Uranium alpha	41.9	mBq
Vanadium, ion	25.2	µg
VOC, volatile organic compounds as C	2.0	mg
Xylene	537.8	µg
Yttrium-90	83.0	nBq
Zinc-65	46.7	µBq
Zinc, ion	1.6	mg
Zirconium-95	294.1	µBq

Emissions to soil

Aluminum	6.6	mg
Arsenic	2.6	µg
Cadmium	113.0	ng
Calcium	26.2	mg
Carbon	20.3	mg
Chromium	32.8	µg
Cobalt	156.0	ng
Copper	779.0	ng
Heat, waste	444.8	J
Iron	13.1	mg
Lead	3.5	µg
Manganese	262.0	µg
Mercury	21.4	ng
Nickel	1.2	µg
Nitrogen	6.0	µg
Oils, biogenic	429.0	ng
Oils, unspecified	4.9	mg
Phosphorus	335.0	µg
Sulfur	3.9	mg
Zinc	106.0	µg

Final waste flows

Chemical waste, inert	8.2	g
Chemical waste, regulated	30.6	g
Coal tailings	206.2	mg
Compost	95.7	µg
Construction waste	54.2	mg
Metal waste	66.6	mg
Mineral waste	143.6	g
Oil waste	129.6	mg
Packaging waste, paper and board	836.8	µg
Packaging waste, plastic	6.8	ng
Packaging waste, wood	33.5	ng
Plastic waste	129.3	mg
Production waste, not inert	5.3	mg
Slags	2.2	mg
Slags and ashes	30.0	g
Waste in incineration	8.0	g
Waste returned to mine	33.2	g
Waste to recycling	105.0	mg
Waste, final, inert	92.7	mg
Waste, industrial	49.4	g
Waste, nuclear, high active/m3	0.0	mm3
Waste, nuclear, low and medium active/m3	0.1	mm3
Waste, solid	-8.2	g
Waste, unspecified	731.5	mg
Wood waste	5.8	mg

STEEL (1 kg + 0.3 kg slag)
Source – World Bank Group and IDEMAT [84, 91]

Resources		
Iron, in ground	8.2E-01	kg
Coal, 29.3 MJ per kg, in ground	5.4E-01	kg
Limestone, in ground	1.6E-01	kg
Transformation, to urban, continuously built	1.6E-04	m2
Occupation, urban, continuously built	1.2E-02	m2a
Materials/fuels		
Scrap (iron) I	1.1E-01	kg
Electricity/heat		
Energy Australia I	4.7E-01	MJ
Bulk carrier I	5.7E-01	tkm
Bulk carrier I	4.2E+00	tkm
Bulk carrier I	1.2E+00	tkm
Train I	4.5E-02	tkm
Bulk carrier I	1.9E+00	tkm
Bulk carrier I	2.4E+00	tkm
Train I	1.9E-02	tkm
Train I	4.9E-01	tkm
Emissions to air		
Carbon dioxide	6.5E-01	kg
Carbon monoxide	3.3E-02	kg
Nitrogen dioxide	1.1E-03	kg
Sulfur dioxide	1.6E-03	kg
Hydrocarbons, unspecified	5.9E-04	kg
Fluorine	8.5E-06	kg
Benzo(a)pyrene	1.8E-07	kg
Fluoranthene	5.4E-07	kg
Particulates, SPM	8.9E-04	kg
Chlorine	7.2E-04	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.0E-10	kg
Hydrogen sulfide	9.6E-05	kg
Aluminum	1.3E-06	kg
Arsenic	8.0E-08	kg
Cadmium	2.5E-07	kg
Chromium	1.0E-07	kg
Copper	1.5E-06	kg
Mercury	7.0E-08	kg
Nickel	7.0E-09	kg
Lead	9.0E-06	kg
Zinc	4.0E-06	kg
Emissions to water		
Kjeldahl-N	2.7E-04	kg
Crude oil	2.0E-07	kg
Cadmium, ion	7.0E-09	kg
Chromium	1.0E-07	kg
Copper, ion	1.6E-07	kg
Mercury	6.0E-09	kg
Lead	2.0E-07	kg
Zinc, ion	1.1E-06	kg
Final waste flows		
Waste, inorganic	3.1E-03	kg
Dust, unspecified	3.0E-04	kg

MANUFACTURING

TIRE MANUFACTURING (1 kg)
Source – EcoInvent, PRé Consultants, J.L. White [17, 78, 88]

Avoided products		
Synthetic Rubber	0.3	g
Materials/fuels		
Energy US I	1.2	kWh
Natural gas to UCPTE S	0.2	m3
Energy US I	0.1	J
Naphtha B250	0.9	g
Synthetic Rubber	1.2	g
Oil light B300	1.7	g
NaOH (100%)	2.4	g
HCl (100%) B250	2.1	g
Silicon I	0.4	g
Lime B250	6.2	g
Cotton fibres I	0.2	g
HDPE B250	0.7	g
Paint ETH S	12.3	g
Synthetic Rubber	0.2	g

Chemicals organic ETH S	0.2	g
Petrol B300	1.7	g
Paper ETH S	1.1	g
Wood FAL	0.2	g
Truck 28t B250	5.2	tkm
Sea ship B250	0.0	tkm
Train electric B250	0.7	tkm
Freighter oceanic ETH S	2.8	tkm
Emissions to air		
VOC, volatile organic compounds	5.9	mg
Particulates	0.1	g
Emissions to water		
COD, Chemical Oxygen Demand	636.8	mg
BOD5, Biological Oxygen Demand	361.4	mg
Oils, unspecified	175.1	mg
Ammonium, ion	13.4	mg
Suspended solids, unspecified	461.0	mg
Copper	0.3	mg
Zinc	2.8	mg
Lead	0.4	mg
Detergent, oil	3.1	mg
Nickel	1.2	mg
AOX, Adsorbable Organic Halogen as Cl	0.3	mg

Final waste flows		
Waste, solid	4.3	g
Wood waste	7.7	g
Dust, unspecified	35.0	g
Waste to treatment		
Recycling ECCS steel B250	13.4	g
Recycling paper B250	4.4	g
Recycling Plastics (excl. PVC) B250	1.3	g
Recycling glass B250	0.4	g
Plastics to HA chemical landfill S	2.4	g
Decarbonizing waste to LA chemical landfill S	8.6	g
Waste to LA chemical landfill S	4.2	g
Steel (inert) to landfill S	2.4	g
Municipal waste to MWI S	1.8	g
Plastics to MWI S	1.3	g
Steel to MWI S	10.3	g
Waste oil to special waste incinerator S	2.1	g
Rubber Incineration	8.2	g
Landfill of Tires	6.8	g
Tire Recycling	12.2	g

TWEEL™ MANUFACTURING (1 kg)
Source – Michelin, EcoInvent, BUWAL [78, 85, 97]

Resources		
Glue	0.3	g
Materials/fuels		
Energy US I	1.334	kWh
Energy US I	0.106605	J
Naphtha B250	1.0695	g
Synthetic Rubber	1.403	g
Silicon I	0.483	g
Chemicals organic ETH S	16.1	g
Petrol B300	1.955	g
Truck 28t B250	7.13	tkm
Sea ship B250	0.005175	tkm
Train electric B250	0.76475	tkm
Freighter oceanic ETH S	3.22	tkm
Ethylene E	3.0705	g
Ethyl acetate	30.705	g
Ethyl acetate	34.5	g

Energy US I	1.84	kWh
Emissions to air		
VOC, volatile organic compounds	8.28	mg
Particulates	0.092	g
Emissions to water		
Oils, unspecified	122.4	mg
Suspended solids, unspecified	249.6	mg
Zinc	2.224	mg
Lead	0.304	mg
Detergent, oil	2.464	mg
Nickel	0.984	mg
Final waste flows		
Waste, solid	4.945	g
Dust, unspecified	40.25	g

USE PHASE

TREAD DEBRIS (1 kg)
Source – PRé Consultants [17]

Emissions to air		
Benzo(a)pyrene	390	µg
Particulates, > 10 um	800	g
Particulates, < 10 um	170	g
Particulates, < 2.5 um	30	g
Fluoranthene	1.11	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.057	g
PAH, polycyclic aromatic hydrocarbons	21.1	mg
Sulfur dioxide	220	mg
Zinc	700	mg
Emissions to soil		
Benzo(a)pyrene	3.51	mg
Fluoranthene	9.99	mg
Zinc	6.3	g

GASOLINE PRODUCTION AND USE (100 L)
Source – BUWAL, IDEMAT, Franklin USA, EPA [30, 57, 91, 97]

Resources		
Bauxite, in ground	6.0	g
Coal, 29.3 MJ per kg, in ground	5.1	g
Energy, unspecified	50.4	MJ
Gas, natural, 36.6 MJ per m3, in ground	967.2	dm3
Iron ore, in ground	3.0	g
Occupation, industrial area	828.8	cm2a
Oil, crude, 42.7 MJ per kg, in ground	15.3	kg
Transformation, to industrial area	35.6	mm2
Water, unspecified natural origin/kg	818.4	g
Emissions to air		
Carbon dioxide	52.2	kg
Carbon monoxide	51.9	oz
Dinitrogen monoxide	10.1	g
Hydrocarbons, unspecified	44.9	g
Hydrogen	56.5	mg
Hydrogen chloride	14.9	mg
Hydrogen sulfide	49.1	mg
Nitrogen oxides	375.7	g
Particulates, SPM	4.5	g
Soot	3.5	g
Sulfur dioxide	23.7	g
VOC, volatile organic compounds	210.0	mg
Emissions to water		
Ammonia	148.8	mg
BOD5, Biological Oxygen Demand	148.8	mg
Chloride	297.6	mg
COD, Chemical Oxygen Demand	595.2	mg
Hydrocarbons, unspecified	297.6	mg
Hydrogen	14.9	mg
Metallic ions, unspecified	14.9	mg
Mineral waste	2.1	g
Slags	744.0	mg

END OF LIFE

RUBBER DERIVED FUEL (1 kg)
Source – EPA [37]

Materials/fuels		
Energy US I	-36.0	MJ
Emissions to air		
Ammonia	-2.4	mg
Butadiene	1.6	mg
Carbon black	-12.4	mg
Carbon dioxide	30.3	g
Carbon monoxide	-197.2	mg
Dinitrogen monoxide	-28.8	mg

Ethene	4.9	mg
Heat, waste	669.8	kJ
Hydrocarbons, aromatic	-2.2	mg
Hydrocarbons, unspecified	-1.3	g
Hydrogen chloride	-31.7	mg
Hydrogen fluoride	-4.1	mg
Hydrogen sulfide	-14.0	mg
Metals, unspecified	-10.8	mg
Methane	-9.4	g
Nitrogen dioxide	277.5	mg
Nitrogen oxides	90.7	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.6	g
Particulates	-811.7	mg
Particulates, < 10 um	8.4	mg
Particulates, < 10 um (mobile)	9.8	mg
Particulates, < 10 um (stationary)	3.4	mg
Particulates, > 10 um	-311.0	mg
Particulates, > 10 um (process)	6.4	mg
Particulates, SPM	-28.9	mg
Silicates, unspecified	1.0	mg
Sulfur dioxide	-103.0	mg
Sulfur oxides	-1.0	g
Unspecified emission	-9.9	mg
VOC, volatile organic compounds	8.5	mg
Zirconium	9.0	mg

Emissions to water

Aluminum	-83.1	mg
Ammonium, ion	-2.2	mg
Barite	7.6	mg
Barium	-5.4	mg
Calcium compounds, unspecified	11.8	mg
Calcium, ion	14.5	mg
Chloride	-238.0	mg
COD, Chemical Oxygen Demand	2.4	mg
Copper	11.2	mg
Fatty acids as C	1.6	mg
Fluorine	-5.7	mg
Heat, waste	14.0	kJ
Hydrocarbons, unspecified	1.8	mg
Iron	-105.1	mg
Magnesium	11.0	mg
Manganese	1.0	mg
Metallic ions, unspecified	-11.3	mg
Nitrate	-0.8	mg
Nitrogen, total	1.5	mg
Oils, unspecified	3.0	mg
Phosphate	-4.6	mg
Potassium	5.7	mg
Salts, unspecified	32.6	mg
Sodium, ion	247.2	mg
Solved substances	4.6	mg
Solved substances, inorganic	-598.5	mg
Strontium	2.6	mg
Sulfate	-1.8	g
Suspended substances, unspecified	-98.7	mg
TOC, Total Organic Carbon	45.7	mg
Undissolved substances	17.9	mg
Limestone waste	-3.9	g
Production waste	-28.7	g
Steel waste	2.0	g
Waste, final, inert	155.3	g
Waste, nuclear, high active/m3	0.1	mm3
Waste, nuclear, low and medium active/m3	6.4	mm3

Emissions to soil

Calcium	1.5	mg
Carbon	1.2	mg
Heat, waste	16.4	kJ

RUBBER – CIVIL ENGINEERING (1 kg)

Source – PRé Consultants [17]

Avoided Products

Synthetic Rubber	1.0	kg

Resources

Water, unspecified natural origin/kg	0.1	kg
Oil	7.3	mg

Materials/fuels

Steel	157.8	mg

Electricity/heat

Energy US I	368	kJ

Final waste flows

Steel waste	56	g

RUBBER – LANDFILL (1 kg)
Source – PRé *Life Cycle Inventories* [115]

Resources

Barite, 15% in crude ore, in ground	1.032	mg
Coal, 18 MJ per kg, in ground	17.53	g
Oil, crude, 42.6 MJ per kg, in ground	6.412	g
Land use II-III	16.36	mm2a
Land use II-IV	1.694	mm2a
Iron, 46% in ore, 25% in crude ore, in ground	2.519	mg
Gravel, in ground	22	mg
Land use II-III	13.42	mm2a
Land use III-IV	1.404	mm2a
Land use II-IV	0.9655	mm2a
Land use IV-IV	0.5616	mm2a
Coal, brown (lignite)	18.38	g
Coal, brown (lignite)	51.53	mg
Limestone, in ground	17.32	g
Lubricant	15.6	mg
Marl, in ground	2.548	mg
Gas, natural, 36.6 MJ per m3, in ground	290	mm3
Gas, natural, 35 MJ per m3, in ground	5.901	dm3
Gas, petroleum, 35 MJ per m3, in ground	16.07	cm3
Energy, potential (in hydropower reservoir), converted	122.3	kJ
Energy, potential (in hydropower reservoir), converted	228.7	J
Water, process and cooling, unspecified natural origin	29.38	mm3
Volume occupied, reservoir	4.994	cm3y
Sulfur dioxide, secondary	3.641	mg
Water, turbine use, unspecified natural origin	1.207	dm3
Uranium ore, 1.11 GJ per kg, in ground	1.866	mg
Water, unspecified natural origin/kg	8.511	g

Materials/fuels

Truck 28t B250	0.1	tkm

Emissions to air

Carbon monoxide	56.55	mg
Carbon dioxide	206.8	g
Particulates	213.6	mg
Iron	3.943	mg
Hydrogen chloride	22	mg
Hydrogen fluoride	1.178	mg
Metals, unspecified	3.432	mg
Methane	12.58	g
Nitrogen	36.53	g
Dinitrogen monoxide	1.288	mg
Nitrogen dioxide	2.613	g
NMVOC, non-methane volatile organic compounds, unspecified origin	59.09	mg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.751	mg
Nitrogen oxides	178	mg
Sulfur dioxide	10.7	g
Sulfur oxides	373.2	mg
Heat, waste	13.33	kJ
Zinc	20.62	mg

Emissions to water

Aluminum	28.49	mg
Barium	3.04	mg
Cadmium	2.014	mg
Chlorine	555	mg
Chloride	353.9	mg
COD, Chemical Oxygen Demand	4.01	g
Chromium	2.885	mg
Copper	41.3	mg
Iron	38.08	mg
Metallic ions, unspecified	4.878	mg
Sodium, ion	3.995	mg
Nitrogen, total	3.84	g
Oils, unspecified	8.388	mg
Phosphate	1.677	mg
Sulfur trioxide	21.68	g
Sulfate	321.7	mg
Suspended substances, unspecified	28	mg
TOC, Total Organic Carbon	8.157	mg
Heat, waste	214.5	J
Waste water/m3	5.363	mm3
Zinc	2.446	g

Emissions to soil

Cadmium	1.312	mg
Chlorine	184.9	mg
Chromium	184.9	mg
Copper	50.63	mg
Fluoranthene	2.498	mg
Heat, waste	24.03	J

Zinc	2.55	g

RUBBER – GRINDING FOR RECYCLING (1 kg)

Source – Corti, Lombardi [109]

Avoided Products		
Synthetic Rubber	0.9	kg
Textile	9.2	g

Resources		
Water, unspecified natural origin/kg	75.0	g
Oil	5.5	mg
Nitrogen, in air	104.1	g
Gas, natural, 35 MJ per m3, in ground	229.6	cm3

Materials/fuels		
Steel	0.2	g

Electricity/heat		
Energy US I	345.9	kJ

Emissions to air		
Particulates	4.1	mg

Final waste flows		
Steel waste	48.1	g

POLYURETHANE – INCINERATION (1000 kg)

Source – Zevenhoven [112]

Avoided products		
Energy US I	5.09	GJ

Resources		
Coal, brown, 8 MJ per kg, in ground	0.243	kg
Gas, natural, 36.6 MJ per m3, in ground	2.64	m3
Coal, 18 MJ per kg, in ground	0.566	kg
Oil, crude, 42.6 MJ per kg, in ground	3.18	kg
Uranium, 451 GJ per kg, in ground	0.0196	g
Wood, unspecified, standing/kg	0.00376	kg
Energy, potential (in hydropower reservoir), converted	1.2	MJ
Water, process, unspecified natural origin/m3	1	m3
Iron ore, in ground	0.000338	kg
Limestone, in ground	6.25	kg
Sulfur dioxide, secondary	0.000743	kg
Sand, unspecified, in ground	0.000147	kg
Sodium chloride, in ground	0.435	kg

Emissions to air		
Particulates	34.5	g
Benzene	0.466	g
PAH, polycyclic aromatic hydrocarbons	0.000615	g
Hydrocarbons, aromatic	0.895	g
Methane, bromotrifluoro-, Halon 1301	0.000747	g
Hydrocarbons, halogenated	0.00166	g
Methane	41.4	g
NMVOC, non-methane volatile organic compounds, unspecified origin	106	g
Carbon dioxide	3190000	g
Carbon monoxide	228	g
Ammonia	8.2	g
Hydrogen fluoride	2.41	g
Dinitrogen monoxide	8.41	g
Hydrogen chloride	12	g
Sulfur oxides	236	g
Nitrogen oxides	658	g
Lead	0.385	g
Cadmium	0.362	g
Manganese	0.000142	g
Nickel	0.00646	g
Mercury	0.0672	g
Zinc	37.7	g
Metals, unspecified	2.77	g
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	11.6	µg

Emissions to water		
Waste water/m3	1.11E-06	m3
BOD5, Biological Oxygen Demand	0.0163	g
COD, Chemical Oxygen Demand	0.466	g
AOX, Adsorbable Organic Halogen as Cl	0.000613	g
Suspended substances, unspecified	12.2	g
Phenols, unspecified	0.0211	g

Toluene	0.0189	g
PAH, polycyclic aromatic hydrocarbons	0.00204	g
Hydrocarbons, aromatic	0.138	g
Hydrocarbons, chlorinated	0.000173	g
Oils, unspecified	4.26	g
DOC, Dissolved Organic Carbon	0.0354	g
TOC, Total Organic Carbon	103	g
Ammonium, ion	1.4	g
Nitrate	0.765	g
Kjeldahl-N	0.0574	g
Nitrogen, total	0.332	g
Arsenic, ion	0.00137	g
Chloride	956	g
Cyanide	0.000623	g
Phosphate	0.039	g
Sulfate	19.2	g
Sulfide	0.00493	g
Solved substances, inorganic	1360	g
Aluminum	0.626	g
Barium	0.442	g
Lead	0.0423	g
Cadmium, ion	0.0367	g
Chromium	0.0078	g
Iron	0.416	g
Copper, ion	2.62	g
Nickel, ion	0.00358	g
Mercury	0.00672	g
Zinc, ion	1.89	g
Metallic ions, unspecified	1.07	g

POLYURETHANE – GRINDING FOR RECYCLING (100 kg)

Source – Zevenhoven, Corti [109, 112]

Avoided products

Polyurethane	100	kg

Electricity/heat

Energy US I	675	MJ

Emissions to air

Particulates	5	g

Final waste flows

Steel waste	6	kg

POLYURETHANE – LANDFILL (1000 kg)

Source – BUWAL [97]

Resources

Gas, natural, 36.6 MJ per m3, in ground	0.321	m3
Oil, crude, 42.6 MJ per kg, in ground	4.24	kg
Uranium, 451 GJ per kg, in ground	0.019	g
Energy, potential (in hydropower reservoir), converted	2.22	MJ

Emissions to air

Particulates	14.1	g
Methane	14800	g
NMVOC, non-methane volatile organic compounds, unspecified origin	89.8	g
Carbon dioxide	131000	g
Carbon monoxide	83	g
Sulfur oxides	46.7	g
Nitrogen oxides	199	g

Emissions to water

Suspended substances, unspecified	12.3	g
Oils, unspecified	5.65	g
TOC, Total Organic Carbon	260	g
Ammonium, ion	48.1	g
Nitrate	154	g
Chloride	158	g
Sulfate	73	g
Solved substances, inorganic	84	g
Zinc, ion	20.9	g

Emissions to soil

Carbon	175	g
Nitrogen, total	3.86	g

STEEL RECYCLING (1000 kg)
Source – BUWAL [97]

Avoided products		
Steel I	900	kg
Resources		
Coal, brown, 8 MJ per kg, in ground	280	kg
Gas, natural, 36.6 MJ per m3, in ground	126	m3
Coal, 18 MJ per kg, in ground	181	kg
Oil, crude, 42.6 MJ per kg, in ground	23.4	kg
Uranium, 451 GJ per kg, in ground	11.9	g
Wood, unspecified, standing/kg	1.77	kg
Energy, potential (in hydropower reservoir), converted	388	MJ
Water, process, unspecified natural origin/m3	13	m3
Scrap, external	1190	kg
Chromium compounds	0.86	kg
Degreasing agent	1.3	kg
Auxiliary materials	11.5	kg
Alloys	5.2	kg
Acids	12.5	kg
Oil	2.2	kg
Emissions to air		
Particulates	1170	g
Benzene	0.965	g
PAH, polycyclic aromatic hydrocarbons	0.0242	g
Hydrocarbons, aromatic	7.34	g
Methane, bromotrifluoro-, Halon 1301	0.0056	g
Hydrocarbons, halogenated	0.0003	g
Methane	2020	g
NMVOC, non-methane volatile organic compounds, unspecified origin	441	g
Carbon dioxide	1160000	g
Carbon monoxide	4600	g
Ammonia	1.87	g
Hydrogen fluoride	15.2	g
Dinitrogen monoxide	5.9	g
Hydrogen chloride	132	g
Sulfur oxides	2860	g
Nitrogen oxides	2670	g
Lead	9.47	g
Cadmium	0.007	g
Manganese	3.54	g
Nickel	0.261	g
Mercury	0.0275	g
Zinc	0.192	g
Metals, unspecified	35.4	g
Chromium	0.19	g
Copper	0.53	g
Radioactive species, unspecified	1040000	kBq
Emissions to water		
Waste water/m3	5	m3
BOD5, Biological Oxygen Demand	170	g
COD, Chemical Oxygen Demand	462	g
AOX, Adsorbable Organic Halogen as Cl	0.0044	g
Suspended substances, unspecified	223	g
Phenols, unspecified	0.18	g
Toluene	0.158	g
PAH, polycyclic aromatic hydrocarbons	0.0153	g
Hydrocarbons, aromatic	1.22	g
Hydrocarbons, chlorinated	0.503	g
Oils, unspecified	35.8	g
DOC, Dissolved Organic Carbon	1.83	g
TOC, Total Organic Carbon	136	g
Ammonium, ion	4.45	g
Nitrate	7.75	g
Kjeldahl-N	0.341	g
Nitrogen, total	2.11	g
Arsenic, ion	0.588	g
Chloride	4980	g
Cyanide	0.0093	g
Phosphate	48.4	g
Sulfate	3080	g
Sulfide	0.0405	g
Solved substances, inorganic	2460	g
Aluminum	293	g
Barium	26.1	g
Lead	1.7	g
Cadmium, ion	0.0171	g
Chromium	6.93	g
Iron	579	g
Copper, ion	1.75	g
Nickel, ion	1.77	g
Mercury	0.0158	g
Zinc, ion	2.94	g
Metallic ions, unspecified	37.6	g
Radioactive species, unspecified	9570	kBq

Final waste flows

Chromium waste	4.5	kg
Iron waste	18.5	kg
Slags	46	kg

Dust, break-out	17	kg
Tinder from rolling drum	16	kg
Rejects	33.3	kg
Waste in inert landfill	10.2	kg

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