

Managing the sustainability of rubber products:

Examining four reclaiming technologies for EPDM roof sheets



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Abstract

The unique properties of rubber make it an important raw material for industrialised nations. However, the lack of a technology that can recycle rubber without reducing the material properties of the compound is a major global problem. This research is commissioned by the company DX-polymers to analyze the competitiveness of their novel mechanical reclaim technology. The research investigates the environmental and technological performance of the chemical, micro-wave, ultra-sound, and mechanical recycling technologies for rubber. The chemical, ultra-sound and micro-wave reclaim technologies are chosen because they also promise to recycle rubber without much loss of quality. The technological performance of the technologies is analyzed with the use of a literature review and five expert interviews. The micro-wave and ultra-sound technologies have shown to cause severe degradation of mechanical properties of rubber making the application of these technologies limited. The chemical and mechanical reclaim technologies are able to deliver the highest reclaim quality. However, the mechanical reclaim technology is currently the most promising technology. The process is the most flexible and requires the lowest reclaim temperature. The environmental benefits of the reclaim technologies are investigated with the use of the Life Cycle Assessment (LCA) framework. The EPDM roof sheet market was chosen as a case because the market is highly suitable for the introduction of a rubber reclaim technology. The mechanical reclaim technology leads to the largest environmental impact reduction of the researched technologies. The technology can improve the sustainability of the rubber industry as well as deliver a cost advantage to rubber manufacturers. To speed up the development of the DX-polymers reclaim technology the company is advised to: investigate the possibilities of a joint-venture with a major rubber manufacturer, develop a report about the effects of the reclaim technology on different rubber compounds and lobby government to shift the focus from low-grade rubber recycling onto high quality reclaiming.

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List of abbreviations

Abrasive wear: the loss of strength of a material due to the sliding across surfaces.

Allocation: partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Backbone: a long chain of carbon to carbon molecules within a rubber polymer to which other atoms can stick.

Chemical reclaim: Chemically remove the crosslinking points in vulcanized rubber to make it fit for re-use in an original compound

Crosslinking points: the molecular bounds that are formed in the rubber during the vulcanization process.

De-vulcanization: Reversing the vulcanization process of rubber so that a material is created with exactly the same properties as the original compound.

Elastomer: a polymer with highly elastic properties.

ELCD database: LCA data base developed by the institute for environment and sustainability of the European commission

Environmental aspect: element of an organization's activities, products or services that can interact with the environment.

EPDM: ethylene propylene diene monomer (M-class) synthetic rubber with good heat, ozone and weather resistance.

EVL: The End-of-Life vehicles directive developed by the European commissions.

Functional unit: quantified performance of a product system for use as a reference unit.

HDA: Hexadecylamine, a chemical used to reclaim rubber.

Impact category: class representing environmental issues of concern to which life cycle inventory analysis results may be assigned.

IPCC: Intergovernmental Panel on Climate Change

Life cycle: consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life cycle assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment (LCIA): phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life cycle inventory analysis (LCI): phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Mechanical reclaim: Subjecting vulcanized rubber waste to mechanical stress to break up the crosslinking points and make it fit for re-use in an original compound.

Novel: new and original.

Petro-chemicals: chemicals derived from crude oil.

PM10: particles with a median equivalent diameter of 10 mm.

Polarity: Tendency of a molecule, or compound, to be attracted or repelled by electrical charges because of an asymmetrical arrangement of atoms around the nucleus.

Polymer: a large molecule composed of repeating structural units.

Polymer network: three-dimensional entity formed by the interconnection of polymer chains.

Product system: collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals.

Reclaiming: High quality recycled rubber which can be mixed in with a virgin batch without significantly reducing the material properties of the end-product.

Reference flow: measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

RIVM: Rijksinstituut voor Volksgezondheid en Milieu.

Sustainable development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

System boundary: set of criteria specifying which unit processes are part of a product system.

Uniform products: Product that have the same continuance throughout the material.

Virgin materials: raw materials which are used for the first time.

Vulcanization: a chemical process for converting rubber or related polymers into more durable materials by addition of sulfur or other equivalent "curatives" before heating the material in an oven.

Zeolites: Hydrated alumino silicates of the alkaline and alkaline-earth metals.

Management summary

Rubber has become one of the critical resources for the modern world. However, the industrial production of rubber and the possibilities it provides in terms of e.g. mobility have come at a cost. The awareness that human actions can have negative effects on the environment has slowly slipped into the public consciousness. During the 1960^s citizens in industrialized countries became increasingly concerned about the detrimental and cumulative health effects of industrial pollution (Vermeulen, 2008). During the last decades it has also become evident that industrial pollution might lead to a shift in the global climate (IPCC, 2007). The European Union has set out clear goals for sustainable development and the efficient management of resources. In the report ‘roadmap to a resource efficient Europe, 2011’ resource efficiency is seen as important strategy to deliver more value with fewer resources. The member states are encouraged to improve products, alter consumption patterns and boost resource efficient production (European Commission, 2011). Legislations such as the End-of-Life vehicles (ELVs), the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and the emission trading scheme (ETS) are forcing companies to recycle more materials and better assess the environmental burden of production (Sutanto, 2006_a; Dijkhuis 2008; Rudén and Hansson, 2009)

The majority of the rubber compounds produced (56%) in the world are made with a synthetic polymer as the binding material (DXP, 2011). Most of the recycling processes currently implemented transform rubber waste into a lower grade material (Eurostat, 2012). The lack of a technology that can recycle synthetic rubber without reducing the material properties of the compound is a major limitation for the re-use of rubber waste (Noordermeer, 2012; Dijkhuis, 2012). The company DX-polymers (DXP) provides a processing service for rubber waste which can recycle rubber into a high quality feedstock so that it can be re-used in the production of the original compound. The company is introducing a novel technology that is able to reclaim rubber in a continuous process without the use of chemicals. The technology developed by DXP can selectively break the crosslinking points formed during vulcanization by applying a controlled amount of mechanical stress to rubber waste. The rubber waste is converted into a material of near-master batch quality so it can be re-used in the original application (DXP, 2012). The company is interested in the performance of their technology relative to other recycling technologies on the market.

This study will compare the environmental and technological performance of the DXP reclaim technology with the three most important competitors: the chemical, ultra-sound and micro-wave reclaim methods. These technologies can also recycle rubber waste into a raw material for the original production process (Sutanto, 2006_a; Dijkhuis 2008). To assess the technological performance of the four reclaiming technologies a literature review and five expert interviews were conducted. The chemical reclaim process for EPDM (Ethylene-Propylene-Diene-Monomer) using HAD (Hexadecylamine) as a reclaim agent has shown to produce a material of sufficient quality to be mixed in with a virgin batch (Sutanto, 2006_a; Dijkhuis, 2008). The energy demand for the process is low, it is fast and relatively cheap. However, the effects of the reclaim chemical can significantly differ between compounds leading to a low flexibility of the technology. The ultra-sound and

microwave reclaim technologies heat the rubber waste to high temperatures which leads to a severe degradation of the main-chain molecules reducing the material properties of the compound (Zanchet *et al.*, 2009; Dijkhuis, 2012; Noordermeer, 2012). The flexibility of both these technologies is low because the efficiency is highly dependent on the nature of the rubber compound that is being processed. The most promising technology is the mechanical reclaim process due to the low energy demand and the fact that the entire compound can be reclaimed. The process is suitable for multiple rubber compounds and is able to produce a high quality reclaim.

To compare the environmental impacts of the reclaim technologies an EPDM roof sheet production process was analysed with the use of the Life Cycle Assessment (LCA) method. EPDM roof sheets are strong and homogenous compounds providing an opportunity for the introduction of novel recycling technologies (DXP, 2011; Noordermeer, 2012). The LCA investigates the benefits of re-using the vulcanized industrial waste (10%) for the production of new EPDM roof sheets. The environmental impact data used to make the LCA model is taken from literature, on-line environmental impact databases and information provided by companies and rubber experts. The information is combined in the free software programme 'OpenLCA' to calculate the environmental impact of EPDM roof sheets production. The impact assessment is based on the ReCiPe method which translates the list of specific environmental emissions into a limited number of environmental impact categories. The production of the EPDM polymer is the most important determinant of the environmental impact of EPDM roof sheets production. The mechanical reclaim technology provides the highest environmental impact reduction of the researched technologies.

The sharp increase in the costs of the raw materials for rubber are making the recycling of rubber for re-use in a new rubber compound far more attractive (Smit, 2012; Dijkhuis, 2012). The initial focus of companies is on recycling their own industrial rubber waste because it is clean and the composition of the material is known. The recycling of end-of-life rubber is more complicated due to the high diversity of compounds used within the rubber industry. Furthermore, rubber products are often enforced with fibers, steel or are made from a blend of compounds. This makes it difficult to collect the rubber waste and recycle it into a high quality compound (Noordermeer, 2012). There is also much skepticism under rubber manufacturers about the quality of the reclaim due the long history of research without success so far. The shredding of end-of-life rubbers for re-use in other applications is currently the most economical solution to the rubber waste problem. However, a successful mechanical reclaim technology can make rubber reclaiming more attractive. The DXP technology is one of several mechanical reclaim processes currently in development (Noordermeer, 2012; Smit, 2012; Ekelenburg, 2012). To gain a competitive advantage the company DXP is advised to seek a joint venture with a major rubber manufacturer to speed up the development of the technology. The company is also advised to publish a report on the efficiency of their reclaim technology on different rubber compounds. Furthermore, lobbying the Dutch government to recognize the mechanical reclaim technology as the Best Available Technology (BAT) for rubber recycling will make it possible to force manufacturers to reclaim more rubber waste. Finally, a sector wide agreement of industry to standardize rubber compounds as much as possible can increase the economic competitiveness of reclaiming.

Chapter 1 – Introduction

Rubber has become one of the critical resources for the modern world. It has grown from being an interesting curiosity into a material which can be found throughout modern societies (White and De, 2001). However, the industrial production of rubber and the possibilities the resource provide e.g. in terms of mobility have come at a cost. The awareness that human actions can have negative effects on the environment has slowly slipped into the public consciousness. During the 1960^s citizens in industrialized countries became increasingly concerned about the health effects of industrial pollution (Tellegen en Wolsink, 1992; Vermeulen, 2008). During the last decades it has also become evident that industrial pollution might lead to a shift in the global climate (IPCC, 2007). In 1983 the United Nations secretary general asked Gro Harlem Brundtland to set up an international organization to investigate worldwide problems and create awareness about sustainability. In 1987 the organization published the report ‘Our common future’ which holds one of the most used definitions of the term sustainability (Brundtland *et al.*, 1987). Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This definition has been adopted by citizens, governments and businesses all over the world. There is a general consensus that the economy should move to a more sustainable direction (United Nations, 1992). The European Union has set out clear goals for sustainable development and the efficient management of resources. In the report ‘roadmap to a resource efficient Europe, 2011’ resource efficiency is seen as important strategy to deliver more value with fewer resources. The member states are encouraged to improve products, alter consumption patterns and boost resource efficient production (European Commission, 2011). Legislations such as the End-of-Life Vehicles (ELVs), the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and the Emission Trading Scheme (ETS) are forcing companies to recycle more materials and better assess the environmental burden of production (Sutanto, 2006_a; Dijkhuis 2008; Rudén and Hansson, 2009).

In 2010, the worldwide production of rubber was around 24.5 million tons. The majority of the rubber compounds produced (56%) was made with a synthetic polymer as the binding material (DXP, 2011). Synthetic rubber compounds are primarily made from oil based products. The price of crude oil has been highly volatile over the past decade due to a slowing growth of production and increased demand. Furthermore, the commodity is a financial asset for investors leading to price ‘bubbles’ e.g. during the summer of 2008 (Dicembrino and Scandizzo, 2012). The increased cost of the raw materials and concerns about the sustainability of the sector is creating a strong economic incentive to increase the recycling rate within the rubber industry (Luiten, 2012; Smit, 2012). However, the current inherent loss of material quality during recycling is a major limitation for increasing the recycling rate within the industry. Today, most of the rubber waste is transformed into a lower grade material, burned for energy recovery or dumped in landfills after use (Leary *et al.*, 2006; Sutanto, 2006_a; Dijkhuis, 2008; Eurostat, 2012). The company DX-polymers (DXP) is introducing a novel rubber recycling technology which can recycle rubber without much loss of quality i.e. reclaiming. The company has developed a 250 kg/h validated prototype machine and is currently in

the phase of gathering sufficient investments to start operations (Ekelenburg, 2012). A central plant will be constructed in Hengelo, the Netherlands to be able to protect the trade secrets of the company. The first operational production unit will have an output of 1 ton per hour and will initially be used to process multiple rubber compounds. However, the efficiency and reliability of the reclaim service can be increased by specializing production units for specific compounds (DXP, 2011). Recycling rubber and re-using the material in a virgin production cycle can save costs, protect the environment and improve the public image of a rubber manufacturer (Polonsky and Rosenberger, 2001; DXP, 2012). The company is interested in the performance of their technology compared to the other reclaim technologies. This study will compare the environmental and technological performance of the DXP technology to three other rubber reclaim technologies: the chemical, micro-wave and ultra-sound reclaim processes. The technologies are the most important competitors to the DXP reclaim process because they can also recycle rubber waste into a new raw material for the original production process (Leary *et al.*, 2006; Sutanto, 2006; Dijkhuis, 2008; Ekelenburg, 2012). The technological capabilities of the technologies are analysed with the use of a literature review and five expert interviews. The environmental performance of the technologies is analysed with the use of the Life Cycle Assessment (LCA) methodology. The 'OpenLCA' software is used to combine the environmental impact data gathered from the literature, online databases and expert interviews to assess the environmental benefits of rubber reclaiming. The results of the research are used to formulate recommendations to DXP for the further development of their technology.

This research will investigate the technological capabilities and environmental performance of the four most important rubber reclaim technologies. In chapter two of this research the context of the study will be discussed in further detail. The chapter provides a historical introduction into rubber and introduces the concept of sustainable development. The chapter describes how synthetic rubber is produced and discusses the current approach to rubber recycling. Furthermore, the chapter introduces the company DX-polymers and the recycling service the company can provide. In chapter three the research design is presented. The chapter will also introduce the 'OpenLCA' software and the expert panel that was consulted for the research. Chapter four provides an overview of the LCA methodology and the ReCiPe impact categories that are used to determine the environmental impact of the product system. Chapter five describes why rubber recycling has proven to be so difficult and analyses the technological performance of the researched reclaim technologies. The chapter will also discuss the influence of legislation on rubber recycling and analyses the future prospects for the rubber market. In chapter six a Life Cycle Assessment (LCA) is presented of EPDM roof sheets production. The LCA investigates the effects of recycling the industrial waste (10%) for re-use in a new production cycle with the use of the studied reclaim technologies. In the discussion the results are compared to findings in other studies. In chapter eight the conclusions of the research and recommendations to DXP are presented.

Chapter 2 – Research context

The rubber industry has been growing almost every year since the discovery of vulcanization around 1850 (DXP, 2011). Rubber has become a strategic resource due to its importance for transportation, health-care and industrial processes. The European Union is heavily depended on the import of rubber polymers (ETRMA, 2010). The increasing demand for rubber products and the growing scarcity of the raw materials are driving up the price of rubber (Luiten, 2012; Smit, 2012). Shortages in the supply of rubber can effect economic growth and poses a threat to public-health e.g. lack of rubber gloves in hospitals. Furthermore, the production of the raw materials for synthetic rubber requires considerable amounts of energy and a finite resource. This is threatening the long-term sustainability of the industry because there are currently no viable alternative sources of rubber polymers (White and De, 2001; ETRMA, 2010; Luiten 2012; Noordermeer, 2012). The rising costs of the raw materials for rubber, increasingly strict regulation, and concerns about the sustainability of the industry are driving manufacturers to increase their recycling rate (Smit, 2012; Luiten, 2012). Plastics, which are the most similar polymer, can be recycled by melting the waste and giving it a new shape (Dijkhuis, 2008). However, this technique is not applicable to synthetic rubbers because the amount of heat required to melt the rubber will destroy the molecular chains making it unfit for re-use (De *et al.*, 2005). The current focus of the recycling efforts is on transforming rubber waste into a lower-grade material. The company DXP provides a novel rubber recycling service in which rubber can be recycled without much loss of quality. The initial focus is on recycling the vulcanized waste left over from a production process. This rubber waste is clean and the composition of the material is exactly known making high quality recycling possible. Recycling the industrial waste will be the first step for proving the viability of high quality rubber recycling. This chapter will first provide a historical introduction into rubber as a natural resource and describe how the main ingredients for a rubber compound are produced. The chapter will then introduce the concept of sustainable development and discusses the current approach to rubber recycling. In the final paragraph of the chapter the service the company DX-polymers provides is introduced.

2.1 The history of rubber

Rubber was first ‘discovered’ over 200 years ago by the Spanish explorers in South America. It has grown from a being an interesting curiosity to a multi-billion Euro industry which expands the globe (Loadman and James, 2010; Wolf and Wolf, 2009). In 1800 rubber was known to only a relatively small group of people but today millions of people use rubber products on a daily basis e.g. tires, shoes, roofing. The unique properties of rubbers make it one of the quintessential products for modern societies. The rubber tree is native to South-America where the material was widely known for its special properties. The first written document on rubber in Western literature was in the *Decades of the new world* by Pietro Martyre d’Anghiera published in 1511. He witnessed the Aztes play with a ball which apparently was ‘made of the juice of a certain herb’ (Wolf and Wolf, 2009 p.12). The material did not attract the attention of the Europeans immediately (John and Loadman, 1998 p.16). Admits of all the wondrous stories about ‘the new world’ the story about a ball seemed insignificant. It took more than a century until other uses of the material are mentioned. A Spanish

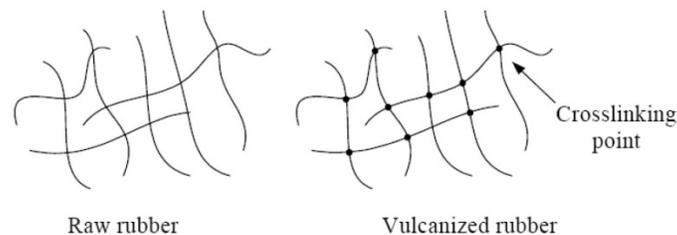
writer in 1615 noted; ‘if the substance is smeared on jackets that it makes exceptionally well raincoats’ (Wolf and Wolf, 2009 p.14). In 1823 the first rubber products were exported from Brazil to the US, the shipment contained 500 pairs of rubber shoes (Wolf and Wolf, 2009 p.24). Rubber was known to the Europeans for over 300 years before the full potential of rubber was unlocked with the discovery of vulcanization. Vulcanization was first observed by an English man named Nathaniel Hayward in the beginning of the 18th century. He rubbed sulfur into rubber sheets and exposed it to sunlight to reduce the stickiness of the material. He had no knowledge of the chemistry that lay behind this process and did not fully realize what he had done (Loadman and James, 2010 p.88; Wolf and Wolf, 2009 p. 241). Two other men did realize the potential of this chemical interaction and began studying the process. One of the first patents on the vulcanization of rubber was given out to Thomas Hancock in England in 1846. The patent describes how rubber can be vulcanized in molds or forms and subjected to pressure to create all kinds of useful products (Loadman and James, 2010 p.89). In the United States Charles Goodyear, born in 1800, became one of the pioneers of rubber vulcanization. Between 1851 and 1855 he was granted nineteen patents related to the production and application of vulcanized rubbers for a range of products. The first vulcanized rubbers on the market were ebonite mixes which are a type of very hard rubbers. (Wolf and Wolf 2009 p. 250; Loadman and James 2010 p. 259). The rubber industry took off from there and is has been expanding ever since. Over time many useful applications for vulcanized rubber were developed and our lives would not be the same without it. Today, more than a billion car tires are produced annually (GIA, 2011). A product that seemed insignificant 200 years ago is now part of everyday life for almost all people on this planet. The first rubbers were all made from natural rubber polymers obtained from the jungle of South- America. In the 1870 some seeds from the rubber tree were taken from the Kew Gardens in London and planted in what is now; Sri-Lanka, Malasia and Vietnam. These countries are still the main producers of natural rubbers in the World (White and De, 2001). The first step in the development of synthetic rubber was the fundamental research into the structure of the natural rubber molecules. The molecule was first split via pyrolysis by G.G. Williams in 1860 into smaller pieces (John and Loadman, 1998 p. 10). The scientific investigations resulted in a better understanding of the structure of the molecule and led to the development of new additives and catalysts for rubber production. However, the price of natural rubber was still low compared to the synthetic rubbers so there was little incentive to further investigate the subject. This change during the First World War when Germany’s supply of natural rubber dried up. Germany pioneered large scale synthetic rubber production however early methods were unreliable and very time consuming (John and Loadman, 1998 p. 11). During the 1930th the speed of development accelerated again. The price of natural rubber had increased and the prospect of a new World War intensified the research. Germany was the first nation that successfully developed synthetic rubbers during the 1930. In the United States synthetic rubber production boomed during the Second World war when their supply of natural rubber was interrupted (White and De, 2001). In 1941 domestic SBR rubber production was less the 3 metric tons a year. The first state owned production plant opened in 1942 and by 1945 the domestic rubber production of the US had risen to over 700.00 metric tons a year (John and Loadman, 1998 p.12; White and De, 2001 p.2). The development of synthetic rubbers made it possible to use other vulcanizing agents and

produce a wider variety of compounds. Research into elastomers continues to this day; new additives are invented as well as techniques to make rubber more durable or recycle used rubber products (John and Loadman, 1998 p. 13). Rubber has become so ubiquitous because it is such a versatile material. It can be moulded into any desired shape or form and has some unique properties which makes that there are no viable alternatives yet except for other natural elastomers (White and De, 2001 p.3; Noordermeer, 2012)

2.2 Synthetic rubber production

Manufacturers of rubber end-products can be characterized as focal companies. These are companies that 1) are able to govern their supply chain 2) are in direct contact with consumers and 3) are involved in the design of the products (Seuring and Müller, 2008). Careful management of the supply chain is essential for focal companies because they depend on others to supply them with raw materials. The majority of the environmental impacts of focal companies are usually caused by the subcontractors providing the raw materials and services. The choice of supplier or services can thus influence the environmental and social burden of the production process (Vermeulen, 2008). Rubber manufacturers mix the acquired raw material into a compound and mold the material into the desired shape. During the mixing process small quantities of sulfur (1% - 3%) are added so that the material can be vulcanized in an oven (Hertalan, 2012). Under the influence of temperature, the sulfur molecules form bonds with the rubber polymer chains. The process creates so called crosslinking point or bridges between the individual polymer molecules, see figure 2.1. This locks the molecules in place resulting in a material that will bend and deform under stress but returns to its original shape when the pressure is released (White and De, 2001). There are currently two sources for the raw materials for a basic rubber polymer i.e. the saps of rubber trees and crude oil. Synthetic rubbers were not only developed to be able to produce rubber from an alternative resource but also to overcome some of the deficiencies of natural rubber (Smit, 2012; Dijkhuis, 2012). Natural rubber has a poorer resistance to light, ozone, oxygen, heat and organic fluids than synthetic compounds. Furthermore, synthetic rubber has the advantage that the structure of the molecules can be designed in more detail (Dijkhuis, 2008; Noordermeer, 2012; Smit, 2012).

Figure 2.1: Visualization of rubber molecular structure in different states



Source: Sutanto, 2006.

The polymers can be given different properties depending on the intended use of the product. For instance, EPDM has a saturated backbone which makes it more resistant to weathering. However, SBR is more resistant to abrasive wear which is why it is used in car tyres (White and De, 2001). The market of synthetic polymers now has over 200 sub categories of elastomers each with different

properties (DXP, 2011). However, all the synthetic polymers and much of the fillers used in the production of rubber compounds are derived from crude oil. The majority of the oil in the world is consumed as energy, around 6% is used for non-energy purposes (Gary and Handwerk, 2001; Speight, 2007). The feedstock for synthetic rubber polymers is the heavy oil by-product of gasoline production. The main method used to refine gasoline out of mineral oil is via the steam-cracking of crude oil. During steam-cracking, crude oil is heated and diluted with hot steam. This sets off a chain reaction of very reactive free radical atoms within the mixture. The free radicals bump into other molecules breaking up the atoms or group of atoms into smaller pieces (Speight, 2007). The process also produces ‘dirt’ carbon molecules which start to build up and reduce the intensity of the chain reaction. This is why two containers are needed; one to regenerate the catalyst, usually fluidized zeolite, and one in which the catalyst can react with the crude oil. Fresh feeds are continuously combined with a recycled catalyst stream. Figure 2.2 shows the petrochemicals that are obtained via this process (Gary and Handwerk, 2001). The petrochemicals derived from the steam-cracking process will need to undergo polymerization to produce a rubber polymer. Polymerization is a complex chemical reaction by which new molecules structures can be formed out a combination of different substances. The polymerization techniques can be divided into two categories: step- and chain-polymerization (Davis and Matyjaszewski, 2002). The step process is mostly used for the processing of naturally occurring rubbers and builds up the molecular structure of the rubber in step-wise reactions. The structure of the molecules stays the same throughout the material. In chain-polymerization an initiator is used to generate a free radical chain-reaction by which new molecular structures are formed (O dian, 2004). EPDM is produced out of the simultaneous polymerization of different substances usually via the solution polymerization technology. In solution polymerization the monomers are dissolved under heat and pressure in an organic compound (White and De, 2001). A free radical chain reaction is induced causing the molecules to grow into longer polymer chains. The polymer-chains grow because each new connection regenerates the active center so that more molecules can be added to the structure. The molecules that are formed do not have the same structure as the original molecules (O dian, 2004). Free radical polymerization has been an important development because it allows for the creation of many different rubber compounds (Davis and Matyjaszewski, 2002).

Figure 2.2: Average molecules obtained via steam cracking

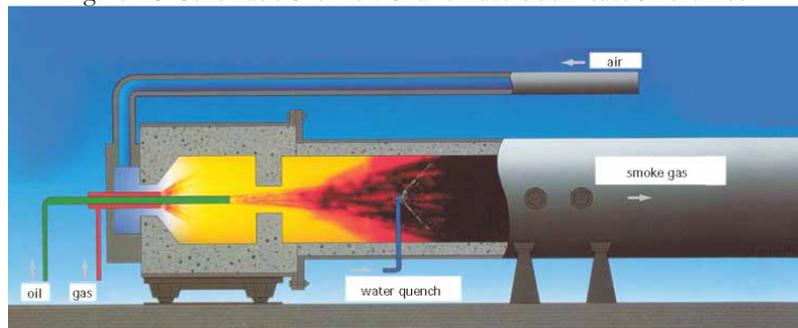
	wt%	vol%
Fresh feed	100.0	100.0
Gas	4.5	
Propane	1.3	2.2
Propylene	2.0	3.4
Isobutane	2.6	4.0
n-Butane	0.9	1.4
Butylene	2.6	3.8
C ₅ + gasoline	40.2	46.7
Light cycle oil	33.2	32.0
Decant oil	7.7	8.7
Residual oil		
Coke	5.0	
Total	100.0	102.2

Source: Gary and Handwerk, 2001

2.3 Fillers and additives

There are a wide variety of fillers and additives used in the rubber industry. Small quantities of e.g. vulcanization and processing agents are added during the mixing of the compounds. The chemicals are added to facilitate the processing of the rubber or e.g. to improve the fire resistance of the compound. Usually around 1% or less of these chemicals needs to be added to the compound (Hertalan, 2012). The filler carbon black is added in large quantities to many rubber compounds. Carbon black reinforces compounds making them stronger and more durable. The re-enforcing effects of carbon black were first discovered at the beginning of the 19th century. This was a significant milestone in the development of more durable rubbers and the automobile industry. Carbon black greatly increased the lifetime of car tires which can now run for several thousands of kilometers (Sanders and Peeten, 2011). The main method of producing carbon black is via the partial combustion of hydrocarbons in a thermal-oxidative process. The raw materials for this process are oil residues from oil refineries and steam-cracking facilities (Büchel *et al.*, 2000). There are oils that could produce a higher yield however petrochemicals are the most economical feedstock due to the large quantities that are available (Sanders and Peeten, 2011). The thermal-oxidative process is usually contained within the so called ‘furnace black process’. Different grades of carbon blacks can be produced in a continuous production cycle. The flexibility of the process has made it the dominating technology for carbon black production (Sanders and Peeten, 2011). Figure 2.3 shows a schematic overview of main element in the production cycle i.e. the reaction chamber (CBN, 2005). The oil and gas feedstock is injected into the reaction chamber via pipes that connect the production facilities. The gasses react with the oil in the first part of the chamber where the process burns up around 50% of the oil feedstock. Reaction temperatures in the chamber range from 1200 to 1800 °C depending on the type of carbon black produced (Voll and Kleinschmit, 2005; Sanders and Peeten, 2011). Water is injected further down in the reactor to halt the reaction and avoid secondary reactions from occurring. The production process produces high amounts of heat which, if captured, can be used to pre-heat the feedstock and all the pipes around the facility. The tail gas of the production system is also still relatively hot and can be used to dry the carbon black or generate electricity (Büchel *et al.*, 2000). Modern plants are able to produce up to three times the amount of electric energy the plant consumes. The lifetime of a carbon black reaction furnace can range from months to several years (Sanders and Peeten, 2011).

Figure 2.3: Schematic overview of a furnace black reaction chamber



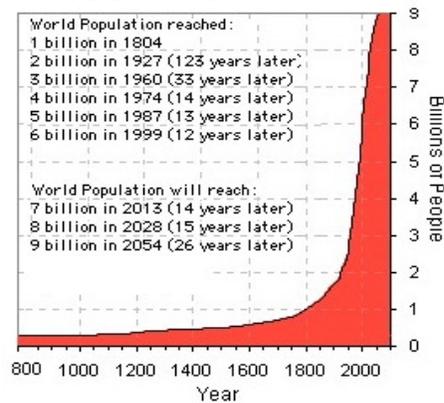
Source: CBN, 2005

The reinforcing qualities of carbon black made it possible to produce strong and durable rubbers which vastly increased the application of rubbers. However, the production of carbon black is energy and resource intensive leading to additional environmental damages caused by the rubber industry.

2.4 Sustainable development

The natural environment and economic activity are intricately related. The biosphere of earth provides the raw materials used to produce goods and services. Furthermore, nature provides for so called ‘eco system services’ such as the purification of water and air (Haines-Young and Potschin, 2007). The natural environment also has the ability to act as a sink absorbing or diluting harmful human produced pollution e.g. store CO₂. Resource depletion, land degradation and accumulating environmental pollution are threatening to undermine these fundamental provisions of natural resources (Harris, 2006). The work of Adam Smith’s ‘*The Wealth of Nations*’ first published in 1776 is one of the most influential theories on industrialization. The value of goods and services is based on the labor and capital costs of production and the willingness of people to buy the product at certain prices i.e. the invisible hand of the market. The theory promoted private property rights and individual economic freedom. The feudal economic models in the West were gradually replaced by free market economics (Rifkin, 2002). Today, the classical economic models are questioned due to rising concerns about the sustainability of current production methods. It is argued that the prices at which products are placed in the market do not reflect the real cost of production. The environmental pollution and resource depletion caused by the production of a good or service are usually not accounted for in the market price. Neglecting these external costs distorts our picture of the real physical reality and is undermining the habitability of the planet for future generations (Harris, 2006). It took millions of years of evolution before the global human population level reached 1 billion around the year 1804. Not many people would expect then that only two hundred years later more than 7 billion of us would inhabit the planet, see figure 2.4 (Malthus, 1798). Over the past two centuries, building upon scientific inquiries and experiments, entrepreneurs introduced world altering products to the market. Inventions such as the electric light, the telephone and the internet fundamentally changed the economy and societies. The industrial revolution, which began in the 18th century, opened up the vast supplies of fossil fuel resources available in the earth’s crust. The abundance of energy provided by coal, oil and natural gas made it possible for the human population to explode on an unprecedented scale (Rifkin, 2002). The achievements made in science and engineering over the last century increased living standards in the West dramatically. Human civilizations are more interconnected than ever before and the speed at which change is adopted in societies increases (Bruun and Hukkinen, 2003). However, on a more crowded planet, natural resources are becoming increasingly scarce and environmental pollution is having a global effect on the climate (IPCC, 2007). The traditional model of industrialization can no longer be applied in a world with diminishing natural resources and major global environmental problems (Harris, 2006).

Figure 2.4: World population growth from the year 800 till 2050



Source: United Nations population prospects, 2004

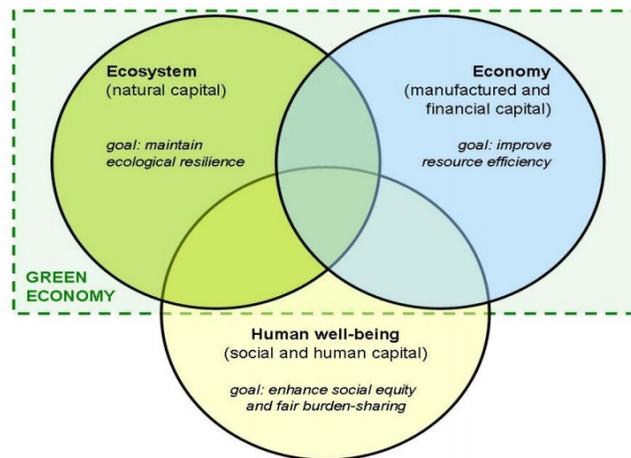
Sustainable development is seen as way to protect the environment as well as to sustain economic growth within industrialized societies. The term has become broadly interpreted and evolved into a well-known and useful concept (Harris, 2006). The European Union has set out clear goals on sustainable development and the efficient management of resources. In the report ‘roadmap to a resource efficient Europe, 2011’ resource efficiency is seen as important strategy to deliver more value with fewer resources. The member states are encouraged to improve products, alter consumption patterns and boost resource efficient production. The vision of the European Union is defined as follows (European Commission, 2011 p3):

“By 2050 the EU's economy has grown in a way that respects resource constraints and planetary boundaries, thus contributing to global economic transformation. Our economy is competitive, inclusive and provides a high standard of living with much lower environmental impacts. All resources are sustainably managed, from raw materials to energy, water, air, land and soil. Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored.”

The increased awareness of the major environmental and social problems is driving individuals and organizations to seek for alternative production methods (Hitchcock and Willard, 2008). The industry in the Netherlands has responded to this need by becoming more energy and resource efficient (Tellegen, 1995). This substantially reduced the environmental damages caused by Dutch economic activity over the past decades. However, due to globalization a large part of the environmental impact caused by Dutch consumers now originates in developing countries (20-35%). The Dutch government has no jurisdiction in other countries and is therefore not entitled to address the production conditions directly. This makes it more difficult to control the environmental damages that are caused by Dutch consumers (Vermeulen, 2008). Globalization has led to a need for more corporate social responsibility in order to reduce the environmental damages of industrial production, distribution and consumption. The environmental and social performance of companies is becoming increasingly important in order to comply with regulation and to maintain a competitive advantage (Cramer, 2005). These considerations are especially important for rubber manufacturers since they are at the centre of a production system. In business terms the triple bottom line is often proposed as a framework to guide the organization towards more sustainable business practices. The three bottom lines are 1) People; which stands for the fair and equal treatment of all parties

involved 2) Planet; which stands for the protection of the environment 3) Prosperity; which stands for ensuring financial sustainability. The decision making within organizations should be based on a balance between the three considerations (Bloomfield *et al.*, 2012). The framework tries to promote transparency combined with financial and environmental stewardship, see figure 2.5. In an increasingly interconnected world we are depended on the stability in other parts of the world. The major environmental and social problems in the world can only be addressed by looking at the system as a whole. The triple bottom line recognizes that economic, social and environmental issues are interconnected and need to be dealt with in a holistic manner (Wexler, 2008). Becoming more sustainable will require companies to rethink their products and productions processes as well as having a strong ethical code of conduct (Hitchcock and Willard, 2008). However, finding out which steps need to be taken for increasing the sustainability of production systems can be difficult.

Figure 2.5: The goals of the triple bottom line approach



Source: European Environment Agency

Life Cycle Assessment (LCA) is a tool that can assist organizations with strategic decisions-making to improve the environmental performance of the company. The environmental impacts of the whole life cycle of a product i.e. from cradle to grave are calculated to estimate the total potential impact of production, see chapter 4 for further details on the LCA methodology (ISO:14040, 2006).

2.5 The current approach to rubber recycling

The tire industry has traditionally been the focus of rubber reclaim-investigations because of the large market for tires (Dijkhuis, 2008; Noordermeer, 2012). However, tires are costly to recycle and the prices of the virgin materials have historically been relatively low. Furthermore, recycled rubber from scrap tires is not able to compete with virgin materials due to high quality standards of the tire industry (Sutanto, 2006_a). Manufacturers are concerned about a reduction of the quality of the end-product and the costs of recycling (Smit, 2012; Luiten, 2012). The main approach currently implemented to deal with rubber waste is by transforming it into a lower grade material (Eurostat, 2012). The main goal of the approach is to reduce the amount of rubber waste while also achieving cost savings by improving the resource efficiency. This will extend the life-time of the material but it does not reduce the demand for new virgin material. Therefore, it does not lead to a significant cost

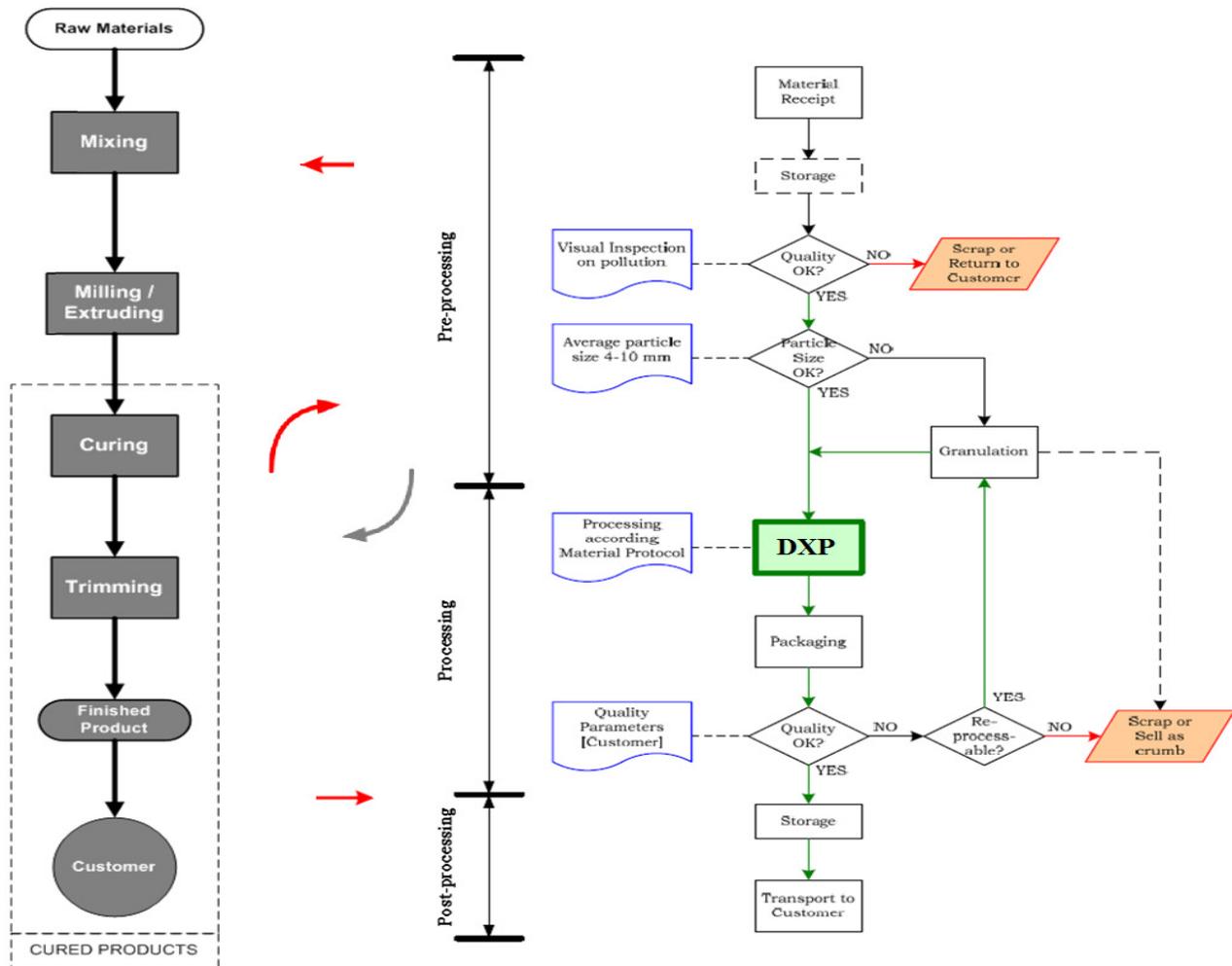
benefit or any improvements in the sustainability for manufacturers of rubber end-products (Braungart *et al.*, 2006). The concepts of cradle-to-cradle (C2C) propose a different route based on the notion that products need to be designed to be recycled either by nature or by humans i.e. to have zero waste (Braungart and McDonough, 2008). Applying this principle in the rubber market will be the most resource efficient solution (Sutanto, 2006_a). By designing products to be recycled the material quality of the compounds can be better maintained and recycling becomes more cost effective (Cagno *et al.*, 2003). Over the past years, some novel solutions to the waste problem have been proposed such as the ultra-sound or mechanical reclaim technologies. Furthermore, under increased market pressures, the chemical and microwave reclaim technologies were further improved upon (e.g. Adhikari and Maiti, 2000; Fukumori and Matsuchita, 2003; Feng and Isayev, 2005; Leary *et al.*, 2006; Rajan *et al.*, 2006; Sutanto, 2006_a; Vega *et al.*, 2007; Ekelenburg, 2012). The initial focus of novel reclaim technologies will be on recycling the industrial waste of rubber compounds suited for recycling (Noordermeer, 2012; DXP, 2011). EPDM rubber is the largest market for rubber in the non-tire sector. The material has very good material properties and can be compounded with fillers to an extremely high level. It is mainly used in the automobile sector for profiles, hoses and seals (Sutanto, 2006_b). However, reclaiming this waste is not practical because of the large diversity of compounds which makes it difficult to create a stable recycled product (Noordermeer, 2012). The rubber reclaim efforts have focused on recycling the EPDM rubber used for roof sheets. This is the third largest market form EPDM rubber and the product is uniform and therefore easier to recycle (Smith, 2012). The company Hertalan is a manufacture of EDPM roof sheets from the Netherlands and is one of the first companies in the world to invest in a mechanical reclaim technology to recycle their industrial waste. The market provides a stepping stone to prove that a reclaim technology works and that the quality of the material can be maintained (Noordermeer, 2012; Smit, 2012).

2.6 The company DX polymers

DX-polymers (DXP) provides a processing service for rubber waste which can recycle rubber into a high quality feedstock for a new rubber compound. The company is introducing a novel technology that is able to recycle rubber in a continuous process without the use of chemicals. The technology developed by DXP can selectively break the crosslinking points formed during vulcanization by applying a controlled amount of mechanical stress to rubber waste. The rubber waste is converted into a material of near-master batch quality so that it can be re-used for the original application. Figure 2.6 shows the diagram of the production system of rubber and the service DXP can provide. The vulcanized waste left over from a production process i.e. cured products can re-processed by DXP so that the material can be incorporated into a virgin batch during mixing or milling. The production waste is clean and the material properties of this rubber are exactly known which makes it possible to produce a stable and high quality recycled material (Smit, 2012; DXP, 2012). The rubber is not recycled into a powder or reclaim-paste but it gets delivered as a dried viscoelastic material. This material can be mixed in a high ratio with a virgin compound without reducing the material properties of the end-product. The technology can deliver a cost advantage, reduce environmental pollution and improve the public image of rubber manufacturers. DXP provides the

option for the client to reconsider the recycling effort if the material quality of the recycled rubber is found to be insufficient (DXP, 2012). The financial risks for the costumer are relatively low because no large investments are needed to increase the recycling rate of a company. DXP will re-sell the recycled waste at a certain percentage of the virgin polymer spot price. This price may be adjusted to volume, quality requirements or the length of a contract.

Figure 2.6: Diagram of rubber production and the steps taken by DX-polymers during the recycling process.



Source: DXP, 2011

DXP costumers are requested to supply relevant information on the main ingredients, the performance criteria and the curing condition of the compound. Based on the information and experimental trails the company can suggest compound optimization to increase the efficiency of the recycling technology. The company positions itself as a supplier of raw materials with a service that can be tailored to the requirements of the costumer (DXP, 2012). Some manufacturers will however be unable to re-use the material due to high quality standards within the industry e.g. gas masks (Ekelenburg, 2012). DXP also offers a service which can re-process rubber waste into a raw

material for an interested third party. The recycling processes can work on multiple polymer compounds and can recycle rubber fast.

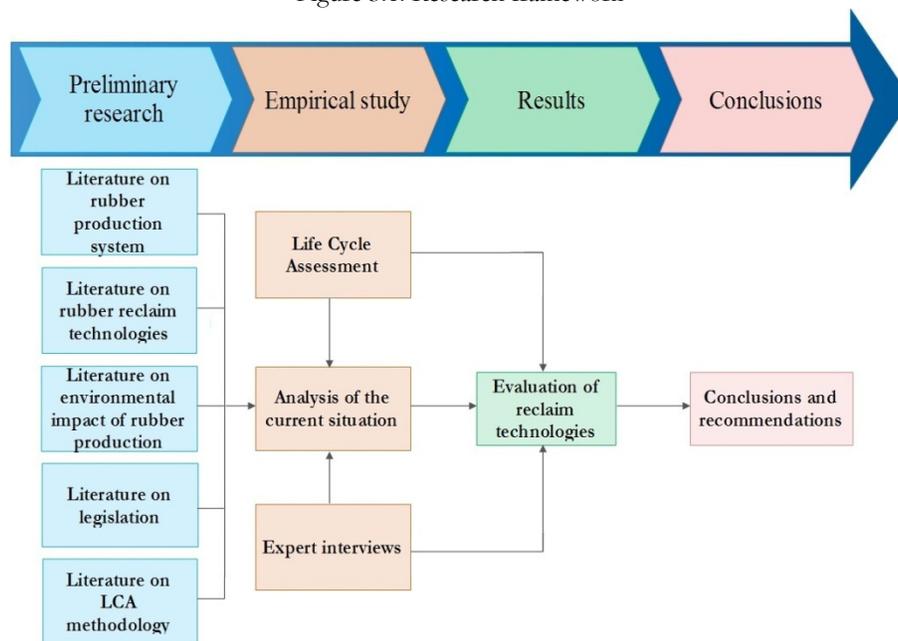
2.7 Concluding remarks

This chapter described how rubber became a vital resource for the modern world due to its importance for transportation and industrial processes. The industry is however confronted with increasingly strict environmental regulation and rising raw material costs. The European commission published the ‘Roadmap to a resource efficient Europe, 2011’ in which the desire to do more with less material is articulated. However, most of the current rubber-recycling processes do not reduce the need for virgin material because the rubber is transformed into a lower-grade material. Recycling rubber so that it can be re-used for the original product application is a more resource efficient option. This research is commissioned by DX Polymers in order to assess the competitiveness of their rubber recycling technology. The company can provide a service which can recycle rubber waste into a high quality material so that the rubber can be re-used in the original application i.e. reclaiming. Reclaiming rubber is only done on a very limited scale leading to a knowledge gap on the effects of applying reclaim technologies in rubber production processes. Most of the technologies have only been tested in an experimental setting. The research will be able to identify the most promising reclaim technology currently under development but the economic competitiveness of the reclaim technologies cannot be assessed before they are able to enter the market place.

Chapter 3 - Research design

The research will assess the competitiveness of the micro-wave, ultra-sound, mechanical, and chemical reclaim technologies for rubber waste. Two main aspects will be assessed: the technological performance and the environmental effects of introducing the technologies into a production process for EPDM roof sheets. EPDM roof sheets are a strong and homogenous compound so the market provides a good opportunity for the introduction of novel recycling technologies (DXP, 2011; Noordermeer, 2012). Figure 3.1 depicts the research framework that is used to assess the quality, flexibility, reliability, and sustainability of the researched recycling technologies. This chapter will first discuss the objective of the research and the research questions that will be answered in the study. In the technical research design the research strategy is presented. The paragraph will also present the expert panel and will introduce the ‘OpenLCA’ software tool.

Figure 3.1: Research framework



The **research objective** of the study can be summed up as follows:

“To compare the sustainability and technological capabilities of rubber reclaiming technologies by analyzing their performance using the life cycle assessment methodology, literature and information gathered from expert interviews.”

During the preliminary research stage the available academic literature was reviewed to gain a perspective on the production process of synthetic rubber and the possibilities for recycling. The performance of the mechanical reclaim technology developed by DXP will be compared to the three main competitors: the chemical, ultra-sound and micro-wave reclaim technologies. The studied reclaim processes are the four main methods for recycling rubber waste into a high quality feedstock for a new rubber compound (Dijkhuis, 2008; Sutanto, 2006; Dijkhuis, 2012; Ekelenburg, 2012; Noordermeer, 2012). The chemical reclaim method has produced good experiments results on EPDM roof sheets (Dierkes *et al.*, 2006; Sutanto, 2006; Dijkhuis, 2008). The ultra-sound reclaim

technology is a unique method of rubber reclaiming which also produced good experimental results on EPDM roof sheets (Yun and Isayev, 2003_a). The micro-wave reclaim technology was one of the first rubber reclaim technologies and continues to be investigated by researchers in experimental trials (Bani *et al.*, 2010; Pistor *et al.*, 2010). The quality, practicality and reliability of the technologies will be assessed with the use of a literature review and five expert interviews. The experts are able to verify some of the assumptions made in the research and can help identify which technology is environmentally sound as well as competitive in today's rubber market. The environmental impact data used to make the LCA models is based on the literature, online environmental impact databases and information provided by companies and rubber experts. The information gathered is combined in the 'OpenLCA' software to calculate the environmental impact of an EPDM roof sheet production process. A non-recycling scenario will serve as a reference flow to assess the environmental benefits of rubber reclaiming. In the alternative scenarios, a recycling technology is included which recycles the industrial waste (10%) for re-use in a new compound. The LCA will give an indication of the environmental effects of rubber production and the possible advantages of rubber reclaiming. The LCA models will be reviewed by an external LCA expert. By using a combination of different research techniques a broad assessment of the technologies can be made. The **main research question** for the project is:

“Which of the following reclaim processes; chemical-, ultra-sound-, micro-wave- or mechanical- reclaim for EPDM rubber roof sheets can be considered the most competitive in terms of environmental and technological performance?”

The main research question is answered by investigating a number of **sub-research questions**. The information from the expert interviews and the literature review will be used to answer the following questions in chapter 5 of this research: *which of the reclaim technologies can deliver the best recycling service in terms of quality, reliability and flexibility?*, *How does regulation influence the recycling rate within the rubber industry?* and *What are the future prospects for the rubber market?*. The LCA will answer the question: *“which of following reclaim technologies: chemical-, ultra-sound-, micro-wave- or mechanical- reclaim can deliver the most favorable environmental impact reduction?”*. The main research question will be discussed in the concluding chapter of the research.

3.1 Technical research design

The relevant information needed for the research is obtained from multiple sources. In the preliminary research stage DXP provided some initial information and possible rubber compounds to study. Two companies were visited namely: Hertalan and Dunlop-conveyer belting to discuss how rubber is produced and the possibilities for rubber recycling. Initially the research intended to assess multiple rubber compounds i.e. EPDM, NR and SBR. However, no environmental impact data was available on the impact of natural rubber production. Furthermore, the products and their application are an important determinant for the practicality of rubber recycling; this made an integral assessment problematic. The EPDM roof market was the most suited market for the introduction of novel recycling technologies and it is therefore selected as a case study. The research includes four possible methods of rubber reclaiming which are chosen on the basis of their ability to recycle rubber into high quality feedstock for a new production process. There are more methods used to recycle rubber into a reusable material e.g. pyrolysis or shredding (Dijkhuis, 2012). The

processes recycle rubber waste into something that can be used by another industry to produce e.g. rubber tiles or sport fields. These applications are not included in the study because they do not reduce the costs or the environmental emissions of rubber production. The most sustainable and cost effective solution for rubber manufacturers is to re-use rubber to produce new rubber compounds of comparable quality (DXP, 2011). The relevant information on the environmental impact of the production chain was gathered after drafting an initial flowchart of the materials and processes used during EPDM roof sheet production. The Joint Research Centre of the European Commission (ELCD¹) database provided a basis for the raw material inputs into the model. The database provides a comprehensive Life Cycle Inventory (LCI) which is based on data gathered from European businesses. The research project is funded by the European Union to provide an accessible LCA database free of charge. Most of the environmental impact data on the modelled production process is calculated on the basis of this data. However, EPDM rubber production was not included in the database. Additional information on the environmental impact of the production process was gathered from LCA studies, experts, companies and additional LCA databases. The impact assessment is done with the use on the ‘OpenLCA’ software. The software is developed by DeltaTC and is made available as an open-source software tool (GreenDeltaTC, 2011). The software was released in 2008 and can be used to incorporate LCI datasets with EcoSpold (ecoinvent), SimaPro (EcoSpold) and ELCD formats. The software is free, easy to use and allows for the construction of detailed LCA models, see www.openlca.org for further details. The most important environmental impacts of rubber production will be presented in normalized charts to provide an overview of the LCA results which can easily be interpreted. The initial research strategy was to gain expert opinions on rubber recycling via the use of the Delphi research strategy. This was however not practical due to the limited number of researchers working in the field of rubber recycling and because companies and researchers are usually fairly secretive about their operations. To be able to assess the technological capabilities of the recycling technologies five respondents were selected to conduct in-depth interviews. The experts are:

- *Henk Van Ekelenburg, DX-Polymers.*

Mr. Henk Van Ekelenburg became the CEO of DXP after he has managed a number of small enterprises. He gained an MSc in mechanical engineering and his last company Pro support focused on assisting companies with research and development projects. Pro-support helped prepare project proposals and compiled large research projects. He is now fully focused on the introduction the mechanical reclaim technology to the market by building prototypes, researching the effects of the recycling process on different compounds and finding the needed investments.

- *Kuno Dijkhuis, Elastomers testing.*

Mr. Kuno Dijkhuis performed a PHD at the university of Twente into the possibilities of recycling rubber with the use of the reclaim chemical HDA. He is currently working at Elastomers Testing B.V. in Deventer, the Netherlands. The company specializes in developing rubber compounds and testing compounds, including recycled materials, for interested third parties. He has an in-depth

¹ <http://lca.jrc.ec.europa.eu/lcaifohub/datasetArea.vm>

knowledge about the subject of rubber recycling and was able to review the results of multiple recycling methods.

- *Jacques W. M. Noordermeer, University of Twente.*

Jacques Noordermeer, professor at the University of Twente, holds the position of 'Professor of Rubber technology' which is a unique title in the Netherlands. He published over three hundred scientific publications, is co-inventor of ten patents, and received a number of awards for his research. Professor Noordermeer is currently investigating the possibilities of recycling rubber using a mechanical reclaim process.

- *Albert Luiten, Dunlop conveyor belting.*

The company Dunlop conveyor belting makes rubber conveyor belts and is one of the largest consumers of rubber in the Netherlands. The company manufactures multiple rubber compounds and has had experience with recycled rubbers. The company is affected by new legislation and is seeking to increase their recycling rate. The person responsible for research and development Albert Luiten had agreed to participate in the research.

- *Bart Smit, Hertalan*

The company is one of the front runners in the development of rubber recycling. The company manufactures EPDM roof sheets and has participated in multiple recycling experiments. Recently, the company invested in a mechanical-reclaim technology to start recycling their industrial waste. It is one of the first companies in the world to invest in a large scale rubber reclaim facility. A representative of the company Bart Smit had agreed to explain the position of the company.

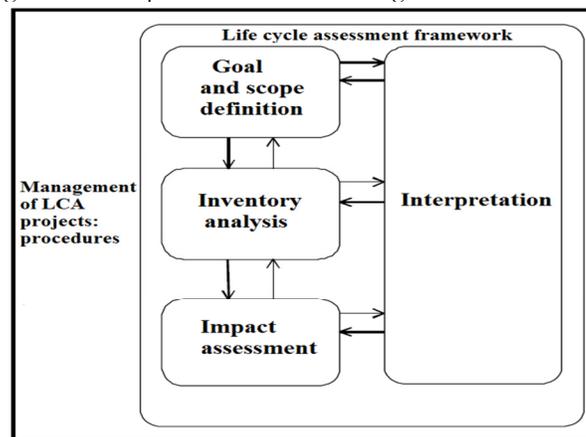
3.2 Concluding remarks

The research is designed to make an integral assessment of the reclaim technologies. The empirical data gained from interviews and the data obtain via desk research provides the basis for assessing the competitiveness of the reclaim technologies. The expert panel is able to provide a good indication of the possibilities of rubber reclaiming since they have in-depth knowledge about the subject of rubber recycling. The EPDM roof sheet market has been identified by many researchers as a good market for up scaling rubber reclaiming facilities. It is therefore chosen as a case for assessing the environmental performance of the technologies with the use of the LCA methodology. One of the major limitations of performing a LCA research is the lack of reliable data. Many of the databases and software programmes are only available at a high fee. The free ELCD database and the 'OpenLCA' software were therefore of vital importance for this research. The results of the study will mostly apply to the EPDM roof sheet market because it difficult to make generalized predictions about the success of rubber reclaiming. The time frame of the research and some key literature search words can be found in appendix one.

Chapter 4 – The LCA methodology

It has become increasingly important for companies in Europe to consider the environmental performance of their production methods to be able to comply with regulation (Askham, 2010). To account for the environmental performance of companies Environmental Management Systems (EMS) were developed. The term encompasses all the provisions that a company takes to account for and control its environmental influence. The EMS can include elements such as identification of environmental impacts, legal obligations and action plans to improve the situation (Kolk, 2000). The LCA framework can be used to analyse a production processes from cradle to grave. The natural resource usage, the toxicological effects and the emission of substances to the air, water or soil, during the life-time of a product, are described in quantitative terms (Baumann and Tillman, 2004). In 1997 the first international standard for the LCA methodology was issued by the International Organization for Standardization (ISO:14040, 1997). The LCA methodology from the ISO organization has become the accepted standard for Life Cycle Assessment by the international community (Guinee *et al.*, 2011). There are four main aspects of a LCA defined by the ISO standards the; *goal and scope definition*, *inventory analysis*, *impact assessment* and *interpretation*, see figure 4.1. The framework has extended from nearly an assessment of end-products to an analytical tool which supports high level decision making within companies on energy systems, eco-labelling and alternative modes of production (Goedkoop *et al.*, 2009). This chapter will introduce the LCA methodology and the ReCiPe impact categories that are used for the research.

Figure 4.1: The phases in LCA according to the ISO standards.



Source: ISO 14040, 2006.

4.1 The LCA framework

- Goal and Scope

In the goal and scope of a LCA study the product to be researched and the purpose of the study needs to be clearly defined. The ISO standards state that *the goal* shall unambiguously state ‘the intended application, the reason for carrying out the study, the intended audience and whether the results are a comparative assertion’ (ISO:14044, 2006 p7.).The definition of the goal and scope forms the basis for chosen modelling of the LCA, i.e. which specific products and processes are

researched. In the *scope* of the research multiple items need to be considered including: the system boundary, cut-off criteria, the functional unit, the allocation and the types of impacts of the studied subject/object (ISO:14044, 2006). The system boundaries can be related to natural systems, geography, time, or can be technical of nature. An LCA should describe the life cycle of products as complete as possible however some material flows or environmental impacts can be excluded from the assessment. In a change oriented LCA, processes not affected by a change e.g. capital goods can be excluded from the study. Furthermore, processes or emissions can be excluded due to their negligible relevance, time constrains, a lack of data or financial resources. Cut-off criteria need to be defined that specify the flows or environmental impacts that are excluded from the LCA study (Baumann and Tillman, 2004). The functional unit will act as a reference by which the different production systems can be compared. The in- and outputs of the product systems need to be quantified in relation to this reference flow (Guinée *et al.*, 2002). The environmental impact of the products will be compared on the basis of delivering a fixed amount of their good or service in order to be able to make a fair comparison (Baumann and Tillman, 2004). The functions that are not taken into account need to be explained and documented. The goal and scope should also include the impact categories and the method of impact assessment used in the study. The ISO standards provide a selection of indicator parameters which could be included e.g. use of mineral resources, carbon dioxide emissions and emissions to soil or water. The goal and scope should furthermore include the major assumptions made, a justification of the system boundaries and the limitations of the research (ISO:14044, 2006).

- Inventory analysis

The first step of the inventory analysis is to clearly define the product system and to construct a flowchart of the technical system under study. The model incorporates processes that are relevant for determining the environmental impact of a product system. The flowchart defines the system boundaries, shows which data needs to be collected and how this is allocated to the environmental loads. Flows such as diffuse heat and water vapour from combustion are not incorporated in the models because they have no environmental impact (Baumann and Tillman, 2004). The models used in LCA are static meaning that the results are not modelled over time. Descriptive, qualitative and numerical data on the following is needed (ISO:14044, 2006 p12) :

- Energy inputs, raw material inputs and other physical inputs
- Products, co-products and waste
- Emissions to air, discharges to water and soil
- Other environmental aspects

Transportation requirements can be an important indicator therefore information may be needed on the distances travelled by the vehicles used in the transportation of the goods (ISO:14044, 2006 p25). Generic data on energy use and default emission models can be used to account for transportation. The use of generic or 'borrowed' data is common within LCA studies. Computer models are used to assign environmental impacts to processes but additional data can be added to the model. When all the relevant data is collected the environmental impact can be calculated. This

is done by the following steps: 1) Normalize the data, 2) Calculate the flows linking the activities with the functional unit as a reference, 3) Calculate the flows passing through the system boundaries, 4) Sum up the resource use and emissions for the system. Normalizing the data implies that the data is made comparable because data can be expressed differently; e.g. yearly, totals or average. The data needs to be adjusted to model the flow that is described in the functional unit (Baumann and Tillman, 2004). It is important to consider how to allocate the emission and resource flows in the case of multiple in and outputs within a production system (Guinée *et al.*, 2002 p42). The final impact calculation is usually done with computer software.

- Impact assessment

The impact assessment phase of LCA is designed to translate the results of the inventory analysis into environmental consequences that the target audience can understand. For instance, it is easier to understand acidification or global warming potential as a concept than interpreting all the effects of e.g. SO₂ or methane emissions. Another important reason for grouping the results from the inventory analysis is the readability of the impact assessment. To make the results clear and understandable, the inventory parameters are combined to create environmental impact categories. This also allows for a comparison of the results from product cycles that use different substances (Baumann and Tillman, 2004). The impacts categories may vary between studies but the selected categories need to reflect ‘a comprehensive set of environmental issues related to the product system studied’ (ISO:14044, 2006 p17). The ISO standard distinguishes a number of sub-phases which need to be implemented during the impact assessment phase namely: impact category definition, classification and characterization. Defining the impact categories is the first step in the process. The environmental impacts that are investigated depend on the goal and scope of the research. In the classification step the data from the inventory parameters is assigned to the chosen impact categories (ISO:14044, 2006 p16). If all the data is ordered into impact categories, the figures can be characterized. This means that the environmental loads within an impact category are expressed in the same unit using *equivalency factors*. For instance, methane is a more potent greenhouse gas than CO₂. These emissions are therefore expressed in their global warming potential so they can be combined in the same category (Baumann and Tillman, 2004). The impact assessment is usually done with LCA databases and software designed to model the effects of the researched processes on the different impact categories. The ReCiPe method will be used in this study to transform the inventory results into a limited number of indicators.

- Interpretation

The interpretation phase is designed to evaluate and analyse the results, to draw up conclusions and to make recommendations for further research. The results need to be checked in terms of consistency, completeness and robustness (ISO:14044, 2006). The completeness check makes sure that all the relevant data is incorporated in the model. An error check, preferably done by an expert, can help uncover false assumptions and check the model choices and data. The overall contribution of the various processes can be analysed by a contribution analysis. The percentage of the total impact is given for specific flows. In figure 4.1, at the beginning of this chapter, the interpretation phase is shown to affect all stages meaning that LCA is an interactive process. After the completion

of each phase the data should be checked because new information could mean the modelling should be changed (Guinée *et al.*, 2001).

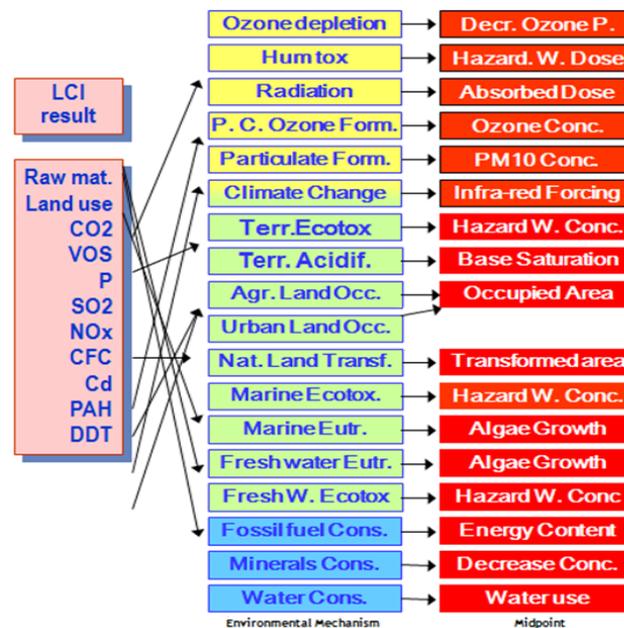
4.2 The ReCiPe impact categories

The ReCiPe method was developed in the Netherlands by a collaboration of experts from the National Institute for Public Health and the Environment (RIVM), the University of Nijmegen, the Centrum Milieukunde Leiden and from PRé consultants. The ReCiPe impact assessment method is based on extensive research and represents the most relevant impacts that can be related to human emissions. The method harmonizes multiple datasets with most of the characterization factors representing central European climatic conditions. The ReCiPe method converts the data from the inventory table into two sets of impact categories: the mid-point and end-point categories. There are eighteen mid-point categories defined based upon the work of Guinée *et al.*, 2002 (Goedkoop *et al.*, 2009):

- Climate change
- Water depletion
- Freshwater eutrophication
- Particulate matter formation
- Photochemical oxidant formation
- Fossil depletion
- Natural land transformation
- Urban land occupation
- Human toxicity
- Freshwater eco-toxicity
- Terrestrial acidification
- Marine eutrophication
- Ionizing radiation
- Ozone depletion
- Metal depletion
- Agricultural land occupation
- Terrestrial eco-toxicity
- Marine eco-toxicity

This research will use these impact categories to determine the environmental impact of the product system. The ReCiPe method relates the LCI results to eighteen environmental impact categories represented by the ‘environmental mechanism column’ in figure 4.2.

Figure 4.2: An overview of the ReCiPe method used to calculate the environmental impact of manmade emissions.



Source: ReCiPe, 2012

The environmental impacts are determined on the basis of seventeen impact parameters which are depicted in the ‘midpoint column’ in figure 4.2. For instance, CO₂ emissions cause climate change which is measured in infrared radiative forcing potential. In the end-point categories, additional risks and damages are related to the environmental impacts. All the environmental impacts are then combined in three end-point impact categories: human health, ecosystems and resources (ReCiPe, 2012). The end-point categories increase the uncertainties in the predictions due to the difficulty of determining the additional risks and damages. For instance, climate change is also related to species extinction and increased human health risks e.g. due to the spread of diseases in the end-point categories. The end-point indicators are more uncertain because they give a single score of the possible environmental damages caused by a product system to human health, ecosystem diversity, and resource availability. The mid-point impact categories are positioned halfway between the environmental mechanisms that can be related to anthropogenic emissions. There is a relative low uncertainty in the models used to calculate these environmental impacts because they can be directly related to the emissions of the product system (Goedkoop *et al.*, 2009). The damages included in the end-point indicators are caused by additional environmental mechanisms of which cause and effect are more difficult to determine. The ReCiPe method allows for the manipulation of the data according to three different cultural perspectives: the hierarchic perspective, the egalitarian world view and the individualist perspective. The individualist perspective has a short-term interest and is optimistic about technological development. The egalitarian world view is ruled by the precautionary principle considering the longest possible time-frame according to current scientific knowledge. The hierarchic perspective is a consensus between the two more extreme positions and is the most used perspective for policy documents. It is also used in this study mainly because it assumes a mean adaptation level to climate change. The individualist perspective assumes full climate adaptation by humans and the egalitarian considers no adaptation to take place (Goedkoop *et al.*, 2009 p19). However, it is more likely that some regions will be able to adapt to the changing climate while other regions cannot leading to a mixed picture of adaptation.

- Climate Change

Climate change is a complicated indicator because multiple environmental mechanisms are involved some of which have a large time-lag. In the ReCiPe method the marginal effects of adding additional greenhouse gases to the atmosphere are modeled based upon predictions made by the Intergovernmental Panel on Climate Change (IPCC). The Climate-change midpoint category is based on the infrared radiative forcing potential of molecules. The IPCC has defined radiative forcing as follows (IPCC, 2007):

“a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in watts per square meter (W/m²)”.

The ReCiPe method uses the equivalence factors developed by the IPCC, 2007 to determine the effects of radiative forcing. The Global warming potential of an emission is expressed in CO₂-equivalents. This means that the influence a certain molecule has on the energy balance of the earth

is calculated relative to the effect of CO₂ emissions. The life-times of molecules are also taken into account so the equivalency factors can significantly vary between substances. CO₂ emissions have become an important indicator for the environmental performance of companies and products. The indicator is usually highly related to the energy use of a process and provides a yardstick to identify energy intensive processes (Goedkoop *et al.*, 2009).

- Ozone depletion

Ozone is a molecule which is continuously formed by chemical reactions in the atmosphere. In 1985 a large hole in the ozone layer above Antarctic was discovered (Farman *et al.*, 1985). Manmade chemicals seemed to destroy the ozone molecules present in the higher atmosphere. The stratospheric ozone is vital for life on earth because it shields the surface from harmful solar radiation. More radiation can increase the risk of skin cancer, cause blindness, increase aging effects, influence the immune system and cause damage to ecosystems. The ozone layer is damaged by so called Ozone Depleting Substances (ODS) which contain chlorine or bromine atoms. These molecules act as free radicals in the stratosphere destroying large quantities of ozone. The Ozone Depletion Potential (ODP) indicator uses CFC-11 as a reference to calculate the potential impact of the different emission. The ReCiPe method only considers damages to human health because of the uncertainties regarding the other areas of effect (Goedkoop *et al.*, 2009). There is already a sharp decline in ODS emissions due to international agreements on emission reductions. The Montreal protocol is one of the most successful international agreements on emissions reductions. The treaty was signed in 1987 and research indicates that the agreement not only protected the ozone layer but also substantially reduced greenhouse gas emissions since the substances also have a global warming potential (Velders *et al.*, 2007). The ReCiPe method calculates the marginal effects of any additional human exposure to harmful radiation relative to the projected decrease of ODS emissions. The ozone hole is projected to close around the turn of the 21st century. There is a threshold value of 1780 ppt. modeled to be reached by 2044 where after emission do not lead to additional environmental damages (Goedkoop *et al.*, 2009).

- Acidification

Acidification refers to a change in the pH value of the soil caused by the emissions of inorganic substances such as nitrates, sulfates or phosphates. The majority of plants species prefer a certain optimum pH value related to the natural environment the species has evolved. A significant altering of the pH value of the soil can lead to a shift in the biodiversity. The characterization factors used in the ReCiPe method are modeled for plant species on a European scale. The Base Saturation (BS) indicator is used to express the pH value. This indicator expresses the degree to which the soil is saturated with basic cations, an atom or molecule with an unequal number of electrons and a positive charge. The positive cations from emissions such as Nox, NH₃ or SO₂ are absorbed by the top layer of the soil which increases its pH level. Locations with high cations exchange capacity are less susceptible to the effects of acidification than sites with a low exchange capacity. Changes in the pH value of the soil can influence which species of plants occur in a certain area (Goedkoop *et al.*, 2009).

- Eutrophication

The term eutrophication refers to the enrichment of the aquatic environments with additional nutrients which affects both fresh and marine waters. In Europe the damage caused by eutrophication is considered to be larger than the damage caused by toxic emissions. The emissions of phosphorus or nitrogen can cause certain species e.g. algae or duckweed to bloom. In marine waters nitrogen is the limiting factor for certain species to bloom but in fresh water systems additional phosphorus leads to eutrophication. Eutrophication is therefore divided into two sub categories freshwater eutrophication and marine eutrophication. The amount of damage depends on the physical conditions e.g. the algal growth is greatly reduced during winter times in northern Europe. However, in many industrial areas the far exceed the natural emission leading to environmental damages (Goedkoop *et al.*, 2009). The excessive high levels of nutrients may cause a shift in the species composition within an area. Furthermore, it can render surface water unsuitable as a source of drinking water (Guinée *et al.*, 2002). The agricultural sector and wastewater treatment plants are the main contributors to phosphorus and nitrogen emission but air born emissions are also transported to rivers, lakes and oceans via the rain water. Eutrophication is an important determinant of ecological quality of inland waters because it can severely disrupt ecosystems (Goedkoop *et al.*, 2009).

- Toxicity

The impact categories of terrestrial eco-toxicity, human toxicity and marine eco-toxicity take into account the accumulation of substance in the human food chain (exposure), the toxicological effects of chemicals (effect) and the environmental persistence of the molecules (fate). The fate and exposure factors are based on a combination of impact models. The effect factor is based on available toxicological data. The commonly applied Uniform System for the Evaluation of Substances developed by the RIVM was adapted to LCA proposes. The model calculates the marginal changes of the steady state concentrations in an environmental compartment due to toxicological emissions. The mid-point impact category for terrestrial and marine eco-toxicity includes the fate and chemical effect factors of the emissions. The effect on species loss has been excluded and is modeled as a constant for both impact categories. The exposure factor was not included because of a lack of data on the buildup of chemicals in marine environments. The human-toxicity indicator includes exposure, fate and effect factors but the effects on life-expectancy are excluded due to a lack of data. The reference chemical for the mid-point calculations is 1,4-dichlorobenzene but it remains difficult to exactly determine e.g. the exposure routes or the carcinogenic potential of substances (Goedkoop *et al.*, 2009).

- Human health damage due to PM10, Ozone and Ionising radiation

Particulate Matter (PM) is a very fine particle of less than 10 μm (PM10) which is formed out of a mixture of organic and inorganic molecules. Emissions of SO_2 , NH_3 and NO_x are known to cause the formation of these potentially harmful particles. PM can cause damage to the respiratory system when people are exposed to them over longer time periods (Polichetti *et al.* 2009). The mid-point category expresses the potential particulate matter formation in PM10-equivalents. The Ozone Formation Potential is used to calculate the photochemical oxidant formation mid-point impact

category. The ozone formation considered in this category is not related to processes high in the atmosphere but it originates from photochemical reactions in the lower atmosphere. NO_x and Non-Methane-Volatile-Organic-Compounds (NMVOCs) are known to accelerate the rate at which ozone is created. Ozone formation is a relatively complex process because the molecules have a short lifetime and formation rate depend on the local physical conditions (Goedkoop *et al.*, 2009). Furthermore, additional molecules can form due to photochemical processes e.g. peroxyacyl nitrates, organic acids and fine particulates. The climatic conditions during the summer increase the amount of photochemical reaction in the lower atmosphere. Ozone is an oxidant which can react with a wide range of biological compounds. The ozone does not penetrate a cell but it can cause a free-radical reaction within other molecules within the cell. The ozone concentrations can cause negative health effects such as, exacerbations of asthma, inflammatory changes in the lung, and structural alterations in the lung at an exposure level above $160 \mu\text{g}/\text{m}^3$ for 6.6 hours (WHO, 2000). The ReCiPe calculations are based on the marginal change caused by an emission relative to the 24h average ozone concentration in the central Europe. The model assumes no threshold value for both the impact categories because no threshold concentrations for these particles have been identified. Particulate Matter and Ozone formation are the most problematic in urban areas because accumulated emissions lead to potentially harmful concentration levels. The ionizing radiation impact category accounts for carcinogenic and hereditary damages caused by the routine release of radioactive particles. The emissions are mostly generated by nuclear power stations and the processing of the related radioactive materials. The majority of the ionizing radiation humans are exposed to originate from natural sources. The impact ReCiPe category takes into account the effects of increasing the natural background radiation levels (Goedkoop *et al.*, 2009).

4.3 Concluding remarks

The LCA framework has become an important tool for assessing the environmental impact of products. The framework presents a set of clearly defined steps which are needed to make a valid scientific prediction on the environmental impact of products. The value of prediction is highly dependent on the quality of the data that is fed into the models. Collecting the data can be a costly process which is why most large environmental impact databases are only accessible at a fee. This study will use the 'OpenLCA' software and freely available environmental impact data. The extraction and processing of the main raw material for synthetic rubber (crude-oil) has been extensively studied due to its importance for industrialized economies. The ELCD database is able to provide a solid dataset to calculate the environmental impact of oil based products. The ReCiPe impact method can be used free of charge and is included in the OpenLCA software. It is an important tool for performing a LCA because it translates complicated environmental emissions into a set of understandable environmental impact categories. This chapter only discussed the environmental impact categories that were relevant for this research. The impact categories of fossil fuel depletion, metal depletion, natural land transformation, agricultural land occupation and urban land occupation are excluded from the LCA, see paragraph 6.3. A short tutorial of the 'OpenLCA' software and the ELCD database can be found in appendix two.

Chapter 5 – Analyses of reclaim technologies

Rubber can be recycled via multiple technologies which can broadly be assigned to four categories: de-vulcanization, reclaiming, shredding or pyrolysis. To be able to de-vulcanized or reclaim rubber the three dimensional networks of crosslinking points need to be cleaved. This can be done by breaking the crosslinking points, the main chain (back bone) or by a combination of the two processes (Dijkhuis, 2008; DXP, 2011). De-vulcanization refers to a recycling process in which the material properties of the original compound are fully maintained. Reclaiming rubber refers to a recycling process for rubber in which the material properties of the rubber are not significantly reduced. Shredding is the most basic form of recycling in which rubber is grinded into small pieces and mixed in with a new material. This can be a new application e.g. asphalt, sports fields or it can be blended in with a new rubber product by the use of activation powder (Dijkhuis, 2008). During pyrolysis rubber waste is subjected to a high temperature which makes it possible to re-use the material as filler for virgin compounds (Duikhuis, 2012). The burned waste has a higher energy value than normal carbon black. However, shredded and burned waste can only be added in small quantities to virgin rubber compounds. There is no technology on the market that can reverse the vulcanization process without also attacking the main chain of the rubber (Dijkhuis, 2012; Noordermeer, 2012). Some of the technologies are able to break up to 95% of the sulfur to sulfur bounds within the rubber but the main-chain is always affected reducing the material properties of the compound (Feng and Isayev, 2005; Sutanto, 2006_a; Leary *et al.*, 2006; Rajan *et al.*, 2006; Dijkhuis, 2008). In order to effectively recycle rubber compounds the material quality of the recycled product needs to be maintained as much as possible. This chapter will investigate why scaling up rubber recycling has proven to be difficult and analyze the economic competitiveness of the research reclaim technologies. Furthermore, the effects of European and national legislation on the rubber market will be discussed as well as the future prospects for the rubber recycling industry.

5.1 The challenge of rubber recycling

The recycling of rubber waste is an important issue for many manufacturers of rubber products (Dijkhuis, 2012). The rising costs of raw materials are making the recycling of rubber for re-use in a new rubber compound far more attractive (Smit, 2012; Dijkhuis, 2012). The quality of the reclaimed material is however an important limitation for the re-use of the material into new rubber compounds. There usually are around 1000 times more carbon to carbon connections than there are sulfur to sulfur crosslinking points within a rubber compound. This makes it far more likely that the reclaim process breaks the main-chain molecules instead of the crosslinking points. It is technically very difficult to recycle the material without also reducing the material properties of the rubber (Noordermeer, 2012). There are many experiments done on rubber reclaiming some of which show good experimental results. However, there is a large start-up barrier due to the high cost involved with the development and testing of the technologies on different compounds. It is very difficult to go beyond experiments due to unforeseen errors during up-scaling or a lack of financing (Dijkhuis, 2012). The guidelines developed by the Dutch government on the tire recycling have not identified a Best Available Technology (BAT) for rubber tire recycling. Reclaiming of rubber waste is not

mandatory because of the lack of processing capacity (VROM, 2009). The rubber waste is now primarily recycled to be transformed into a lower grade material. For EPDM roof sheets some reduction of the material properties is however acceptable because the performance of the material far exceeds the standards needed for roofing material (Dijkhuis, 2012). The composition of the material can influence the efficiency of the reclaim process which means there can be large differences in the effects of a reclaim technology on different rubber compounds. There are many parameters which can affect the reclaim process making that comparable pyrolysis techniques can yield totally different results (Dijkhuis, 2012). It is important to have clean waste which is of the same constituency to be able to make a high quality reclaim (Ekelenburg, 2012). The EPDM polymer is the substance which binds the ingredients together into one stable rubber compound. The additional ingredients are usually added following a unique recipe which is kept secret by the manufacturers (Noordermeer, 2012). Rubber reclaiming is very complicated because there are so many different compound formulas used within the industry which makes it difficult to reclaim rubber competitively. The largest market for EPDM rubber is the car industry. However, it is practically impossible to collect and separate the waste of the car industry according to the compound formulas. The wide variety of recipes used in the industry make it impossible to create a homogenous product out of the waste collected from e.g. used cars. The material performance of the reclaimed material will decrease due to the different blends of rubber (Noordermeer, 2012; Ekelenburg, 2012). This problem is less severe in the EPDM roof sheet market because of the limited number of formulas used within the industry (Noordermeer, 2012). The possibility of reclaiming used EPDM roof sheets is still under investigation (Smit, 2012). The material quality of rubber deteriorates during the use of the product. Roof sheets are exposed to environmental influences such as weathering, direct sunlight and high temperatures during the summer time. Furthermore, the roof sheets are wet around 50% of the time which can cause molecules to get absorbed into the rubber (Dijkhuis, 2012). Rubber that is used e.g. in industrial applications can also get polluted with unwanted chemicals. The influences of pollution and ageing effects on reclaim efficiency and quality are not yet fully understood (Luiten, 2012; Dijkhuis, 2012; Smit, 2012). EPDM has a limited number of positions to which the sulfur crosslinking points can stick onto the main chain. If the material is too much degraded it will be impossible to re-vulcanize the material. To be able to reclaim aged and polluted EPDM rubbers the reclaim technology must predominantly break the crosslinking point and leave the already affected main chain intact as much as possible (Dijkhuis, 2012; Noordermeer, 2012). The temperature during the reclaim process is an important determinant for the amount of main chain molecules that are broken. The higher the temperature during the reclaim process the more molecular bounds within the rubber are broken. In many markets it remains difficult to economically recycle rubber because of the high performance requirements of some compounds e.g. tires or gas masks. Manufacturers are skeptical on the quality and the performance of reclaim technologies due to the technological difficulties of rubber recycling. A loss of product quality could harm the reputation of the company which leads many compounders to be conservative in the acceptance of reclaim technologies (Dijkhuis, 2012; Ekelenburg, 2012; Noordermeer, 2012). The re-use of rubber waste as a filler in new rubber compounds is not the most ideal solution to the waste problem due to the inherent loss of quality. However, the large volumes

of rubber waste make that increasing the reclaiming rate with 5 or 10% can already be a big achievement (Noordermeer, 2012; Dijkhuis, 2012). There are now two large scale rubber reclaim facilities being built that are scheduled to reclaim EPDM roof sheets, one in the Netherlands and one in the USA, (Noordermeer, 2012). The companies will initially focus on reclaiming their own industrial waste because the waste is clean and the composition of this material is entirely known (Ekkenburg, 2012; Smit, 2012) This will be the first step for many companies because the possibilities for recycling used rubber are not yet fully assessed (Luiten, 2012; Dijkhuis, 2012; Smit 2012).

5.2 Evaluation of the reclaim technologies

- Chemical reclaim

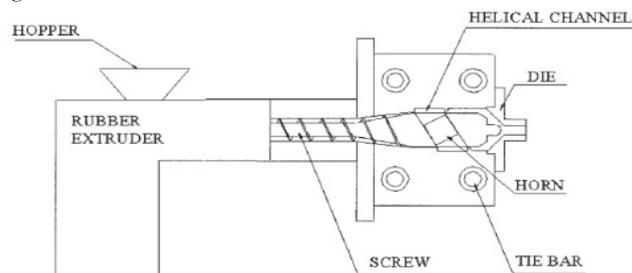
The chemical reclaim process was the first technology developed for rubber recycling. Chemically reclaimed Natural Rubber (NR) has been on the market for many years. This is usually reclaimed via a batch process which produces a compound with a high elasticity (Noordermeer, 2012). The heater or pan process is one of the oldest technologies used chemical reclaiming. In this method the rubber is subjected to steam and pressure for about 48 hours where after it is possible to reuse the material in a new production cycle (Dijkhuis, 2008). However, in many compounds the quality of this reclaim is too low for re-use (Luiten, 2012; Ekelenburg, 2012). Studies have shown that synthetic rubber can be reclaimed in a continuous process in an extruder via the help of small quantities of reclaim chemicals (Sutanto, 2006_a; Dijkhuis, 2008). There are several processes patented using different chemicals and reaction conditions but the basic principles are the same. Due to a combination of temperature, shear force and chemicals the molecular chains break down increasing the plasticity of the rubber. The process usually breaks up to 80% of the individual crosslinking bounds (De *et al.*, 2005). However, the process could theoretically break all the individual crosslinking bounds whereby the rubber is fully de-vulcanized (Dijkhuis, 2012). The anime Hexadecylamine (HDA) is one of the latest additions to the wide range of reclaim chemicals that have been investigated. Research shows that the process is able to produce a high quality material. The HDA reclaim chemical directs the forces onto the crosslink points leaving more of the main chain intact (Noordermeer, 2012; Dijkhuis, 2012). However, because the carbon to carbon bounds are usually more numerous than the sulfur to sulfur bounds the main chain is also degraded (Sutanto, 2006_a; Noordermeer, 2012). EPDM roof sheets composed of 100% HDA-reclaimed material that can still meet application standards (Dierkes *et al.*, 2006; Sutanto, 2006_a; Dijkhuis, 2008). However, EPDM roof sheets have far better material properties than strictly necessary for the intended application of the product. This means that there is a large area in which the material properties can be reduced while the performance standards for the material can still be met (Dijkhuis, 2012). This will not be possible for all applications of rubber but research indicates that at least 25% reclaim can be mixed in without a significant loss of material quality (Sutanto, 2006_b). An experiment in Maastricht on reclaiming EPDM rubber with the HDA reclaim process also showed good results. Significant de-vulcanization was achieved but more research was needed to improve the reclaim efficiency. The material produced was not good enough for the intended product application (Dijkhuis, 2012). The efficiency of the reclaim method depends on the molecular structure of the rubber (Sutanto, 2006_c;

Verbruggen *et al.*, 2008) In some rubbers the chemical spreads evenly throughout the compound while in others it is only absorbed by the outer layers leaving still vulcanized areas in the middle (Dijkhuis, 2012). The reclaim temperatures range from 100° to around 150° and up to 250° Celsius (Yehia *et al.*, 2004; Verbruggen *et al.*, 2008; Sutanto, 2006_a; Duikhuis. 2008). The chemical reclaim technology is difficult to control which makes creating a homogenous reclaim problematic (Sutanto, 2006_a; Dijkhuis 2008). Chemically reclaimed Natural rubber has been available on the market for many years but most of these reclaims have reduced material properties making their application limited (Luiten, 2012; Ekelenburg, 2012). The chemical reclaim process using the HDA reclaim chemicals in a continuous extruder process showed good experimental results. The technology could be competitive if the ecological sustainability of the reclaim chemical can be guaranteed.

- Ultra-sound reclaim

The ultra-sound reclaim technology is developed by Dr. Avraam I. Isayev working at the Institute of Polymer Engineering in Akron, USA. His research team has published multiple papers on the effects of the ultra-sound reclaim technology on different rubber compounds. The use of ultra-sounds to reclaim e.g. EPDM roofing sheets has shown to be possible without a significant loss of quality (Ghose and Isayev, 2002; Yun and Isayev, 2003; Yun *et al.*, 2003; Yun *et al.*, 2004; Leary *et al.*, 2006). However, this is also due to the fact that the material properties of EPDM roofing rubber can be significantly reduced without the end product failing to meet the application standards (Dijkhuis, 2012). The process is suited for multiple rubber compounds and can be performed in a standard extruder equipped with an ultra sound generator (Yun and Isayev. 2003_a; Sun And Isayev, 2006). Rubber particles of about 0.5 mm are subjected to a 20 Khz sound frequency with an amplitude of 5 to 10 microns. The grooved barreled reactor is usually used to perform the de-vulcanization step. Figure 5.1 shows a schematic overview of the ultra sound reclaim process using the grooved barrel technology (Leary *et al.*, 2006).

Figure 5.1: Schematic overview of ultra-sound reclaim technology.



Source: Leary *et al.*, 2006

The extruder mechanically heats up and softens the rubber which is then exposed to an ultrasonic frequency. The combination of heat, pressure and ultrasounds breaks the molecular bounds. The crosslinking points as well as the main-chain molecules are affected during the process which increases the elasticity of the rubber (Rajan *et al.*, 2006). The rate at which the main chain shortens is however smaller than the number of crosslinks breaking up (Feng and Isayev, 2004). Under the right reclaim condition a product can be created which can be mixed in with a virgin batch (Yun and Isayev, 2003_b). The efficiency of the reclaim process is affected by (Sutanto, 2006_a); 1) the acoustic

property of the rubber, 2) the amplitude of the ultrasound, 3) the reaction time and 4) the pressure within the reaction chamber. The process is also influenced by the fillers contained within the rubber (Oh and Isayev, 2003). For instance, there is a complicated relationship between reclaim efficiency and the carbon black content of the rubber. The carbon black restricts the mobility of the particles making it easier to break the molecular bounds. However, more bounds need to be broken and the carbon black can absorb some of the polymer molecules making the carbon black ineffective as filler. The material properties of the reclaim are shown to decrease with an increase in carbon black content (Sutanto, 2006_a; Yun *et al.*, 2003; Sun *et al.* 2004_a). To maintain the material properties of the end product additional carbon black can be added to the virgin batch. An increase in ultrasound energy generally leads to more de-vulcanization. However, in the case of natural rubber the rubber starts to re-vulcanize after a certain energy level (Tapele and Isayev, 1998; Scuracchio *et al.*, 2004). With EPDM rubbers the de-vulcanization keeps increasing with an increase in power. The temperatures reached within the process range from 400° till 500° Celsius (Yun *et al.*, 2003; Yun *et al.*, 2004). The process is fast and no chemicals or solvents are needed to reclaim the rubber. The ultra sound technology was developed over 15 years ago however there are currently no ultra-sound reclaim facilities for EPDM roofing in the world (Noordermeer, 2012). The composition of the compound determines the reclaim efficiency of the technology. This makes it more difficult to produce a stable and high quality reclaim from rubber waste because the compound formulas are not always known. The quality of the reclaimed material is also low due to the high temperatures reached during reclaiming. This leads to a severe degradation of the molecular backbone within the compound. The technologies can be considered more as a pyrolysis technique rather than a reclaim technology (Dijkhuis, 2012; Noordermeer, 2012). The efficiency and quality of the reclaim method can be improved by optimizing the vulcanization recipe (Hong and Isayev, 2000). This makes it theoretically possible to create a product of sufficient quality to use in virgin batch. The process is however very complicated because of the large numbers of parameters that can affect the efficiency reclaim process. Currently, the technology is uncompetitive due to its low flexibility and the significant reduction of the material properties during processing (Ekelenburg, 2012; Noordermeer, 2012).

- Micro-wave reclaim

The micro-wave reclaim process is similar to the ultra sound method but utilizes micro-wave energy to reclaim rubber. The micro-wave reclaim technology was first developed in the late 70th by Goodyear Tire Company (Leary *et al.*, 2006). Efforts to scale up the technology have proven to be unsuccessful due to the low quality of the reclaimed material. However, the renewed interest in rubber recycling has led researchers to further investigate the possibilities of micro-wave reclaim (Bani *et al.*, 2010; Pistor *et al.*, 2010). The energy forces the molecules within the rubber to move, thereby creating friction which quickly heats up the material to around 260-350°C (Sutanto, 2006_a; Pistor *et al.*, 2010). This breaks the molecular bounds making it possible for the rubber to be re-used (Bani *et al.*, 2010). The composition of the rubber determines how the micro-wave energy reacts with the compound. For instance, the micro-wave technology has shown to cause re-vulcanization within natural rubber during processing (Bani *et al.*, 2010). The rubber has to be able to absorb the energy

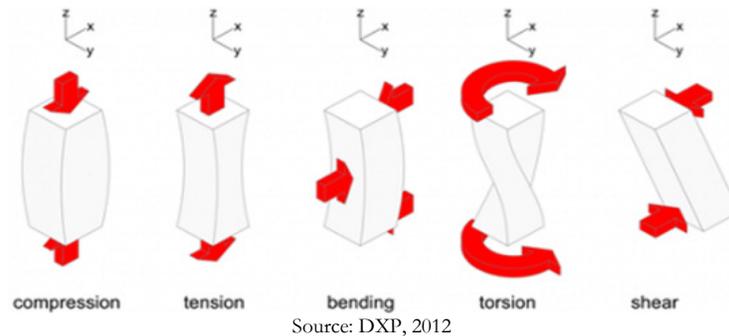
i.e. be polar for the molecules to heat up (Rajan *et al.*, 2006). Not all rubbers are polar e.g. EPDM but non-polar rubber can be reclaimed via micro-waves if sufficient amounts of carbon black are present within the material. Carbon black particles are able to absorb the energy and act as a medium by which the heat can disperse. The energy required for the technology is relatively low but the energy needs to be distributed uniformly in the rubber. The microwave process is very fast and can break between 90% and 95% of the sulfur bounds present within the material (Sutanto, 2006_a). However, the micro-wave reclaim method causes severe degradation of the main chain because of the high temperatures reached during reclaiming (Zanchet *et al.*, 2009). This can lead to ineffective re-vulcanization of the reclaim material. Furthermore, the technology has difficulty controlling the reaction conditions and the equipment is expensive (Bani, 2006; Rajan *et al.*, 2006). To improve the quality of the reclaim some researchers removed the mineral oil or added a reclaim chemical to be able to reclaim the rubber at a lower temperature of around 200°C. This increases the quality of the reclaim thereby making it possible to mix in the reclaimed material with virgin compounds. However, it remains difficult to create a homogenous product and there is still no effective control mechanism for the reclaim temperature (Pistor *et al.*, 2010; Bani *et al.*, 2010). The technology is not competitive yet due to the loss of material quality and more research will be needed to optimize the reclaim process (Bani *et al.* 2010, Pistor *et al.* 2010, Dijkhuis 2012)

- Mechanical reclaim

The mechanical technology uses a high shearing force to tear down the molecular bounds within the rubber. The crosslinking points can be broken by a purely mechanical process because they have a lower energy bound than the main chain carbon to carbon bounds. By applying a precise amount of stress to the rubber the material can be reclaimed without much loss of quality (Dijkhuis, 2012; Noordermeer, 2012; Ekelburg, 2012). There are multiple mechanical reclaim processes in development some of which are capable of producing a material which has similar properties as the original compound (Ekelburg, 2012; Fukumori and Matsushita, 2003). The Toyota Company was one of the first companies to develop a mechanical reclaim process. In this method virgin material is mixed with shredded vulcanized rubber waste and exposed to heat and mechanical stress (Sutanto, 2006_a). This de-vulcanizes the rubber waste and allows for the formation of new bounds with a virgin material. Additional reclaim agents were used to facilitate this process (Sutanto 2006_a; Dijkhuis, 2008). The research done at the University of Twente showed that the reclaim chemical HDA was not necessarily needed to induce de-vulcanization in EPDM rubber (Dijkhuis, 2008; Noordermeer, 2012). The kinetic model of the EPDM mechanical/chemical reclaim process is not yet fully understood but significant de-vulcanization can be achieved by mechanical stress only (Verbruggen *et al.*, 2008; Noordermeer 2012). The research done at the University of Twente has now focused on mechanical reclaiming (Noordermeer, 2012). The reclaim technologies that are being developed by Hertalan and DXP are also based on a mechanical reclaim process. A large advantage of the reclaim method is that it can be performed at a relative low temperature which is beneficial for the quality of the reclaim. Car tires are recommended to be used at a maximum of around 100°C after which the material integrity of the rubber cannot be guaranteed (Dijkhuis, 2012). The mechanical reclaim process developed by DX polymers will heat the rubber to a maximum of

90°C. The prototype machine the company developed uses a complicated geometry to break the crosslinking points within the rubber, see figure 5.2. The technology mostly breaks the cross-links points except if a misalignment leads to a rupture of the backbone. The process can reclaim multiple rubber compounds because the shear force can be adapted for the strength of the molecular bounds within the rubber waste. The technology is in the early stages of development but experiments have shown that it is able to produce a high quality reclaim from multiple rubber compounds (Ekelenburg, 2012). A mechanical reclaim process is also described in a paper by Fukumori and Matsushita, 2003. The process requires a rubber feedstock of around 5 to 10 mm. The first step is to crush the rubber into finer pieces and quickly heat up the particles to around 100° C.

Figure 5.2: A schematic overview of the mechanical stress applied to rubber waste during the mechanical reclaim process developed by DXP.



The material is then fed into the reaction zone where the shear force pulls the molecular bounds apart. By controlling the speed and configuration of the crews the mechanical properties of the reclaimed material can be guided. Experimental settings show that the energy requirements are around 0.4 kWh per kilogram. The reclaimed material obtained via this method maintains most of its original mechanical properties. However, the odor of the reclaim can limit the practical use of the technology so deodorization of the reclaim might be needed. This can be done by injecting water under high pressure into the reaction chamber. This soaks up the odor releasing particles and creates a reclaimed product with far less odor (Fukumori and Matsushita, 2003). The mechanical reclaim technologies are able to reclaim rubber fast without significantly affecting the material quality of the end product due to the relative low temperatures reached during processing. The technology developed by DX polymers uses an extruder like process in which the deodorization of the rubber is not required. The information provided on the principles of the different prototype machines was limited due to the protection of trade secrets. However, most of experts confirmed that the mechanical reclaim process is one of the best technologies currently in development (Smit, 2012; Noordermeer, 2012; Dijkhuis, 2012; Ekelenburg, 2012). No additional chemicals or heating is required which means that there are less parameters that complicate the reclaim process. The mechanical reclaim process is currently one of the most promising reclaim technologies.

5.3 Influence of legislation of rubber recycling

The European Union has made a strong commitment to the development of more sustainable production methods. European initiatives such as ELV (End of Life Vehicles) and REACH

(Registration, Evaluation, Authorisation & restriction of Chemicals) have played an important role in translating this vision into concrete legislation (European Commission, 2011). These European directives have now become part of state legislation in almost all member states of the European Union. The European industry became responsible for the reporting and testing of the substances that they use in for the production of products. The REACH directive is meant as an integrated system to regulate all chemical substances in the European Union. The directive is seen as a major step forward in the registration and risk assessment of chemical substances. Under the previous legislation it took more than 14 years to assess and manage 141 high hazarders' chemicals. The REACH directive aims developed a risk and impact assessment of over 30.000 chemicals during an eleven year timeframe (Witmond *et al.*, 2004). The directive became active on the first of June in 2007 and will be gradually phased in. The legislation obliges companies who produce more than a ton of chemicals per year to report on the toxicological effect and register the substance with the EChA (European Chemicals Agency). The regulation becomes stricter for companies as they produce more quantities of a substance. Substances that are unable to comply with the regulation or that are found to be to hazardous can be forbidden to be sold in Europe (Rudén and Hansson, 2009). This has had a significant impact on the rubber industry. From 2010 onwards the rubber industry was forbidden to use aromatic oil in their compounds. The substance is carcinogenic and is released into the environment e.g. due to the wear of tires. Much effort has been put into the development of safer alternatives to replace the aromatic oil. However, no substance has been developed yet that can mimic the material properties of the banned aromatic oil (ETRMA, 2012; Dijkhuis, 2012; Luiten, 2012). Both companies that were consulted had dedicated man-hours to monitor the effects and produce the necessary paperwork needed under the REACH directive (Smit, 2012; Luiten, 2012). In the short term the REACH directive has negative effects on the competitiveness of European industries. However, the public health benefits and increased product innovations are expected to make the legislation a competitive advantage in the long-run (Witmond *et al.*, 2004). The European Commission publishes periodic progress reports on the effects of the REACH directive on European industries. There is much discussion on what types of data should be collected and what tests are needed to make valid scientific predictions (Rudén and Hansson, 2009; Postle *et al.*, 2011). For the companies that were consulted it was unclear how the legislation would affect the reclaiming of rubber (Smit, 2012; Luiten, 2012). Reclaimed rubber can be considered a new compound since it has different properties then the original product. This could have implications for the reporting needed under the REACH directive. In July of this year a study of the European Commission will be published which specifically addresses the issue of polymers under the REACH directive. The research will address the following issues making it an important study for companies within the rubber industry to consider (European Commission, 2012):

- The possibility to assess the hazardous properties of polymers from the information provided in registration dossier in particular of monomers;
- The risks posed by polymers in comparison with other substances;
- How these risks are managed or not through the existing registration obligations in REACH;
- Possible ways of selecting polymers for registration in a practical and cost-efficient way and on the basis of sound technical and valid scientific criteria.

The EVL's legislation is now implemented in almost all EU countries with most members achieving a recycling rate of 80% or higher (Eurostat, 2012). In the Netherlands the new legislation has led to a significant shift in the re-use of old tires. Under the new legislation producers and importers of tires are made responsible for retaking old tires and recycling them to usefully purposes (VROM, 2012). To facilitate the recycling, the Dutch government imposed a waste removal fee to finance the development of tire recycling facilities. The company RecyBEM B.V. is made responsible for the collection of used tires and the development of processing facilities. Table 5.1 shows the recycling rate of waste tires according to the intended re-use of the material. The material re-use of tires increased from 25% in 2004 to 58% in 2011. The burning of tires for heat recovery has drastically gone down from 46% in 2004 to 16% in 2011. The majority of used tires is now shredded and re-used as a raw material for other compounds e.g. sound isolation, tiles and sports fields. Under the pressure of new legislation the recycling rate of used tires in the Netherlands has significantly improved (RecyBEM, 2012). The ETRMA (European Tyre & Rubber Manufacturers Association) has focused on the retreading of truck tires which now represents around 40% of the European replacement truck tires (ETRMA, 2012). The legislation led to the development of alternative uses of rubber granulates and an increased interested in retreading tires. However, it has not identified a Best Available Technology (BAT) for rubber recycling and is primarily concerned with finding a solution the problem of rubber waste (VROM, 2012). Most of the current recycling efforts for rubber are not able to deliver a significant cost advantage to rubber end-product manufacturers. Reclaiming or de-vulcanization of rubber is the most environmentally friendly solution and can deliver a significant cost reduction for rubber manufacturers. If a reclaim or de-vulcanization technology gets recognized by the government as BAT than rubber companies can also be forced to reclaim at least some of the rubber used for production.

Table 5.1: The recycling rate of waste tires according to the intended re-use of the material

Re-use of rubber waste as:	2004	2005	2006	2007	2008	2009	2010	2011
Use as a second hand tire (export)	16%	17%	16%	17%	16%	18%	21%	23%
Retreading (export)	11%	13%	9%	7%	5%	4%	2%	2%
Material Reuse	25%	28%	56%	59%	57%	58%	59%	58%
Alternative Reuse	2%	10%	1%	1%	1%	1%	2%	1%
Thermal recycling HR	46%	32%	18%	16%	21%	19%	16%	16%

Source: RecyBEM, 2012

5.4 Future prospects for the rubber market

Currently only a small proportion of used tires are reclaimed and used for the production of a new tire (Eurostat, 2012). The rubber is now mostly re-used for other purposes whereby the demand for oil and natural rubber to produce new compounds is maintained. Rubber is a strategic resource for industrial economies because of its importance for e.g. the transportation sector. The European Union is heavily dependent on the import of natural rubber and oil to be able to make rubber products. The costs of these resources are rising because of increased demand and speculation on natural resources (ETRMA, 2010). The high oil prices and the fact that there is a finite supply of oil are threatening the continuity of the rubber industry (Luiten, 2012). However, the quality of the

recycled material remains a significant barrier for increasing the use of reclaimed rubber. Another way to possibly reduce the environmental impact of rubber production would be to look for alternative raw materials to produce a comparable compound. However, natural rubber will not be able to provide an alternative for the synthetic rubbers. Natural and synthetic rubbers have such different properties that it is usually not possible to substitute a synthetic polymer with one that is naturally produced (Smit, 2012; Noordermeer, 2012). The natural rubber polymer has been researched for over 150 years but modern science is still not able to create the same molecular structures. Natural rubber is made out of 100% so called *cis*-groups which cause a crystallization effect when the material is stretched giving it superior strength. Synthetic rubbers also have around 2 or 3 % *trans*-groups which prohibits the crystallization effect of the molecules leading to different material properties (Dijkhuis, 2012). The synthetic compounds cannot stretch as well as natural polymers but they can have other mechanical properties e.g. ozone resistance that are superior to natural rubber. The structure of a synthetic rubber molecule can be adjusted to the intended application of the product giving it greater flexibility (White and De, 2001). This means that even if the more natural rubber can be produced in a sustainable way, oil will still be needed to produce synthetic compounds. The DSM has been experimenting with bio based EPDM polymers derived from ethanol produced from sugarcane. However, the process is only able to produce one out of the three substances needed to create an EPDM base polymer. The other monomers still need to be derived from oil. The project is currently of little real practical value because it will be far too expensive to make large quantities of the substance and there is limited capacity to process it (Noordermeer, 2012; Ekelenburg 2012). Substitute oil for an alternative resource will require many years of research (Smith, 2012; Noordermeer, 2012). Synthetic rubbers are likely to remain the dominant source of rubber polymers for the foreseeable future (Smit, 2012).

5.5 Concluding Remarks

Increasing the reclaim rate within the rubber industry is an important step to reduce production costs and ensure that the market is able to sustain its growth. Rubber reclaiming is still in the early stages of development but the current market pressures are providing a strong incentive to accelerate the speed of development. There are large differences between rubber compound formulas which make it very difficult to reclaim most rubber waste in an economically efficient way. The first step will be to recycle the industrial rubber waste of the production processes that are suited for rubber reclaiming. The EPDM roof sheets market provides a stepping stone to prove the possibilities of novel reclaim technologies. The micro-wave and ultra-sound reclaim technologies reduce the material properties of the rubber making their application limited. However, the material properties of EPDM far exceed the requirements needed for a roofing material. It is therefore possible to use the technologies to reclaim the industrial waste of an EPDM roof sheet production process. The mechanical and chemical reclaim methods have shown to be able to produce a high quality reclaim. The technologies will be able to recycle the industrial waste of an EPDM production process without affecting the material properties of the end product. Furthermore, the technologies could be used to reclaim end-of-life rubber to increase the reclaim ratio but this will also require innovations in the separation and collection of waste.

Chapter 6 – A Life Cycle Assessment of EPDM roof sheets

The unique properties of a rubber polymer make it an essential raw material for industrialised economies. However, the sustainability of current production methods has become a major concern for the industry. The most efficient way to increase the sustainability of the industry is by recycling rubber and using it to produce a new rubber compound i.e. reclaiming (Sutanto, 2006_a; Ekelenburg, 2012). However, it has proven to be difficult to undo the vulcanization process without seriously reducing the material properties of the reclaimed material. The relative low cost of the raw materials for rubber also provided little incentive to further investigate recycling technologies (Sutanto, 2006_a). Today, stricter regulations and rising costs of raw materials are driving an increasing interest into rubber reclaiming (Dijkhuis, 2008; Smit, 2012). Experiments indicate that rubber can be recycled without seriously reducing the material properties of the recycled material but the previous chapter showed that most of the reclaim technologies are not yet able to compete in today's rubber market (e.g. Adhikari and Maiti, 2000; Fukumori and Matsuchita, 2003; Feng and Isayev, 2005; Dierkes *et al.*, 2006; Leary *et al.*, 2006; Vega *et al.*, 2007; Dijkhuis, 2008). However, the study of Dijkhuis, 2008 reported that an EPDM roof sheet consisting of 100% chemically reclaimed materials was still able to meet the application standards (Dijkhuis, 2012). The rubber used for roofing applications usually has far better material properties than strictly necessary for the product and the product is homogenous which makes it easier to produce a high quality reclaim (Smit, 2012). The market provides an opportunity for the further development of the rubber reclaiming technologies. This chapter will present a life cycle assessment of EPDM roof sheets production and will investigate the environmental benefits of using the ultra-sound, micro-wave, chemical, and mechanical reclaim technology to recycle the industrial waste (10%) generated during production.

6.1 Goal and scope

The goal of the LCA is to analyze the environmental benefits of re-using industrial rubber waste in a virgin production process. Four technologies are studied; chemical, ultra-sound, micro-wave and mechanical -reclaim. These technologies are all able to recycle rubber in such a way that the material can be mixed in with a virgin production cycle of EPDM roof sheets. The roof sheets have a uniform molecular build-up and are not re-enforced with fibers or steel. This makes it possible to create a homogenous product from the rubber waste (Noordermeer, 2012; Ekelenburg, 2012). The average waste created during the production of rubber end-products is around 10% of the total production volume (Sutanto, 2006; Dijkhuis, 2008; DXP, 2011). The aim of the LCA is to quantify the environmental benefits of mixing recycled rubber with a virgin batch so less virgin raw materials are needed to produce a new compound. The research is commissioned by DX polymers in order to determine the possible environmental advantages of their novel mechanical reclaim process. The result of the study will be used to help identify the best available technology for the optimization of rubber production. The research project will serve as a master thesis for the program Urban Environmental Management of Wageningen University. The research aims to make a public comparative assertion so the LCA will be reviewed by experts. The intended audience for the study

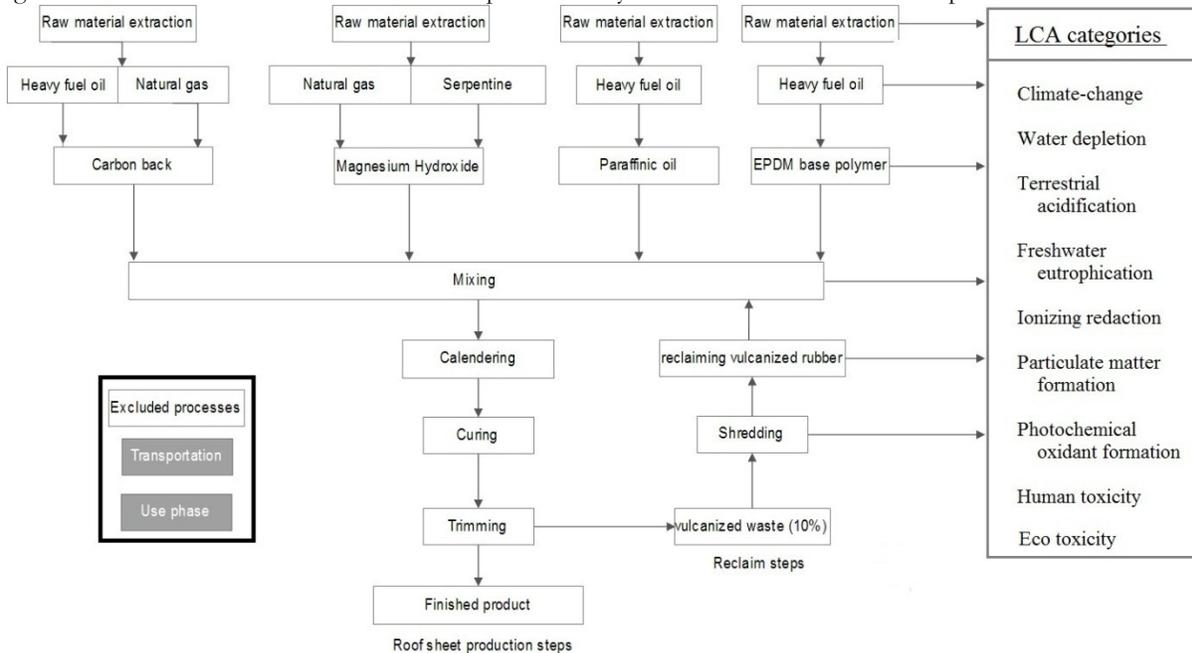
is DXP, the scientific community interested in LCA and companies operating in the rubber processing market. The functional unit of the LCA is defined as follows:

“1 tonne of EPDM rubber used for roof sheet production consisting of 10% recycled materials from post-industrial waste which is of sufficient quality to meet the application standards of the original product”.

6.2 Product and scenarios description

The scope of the LCA includes the synthetic rubber compound EPDM used in the production of roof sheets. The geographical scope of the research is the European Union but the energy use is modelled specifically for the Netherlands. Figure 6.1 shows the flow chart of the raw materials, the production steps and the LCA categories that are modelled in the LCA.

Figure 6.1: Flow chart of the EPDM roof sheet production system and the environmental impacts modelled in the LCA



The appropriate energy use is modelled for all the processes. The vulcanization and process agents are not included in the scope of the research. These chemicals need to be added to every new batch because they facilitate the vulcanization of the rubber. Reclaiming rubber will not reduce the need for these chemicals (Ekelenburg, 2012). After trimming, 10% of the total weight of the batch is left over as waste. The model uses this waste as a raw material for the reclaim process which is represented by the reclaim steps. There is no large difference between the technologies in the steps required to reclaim rubber. The rubber always needs to be shredded before it can be recycled and the technologies all make use of an extruder type machine. Furthermore, capital goods are often excluded from LCA studies due their small contribution to the total environmental impact (Baumann and Tillman, 2004). The scope of the research does not include the use phase of the product. It is theoretically possible to also reclaim used EPDM roofing sheets. However, the reclaiming of used EPDM roofing is complicated because during the lifetime of roofing sheets the

material is affected by e.g. weathering, heat and tension stress (Dijkhuis, 2012). Furthermore, the material can be contaminated with chemical substances and the material is usually glued to the top of the roof. The contamination could reduce the material properties of the reclaimed material. Recent efforts to scale-up EPDM reclaiming have therefore focused on re-using industrial waste (Smit, 2012). The environmental benefits of the reclaim technologies will be assessed by comparing the impact of the reclaim scenarios with a reference scenario in which no reclaim technology is used. The composition of the EPDM roof sheets compound that is considered can be found in table 6.1 (Hertalan, 2012).

Table 6.1: Ingredients for EPDM roof sheets

Raw materials:	Percentage of total mass
EPDM base polymer	34.60%
Carbon Black	20.90%
Mineral oil	10.10%
Magnesium Hydroxide	31.10%
Additives:	
Sulphur	0.50%
Zinc oxide	1.00%
Other	1.80%

The listed ingredients in the table constitute the raw materials for EPDM roof sheets (Smit, 2012). The base polymer is the main ingredient in the compound. Carbon black and mineral oil are standard ingredients for most synthetic rubbers but magnesium hydroxide is also added to the EPDM rubber. The raw material for magnesium hydroxide is a mineral called serpentine. The mined rocks are boiled at around 400°C where after the mineral can be extracted and further processed to produce magnesium hydroxide or $Mg(OH)_2$ (Nduagu *et al*, 2011). The additives listed cannot be reclaimed and need to be added to every virgin mix. The raw materials are transported to the EPDM roof sheet manufacturers where they are mixed in an external mixer. This process produces lumps of un-vulcanized rubber which are fed into a calender where large continuous sheets can be made. The roles of sheets are then fed into an oven of around 170°C to induce the vulcanization of the rubber. After the vulcanization is completed the roles of rubber are checked and further refined (White and De, 2001). The main source of vulcanized industrial waste are the loose ends cut off the roles but waste may also include e.g. un-soled or failed products (DXP, 2011). To reclaim the vulcanized waste it first needs to be shredded. The shredded waste can then be reclaimed via chemical, ultra-sound, micro-wave or mechanical reclaim. The processes make it possible to mix the material in with a virgin batch and re-vulcanize the entire compound. The models aim to quantify the environmental advantage of using 10% reclaimed rubber to produce one tonne of EPDM roof sheets.

6.3 Environmental impact considered

The ReCiPe impact categories are used to calculate the environmental impact of the product system. The research uses the Hierarchic perspective which considers the environmental damages caused over a 100 year timeframe, see paragraph 4.2. The ReCiPe method generates eighteen mid-point

impact categories but not all of the impact categories are relevant for the researched product system. The environmental impact of the production process will be analyzed on the basis of the following impact categories:

- | | |
|-----------------------------------|--------------------------------|
| - Climate change | - Water depletion |
| - Terrestrial acidification | - Freshwater eutrophication |
| - Ionizing radiation | - Particulate matter formation |
| - Photochemical oxidant formation | - Human toxicity |
| - Eco-toxicity | |

Five impact categories i.e. fossil fuel depletion, metal depletion, natural land transformation, agricultural land occupation and urban land occupation, are excluded because no score was generated for these categories. The main raw material for synthetic rubber is crude oil for which no agricultural lands or metals are required as a direct input. No score was generated for the categories of urban land occupation and natural land transformation because the LCI data did not include any parameters on land use due to a lack of data. However, large volumes of rubber can be produced in a relative small area so the impact on these categories is expected to be of minor relevance for the product system. The fossil fuel depletion indicator has not generated a score because it is based on the energy content of the oil. However, in the case of rubber the oil is not burned for energy but used to produce a material. The impact categories of freshwater eco-toxicity, terrestrial eco-toxicity and marine eco-toxicity are combined into one category eco-toxicity. The scores on the eco-toxicity categories were relatively small and they are expressed in the same units making it possible to sum them up into one category to improve the readability of the results. The Ozone depletion is excluded from the assessment due to the insignificant impact of the product system on this indicator (0.00006 kg CFC-11-Eq/per ton EPDM). Reclaiming the 10% waste will not lead to any notable reduction of the environmental impact on this impact category. Marine eutrophication is excluded because the impact scores are exactly the same as for freshwater eutrophication and freshwater eutrophication is considered to be more important (Goedkoop *et al.*, 2009).

6.4 Inventory analysis

The models include the essential material and emission flows such as energy, resources and CO₂ emissions. The transportation emissions are excluded from the LCA since there is no significant difference to be expected from recycling the 10% industrial waste. The reduction of emissions from the reduced need for the transportation of raw materials is largely compensated by the need to transport the waste and recycled rubber from and to the factories. The environmental impacts caused by the production of the machinery used in the production processes i.e. the capital goods are excluded from the study. The capital goods are excluded because the contribution of the processes to the total environmental impact is expected to be less than 1%. Furthermore, including these processes will require a considerable amount of time. Minor adaptations to the models are made depending on energy use and compound formula needed for the reclaim methods. In order for rubber waste to be processed and reclaimed it first needs to be shredded. The sizes of the particles depends on the technology used for reclaiming but a fine sized feedstock of around 10 to 30 mesh (particle size distribution) is required for most of the technologies (De *et al.*, 2005). Once

the rubber is shredded reclaiming can then be achieved by; chemical, ultra-sound, micro-wave or mechanical reclaim. The reclaim technologies discussed in the LCA are only implemented in experimental settings. There is no broad base of environmental data available on the reclaim methods. The reclaim technologies described could potentially emit gaseous chemical compounds during reclaiming but the emissions are expected to be relatively small (Leary *et al.*, 2006). These emissions are excluded due to the lack of data. The water use for the EPDM roof sheet production process is not considered because the water was managed in a closed loop system by the company providing the data on EPDM production (Smit, 2012). Furthermore, no specific data was available for the water use of EPDM base polymer production, carbon black production and the recycling processes.

- The EPDM model

The base polymer is modelled to contain 60% ethylene, 35% propylene and 5% diene. The data for the production processes of these raw materials is taken from the ELCD core database version II. One tonne of EPDM base polymer is modelled to contain 50 kg polybutadiene granulate (PB), 600 kg of polyethylene high density granulate (PE-HD) and 350 kg of polypropylene granulate (PP). These chemicals are processed via polymerization into the base polymer for EPDM. The data on the energy needed to produce the EPDM polymer-chains is taken from the Probas life cycle data base² made available online by the Oeko-institute. The polymerization process uses $900 \cdot 10^{-9}$ TJ of electric energy and $3.1 \cdot 10^{-6}$ TJ of process heat from natural gas to produce one kilogram of EPDM polymers. The emissions generated during the production of the raw material for carbon black are based on the ELCD data base. 1640 kilograms of heavy fuel oil (41,2 kJ/kg) and 175.1 kilogram of natural gas (38,7 MJ/kg) are modelled to produce 1 tonne of carbon black. The data on the resource requirements for 1 tonne of carbon black was made available by Carbon Black Nederland (CBN, 2012). The information is combined with data from their environmental reports over the years 2000 till 2005. The CO₂, SO₂ and NO_x emission of the carbon black production process are based on the average emissions of CBN between 2000 and 2005. No electricity use is modeled because the excess heat generated by the production process can produce more electric energy than the process itself needs which is usually sold to the grid. The mineral oil used for EPDM production is modeled as the heavy-oil naphtha taken from the ELCD data base. The raw materials needed to produce magnesium hydroxide are based on a LCA done by Nduagu *et al.* 2011. 1892 kg of the mineral serpentinite, 404 kg of iron ore, 254 kg of natural gas (46,8 MJ/kg) and 330 kWh of electric energy is needed produce 1325 kg of magnesium hydroxide. However, the mineral serpentinite was not available in the databases so a flow was manually created in the 'OpenLCA' software without being able to assign any emissions to the process. Only the CO₂ emissions reported by Nduagu *et al.* 2011 could be taken into account as direct emissions from magnesium hydroxide production. The electricity use for this process is modelled for Germany since the product is produced there. The energy demand for the roof sheet production process was provided by Hertalan, 511.11 Kwh of electric energy and 337.78 Kwh of heat are needed to produce 1 tonne of EPDM roof sheets.

² <http://www.probas.umweltbundesamt.de>

- The reclaim technologies

The energy demand for the shredding process is modelled to be 0.15 Kwh per kilogram (Smit, 2012). The chemical reclaim process works by chemically dissolving the crosslinking points within vulcanized rubber. The energy demand modelled for this process includes the use of an extruder at 0.25 Kwh per kilogram (Noordermeer, 2012). The reclaim chemical Hexadecylamine (HDA) which was used in the study of Dijkhuis, 2008 was not available in any of the LCI databases. The chemical ammonia is part of the same group of chemicals and used to represent the HDA reclaim chemical. The emissions of the process are taken from the U.S. Life-Cycle Inventory Database³. The reliability of the data on the toxicological effects of the reclaim chemical is reduced by this assumption. However, the assumption is made that the chemical ammonia provides a good indication of the effect of using additional chemicals to reclaim rubber. The ultra-sound technology is modelled to use 0.44 Kwh per kilogram which is based on the values found within the literature (Hong and Isayev, 2000; Ghose and Isayev, 2002; Yun *et al.*, 2002; Scuracchio *et al.*, 2004; Leary *et al.*, 2006; Feng and Isayev, 2006). However, the studies only report on the power use of the ultra-sound machine during reclaiming. To complete the model 0.17 KWH is added to include the use of a single extruder leading to an energy use of 0.61 KWH per kilogram (Meiher and Elemans, 1988). The energy demand of micro-wave generator is around 0.24 KWH per kilogram rubber (Adhikari and Maiti, 2000; Leary *et al.*, 2006; Vega *et al.*, 2007). Studies indicate that the paraffinic oil needs to be removed from EPDM rubber before it can be reclaimed. This can be done by heating up the rubber in an extruder so an extra 0.25 Kwh is modelled for removing the oil within EPDM (Pistor *et al.*, 2010). The oil is re-added to a virgin mix in the micro-wave reclaim scenario (Bani *et al.*, 2010). The energy demand for mechanical reclaim is modelled to be 0.5 Kwh per kilogram. The value is provided by DX polymers and is consistent with values found within the literature (Fukumori and Matsuchita, 2003; Leary *et al.*, 2006)

- Data Quality

The data collected for the impact assessment was gathered from multiple sources and combined within the OpenLCA software. The most important data source is the ELCD core database version II. The environmental emissions within the database are based upon multiple studies done within Europe. The database is made available by the European Commission and is developed by a joint research project with the industry. The reliability of the data on the production of oil based products and the emissions caused by the use of energy consumption is considered to be high. The processes have been extensively studied because of the vital importance of the resources for modern economies. The reliability of the data provided by the companies on energy and resource use of their own processes is also expected to be high. The energy demand for the reclaim technologies was gathered from the literature and checked by multiple experts. The quality of the data on the toxicological effects of rubber production and reclaiming is low. The effects of the chemicals on humans and the wider environment are difficult to quantify. The LCA will provide an overview of the energy savings of reclaiming but will not be able to provide a comprehensive review of the toxicological effects of the product system.

³ <http://www.nrel.gov/lci/database/>

6.5 Impact assessment

The impact assessment has been generated using the ReCiPe (H) mid-point impact categories and the OpenLCA software. During the impact assessment the inventory table results are expressed in equivalency factors and assigned to environmental impacts categories. For instance, all the emissions that contribute to global warming are expressed in kg CO₂-equivalence. The included impact categories reflect the most important issues related to the production of EPDM rubber roof sheets. The functional unit of the LCA is “1 ton of EPDM rubber used for roof sheet production consisting of 10% recycled materials from post-industrial waste which is of sufficient quality to meet the application standards of the original product”. Four reclaim technologies i.e. the chemical, ultra-sound, micro-wave and mechanical reclaim technologies are considered. The LCA will investigate the environmental benefits of using the industrial waste (10%) generated during the production process for re-use in a virgin production cycle. The environmental impacts of the reclaiming scenarios are compared to a reference flow, the production of 1 ton of EPDM roof sheets without any reclaim technology. Table 6.2 shows the characterization results for the reference flow. The contribution of the individual processes to the three main environmental impacts: Water depletion, Climate-change and Freshwater eutrophication will be discussed in further detail to be able to identify the most polluting processes. Furthermore, the build-up of the eco-toxicity indicator will be presented. An overview of the remaining indicators can be found in appendix three.

Table 6.2: The LCIA results of the EPDM roof sheet production system using the ReCiPe (H) characterization factors.

LCIA Category	Amount	Unit
Water depletion	4916.5	m ³
Climate-change	3073	kg CO ₂ -Eq
Freshwater eutrophication	3072.7	kg P-Eq
Ionising radiation	78.4	kg U235-Eq
Human-toxicity	14.6	kg 1,4-DCB-Eq
Photochemical oxidant formation	10.9	kg NMVOC
Terrestrial acidification	8.3	kg SO ₂ -Eq
Particulate matter formation	2.3	kg PM ₁₀ -Eq
Eco-toxicity	0.2	kg 1,4-DCB-Eq

The energy use of the processes is highly correlated with the greenhouse gas emissions of the product system. Figure 6.2 depicts the contribution of the individual processes to the Global Warming potential indicator. Most of the greenhouse gas emissions are generated during the production of the EPDM base polymer indicating that this is a very energy intensive process. The emissions generated during the production of the carbon black, the magnesium hydroxide, the mineral oil Naphtha as well as the emissions generated during the processing of the materials into EPDM roof sheets are depicted separately. The impact assessment indicates that the production of EPDM roof sheets requires considerable amounts of water. Figure 6.3 shows the contribution of the processes to the water depletion indicator. The electricity use of the processes is the most important factor that determines the water consumption the production processes. The production of the base polymer and the processing of the materials into EPDM roof sheets are the most water intensive processes due to the high electric energy demand of these processes. It must be noted that the water

used for the processing of the EPDM roof sheet is not taken into account. Furthermore, no data was available on the water use of the Carbon black production process. Figure 6.4 shows the results for the freshwater eutrophication and again the EPDM base polymer production is by far the most significant production process. The results of the LCA show that the production of the base polymer, carbon black and the processing of the materials into roof sheets are the most important processes for determining the environmental impact of EPDM roof sheet production.

Figure 6.2: ReCiPe midpoint (H) – Global warming potential – results for supply chain of ‘EPDM roof sheets production’ **Total: 3073 kg CO2-Eq**

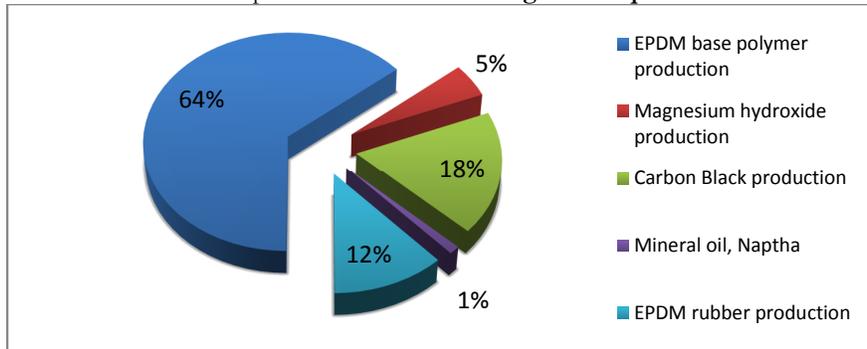


Figure 6.3: ReCiPe midpoint (H) – Water depletion – results for supply chain of ‘EPDM roof sheets production’ **Total: 4916.5 m3**

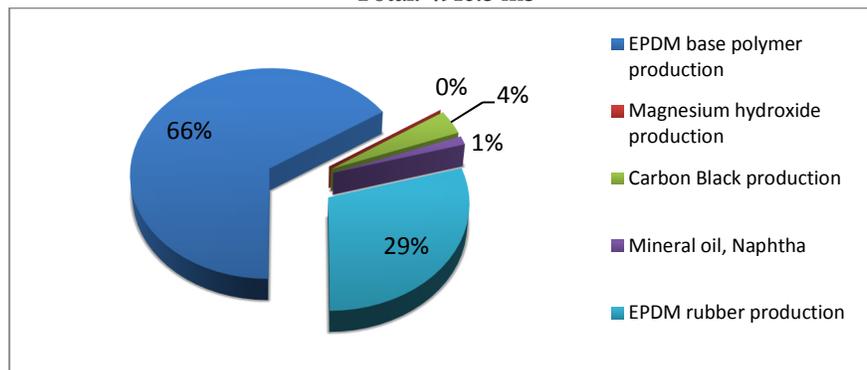
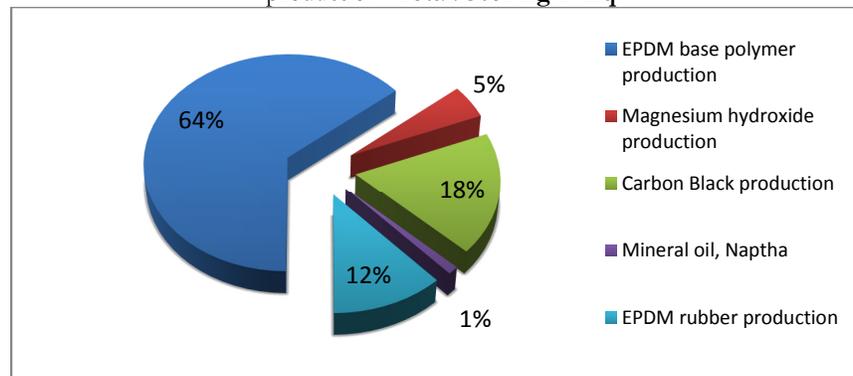
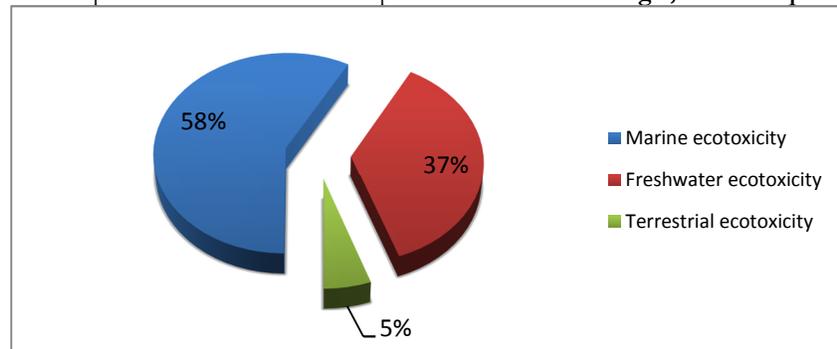


Figure 6.4: ReCiPe midpoint (H) – Freshwater eutrophication - results for supply chain of ‘EPDM roof sheets production’ **Total: 3072 kg P-Eq**



To improve the readability of the results the mid-point indicators of marine eco-toxicity, freshwater eco-toxicity and terrestrial eco-toxicity are combined into one indicator namely: eco-toxicity. Marine eco-toxicity is the most important category contributing to this combined indicator, see figure 6.5. The most important process that determines the marine eco-toxicity is carbon black production which is responsible for around 50% of the environmental impact on the marine eco-toxicity indicator, see appendix three for further details.

Figure 6.5: ReCiPe midpoint (H) - The contribution of the individual eco-toxicity indicators to the total Eco-toxicity impact of 'EPDM roof sheets production'. **Total: 0.2 kg 1,4-DCB-Eq**



- Comparative analysis of the reclaim technologies

To make the comparison between the reclaim technologies and the reference scenario more presentable the environmental impacts of the products systems are normalized, see figure 6.6 and 6.7. The environmental impact of the alternative product systems are scaled to the data from the reference scenario. For instance, figure 6.6 includes the normalized data for the water depletion indicator. When the ultra-sound technology is incorporated into the supply chain around 97% of the water depletion impact is maintained. This means that using the technology leads to a 3% reduction of the overall water use of the product system. The chemical and micro-wave reclaim technologies show the most significant reduction in the use of water. The impact reductions are highly correlated with the electricity use of the processes. The reduction of the environmental impact on the water depletion indicator is lower than in most other categories. This is due to the fact that the emissions are largely generated by the electric energy consumption of the EPDM roof sheet production process. This energy consumption is not significantly altered when a reclaim technology is used because the energy required to process the rubber into roof sheets remains the same. Figure 6.6 also includes the normalized data for the global warming potential impact indicator. The chemical reclaim technology has the highest contribution to this indicator compared to the other reclaim technologies. The chemical reclaim process itself has low energy intensity but the energy used in the production of reclaim chemical is added to the product system. This leads to an increase in the greenhouse gas emissions attributed to the reclaim process. The mechanical and micro-wave reclaim technologies lead to the most significant reductions of greenhouse gas emissions. On the freshwater eutrophication indicator the chemical reclaim technology scores the highest. The higher score is due to additional emissions caused by the production of the reclaim chemical. The reduction of the environmental impact is the lowest for the ionizing radiation impact category. The indicator is strongly connected to the primary electric energy use of the process since most of the emissions are

generated in nuclear power plants. A relative small reduction of the electric energy use and the long life-time of ionizing radiation emissions are leading to a smaller reduction of the environmental impact for this impact category.

Figure 6.6: Normalized data for the Water depletion, global warming potential, freshwater eutrophication and ionizing radiation comparing the reference scenario to alternative product systems with a reclaim technology included.

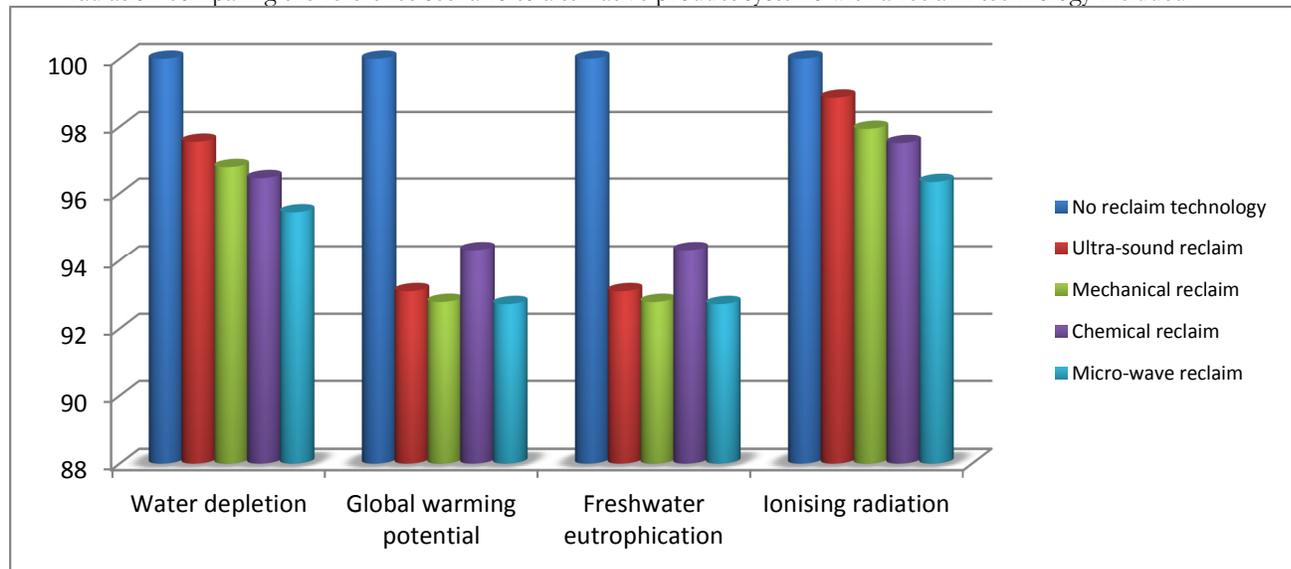
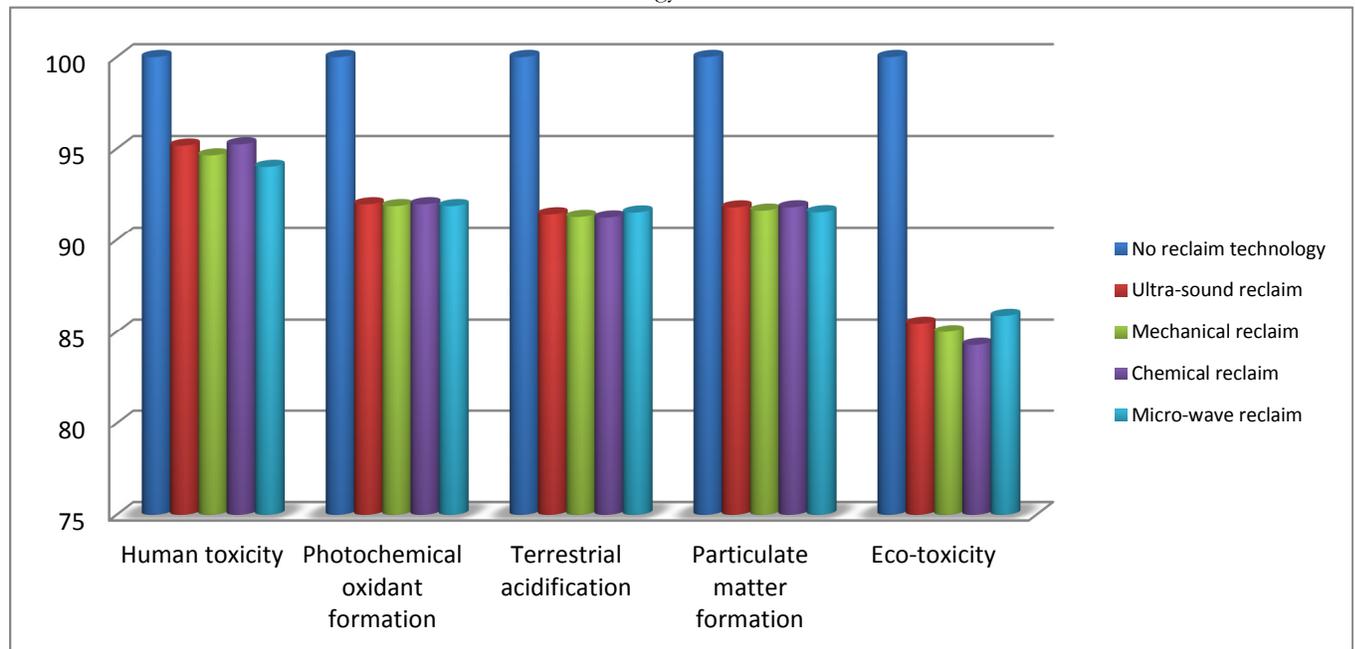


Figure 6.7 shows the normalized scores for the reclaim technologies on the human toxicity, photochemical oxidant formation, terrestrial acidification, particulate matter formation and eco-toxicity indicators. The electricity consumption of the production process is the main contributor to the human toxicity indicator. The carbon black production process is also important for this indicator primarily because of the use of heavy fuel oil. The photochemical oxidant formation indicator refers to the contribution of the product system to an increase in harmful ozone molecules in the lower atmosphere. The biggest contributor to this impact category is the processing of the materials into EPDM roof sheets. Small amounts of non-methane volatile organic compounds (NMVOC) are released into the atmosphere due to the heating of the compound. The reduction of the environmental impact on this indicator in the alternative product systems is largely due to the reduced need for virgin carbon black and base polymer materials. Terrestrial acidification refers to the change in the pH value of the soil due to the emission of inorganic substances. The carbon black production process has the highest contribution to this impact category because of the release of nitrates and sulfates to the environment during production. The micro-wave reclaim scenario has the lowest impact reduction of the alternatives on the terrestrial acidification indicator due to the increased need for mineral oil. The carbon black production process is responsible for nearly 50% of the score on the particulate matter formation indicator. The environmental impact reduction in this category can largely be assigned to the reduced need for virgin carbon black. The impact reduction on the eco-toxicity is higher than in the other categories because there are three categories combined in the indicator. The carbon black production process is the main contributor to the impact category because of its importance for the marine eco-toxicity indicator. The micro-wave technology scores

the highest due to the need for additional mineral oil. The differences between the environmental impact reductions are smaller in the categories depicted in figure 6.7 than in those in figure 6.6. This is due to the fact that relative small amounts of substances are emitted on most of the categories. This makes selecting the most environmentally friendly solution on the basis of these indicators difficult. The categories depicted in figure 6.6 are the most important for determining the environmental benefits of the reclaim technologies.

Figure 6.7: Normalized data for the Human toxicity, Photo-chemical oxidant formation, Terrestrial acidification, Particulate matter formation and eco-toxicity comparing the reference scenario to the alternative product systems with a reclaim technology included.



6.6 Interpretation

The environmental impact assessment gives a robust overview of environmental impacts related to the energy and raw material consumption of an EPDM roof sheets production process. The ELCD database provides a comprehensive dataset to calculate the environmental impacts of the production of oil based products within Europe. Furthermore, several experts were consulted to confirm the energy demand of the reclaim processes and the models build within the ‘OpenLCA’ software. The models include the most relevant data to determine the environmental impact of EPDM roof sheet production. The high score of the product system on the global warming indicator show that the production of EPDM roof sheets requires considerable amounts of energy. The production of the EPDM base polymer is the most energy intensive process and subsequently the largest contributor to the environmental impact of EPDM roof sheet production. The results of the impact assessment show that the environmental impact of the production process can be significantly reduced if reclaimed material is re-used in virgin production cycles. The impact assessment indicates that chemical reclaim process leads to the smallest environmental impact reduction on the Global warming indicator. The chemical reclaim process has the lowest primary energy input of the

researched reclaim technologies but the emissions caused by the production of the reclaim chemical increases the environmental impact of the reclaim technology. The results show that reclaiming rubber without the use of chemicals is more environmentally friendly. It must be noted that the production process of the reclaim chemical HDA was not available in any of the databases. The emissions of the production process are based on the emissions caused by the production of the chemical ammonia which reduces the validity of the results. However, only small quantities of the chemical are needed and the impact assessment is primarily used to assess the relative performance of the reclaim technologies. The higher scores of the chemical reclaim method on the global warming, fresh water eutrophication, and human toxicity indicator are caused by the additional energy needed to produce a reclaim chemical. These results are not expected to significantly change if the HDA can be modeled in more detail. The ultra-sound reclaim technology has the highest primary energy consumption of the researched technologies which is reflexed in the high overall score of the technology. However, the differences between the energy consumption of the reclaim processes are relatively small leading to a fairly similar impact reduction on most of the indicators. The best performing technologies are the micro-wave and mechanical reclaim processes. The micro-wave reclaim technology is modeled to use slightly less energy than the mechanical reclaim technology which is why it has the lowest score on many of the impact categories. However, on the eco-toxicity and terrestrial acidification technology scored the highest. The mechanical reclaim process has the most consistent score in the impact assessment. The process has low energy consumption, no reclaim chemicals are needed and there are no resources lost during recycling. The mechanical reclaim technology leads to the largest overall reduction of the environmental impact of EPDM roof sheet production.

6.7 Conclusion

The life cycle assessment identified several major environmental consequences of EPDM roof sheets production and analyzed the effects of recycling the industrial rubber waste to reduce the demand for virgin materials. The ReCiPe mid-point (H) method was used to calculate the environmental impact of the product system. The impact assessment showed that the energy use of the different production processes is a major determinant of the environmental impact of the production process. The EPDM base polymer is the main ingredient for EPDM roof sheets and it is also the most polluting production process. The impact assessment indicates that rubber production requires considerable amounts of water which is largely due to the electric energy demand of the production process. The results show that the chemical reclaim process is the least sustainable option due to the use of a reclaim chemical. The micro-wave reclaim scored low on most of the indicators but the mineral naphtha needs to be re-added to the virgin mix leading to higher emissions on the terrestrial acidification and eco-toxicity indicators. The best performing technology was mechanical reclaim due to the low energy demand and the fact that the entire compound can be reclaimed. The LCA shows that the base polymer is the most urgent part of the supply chain to recycle because of the energy intensity of the production process. The results support the premise that the environmental impact of the rubber industry can significantly be reduced by increasing the reclaiming rate within the industry.

Chapter 7 - Discussion

The need to develop more sustainable means of production is internationally recognized and many organizations implement strategies to reduce their environmental impact (United Nations, 1992; Hitchcock and Willard, 2008). This research investigated the environmental and technological performance of the chemical-, ultra-sound-, micro-wave-, and mechanical-reclaim technologies for rubber waste. The research of Dijkhuis, 2008 and Sutanto, 2006_a showed that EPDM roof sheets can be reclaimed without the product failing to meet the application standards. A literature review and several expert interviews were conducted to assess the technological performance of the technologies. Furthermore, the LCA methodology was used to investigate the environmental benefits of re-using the 10% industrial waste of an EPDM roof sheet production process for a virgin production cycle. The company Hertalan reported to have only around 5% industrial waste. However, the industry average was used because the DXP technology can be used for multiple rubber compounds. The research showed that the mechanical reclaim technology can be considered the most sustainable and can deliver the highest reclaim quality. The EPDM roof sheet market has been investigated by many researchers indicating that the market is well suited for scaling up novel recycling technologies (Yun and Isayev, 2003_a; Sutanto, 2006_b; Dijkhuis, 2008; Noordermeer, 2012; Ekelenburg, 2012). Hertalan is one of the first companies in the world to invest in a mechanical reclaim technology indicating that reclaiming EPDM roof sheet is economically viable (Smit, 2012). A life cycle assessment of EPDM roof sheet production was also conducted several years ago by the company PRé consultants (Noordermeer, 2012). This information is however not freely available because it is included in the professional LCA software SimaPro. However, in a demo-version of the program the input data for EPDM rubber production can be viewed (Simpro, 2012). In the Simapro model the raw materials for the base polymer are directly added to the compound production process and there is no additional step modeled for the polymerization process. It is however important to make a clear distinction between the production of a rubber compound and the polymerization of petrochemicals (Voll and Kleinschmit, 2005; Sanders and Peeten, 2011). The process is included separately in the model used for this research which could lead to a significant difference in the LCA results. However, because the software is not freely available it was not possible to verify this assumption. The study done by Clauzade *et al.* 2010 used the LCA framework to investigate the environmental benefits of nine recovery methods for used tires. The study concluded that the use of rubber granulate to produce synthetic turf or molded objects delivers the largest environmental savings. The re-use of EPDM granulate in the production of synthetic EPDM floors was also included in the study but it was among the lowest scoring options. The replacement of high energy consuming materials with rubber granulate can significantly reduce the environmental impact of that production process. The study of Clauzade *et al.* 2010 supports the assumption that the effects of transportation on the total environmental impact are relatively small. The focus of the current recycling efforts is on solving the rubber waste problem by extending the life cycle of rubber materials (Clauzade *et al.*, 2010; RecyBEM, 2012). Rubber is currently not included as a critical resource in the European raw materials initiative. However, the European Union is heavily dependent on imports and there are no viable alternatives for the main ingredients for rubber

compounds. The demand for rubber products is projected to increase while the supply of oil is decreasing and the production of natural rubber has not grown with increased demand. The price of oil has nearly tripled since 2000 and the cost of natural rubber has increased by 400% (ETRMA, 2010). Therefore, the research focused on the possibilities of recycling rubber so it can be used to produce the original compound. The relationship between the LCA framework and the REACH directive is discussed in a paper by Askham, 2010. The greater availability of toxicological data developed under the REACH directive can strengthen the LCA methodology since an important limitation of the LCA methodology is the lack of reliable data e.g. for determining the toxicological effects of substances. Furthermore, the LCA methodology can help companies develop a framework for the impact assessments required under the REACH directive (Askham, 2010). The OpenLCA project is therefore an important development since it provides a free LCA software tool which can be used by companies to integrate environmental impact data. The software can support the development of the environmental impact assessments needed for the REACH regulation. The results from the LCA study assessed the potential direct impact of the production system without covering indirect effects such as land use, market mechanisms or rebound effects. In a paper by Guinee *et al.* 2011 the need to develop Life Cycle Assessment into a broader framework called Life Cycle Sustainability Analysis (LCSA) is discussed. The framework broadens the scope of the analysis from product oriented to include a sector wide analysis of a product. The scope of the impact indicators is also broadened by including economic and social aspects (Guinee *et al.*, 2011). The LCSA provides a comprehensive framework to compare the benefits of reclaiming with the recycling of rubber into lower grade materials. The technologies that were included in this studied have only been implemented on an experimental scale. The success of the technologies in experimental settings does not guarantee the real practical value of the technology (Dijkhuis, 2012; Noordermeer, 2012). Therefore, this research focused on the environmental and technological aspects of rubber reclaiming without assessing the economic benefits of reclaiming. The use of a Delphi questionnaire was initially intended for this research however concerns about the protection of trade secrets, the limited number of researchers and time constraints made a Delphi round impractical. Companies were only willing to share limited details about their product composition, production costs or novel recycling processes. Furthermore, the reclaim technologies all require specific know-how which makes it more difficult for experts to form an opinion on results of other reclaim methods. Therefore, a combination of an extensive literature research and in-depth interviews with carefully selected experts was chosen to be able to acquire the relevant information. In the United States used EPDM roof sheet are already recycled on a large scale. In 2006, the EPDM Roofing Association (ERA) took the initiative to start large scale recycling of EPDM roof sheet in conjunction with roof sheet manufacturers. The rubber waste is granulated and used in the production of new EPDM roof sheets or used to produce other products. The recycling has shown to deliver a significant cost benefit to EPDM roofs sheet manufacturers (Evanko, 2010). The granulation of rubber and the re-use of the material for other products is currently one of the most economical solutions to the rubber waste problem. However, the mechanical reclaim technology will be the first technology able to prove the viability of rubber reclaiming by providing a competitive alternative for virgin materials and granulation recycling.

Chapter 8 – Conclusions and recommendations

The unique properties of rubbers make it an important raw material for industrialised nations. The rubber industry is however confronted with a sharp rise in the cost of the raw materials and increasingly strict regulations such as the European REACH and ELV directive (ETRMA, 2010; Luiten, 2012; Smit, 2012). DX-polymers is a start-up company that can deliver a reclaim service to rubber manufacturers. The company developed a technology that is able to produce a stable and high quality reclaimed material. The recycled product can be mixed in up to 25% with a virgin compound without a substantial loss of quality. However, the rubber waste has to be clean and homogenous making reclaiming of many rubber products difficult e.g. tires (DXP, 2012; Ekelenburg, 2012). This research therefore focused on reclaiming the industrial waste generated during the production of EPDM roof sheets. The research used the LCA methodology, expert interviews and a literature review to assess the performance of the DX-P technology relative to other reclaim processes currently under development: the chemical, ultra-sound, and micro-wave reclaim technologies. The chemical reclaim process with HDA as a reclaim agent has shown to produce a material of sufficient quality to be mixed in with a virgin batch (Dijkhuis, 2008). However, the effects of the reclaim chemical can significantly differ between compounds leading to a low flexibility of the technology (Dijkhuis, 2012). Furthermore, the use of additional chemicals was one of the reasons for Hertalan to look for an alternative solution (Smit, 2012). The ultra-sound and micro-wave reclaim technologies can be considered more pyrolysis techniques than reclaim technologies due to the high temperatures reached during processing. This leads to a severe degradation of the main chain molecules reducing the material properties of the compound (Zanchet *et al.*, 2009; Dijkhuis, 2012; Noordermeer, 2012). Both technologies have been under investigation for many years but neither has proved to be economically viable (Ekelenburg, 2012; Noordermeer, 2012). The material properties of the rubber are severely affected by the reclaim processes and their flexibility is low because the efficiency is highly dependent on the nature of the rubber compound that is being processed (Yun *et al.*, 2003; Yun *et al.*, 2004; Bani *et al.*, 2010; Pistor *et al.*, 2010). The best performing technology is the mechanical reclaim method since it is able to produce a high quality reclaim because of the low temperatures during processing (Fukumori and Matsuchita, 2003; DXP, 2012). Furthermore, the process is suitable for most rubbers and the entire compound can be reclaimed. The Life Cycle Assessment showed that the energy use of the different production processes is a major determinant of the environmental impact of EPDM roof sheet production. Recycling rubber so that it can be used for the production of the original product i.e. reclaiming requires far less energy than making the same amount of materials from virgin materials. Increasing the amount of rubber that is reclaimed can reduce cost, improve the environmental performance as well as ensure the future growth of the rubber industry. The ELV regulation has already led to a sharp increase in the re-use of old tires to produce new products e.g. via the granulation of rubber. The new legislation implemented by the Dutch government is leading to a large incentive for the re-use of rubber waste of other purposes (RecyBEM, 2012). This is currently the best way to solve the rubber waste problem because the composition and cleanness of the waste is less important if the material is re-used in an inferior compound. Increasing the reclaim rate within

the rubber industry will not be easy due to the complicated nature of many rubber products and the conservatism within the industry. Furthermore, the compounds used within the rubber industry cannot easily be redesigned to better facilitate a reclaim process (Smit, 2012; Luiten, 2012). However, the European Union is heavily dependent on the import of rubber and a lack of reclaim facilities could threaten the long-term sustainability of the industry (ETRMA, 2010; Luiten, 2012). The EPDM roof sheet market provides a stepping stone for the rubber reclaim technologies to prove their economic and technological capabilities. The company DXP decided to build one central plant and provide a reclaim service to rubber manufacturers. However, rubber manufacturers are very secretive about their products and there is still much unknown about the possibilities of reclaiming end-of-life rubber materials. Therefore, major rubber manufacturers could also be interested in a joint venture to develop the technology on their facility to be able to protect trade secrets and to study the reclaim process in more detail. This could speed up the pace of development and prove the large scale feasibility of the technology. A solid base of scientific information to support the DXP reclaim technology will make it easier to convince the rubber industry of the value of the technology. Based on the research the following recommendations are made:

- The competition may be higher than expected because the DXP technology is not the only mechanical reclaim method currently under development. It is important for the DXP technology to prove itself under market conditions as soon as possible. Seeking a joint venture with a major rubber producer can speed up the research and development of the technology.
- To counter the skepticism among rubber manufacturers it is recommended that DXP publishes a report on their internet site on the effects and the efficiency of the reclaim technology on different compounds.
- The government can legally require companies to reclaim rubber if a reclaim technology is labeled as the best available technology for rubber recycling. The possibility that the mechanical reclaim method receives this label should be investigated.
- Governments should be encouraged to recognize rubber as a vital resource for the European Union to increase the incentive for rubber reclaiming.
- Sector wide agreements with the rubber industry on the standardization of rubber compounds can increase the economic competitiveness of reclaiming.

Recommendation for further research:

- A Life Cycle Sustainability Analysis is suggested in which the mechanical reclaim technology is compared to the recycling technologies that are currently the most important i.e. the shredding and pyrolysis of rubber for the re-use in other compounds.

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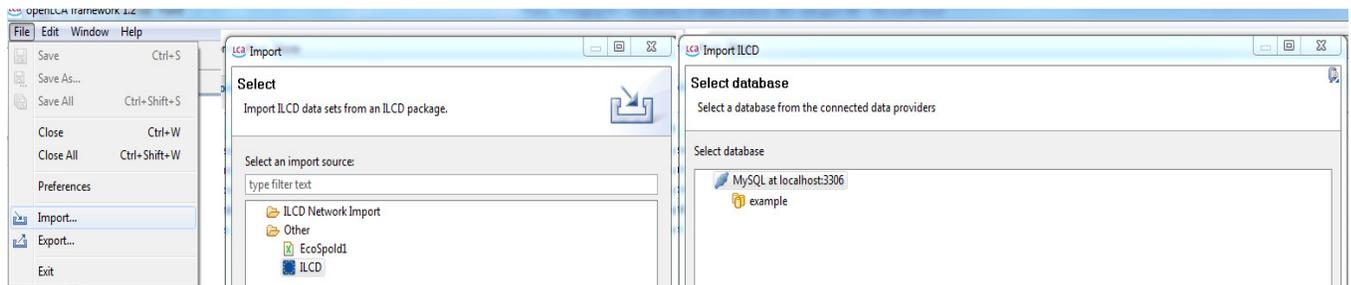
Appendix

Appendix 1: Research planning

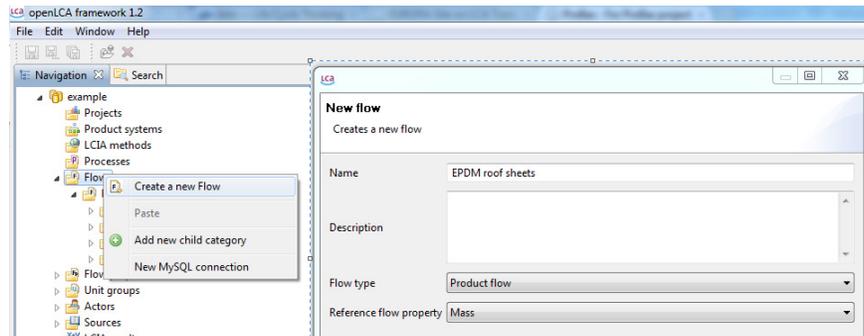
Phase:	Start:	Finished by:	Steps to be taken:
<u>Preliminary research</u>	1-11-2011	01-02-2012:	Reviewing literature on LCA, rubber recycling, the environmental impact of rubber production, and legislation. *
			Find relevant LCA data
			Contact companies for a first visit.
<u>Empirical study</u>	02-02-2012	01-03-2012	Construct flow charts
			Collected data from industry
			Collect data from literature
			Decide on impact categories
			Construct models in open LCA software
			Conduct interviews
<u>Results</u>	01-04-2012	01-05-2012	Evaluation of reclaim technologies
			Check LCA and LCA with experts
<u>Conclusions</u>	02-05-2012	20-05-2012	Draw conclusion
			Editing
<u>Critical review</u>	01-06-2012		<u>Final editing</u>
* <u>Words for literature search</u>			Rubber recycling + Reclaiming rubber + mechanical reclaim

Appendix 2: The OpenLCA software

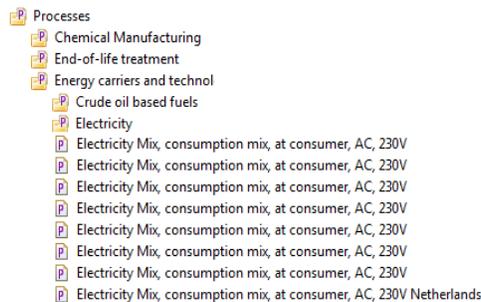
The Openlca is a free software tool which can be downloaded at <http://www.openlca.org>. You can start a LCA by right clicking on MySQL and selecting create new database. The program does not include any environmental impact data so this will need to be added to the new database. The free ELCD data base developed by the European Union provides a large LCI database and can be used as a starting point for a LCA, you can download the data set at <http://lca.jrc.ec.europa.eu/lcainfohub/download.vm>. To import the data into the OpenLCA software go to, file and click on import:



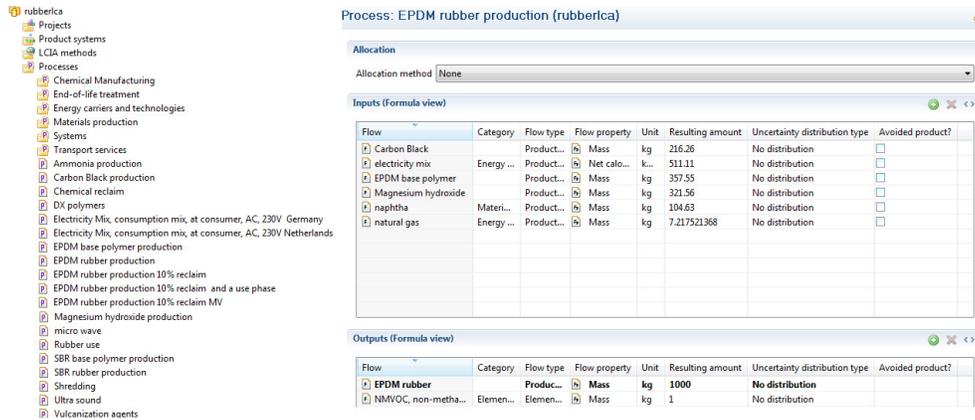
Additional environmental impact data can be gathered from literature, companies or can be found in online environmental impact database e.g. <http://www.probas.umweltbundesamt.de>. The missing processes will need to be added manually to OpenLCA software. To be able to create a product system there first needs to be a flow of the product that is researched. A new flow can be created by right clicking flow, and selecting create a new flow:



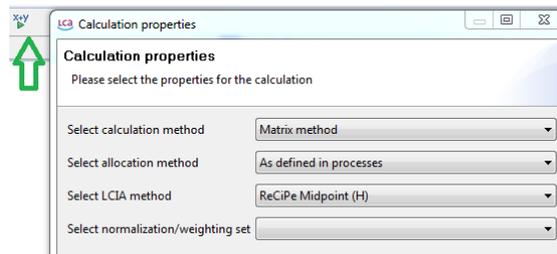
The creation of a flow is always the first step in building a new product system or adding new production processes. Now that the flow is created the production process can be created by right clicking processes and selecting new process. After giving the new process a name and selecting the product that is being produced by picking the corresponding flow of by the process, it is added to the list. Now it is possible to select the in- and outputs for the new production process. The ELCD database can be used to model the extraction of raw materials and can account for the emissions caused by the use of energy on a country specific level. However, it might take some time to find the right process to model the electricity use because they are all given the same name:



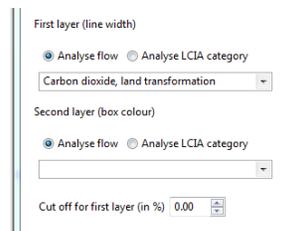
By opening the electricity mix in the editor you can find which country is modeled. You can add the country to the name of the process to make it easier to find it back, the use of natural gas can also be modeled according to the country of origin. The figure below shows an example of the inputs and outputs of the product system that is modeled for this research. Some of the product flows are directly taken from the ELCD database while other production processes are manually constructed.



Now that all the relevant processes are added to the production process a new products system can be created by right clicking on product systems. The reference process is the flow that is being researched e.g the flow created earlier: EPDM roof sheets. The flow chart can be viewed by clicking on model and moving to the tap Graph. It is important to check all the inputs before the impact assessment is done. Additional process can be directly dragged in from the listed process on the left and connected to the product system which makes building the models easier. The impact assessment can be done by clicking on the x+y bottom in the top of the screen



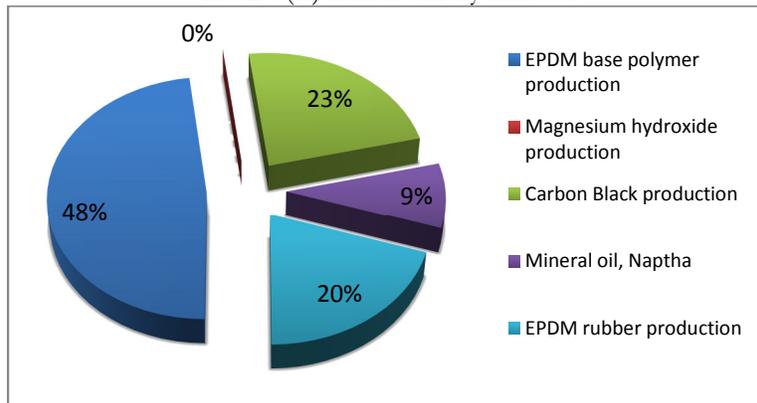
After calculating, the results of the LCA can be viewed in the characterization tab found under results. This data can easily be exported to excel by clicking on the Excel logo in the top left corner. The analysis tab is important for checking the results of the LCA. The contribution of the individual processes to the environmental indicators can be viewed in more detail. This can be used to make charts or figures showing the buildup of the different environmental impact categories. The sankey diagram is an important tool for tracking the environmental emissions. To easily see how the different processes contribute to e.g. the Global warming indicator select Carbon dioxide land transformation and put in 0% cut off to be able to view all processes.



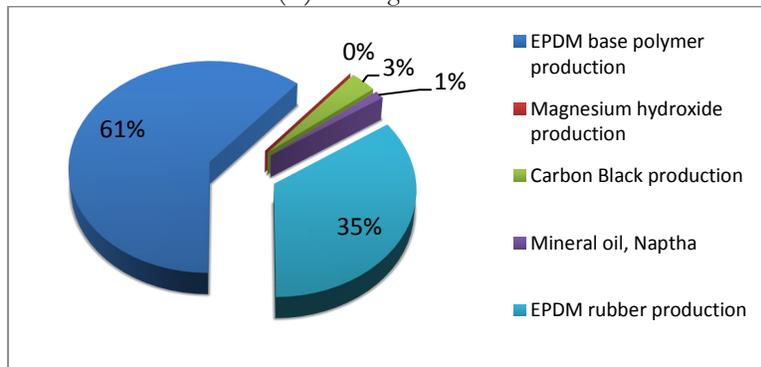
For further information see http://www.openlca.org/documentation/index.php/Main_Page.

Appendix 3: Impact assessment results

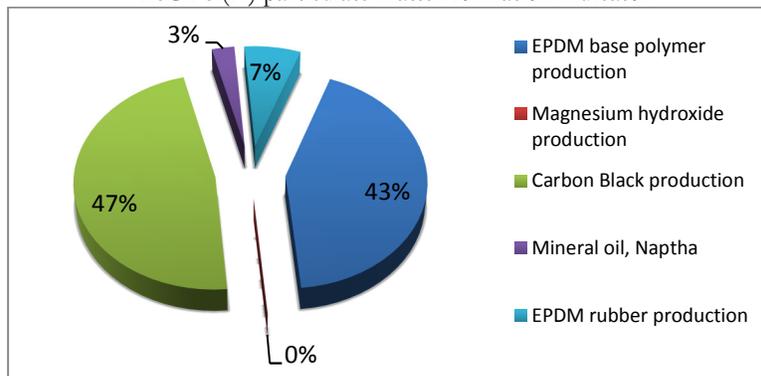
ReCiPe (H) human toxicity indicator



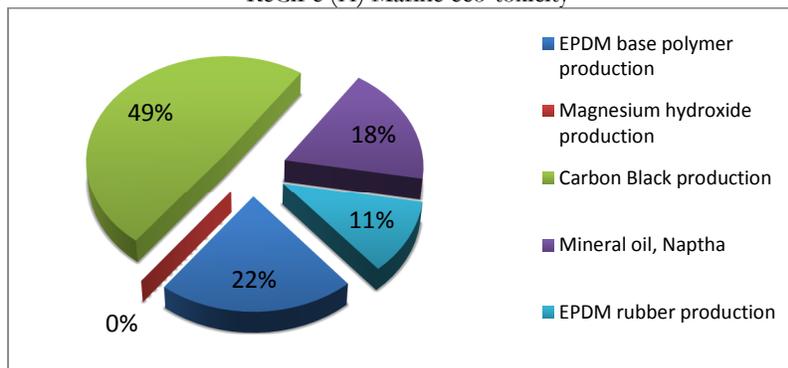
ReCiPe (H) ionising radiation indicator

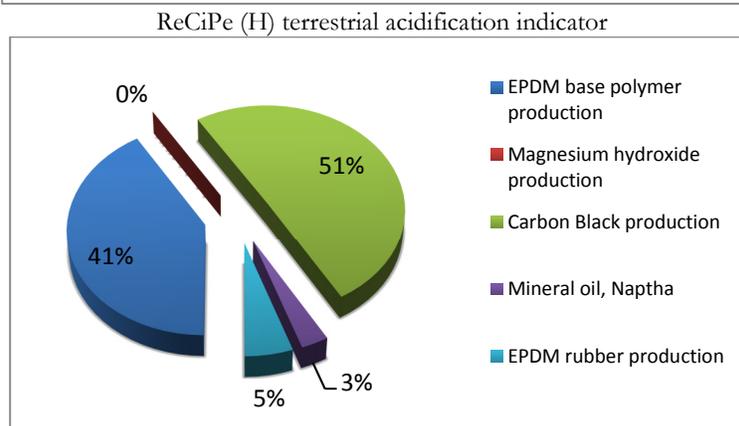
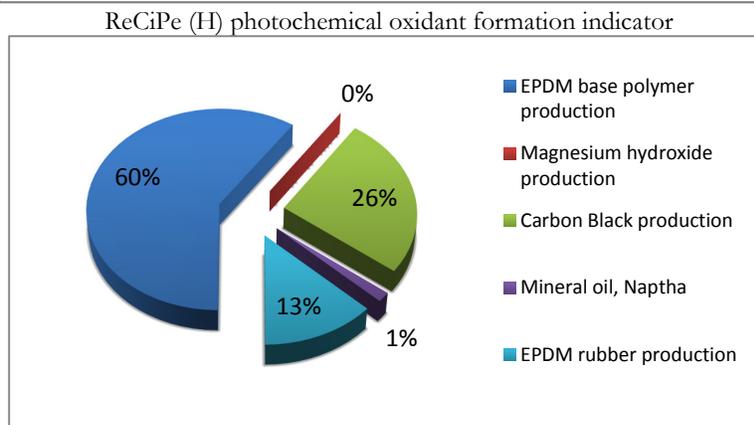
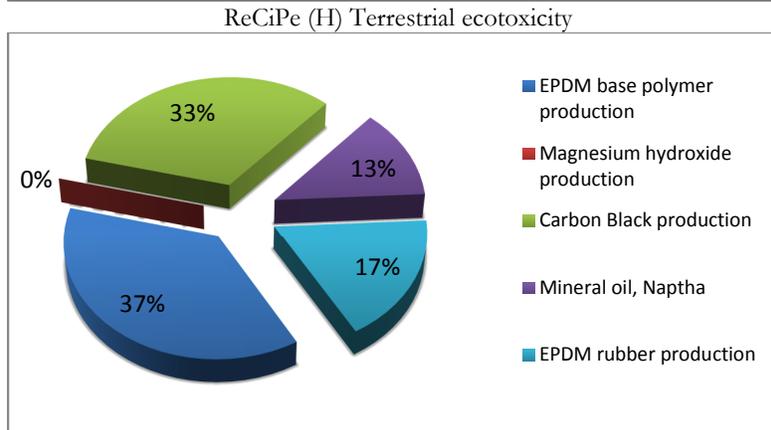
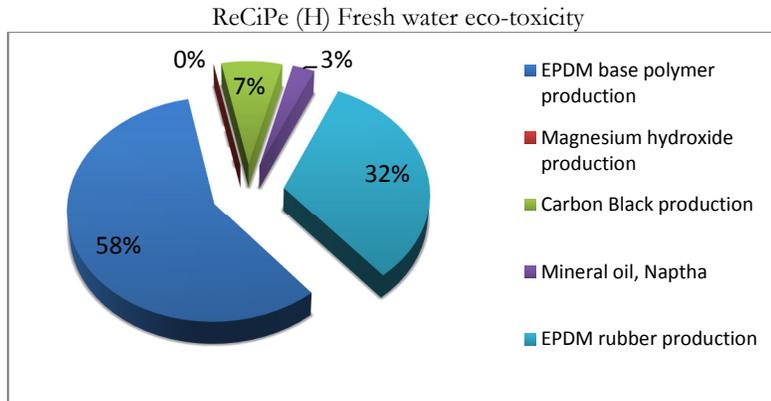


ReCiPe (H) particulate matter formation indicator



ReCiPe (H) Marine eco-toxicity





Appendix 4: Transcripts of the interviews in Dutch

Kuno Dijkhuis: Elastomer Research Testing B.V.

- **Wat voor een service biedt het bedrijf Elastomer Research Testing B.V.?**

Elastomer Research is een test en onderzoekscentrum naar alles wat met rubber te maken heeft. We ontwikkelen nieuwe rubber materialen, testen rubber compounds en geven opleidingen op het gebied van rubber. Het is een consultancy bureau voor advies op het gebied van het rubber productie proces, de materialen en rubber recycling.

- **In Uw proefschrift noemde U de nieuwe wetgeving voor de auto-industrie. Is er een verschil merkbaar in het aantal vragen over rubber recycling technologieën?**

Er zijn verschillende wetgevingen die van invloed zijn op rubber producenten. Ik geloof dat vanaf 2010 de rubber industrie in Europa geen aromatische olie meer mag gebruiken. De aromatische olie is nu geïdentificeerd als kanker verwerkende stof en doordat een autoband slijt komen de deeltjes van het milieu terecht. Daarom moet de olie vervangen worden. Alleen de stoffen die de olie moeten vervangen zijn nog niet van dus danige kwaliteit dat ze dezelfde eigenschappen hebben als het oude product. Er wordt nu druk gewerkt aan het ontwikkelen van betere alternatieven. Dit heeft niet direct gevolgen voor het recyclen van rubber want het is vooral een milieu eis. Het ELV wetgeving heeft ook invloed gehad op de rubber industrie maar ik weet niet wat de status nu is. Het is wel een redelijk gewicht van een auto, over de 5% maar ik weet niet of dit percentage al is gehaald. Wat wij wel merken is dat er steeds meer vraag is naar het onderwerp rubber recycling. 5 jaar geleden toen ik hier kan werken was er 1 klant die er veel mee bezig was en nu zijn er een stuk of 6 7 mee bezig, een redelijke toename dus. We krijgen veel aanvragen en zien wel dat recycling een hot-topic is. Er zijn verschillende methodes waar deze bedrijven gebruik van maken, sommige proberen het te de-vulkaniseren of reclaimen en anderen proberen het op via pyrolyse of shredding. Pyrolyse is eigenlijk totaal verbranden van een auto band om ze de verschillende bestand delen weer te kunnen gebruiken. De rubber resten worden verband om zo een materiaal te maken met een hoge activerings energie. Dit heeft meer energie in zich zitten dan normaal koolstof. Ze willen dit weer op de markt brengen als carbon black filler maar het is niet zo zuiver als nieuwe materialen en dat zie je snel terug in de eigenschappen. Een autoband is opgebouwd uit verschillende elementen die na pyrolyse door elkaar komen te zitten waardoor het end product verschillende materialen bevat maar er zijn ook ideeën om het te gaan scheiden. Het staal draad en de vezels worden als wel succesvol gerecycled om apart te verkopen. De rubber resten blijft moeilijk gezien het geen homogene materialen zijn. Deze technieken recyclen voor een vul stof maar je hebt ook nog het reclaimen of de-vulcanizatie van rubber. Bij deze methode ga je niet terug na een ingrediënt voor een rubber compound maar dan behoud je de samenstelling van het product en kan het dus volledig worden innengt. Men is wereld wijd opzoek naar mogelijkheden om het rubber uit auto banden zo veel mogelijk te kunnen recyclen omdat het de grootste markt is voor rubber. De kwaliteit van de het gerecycled product is niet het alle belangrijkste omdat er nog veel ruimte is voor het verhogen van het

recycling percentage. Er is voor beide methoden, wat te zeggen maar er is alleen nog geen techniek op de markt die een dusdanig kwaliteit kan leveren dat materialen 100% hergebruikt kunnen worden. Rubber wordt ook wel vermalen en dan direct gebruikt als grondstof voor andere producten maar dit is nog maar een klein deel van de totale rubber banden. Met de-vulkanisatie of pyrolyse technieken voor auto banden kunnen een oplossing zijn om het probleem grootschalig aan te pakken.

- **De resultaten van Uw PDH thesis waren positief, is de technologie daarna opgeschaald?**

In mijn studie heb ik puur gekeken naar EPDM en voorgangers van mij hebben gekeken naar natuurlijk rubber. Dat blijkt al niet 1 op 1 te gaan want, wat bij natuurlijk rubber werkt, werkt bij EPDM niet, en andersom ook. Natuurlijk rubber laat zich iets makkelijkere recyclen maar met bijv. auto banden heb je natuurlijk verschillende compounds en die kun je later niet meer uit elkaar halen. Het materiaal zou wel in een bepaalde verhouding weer ingemengd kunnen worden e.g. 5-15%. Het hoeft niet volledig recyclebaar te zijn als je het maar kan inmengen zonder dat de kwaliteit achteruitgaat van het eindproduct. Als je van alle autobanden 10 of 15 % kan hergebruiken dan ben je al een eind op weg om het afval probleem op te lossen alleen de banden fabrikanten moet je nog wel kunnen overtuigen om je materiaal te gaan hergebruiken. Dat wordt nog een hele slag, dus A het is al moeilijk om het materiaal goed te krijgen en daarnaast is het erg moeilijk fabrikanten te overtuigen omdat de rubber wereld aardig conservatief is. Wetgeving kan helpen maar de auto banden wereld is groot met veel meer landen zoals China die banden produceren. Als straks alleen Europa de regels heel streng maakt dan heeft het nog niet veel zin te hebben want daar zijn de eisen niet zo streng, Maar goed, als ze willen gaan exporteren dan moeten ze aan Europese eisen voldoen dus ook daar zou het recyclen dan ook moeten toe nemen. Het is wel een trend die je ziet dat China ook kwaliteit goede producten moeten gaan kunnen leveren.

In ons onderzoek hebben de technologie experimenteel opschaaft waar mee we een goed product hebben kunnen produceren. Dit hebben we gedaan in samenwerking met Hertalan die ons product heeft ingemengd met hun bakbedekking. Op lap-schaal werkte het en daar bleek uit dat zelfs 100% gereclameerd materiaal ook kon voldoen aan de kwaliteitseisen voor dakbedekking. Daar moet ik wel bijzeggen dat de EPDM van zichzelf al dusdanig goede eigenschappen heeft dan functioneel noodzakelijk voor de toepassing. Dus er is een heel groot gebied waarin de eigenschappen van het product naar beneden konden. Want door te reclaimen gaan de eigenschappen van het product gewoon naar beneden maar door het in te mengen kan het nog steeds gebruikt worden voor de toepassing van het materiaal. Dat geluk heb je met de dakbedekking. De HDA methode hebben we verder opgeschaald in Maastricht en dat was eigenlijk redelijk veel belovend. We hadden nog niets gedaan met de settings van de extruder omdat we maar 1 test hebben kunnen doen. Met de settings die we toen hadden van Rubber resource in Maatschicht bleek dat de kwaliteit heel goed was. Alleen

er zaten her en der nog harde stukken i.e. gel deeltjes in. Je kunt je voorstellen dat voor een raam of deur profiel van EPDM is dit niet gewenst is. Dat moet heel glad zijn dus het was niet praktisch voor de toepassing. Ik heb begrepen dat er in Amerika pogingen waren gedaan het proces op te schalen waar het nu weer in EPDM dak bedding gestopt. Maar zelfs bij de HDA methode zie je dat het bij sommige processen wel en soms niet werkt. Wat belangrijk is het vulkanisatie system, dit zegt je iets over het aantal crosslinks in de rubber en bijv. wat de lengte is van de moleculen. Bij zwavel gevulkaniseerd rubber kun je veel of weinig crosslinks hebben en daarnaast heb je polysofilise, disofilise en monosofilise rubber. Ik heb in mijn proeft schift laten zien dat als HDA gebruikt wordt het soms recht door de rubber compound heen gaat en dat het bij andere rubber het de lagen als een ui afpelt. Dan houdt je dus een gedeelte over met dezelfde crosslinks-point als het originele compound. Het de-vulkaniseren is het verbreken van de crosslinks in de rubber zonder de rest van het materiaal aan te tasten. Met reclaiming maak je van de rubber eigenlijk een nieuw materiaal. Dit kan ook betekenen dat je het hoofd polymeer ketting i.e. de back-bone aan tast. De gebroken kettingen vormen een soort sterretjes in de rubber die weer opnieuw aan elkaar gemaakt kunnen worden door middel van vulkanisatie. Dat is het verschil, er is nog geen de-vulkanisatie methode op de markt omdat in bijna alle gevallen ook de hoofd ketting aangetast worden. Het is alleen wel belangrijk dat je alle crosslinks gebroken hebt want anders is het materiaal nog niet plastisch genoeg. Dan blijven grotere moleculen aan elkaar gelinkt.

- **In het report wordt genoemd dat het rubber cryogenically word geshredded, is echt dat nodig?**

Dit weet ik niet maar opdat wij op de universiteit geen andere mogelijk hadden hebben we de rubber met vloeibaar stikstof behandeld om het te kunnen shredden. Je hebt knijp messen en scheur apparatuur nodig om rubber klein te kunnen maken. Wij hadden alleen een hakmachine maar met te weinige kracht om kleine deeltjes van te maken. Op deze manier konen we toch kleine hoeveelheden verkrijgen.

- **Wat is de invloed van tempratuur op de-vulkanisatie/reclaim proces en is een lagere tempratuur beter?**

Het is altijd een combinatie die nodig is voor optimaal rendement. Trek kracht heb je altijd nodig en de rubber wordt daarnaast altijd warm. Echter niet alleen de tempratuur is van belang want als ik het in een oven leg werkt het niet. De HDA zorgt er voor dat je meer op de cross links focust en niet de hele verbindingen afbreekt. Ik kan me voorstellen dat een lagere tempratuur gunstig is voor het reclaim proces. Als je rubber verhit ben je het eigenlijk ook aan het verouderen. Als je puur praat over auto banden, het SBR of natuurlijk rubber daarbij gebruikt wordt heeft een maximaale gebruiks-tempratuur van rond de 90 tot 100 graden, daarna degraderen ze. Je kunt wel goede plasticiteit behalen met reclaiming onder hoge tempraturen maar het polymeer heeft een dusdanige hitte behandeling gehad dat het verouderd is. De testen die ons bedrijf uitvoert is op het eind materiaal dus ik heb geen idee waar alle bedrijven precies mee bezig zijn en wat de omstandigheden zijn. Mijn onderzoek deed het met een tempratuur van rond de 200C 250C graden en als ik onder de

175 kwam dan gebeurde er gewoon niks. Zoals als wij het gedaan hadden dan moest de temperatuur redelijk hoog zijn. Het is altijd een combinatie van het breken van de crosslinks en een deel van het polymeer kettingen onder de juiste temperatuur en trek kracht. De C/C verbindingen hebben een hogere energie verbinding dan de S/S links dus ik zou me theoretisch kunnen voorstellen dat het alleen onder temperatuur en trek kracht gereclaimed kan worden. Maar normaal gesproken als jij de kracht uit oefent op rubber om de crosslinks te breken ontstaat er ook water, hoe je hier mee omgaat onder de 100 graden is mij niet duidelijk.

- **Was de HDA terug te vinden in het eind materiaal en heeft dat mogelijk gevolgen voor rubber bedrijven onder het REACH directive?**

We hebben 1 tot 2,5% HDA gebruikt voor onze tests en er zal vast wel wat achter blijven in het eind product. We hebben dit niet onderzocht maar je moet dus wel een zo milieu vriendelijk mogelijk product gebruiken. De effecten op het verder productie proces zullen verder onderzocht moeten worden. HDA was geen schadelijk product voor de mens om mee te werken.

- **In Uw proef schrift werd microbe reclaim aangestipt, zijn hier nog verder ontwikkelingen in geweest?**

Nee, ik had het genoemd als een techniek die ook eens was geprobeerd. Het was toen al niet zo heel veel belovend en ik er nog nooit iets van gezien. Ik hoor er ook niets meer over, de-vulkanisatie, reclaim en pyrolyse is waar je de laatste tijd veel over hoort.

- **Zijn de technologieën die ik heb gekozen in principe allemaal in staat rubber te reclaimen?**

Het is in elk geval allemaal geprobeerd in het verleden met meer en mindere mate van succes. Met de ultra sound en microwave ga je eigenlijk al meer naar pyrolyse toe omdat het onder hoge temperaturen plaat vindt. Het eindproduct is dus eigenlijk meer een vulmateriaal. In de mechanische en chemische processen word het wel mogelijk het echt als volledig grondstof in te zetten. Je krijgt dan namelijk een compound met vergelijkbare eigenschappen als het originele materiaal omdat de polymeer ketting beter intact blijven. De ultra-sound en micro-wave werken onder zulke hoge temperaturen dat delen van de originele compound verloren gaan. De olie komt er uit en je houdt een as rest over, je krijgt dus weer verschillende producten. Het is dus een verbranding proces en er komt volgens mij ook maar weinig bruikbaar polymeer uit. De micro-wave methode heb ik nog nooit dus danige materialen van gezien dat het de moeite waard is om op te schalen. Maar het zou kunnen als je instaat ben de ingrediënten zuiver te maken. De ultra-sound ben ik verder niet zo bekend mee. De andere methode zijn wel goed in staat rubber te reclaimen.

- **Wat is de invloed van e.g. carbon black op het succes van de reclaim processen?**

Rout is goed in staat bepaalde golven te absorberen dus ik kan me voorstellen dat er verschillen zijn in de soorten compounds. Rout heeft heel veel verschillende soorten, types en grote dus het kan zijn

dat compound hierdoor anders reageert. Wij hebben verschillende klanten die met pyrolyse bezig zijn maar wij krijgen wel totaal andere materialen. Ik weet niet precies hoe ze het proces inrichten maar de ene betere kwaliteit door bijv. betere controle, schonere rubber of een andere dikte maar hier hebben wij geen inzicht in. Het is wel duidelijk dat zelfs met een vergelijkbare technologie er verschillen kunnen zitten in kwaliteit omdat het proces zo verschillend kan worden ingericht.

- **Wat zijn de effecten van veroudering op de kwaliteit van rubber en de mogelijkheden om rubber te recyclen?**

Het zal een effect hebben op de rubber want veroudering van rubber maakt het van mindere kwaliteit. EPDM is zo gemaakt dat het niet wordt aangetast door ozon of zuurstof en het zal niet veel scheuren krijgen van veroudering. Het is wel zo dat het harder wordt omdat er stoffen uit verdampen en het heeft jaren lang onder spanning gestaan wat niet goed is voor rubber. Rubber wat buiten ligt is daarnaast ongeveer 50 % van de tijd vochtig door regen, dauw of andere oorzaken. Dit komt uiteindelijk wel in het materiaal terecht. Door warme lucht breken de moleculen ook langzaam af waardoor de kwaliteit van het product achter uitgaat. Als je het dan ook nog eens gaat recyclen, wat nog een verouderings stap is, dan gaat het nog verder achter uit. Het kan het recyclen wel vergemakkelijken maar dat betekent niet dat je het allemaal kunt her-vulkaniseren. De zwavel kan alleen op bepaalde plekken verbindingen aan maken. Als deze plekken er niet meer zijn dan kunnen er ook minder crosslinks gemaakt worden. Je hebt bepaalde dubbele verbindingen nodig, EPDM heeft van zich zelf al erg weinig dubbele verbindingen die er speciaal aan toegevoegd zijn. De kwaliteit van het product zal zeker minder zijn als het zo lang op een dak heeft gelegen.

- **Is het mogelijk om rubber van alternatieve grondstoffen te maken?**

Er is 1 soort synthetische rubber die dezelfde chemische verbinding heeft als natuurlijk rubber, Isobutylene. Deze is gemaakt om natuurlijk rubber na te maken maar de andere soorten hebben een totaal andere moleculaire samenstelling. De natuur is in staat een polymeer te maken met 100% sis groepen daardoor is het heel sterk. Wij kunnen dit niet na maken en de synthetische rubbers hebben altijd een 2-3 % trans deel. Hierdoor is er geen kristallisatie effect als je het materiaal uitrekt. De andere synthetische rubbers zijn eigenlijk een nieuw soort materiaal omdat ze totaal andere eigenschappen hebben. EPDM kan goed tegen water en is niet gevoelig voor veroudering. Als je dak bedekking met natuur rubbers gaat maken dan krijg je allemaal scheurtje in het materiaal doordat het word aangevallen door de ozon. Dit gaat leiden tot lekkages dus het is niet mogelijk dit te vervangen met natuurlijke rubbers. Bbio-polymeren wordt nu ook aan gewerkt en is ook wel een hot topic. Waar vroeger de Cradle to Cradle hot was is het nu bio-based. Green polymers die de zelfde eigenschappen hebben als normale rubber gaat zeker een keer mogelijk zijn. Ik weet niet precies hoe het allemaal gemaakt wordt maar het zou mogelijk kunnen zijn om uit andere soorten bijv. plantaardige oliën rubber te maken.

- **In welke markt kan een recycling technologie worde opgeschaald?**

Ik heb hier nog geen product gezien waarvan ik zeg dit moet je gelijk commercieel op de markt brengen. Ik moet eerst goede resultaten zien voor dat ik echt enthousiast kan worden. Er zijn wel veel mensen en bedrijven op dit moment mee bezig. We krijgen veel binnen, de ene is heel enthousiast maar dan blijkt het opschalen problematisch. Andere hebben leuke resultaten maar het is heel moeilijk om van een idee naar een pilot project te gaan omdat er is veel geld voor nodig is. Zo zien we soms echt iets moois voorbij komen maar dan hoor je er weer niets van omdat het geld niet binnen is om de volgende stap te maken. Je moet de grondstoffen, apparatuur en mensen ook ergens vandaan zien te halen dus er zitten redelijk wat kosten aan.

- **Is het materiaal makkelijker te verwerken als het gereclaimed is?**

We zien beide. Je hebt sommige die door harde deeltjes moeilijker te verwerken zijn maar het is soms ook makkelijker. Het gereclaimed materiaal is vaak wat plastischer wat gunstig kan zijn voor de verwerking. Het moet alleen niet te plastisch zijn want dan kan het de eigenschappen niet vast houden. De eigenschappen zijn meestal minder en je moet op een zelfde viscositeit zitten. Het product moet zo veel mogelijk hetzelfde zijn als het originele materiaal dus het zou niet zo veel uit moeten uitmaken.

Professor Noordermeer: Universiteit Twente.

- **Worden de batch processen nog steeds gebruikt?**

Dat zijn verouderde reclaim processen maar daar doen we geen onderzoek meer na. Dit zijn de processen die na de tweede wereld oorlog zijn ontwikkeld. Ze worden nog steeds toegepast voor natuurlijke rubber gezien die wat gemakkelijk is te reclaimen. Voor de synthetische rubbers werkt dit niet want dan heb je veel meer kracht voor nodig om de verbindingen te kunnen breken.

- **Is er al meer bekend over het kinetisch model van HDA reclaimen?**

Het onderzoek naar het kinetisch model van HDA reclaimen is niet verder gekomen nadat Kuno was gepromoveerd. Het is blijven steken wegens onvoldoende interesse vanuit de inductie. Er zijn nu twee fabrieken in aanbouw die een reclaim of de de-vulkanisatie techniek willen gaan toepassen voor EPDM dak bedekking. Een in kampen bij Hertalan en een in Amerika voor 7000 ton per jaar. Die zijn tevreden met wat ze in het onderzoek hebben gevonden. Je hoeft niet helemaal het mechanisme te begrijpen om een fabriek te kunnen bouwen. Als het werkt dan weet je genoeg, dat is de situatie nu. Het verkrijgen van het model zal niet veel uitmaken voor de efficiency van de reclaim methode. Het zal wel helpen met vervolg studie naar andere rubber en daar zijn we nu mee bezig voor SBR rubber. Dat is veel moeilijker te recyclen dan EPDM maar we kunnen onze kennis van

EPDM recycling wel goed gebruiken om het onderzoek over SBR verder uit te diepen. Voor een fabriek is dit niet zo belangrijk als het werkt dan is het goed.

- **De resultaten van de studies naar HDA waren aardig positief waarom is het niet opgeschaald?**

De resultaten waren goed en daar is ook uitgekomen dat HDA niet noodzakelijk is rubber te kunnen reclaimen. We zijn nu nog steeds bezig met dit onderzoek. Door alleen mechanische en thermische stress te gebruiken zijn we er achter gekomen dat je zonder HDA ook een heel eind kunt komen. Het hangt van de extruder af hoe de hitte en stress over worden gebracht op de rubber. Er zijn extruders die vanzelf zelf rubber genoeg opwarmen zodat je niet hoeft bij te verwarmen maar er zijn ook extruders die verwarmt moeten worden. Ik hanteer altijd een gebruik van 0,25 KWH per kilogram voor een twin extruder een singel extruder gebruikt minder.

- **Wat is de invloed van e.g. carbon black op het succes van de reclaim processen?**

Er is eigenlijk niet 1 soort rubber want iedereen maakt zijn eigen soort rubber. De basis grondstof is EPDM of SBR rubber maar in het geval van EPDM worden daar ongeveer nog 2 x zoveel additieven aan toegevoegd. De rubber zelf is het bind middel en daar in zit roet, minerale vulstoffen en in EPDM zit vaak ook nog een heleboel olie. Dat wordt tot een soort kauwgom gemaakt en daarna wordt het ge vulkaniseerd. Als je gaat de-vulkaniseren dan krijg je dat het hele materiaal weer na zijn plastische vorm terug. Maar de samenstelling van dit soort recepten, dat is het geheim van de smit. Elke rubber verwerker houdt er zijn eigen recept op na. Ik ben zelf 30 jaar EPDM leverancier geweest maar ik wist niet precies waar de rubber van gemaakt werden. Ze zullen je niet precies vertellen wat de verhouding zijn in de rubber. Dus elk rubber artikelje van elke producent is anders. Het gemak waarmee iets is te de-vulkaniseren hangt erg af van de toevallige receptuur van de producent. Dat maakt reclaimen heel moeizaam want je moet voor elk product het proces gaan optimaliseren en dat is haast onbegonnen werk. Daarom is ook dak folie een interessante markt want daar zijn zeer grote hoeveelheden van maar die zitten wel allemaal ongeveer op de zelfde compound formule. Je kunt de producten van de verschillende producenten allemaal tegelijk reclaimen en er vanuit gaan dat het allemaal ongeveer hetzelfde is. Dan heb je tonnen waarmee je wat kunt beginnen want voor een paar honderd kilo ga je geen installatie aanschaffen. De grootste afzet van EPDM zijn auto ramen profielen. Alleen, die zijn allemaal verschillend per merk auto en per leverancier. Uiteindelijk gaat een auto naar de sloop en staan ze willekeurig bij elkaar. Dan kun je de profielen er wel uithalen maar daar is niet veel mee te beginnen. Een andere grote EPDM markt is radiator slangen maar daar zit je met hetzelfde probleem. Je kunt het malen/shredde maar als je dit inmengt dan zakken de eigenschappen van het originele product snel. Dit is niet optimaal, het beste is als je het helemaal opnieuw kunt gebruiken. De dakbedekking is ongeveer de derde toepassing en er zijn daarnaast niet zo verschrikkelijk veel leveranciers dus dat maakt het wat overzichtelijker. De auto industrie levert het grootste aantal tonnen in EPDM afval maar gezien het grote verschil tussen de profielen is hier helaas niet veel mee te beginnen.

De belangrijkste toepassing van natuur rubber zijn vracht wagen banden. Die zijn allemaal ongeveer hetzelfde in de wereld. Als je dus een oude vrachtwagen band pakt en die gaat reclaimen dan heb je dus weer tonnen en dat gaat redelijk goed. Personen auto banden zijn voornamelijk uit synthetisch rubbers gemaakt en dat is veel moeilijker. Europa heeft hele andere banden dan Amerika en Azië maar ze komen wel over de hele wereld terecht. Als ze afgedankt worden dan komen ze meestal op een grote hoop terecht. Het is moeilijk om dit te recyclen. Het inmengen als filler van dit materiaal is ook geen optie want dan gaan de eigenschappen van het materiaal te hard achter uit. Jaarlijks worden er ongeveer 1 miljard banden geproduceerd en er worden zowat 800 miljoen afgedankt. Als je 25 centimeter per band zou rekenen dan zou je 5 x om de aarde kunnen of op twee derde naar de maan zijn per jaar als je ze opstapelt. Er wordt rubber vermalen voor onder sport velden of het kan als filler worden ingemengd tot max. 5% in nieuwe banden. Veel van de banden worden daarnaast gebruikt in cement fabrieken. Het as en staal worden ook in het cement verwerkt waardoor de kwaliteit van het product wordt verbeterd.

- **Is het mogelijk om rubber van alternatieve grondstoffen te maken?**

Het mooiste zou zijn als er weer nieuwe banden gemaakt kunnen worden van rubber afval of in elk geval dat er meer kan worden ingemengd dan 5%. Er liggen hele grote stapels banden ergens op de aarde. Als dat in de brandt gaat, wat ook al eens is voor gekomen, dan krijg je dat haast nooit meer uit. Als er een stapel met miljoenen banden staat te branden dan wordt het een soort stroop en daar helpt geen blussen meer aan. Daarnaast hebben we geen goede alternatieve voor rubber en als we geen banden konden maken dan reden we nu nog op houten wielen. De natuurlijke rubber en de synthetische rubber zijn wezenlijk andere soorten materialen. Het zal afhangen van het soort polymeer dat je wilt maken. Je hebt voor de productie van synthetische rubber monomeren nodig, voor EPDM is dat etheen en propaan die worden gewonnen uit olie. Het is nog nooit geprobeerd om grootschalig van een natuurlijk olie rubber te maken. De DSM fabriek, nu Lanexx, heeft een fabriek in Brazilië naast een suiker riet plantage. Daar wordt suikerriet vergist om alcohol van te maken wat weer wordt ingemengd met de benzine in het land. Die alcohol heeft Lanexx gebruikt om etheen van te maken, voornamelijk alleen nog om promotionele overwegen, voor een bio EPDM. Dit is EPDM deels gemaakt uit de alcohol die gewonnen wordt uit de suikerriet. Maar de propeen komt nog steeds uit olie want dit kun je niet uit alcohol maken dan kom je een c te kort. Echter methanol wordt ook veel gemaakt in deze wereld en dat zou wel propeen kunnen worden.

Het maken van dit soort alternatieven voor 'olie rubbers' is al sinds de tweede wereld oorlog een gebied van interesse. Fischer en Trops hebben tijdens de tweede wereld oorlog in Duitsland een methoden ontwikkeld om olie te maken door hout of kolen te koken. Het proces maakt laag moleculaire koolstof verbindingen die je daarna weer onder druk aan elkaar kan rijgen tot c4 of c5 i.e. synthetische benzine. Dit zou je ook kunnen gebruiken om rubber polymeren te maken. Je hebt nu daarnaast nu steeds meer aardgas installaties o.a. in het midden oosten. Veel gaat verloren aan energie o.a. door afbrand gas. Het is mogelijk om het gedeeltelijk te verbranden om er ethanol van te maken. Hier is nog wel wat te halen want als je het verstoekt ben je het gewoon kwijt. Dus er zijn zeker mogelijkheden om dit te doen maar ik kan nu niet zeggen dat het op grote schaal gebeurt. Het

gaat natuurlijk ook om de centen want het is hartstikke duur dus voorlopig is het niet echt rendabel om rubber echt van wat anders te maken.

- **Wat is de invloed van temperatuur op de-vulkanisatie/reclaim proces en is een lagere temperatuur beter?**

Het is beter om een zo laag mogelijke temperatuur te houden om het materiaal te kunnen beschermen. Echter, de koolstof tot koolstof verbindingen zijn ongeveer 1000 maal zo veel voorkomend in de rubber als de zwavel verbindingen. Je kunt dus een berekening maken met hoeveel crosslink points je kan breken maar de kans dat je een zwavel verbinding breekt is 1000 maal kleiner dan een koolstof verbinding. Het is dus heel moeilijk om het gescheiden te houden. Tuurlijk kan je voornamelijk de zwavel verbindingen breken maar er zullen ook koolstof verbindingen gebroken worden, dit is een kans berekening. Dit is inherent aan rubber recycling want als je met een groot kanon op rubber schiet dan ga je ook andere verbindingen raken. Het is dus niet alleen een puur energetisch verhaal maar er zit dus ook een kans berekening aan vast. Het streven is natuurlijk wel het breken van alleen de zwavel banden maar dan moet je dus heel voorzichtig gaan manoeuvreren om de rubber niet te beschadigen. De HDA maakt de bruggen wat soepeler zodat we hopelijk meer op de zwavel verbindingen breken maar het zal er altijd ergens tussen in zitten.

- **Zijn de ultra sound en micro-wave pyrolyse methods?**

Ik ben het wel eens met Kuno dat de Ultra-sound en Micro-wave meer naar pyrolyse gaan en dat de chemische en mechanische meer bij de de-vulkanisatie in de buur komen. De temperatuur wordt zo hoog dat het de kwaliteit van de reclaim aantast. Ik verwacht dat de kwaliteit van deze reclaim minder is tot het tegendeel bewezen wordt natuurlijk. Er zijn nog geen voorbeelden van buiten experimentele settings waar het gelukt is. Er liggen nog geen dakbedekkingen met ultra sound reclaim ergens op een dak. Het is eigenlijk de rubber gigantisch hard opstoken en dan is het moeilijk te bepalen wat er gaat branden. Je zult de goede balans moeten vinden tussen het plastisch maken van de rubber door de crosslinking point te verbreken en intact houden van het materiaal.

- **Is er ook een nadeel aan een lagere temperatuur?**

Dat weet ik niet precies. Wat wel zo is, rubber is vaak erg smerig met bijv. mos en modder en kan stoffen hebben opgenomen. Je moet het dus wassen voordat je het gaat reclaimen. Wil je dit weer eerst helemaal droog maken voordat je gaat reclaimen moet je er weer extra energie in stoppen. Dit kost allemaal geld maar het kan zijn dat als je een te lage temperatuur hebt er meer rommel in je rubber terecht komt.

- **Merkt U ook dat het de rubber producenten conservatief zijn?**

Ja, ik ben al jaren bezig met het onderzoek maar voorlopig zit er nog niet veel schot in de zaak. Ik ben het eens met Kuno dat er nog niet veel goede reclaim technieken zijn. Voor EPDM zijn we een redelijk eind maar de kwaliteit van andere reclaim is nog niet over naar huis te schrijven. Daarnaast

werkt het ook alleen als je een grote eenduidige hoeveelheid hebt zoals dak bedekking. In andere EPDM markten is het momenteel haast niet te doen om het te gaan recyclen.

Henk van Ekkenbrug: DX polymers

- **Is het nodig om het rubber afval te shredden voordat het gerecycled kan worden?**

Uit kwaliteit overwegingen is het vaak standaard voor de meeste rubber om het te shredden voordat het gerecycled kan worden en in ons geval mag dat ook door iemand anders gebeuren. Het is echter wel belangrijk dat het afval schoon is. Als er bijvoorbeeld een koffie bekertje tussen zit als het materiaal geshredded wordt dan is het moeilijk dit er later weer uit te halen. Je moet zien te voorkomen dat er andere materialen zoals plastic tussen het afval terecht komen. In sommige gevallen bijvoorbeeld sealings van autoramen kan het direct in de machine worden gedaan. Het formaat van dit afval is dus dusdanig klein dat het niet geshredded hoeft te worden. Bij de productie van deze strips wordt veel afval geproduceerd omdat in de eerste paar minuten de machine nog niet op de juiste temperatuur is. Dit creëert veel afval wat via onze machine kan worden gerecycled en kan worden gebruikt voor een nieuw productie proces. Je krijgt nu steeds meer dat producenten kleine voorraden aanhouden en daarnaast zijn er veel verschillende auto modellen op de markt. De maten voor de sealing kunnen verschillen waardoor steeds een nieuw productie proces gestart moet worden en hoe vaker je wisselt van profiel hoe meer afval je hebt.

- **Hoe werkt het DXP reclaim proces?**

Wij hebben een continu proces wat plaats vind in een machine wat vergelijkbaar is met een extruder. In onze machine zit een schroef met een speciale vorm waardoor de juiste energie op het materiaal uit wordt geoefend zodat de crosslinking points breken. Het is een 100% mechanisch proces en wat heel belangrijk is dat het materiaal niet warmer wordt dan 90C graden. Dit betekent dat je minder energie nodig hebt maar vooral ook dat de kwaliteit van het materiaal beter behouden blijft. Onze feedstock mag daarnaast vrij grof zijn. Het rubber wordt vloeibaar in de machine omdat de stress de crosslinkingpoint breekt. Er ontstaat er een flow aan gerecycled materiaal wat als een lange sliet uit de machine komt. Het eindproduct is te vergelijken met een soort pasta. De persoon die deze technologie heeft ontwikkeld is een van de weinige mensen op de wereld die precies kan vertellen hoe een extruder werkt. De kwaliteit van het product is veel belovend en omdat het een mechanisch proces is werkt het vrijwel op alle soorten rubbers. Daarnaast werkt het ook op andere crosslinking systemen dan zwavel en bijv. de carbonblack inhoud maakt niet zoveel. Het zal alleen wel meer energie kosten om sterkere materialen te recyclen.

- **Wat zou het voor de DX polymeer techniek makkelijker maken om rubber compounds te kunnen recyclen?**

Het is belangrijk dat het materiaal zoveel mogelijk homogeen is, dat wil zeggen bestaande uit 1 soort rubber compound. Opzich kunnen wij wel een rubber bestaande uit verschillende compounds recyclen alleen het probleem is dat ze gaan mengen en je dus eigenlijk een nieuwe compound krijgt.

Een auto band is bijvoorbeeld gemaakt uit verschillende soorten rubber. Het loopvlak mag niet slijten en is dus erg stug. De zijvlakken moeten juist meer trek kracht kunnen weerstaan en flexibel zijn. Het zal moeilijk worden dit uit hetzelfde materialen te maken. Wat ook een probleem is zoals bij bijvoorbeeld koeien matten is dat ze worden aangetast worden aangetast door mest, chemicaliën en ozon. Je weet niet precies hoe het materiaal hier op gaat reageren. In zijn algemeenheid is de zuiverheid van het materiaal het belangrijkste. Als het een schoon en homogeen product is dan word recyclen makkelijker. Als het bijv. aan karton of staal zit dan hangt het van de applicatie af of het kan worden gebruikt. Voor sommige klanten zou een lichte vervuiling acceptabel kunnen zijn. Over het algemeen vind ik wel dat het ontwerp aspect van producten wordt ondergewaardeerd.

- **Zijn er andere grondstoffen mogelijk voor rubber naast olie?**

In principe zouden ook andere fossiele grondstoffen zoals gas of kolen omgezet kunnen worden in een rubber polymeer. Het voordeel van olie is dat het beschikbaar is wanneer jij dat wil en daarnaast levert het een prima polymeer op. De natuurlijk rubber boom komt alleen voor in vochtige en warme gebieden maar is bijna uitgeroeid in Brazilië waar die vandaan kwam. Er zijn nu een paar landen in zuid oost azie die in bijna alle natuurlijke rubbers voorzien. De boom heeft last van ziektes, droogte en natuurrampen waardoor de levering in gevaar kan komen. Rubber is ook een strategische grondstof dus het gebruik van alternatieven grondstoffen zoals olie is belangrijk. Je zou het ook kunnen winnen uit andere grondstoffen zoals de Russische paarden bloem. Het witte spul wat daar in zit is een soort latex en kan ook gebruikt worden voor rubber productie. Dit kan ook worden verbouwd in noordelijke klimaten en er zijn meer planten die het kunnen. Het is daarnaast niet alleen de olie maar ook de verwerking capaciteit die belangrijk is. Je moet een fabriek hebben die olie of een andere grondstof om kan zetten in een polymeer. De beperkte capaciteit is een limiterende factor voor elke alternatieve bronnen. Er is op zich nog genoeg olie om de rubber markt nog jaren van grondstoffen te voorzien. Er zit nog genoeg olie in de grond alleen op veel plaatsen is het te duur om energie mee te winnen. De olie zou daar theoretisch nog wel gewonnen kunnen worden mocht het nodig zijn voor rubber productie.

- **Is het altijd mogelijk om rubber te recyclen bij ook na 20 jaar?**

Rubber is van zich zelf redelijk inert maar omgevingsfactoren zoals bijv. ultraviolet straling hebben een impact het materiaal. Hierdoor kan rubber gaan verbrossen zoals bij bijvoorbeeld de rubber ringetjes in een kraan die onder invloed van kalk hard worden. Dit gaat echter om kleine hoeveelheden dus het zal veel energie kosten om dit in te zamelen. En dan moet je ook maar hopen dat het hetzelfde rubber is want met verschillende meningen krijg je een ander product, nieuw product. Dit kan voor bijvoorbeeld bad slipper geen probleem zijn maar wij mikken niet op de down-cycling van producten. Op die manier zit er altijd een einde aan de kringloop terwijl wij graag materialen echt willen recyclen zodat het in dezelfde toepassing weer gebruikt kan worden. Het is natuurlijk zo dat het meeste rubber uiteindelijk wel verbrand wordt om energie mee terug te winnen maar dit moet je zo lang mogelijk zien uit te stellen.

- **Hoe vaak zou het rubber gerecycled kunnen worden?**

Het is nog niet precies bekend hoe vaak je rubber kan recyclen maar we weten wel dat als je onder de 30% blijft dat het geen issue is. Er wordt dan uiteindelijk zo kleine fractie ge re-reclaimed dat het niet merkbaar is. De meest bedrijven willen waarschijnlijk toch niet meer innemen dan hun eigen productie afval. Dit zo genoemd schoon afval is compleet bekend in de samenstelling. Dat afval zamelen we in om te recyclen maar we voegen niets extra toe. Het zal afhangen van de applicatie van het materiaal en van de wetgeving of het op een bepaalde markt werkt. Sommige bedrijven worden door wetgeving gedwongen om hun recycling ratio omhoog te brengen e.g. de auto industrie. Bij andere bedrijven zoals bijv. gas maskers is het anders. Deze producten hebben een hoge marge en gezien het om leven of dood kan gaan is de kwaliteit zeer belangrijk. De kwaliteitseisen van het product zijn zo hoog dat ze niet snel gerecycled materiaal zullen gaan gebruiken.

- **In welke markt kan de technologie worde opgeschaald?**

De markten waar wij als eerste op mikken zijn die van EPDM en NR want hier is veel van te krijgen. Het is daarnaast een zacht materiaal en zeer geschikt voor onze reclaim technologie. EPDM wordt naast dak bedekking ook gebruikt in bijvoorbeeld de rubber van de ramen in auto's. Bijna alle afdichting tegen water van zoals bijv. buizen en pijpen onder de grond zijn van EPDM. De markt leider van dit product heeft ongeveer 8000 ton afval per jaar. EPDM is dus een heel interessante markt. SBR is daarnaast ook een grote markt. Dit wordt vooral gebruikt in auto banden en het zou mogelijk zijn om het loop vlak er af te halen. Echter, dit is maar klein deel van het gewicht van de band. Een band zou eventueel ook in 1 keer in onze machine kunnen alleen dan heb je een ongedefinieerd product. Gezien de industrie moet gaan recyclen zou het best een interessante markt kunnen zijn. Je zou kunnen kijken of je er geen ander product van kan maken. Het is wel zo dat wij ons zelf aan prijzen als een grondstof leverancier en niet als een end of pipe solution. Recycling wordt toch nog vaak gezien als kosten besparing maar wij willen uitgaan van de waarde van het product. Ons product heeft dezelfde eigenschappen als virgin materiaal en is dus een grondstof. We gaan daarom iets onder de markt prijs van de virgin grondstoffen zitten om een kostenvoordeel te kunnen leveren met dezelfde kwaliteit materialen. Veel autobanden worden nu op industriële schaal verwerkt naar bijvoorbeeld een laag onder een sport veld of ze worden verbrand in de cement industrie. Ons bedrijf richt zicht niet op laagwaardige verwerking van rubber afval maar deze manier van recycling wordt wel gestimuleerd door de wetgeving. Om het hergebruik te stimuleren is er een picking fee van 2 euro 50 per band om het materiaal te kunnen hergebruiken. Dit is dus een alternatief voor onze technologie maar mocht die fee nog verdwijnen dan word echt recyclen interessanter. Wij hebben hogere kosten om het afval per kilo te verwerken omdat het allemaal schoon moet zijn en netjes ingepakt moet worden om het terug te kunnen sturen naar de klant.

- **Wat is de status van technologie?**

Wij staan aan het begin van de ontwikkeling van onze technologie. We zijn begonnen met een kleine machine die we daarna een factor 10 groter gemaakt hebben. We hebben de machine groter gemaakt maar ook simpeler zodat het makkelijker is om er testen mee uit te voeren. We kunnen zo beter

meten en zien wat elke stap doet maar versimpelde machine heeft een wat slechtere koel capaciteit. De machine maakt gebruik van een ingewikkelde geometrie om beheersbaar en simpel proces te maken. De machine zou door iedereen bediend kunnen worden en we zijn ook zeer bezorgd dat iemand de machine na maakt zonder dat we er iets aan kunnen doen. Als de machine ergens in Azië nageemaakt wordt is het bijna onmogelijk daar nog iets aan te doen. Daarom houden wij de technologie erg tegen de borst en laten de klanten het eind product zien maar niet de machine. De markt heeft een grote potentie er is ongeveer 3 miljard ton rubber afval per jaar in de wereld. Het zal met kleine stapjes beginnen want iedereen is sceptisch. Als de technologie is opgeschaald en het heeft zich bewezen dan kan het gaan beginnen te lopen.

- **Zijn er concurrenten op de markt?**

Er is een concurrent die dezelfde kwaliteit kan leveren maar hij maakt gebruik van een batch proces. De investering is hetzelfde maar hij kan 100 kilo per uur verwerken en wij 1000 kilo per uur. Het energie gebruik is hetzelfde maar wij hebben meer kilo's per uur dus per kilo is het een factor 10 minder. Het batch proces, een grote kuip rubber malen, is erg energie intensief. Wij gebruiken alleen de energie daar waar het nodig is. Het is ook moeilijk om de batch technologie op te schalen omdat je een steeds grotere kuip nodig zult hebben waardoor het erg arbeidsintensief wordt. De mechanische reclaim die ontwikkeld is in Japan werkt met een extruder waarbij een hogere temperatuur wordt bereikt. Er moet meestal olie bij toe worden gevoegd om het materiaal soepel te houden. Rubber is een materiaal wat erg snel opwarmt maar de vraag is hoe ga je de temperatuur beheersen. De technologie heeft een minder constante kwaliteit en een extruder is duur. Er zijn partijen geïnteresseerd in onze technologie omdat we een goede prijs en kwaliteit kunnen leveren. Ons business model is interessant voor bedrijven omdat ze zelf geen investeringen hoeven te doen. Als je zelf een extruder koopt dan ben je zo meer als een miljoen euro kwijt en dan ga je niet opeens weer wat anders proberen. Als een klant onze service niet van de juiste kwaliteit vindt dan kan de klant wat anders proberen of alsnog een grotere investering doen, een veel lager risico dus. Het is alleen nog niet duidelijk in hoeverre onze technologie opgeschaald kan worden hierdoor zijn investeerders terughoudender.

We hebben ook monsters gezien van ultra-sound gerecycled materiaal. Er was onvoldoende energie in het materiaal gekomen waardoor de kwaliteit niet heel goed was. De ultra-sound technologie bestaat al 15 jaar en wij zijn nog maar net bezig. Hoewel het proces werkt waarom is het dan nog niet veel toegepast? Het blijft kennelijk toch moeilijk om het proces stabiel te houden. Daarnaast reageren materialen verschillend op de ultra-sound waardoor het moeilijker is de juiste hoeveelheid energie toe te passen. Bij onze technologie zijn die eisen wat minder stikt omdat we gebruik maken van een mechanisch proces.

Bart Smit: Hertalan B.v.

- **Ik heb een paar onderzoeken gelezen over experimenten die jullie hebben uitgevoerd met een reclaim methode, zou je hier wat meer over kunnen vertellen?**

Dat is van voor mijn tijd en toen werkte ik hier nog niet en daar ben ik ook niet bij betrokken geweest. Wat ik wel kan vertellen is dat we gebruikt maakte van een chemisch reclaim proces en dit vonden wij toch wel een probleem. Dit wilden we niet in het eind product terug hebben en daarnaast, wat is dan nog het idee van recyclen? Als je allemaal extra chemicaliën moet gaan toevoegen. Dit wilden wij niet en daarnaast was de technologie commercieel en productie technische niet beschikbaar. We hebben nu een techniek waar het zonder chemicaliën kan en dat zijn we nu verder aan het onderzoeken.

- **Zou je iets kunnen vertellen over de plannen die jullie hebben voor recycling?**

Ik kan hier niet te veel over kwijt gezien wij zelf ook nog midden in het onderzoek zitten. De planning is om het materiaal wat wij hier als bedrijfsafval hebben, het schone afval, te gaan hergebruiken. Het idee is om dit weer als volwaardige grondstof in te kunnen zetten. Je vervangt hiermee dus een deel van de olie grondstoffen die nodig zijn voor de productie van EPDM. De vulkanisatie stoffen etc. zul je wel opnieuw moeten toevoegen. Je weet bij het schone afval precies waar het materiaal van gemaakt is dus het is makkelijker opnieuw te gebruiken. We maken verschillende soorten compounds maar de sheets bestaan wel allemaal uit dezelfde soort rubber, het is een homogeen product. Omdat de dakbedekking niet uit verschillende lagen rubber is gemaakt kan het materiaal makkelijker gerecycled worden.

- **Hoe heeft de wetgeving invloed gehad op de bedrijf voering bijv. het Reach directive en wat verwacht u van de toekomstige wetgeving?**

Het REACH directive is zeker belangrijk en mijn collega houdt zich daar ook mee bezig. Dat zal ook allemaal uitgezocht moeten worden. Je maakt eigenlijk een nieuwe stof door het materiaal te recyclen dus hier zouden gevolgen voor kunnen zijn onder het Reach directive. We hebben niet gemerkt dat er stoffen die wij gebruiken van de markt zijn verdwenen. Je merkt wel dat sommige bedrijven stoffen niet meer leveren vanwege het Reach directieve.

- **Is het mogelijk om de kwaliteit van het materiaal te behouden zelfs nadat het al vele jaren gebruikt is?**

Wij kijken voorlopig alleen nog maar naar het recyclen van materialen binnenshuis. Een volgende stap is het recyclen van gebruikte dak bedekkingen. Het probleem hierbij is alleen de ernstige vervuiling die in de rubber terecht komt tijdens het gebruik. Het zit vaak aan het dak vast gelijmd dus je krijgt oa. lijm resten in het afval. Je moet het dan dus gaan schoon maken maar hier zijn we op het moment nog niet mee bezig. Wat natuurlijk wel veel gebeurt is dat mensen het inzamelen en

voor andere doeleinden gebruiken. We beginnen met ons productie afval te verwerken en als dat goed werkt dan kunnen we gaan kijken of we meer kunnen gaan recycleren.

- **Wat zijn de belangrijkste barrières voor de verhoging van het recycling percentage in de rubberindustrie?**

We gaan dus in eerste instantie ons eigen afval recyclen maar we hebben ook gekeken naar EPDM van 40 jaar gelden en wat je daar mee kunt doen. We hebben nog geen testen gedaan maar als we een machine hebben kunnen we dat gaan proberen. Echter, het proces van inzamelen, schoonmaken en scheiden van het afval moet nog ontwikkeld worden en daarnaast is er nog weinig bekend over de kwaliteit van dit materiaal. Over de tijd breken de moleculen langzaam af onder invloed van UV straling maar dit doe je eigenlijk ook in een recycling proces. Als je het weer vulkaniseert en de ketens weer aan elkaar verbind dan zou het weer zijn sterke terug kunnen krijgen. Wij hebben hier alleen dus nog geen testen mee gedaan en momenteel weten we eigenlijk niet wat de invloed van veroudering is op het materiaal.

- **Is het mogelijk om naast rubber andere grondstoffen te gebruiken voor het productie proces?**

Nou, het produceren van natuurlijk rubber is niet heel milieu vriendelijk en daarnaast kan er nooit genoeg worden gemaakt om aan de vraag te kunnen voorzien. Het zou mogelijk kunnen zijn om iut andere bronnen een natuurlijk polymeer te ontwikkelen maar dit is nog steeds een natuurlijk polymeer. De eigenschappen van dit product zijn niet het zelfde als van synthetische EPDM zodoende is het geen goed alternatief voor ons product. Het zal waarschijnlijk nog lang duren voordat er een goed alternatief komt voor een rubber polymeer gemaakt van olie.

- **Hoe zou U de ontwikkelingen van recycling technologieën voor rubber over de laatste jaren willen duiden?**

De extra interesse in recycling heeft vooral met een economische achtergrond te maken. De laatste jaren zijn de prijzen van de grondstoffen erg toegenomen. Ze zijn schaarser geworden en heel veel duurder. Dan wordt het dus interessanter om naar recycling technieken te kijken om grondstoffen losten uit te sparen. International concurrentie hebben wij nog niet zo heel veel last van in de EPDM markt. De markt voor onze producten is nog steeds groeiende in west Europa dus hier maken wij ons niet veel zorgen over.

- **Hoe vaak zou rubber terug gewonnen kunnen worden?**

Dit weten we niet maar ons product ligt natuurlijk lang op het dak dus het zal waarschijnlijk geen groot probleem zijn bij ons productie proces zijn. Het zal namelijk lang duren voordat het product weer in de kringloop komt.

- **Merken jullie dat het makkelijker wordt om het product te verwerken als er gerclaimed rubber wordt gebruikt?**

Daar hebben we nog niet genoeg gegevens voor om dat vast te stellen maar wij denken dat het vergelijkbaar is.

Albert Luiten: Dunlop Conveyor Belting

- **Wat zijn de belangrijkste barrières voor de verhoging van het recycling percentage in de rubberindustrie?**

Allereest zijn er twee soorten afval te onderscheiden; ongevulkaniseerd en gevulkaniseerd afval. Het gevulkaniseerde afval moet eerst via een shredder worden vermalen om het te kunnen recycelen. De ongevulkaniseerde rubber wat ontstaat tijdens ons productie proces kan niet in een shredder vermengd worden omdat het materiaal nog te stroperig is. Het is ook vaak niet mogelijk om dit afval zo maar terug te mengen in een nieuwe compound omdat het meestal voor een rede is afgekeurd.

Een ander probleem met zowel het afval binnen ons productie proces als het recycelen van al gebruikte producten is dat het moeilijk is de verschillende lagen in de transport banden uit elkaar te halen. In ons product zitten verschillende lagen rubber op elkaar geperst met een vezel membraam in de band om er meer sterkte aan te geven. Er zitten dus verschillende compounds en vezels dicht op elkaar gepakt en het is moeilijk om deze weer te scheiden van elkaar. Daarnaast maken we binnen ons bedrijf gebruik van chemisch gereclameerd rubber. Deze rubber is wat zachter en is goed geschikt voor bepaalde doeleinden. Ik kan je niet vertellen in welke verhoudingen we dit in mengen maar ik kan wel zeggen dat de kwaliteit van dit product duidelijk minder is. Het kan niet de trekkracht aan die Virgin materialen wel kunnen hebben. De kwaliteit van het gerecyclede product is een probleem voor het inpassen van een recycling techniek.

Het recycelen van een end producten zijn we wel aan het onderzoeken. We denken na over het Cradle to Cradle principe en zijn aan het kijken of dit ook in ons productie proces kan worden toegepast. Een bijkomend probleem van het recycelen van al gebruikte transportbanden is wel dat ze bij een levensduur van bijv. 10 jaar in aanraking komen met verschillende stoffen. Vooral bij industriële doeleinden vallen er tijden de levensduur van een transportband geregeld bijv. Olie of chemicaliën op de band. Deze stoffen trekken in het materiaal en kunnen schadelijk zijn maar daarnaast kan de kwaliteit van het gerecyclede materiaal ook negatief beïnvloed worden. We zijn de mogelijkheden aan het onderzoeken maar we hebben nog geen beslissingen genomen.

- **Hoe belangrijk is de olie prijs voor U?**

De prijs van olie is natuurlijk erg belangrijk voor rubber producenten. Bijna al onze grondstoffen komen van olie en daarnaast is de bedrijfsvoering redelijk energie intensief. Als de prijs van olie stijgt dan merken wij dat direct bij de aankoop van onze grondstoffen en later in het jaar ook op de energie rekening. Dit is ook een belangrijke rede voor ons om te kijken of we meer kunnen gaan recycelen. Daarnaast zijn wij ons er van bewust dat olie een niet hernieuwbare grondstof is en dat het dus vroeg of laat op zal zijn. We zullen om de continuïteit van ons bedrijf te kunnen garanderen opzoek moeten gaan naar alternatieven voor onze grondstoffen.

- **Is het mogelijk om rubber van alternatieve grondstoffen te maken?**

Het gebruik van alternatieve grondstoffen voor een rubber polymeer wordt op meerder fronten onderzocht. Ik weet hier niet het fijne van maar ik geloof dat de DSM aan het kijken is of van suiker riet een goede rubber polymeer gemaakt kan worden. Opzich vinden wij dit een interessante ontwikkeling en zullen wij hier serieus naar kijken mochten er alternatieve grondstoffen op de markt komen. Het is alleen wel zo dat olie niet alleen gebruikt wordt omdat het relatief voordelig is maar ook omdat het een hele goede polymeer oplevert. Een nieuwe grondstof moet wel aan onze eisen kunnen voldoen om het te kunnen toepassen in ons productie proces. Het is voor ons erg belangrijk dat we de kwaliteit van ons product kunnen blijven garanderen.

- **Wat zijn U verwachting voor de rubber markt voor de komende vijf jaar?**

Er is al een hoop veranderd in de rubber markt over de laatste 20 jaar. Allereerst is de internationale concurrentie sterk toegenomen. 20 jaar geleden was de prijs van ons product minder belangrijk als nu. Door meer concurrentie uit opkomende economieën is het veel belangrijker geworden om de producten zo goedkoop mogelijk aan te bieden. Daarnaast is er een duidelijke trend in het verscherpen van de regulatie vanuit Europa en het rijk. Zo is er bijvoorbeeld het REECH European directieve. Dit is gaat over het reguleren van alle chemische stoffen die in de industrie gebruikt worden. De rubber industrie maakt veel gebruik van chemische stoffen en er zijn door de regelgeving al meerde stoffen van de markt verdwenen die gebruikt werden voor onze producten. Dit dwingt ons tot het zoeken naar alternatieven voor deze chemicaliën. Er zullen in de toekomst misschien meer stoffen van de markt gehaald worden dus het is zeer belangrijk voor ons om de wetgeving in de gaten te houden.

- **Is het mogelijk om het product ontwerp aan te passen om het recyclen van rubber te vergemakkelijken?**

Wij zijn niet direct aan het kijken of we ons product moeten aanpassen om het recyclen te vergemakkelijken. De eerste optie die we onderzoeken is het hergebruiken van bestaande transportbanden. Het zal erg moeilijk worden om het ontwerp van het product aan te passen. Zo is het niet mogelijke om bijvoorbeeld 1 soort rubber te gebruiken gezien het dan onmogelijk is om nog aan alle kwaliteitseisen te voldoen. Het gebruik van industrieel afval en de mogelijkheden om al bestaande transport banden her te gebruiken is onze eerste optie.