Tampereen yliopisto

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TIRE RECYCLING CONCEPT

Reducing tire and tire plant carbon emissions by recycling

Master of Science Thesis
Faculty of Engineering and Natural Sciences
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ABSTRACT

Mikko Siren: Tire Recycling Concept
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A significant number of end-of-life tires are accumulated annually. A suitable recycling concept is therefore required to process these tires. Currently, methods to process end-of-life tires are landfill, energy recovery, and recycling. Landfill and energy recovery methods do not recover any of the materials and thus recycling is considered a better option for processing end-of-life tires.

Different recycling technologies were evaluated in this study for creating a scalable recycling concept for a tire plant, by identifying their characteristics and possible side streams. Characteristics were evaluated by public data and more details were acquired from suppliers by interviews. Finally, technologies were compared using an analytical hierarchy process. Factors used to evaluate the technologies were investment costs, profitability, feasibility, and GHG reduction. Surveys and interviews were used to identify costs relating to the recycling process. Collection costs were collected from end-of-life management organizations using survey research. Operating and investment costs, where acquired by interviewing suppliers. Feasibility was analyzed according to the rate of plant waste that compared technologies could handle. GHG reduction was analyzed by calculating carbon footprint for each case according to the ISO 14067 standard.

According to the analysis, characteristics of the recycling technologies vary and thus identifying feasibility according to the use case is important. The analysis identified that devulcanization technology can replace larger quantities of raw material and at the same time has a higher potential in reducing the carbon footprint. Pyrolysis was also identified to be profitable but had a smaller carbon footprint reduction potential. However, pyrolysis was seen a more feasible option than devulcanization since it can process all the rubber waste generated during tire manufacturing. Thus, embedding a recycling facility in the tire plant is reasonable.

Keywords: Recycling, Pyrolysis, Devulcanization, Tire, Tire Plant

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TIIVISTELMÄ

Mikko Siren: Renkaiden kierrätyskonsepti
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Vuotuisesti kertyy huomattava määrä käytettyjä renkaita. Käytettyjä renkaita varten tulisi siis olla soveltuva kierrätyskonsepti. Tällä hetkellä käytetyt renkaat käsitellään, joko kaatopaikoille, energiaksi tai kierrätetään. Kaatopaikka ja energian talteenotto eivät palauta renkaiden materiaaleja uusiokäyttöön, joten kierrättäminen on nähty parempana ratkaisuna.

Erilaisia kierrätystekniikoita arviotiin tässä tutkimuksessa skaalautuvaa kierrätyskonseptia varten, tunnistamalla eri teknologioiden ominaisuudet ja mahdolliset sivuvirrat. Ominaisuuksia arvioitiin julkisten lähteiden avulla ja tarkempaa tietoa hankittiin toimittajilta haastatteluiden avulla. Teknologioita vertailtiin hyödyntämällä analyyttista hierarkiaprosessia. Vertailuarvoja, joita hyödynnettiin teknologioiden vertailuissa, olivat investointikulut, tuottavuus, soveltuvuus ja hiilidioksidipäästöjen vähennys. Kierrätykseen liittyviä kuluja tunnistettiin kyselyiden ja haastatteluiden avulla. Kyselytutkimuksen avulla selvitettiin keräykseen liittyviä kuluja, käytettyjen renkaiden vastaanotto-organisaatiolta. Haastattelemalla teknologioiden toimittajia selvitettiin investoinnista ja operoinnista syntyvät kulut. Soveltuvuutta arvioitiin tehdasjätteen käsittelymahdollisuuksien mukaan. Hiilidioksidipäästöjen vähennystä arvioitiin laskemalla jokaisen tapauksen hiilijalanjälki ISO 14067 standardin mukaan.

Analyysien pohjalta voidaan todeta, että eri kierrätysteknologien ominaisuudet eroavat, joten niiden soveltuvuutta tulisi arvioida käyttökohteen mukaan. Analyysit tunnistivat, että devulkanointiteknologia pystyy vähentää enemmän raaka-aineiden hankintaa ja hiilidioksidipäästöjä. Pyrolyysi tunnistettiin myös taloudellisesti kannattavaksi teknologiaksi, mutta hiilidioksidin vähennyspotentiaali oli pienempi. Pyrolyysi nähtiin kuitenkin kannattavampana vaihtoehtona kuin devulkanointi, koska sillä pystytään käsittelemään kaikki tehtaalla syntyneet jätteet. Tämän takia on järkevää sijoittaa laitos rengas tehtaan yhteyteen.

Avainsanat: Kierrätys, Pyrolyysi, Devulkanointi, Rengas, Rengastehdas.

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

FOREWORD

This thesis is responding to the rising interest in recycling and environmentally sound tire manufacturing from the industry. Since I share the industry's growing interest this thesis was a great fit for me. I am relieved that despite the delay in a third-party organization I was able to make continuous progress by changing the angle of the thesis. Due to angle change the end results were even better in my opinion, identifying a wider view of recycling possibilities.

First, I would like to thank Martti for providing me this interesting opportunity. Also, I would like to thank Jarkko and Eeva for their great support and for sharing their knowledge during the process. Not forgetting support from Tampere University, especially my examiners Hasse and Tero for the guidance.

Finally, I would like to express my gratitude to my family and friends who have been listening to some wailing and stress releasing during my thesis and studies in general. I would like to thank my friends also for all those sauna evenings or activities at Pellinki or on S/Y Sylvie just to name a few.

Tampere, 22.12.2020

Mikko Siren

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LIST OF SYMBOLS AND ABBREVIATIONS

AD	Annual Demand
AHP	Analytical Hierarchy Process
ASTM	American Society for Testing and Materials
AW	Annual Waste
BR	Butyl Rubber
BSI	British Standards Institution
CB	Carbon Black
CF	Carbon Footprint
EOLT	End-of-Life Tire
EPR	Extended Producer Responsibility
ETRMA	European tyre & rubber manufacturers association
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
IW	Incineration of Waste
JATMA	Japan Automobile Tyre Manufactures Association
JEMAI	Japan Environmental Management Association for Industry
LCA	Life Cycle Assessment
LCP	Large Combustion Plant
NR	Natural Rubber
NS	Number of Shifts
OD	Operating Days
OW	On Waste
PC	Plant Capacity
rCB	Recovered Carbon Black
RSS	Ripped Smoked Sheets
SBR	Styrene-Butadiene Rubber
SMR	Standard Malaysian Rubber
TDP	Tire Delivered Polymer
TSR	Technically Specified Rubber
TIP	Tire Industry Project
WBCSD	World Business Council for Sustainable Development
WR	Waste Rate
WRI	World Resources Institute

1. INTRODUCTION

Environmentally friendly business is considered as a future megatrend and demand for development towards environmentally friendly process is increasing. The motive of this study is to identify the impacts of tire recycling on tire and tire plant emissions. Recycling technologies can be divided into mechanical and thermodynamic technologies. The most typical recycling methods today are ground tire rubber and energy recovery. Ground tire rubber recycling utilizes rubber granulates in new products such as playground safety mats or football fields. The scope of this study is the reuse of reclaimed material in the tire and other recycling methods are excluded. Utilizing reclaimed material in tire manufacturing reduces the number of raw materials required, and thus enhances environmentally friendly business.

The first part of the paper is theoretical background research where characteristics and volumes of used tires and different management systems for used tires are identified. The tire manufacturing process is evaluated to identify waste streams and tire structure. After identifying the different waste streams possible, recycling technologies are studied. Recycling technologies are preferred to separate materials for reuse than to recover energy from materials. By reusing tire materials need for oil-based rubber can be reduced.

After identifying available recycling technologies, suitable technologies are chosen for a further case study where their qualitative and quantitative properties are studied. Qualitative properties are studied to identify the basic characteristics of recycling technologies. Quantitative studies focus on a comparison of the recycling technologies. Quantitative measures that are used in the comparison are monetary, material, and environment related.

Research questions that are studied are listed below:

RQ1 How tire plant waste and end-of-life tires can be reused?

RQ2 What are the characteristics and side streams of different recycling technologies?

RQ3 What are the economic and environmental impacts of recycling tire plant waste and end-of-life tires?

RQ1 and RQ2 can be answered simply by theoretical study and additionally by open-source internet research for identifying the commercial availability of different technologies. For RQ3, a more detailed empirical study is required. To answer economic impacts from recycling plant waste and end-of-life tires, monetary factors should be identified. Possible end-of-life tire costs, were studied using survey research, send to collecting organizations. Operating costs were estimated using the information provided by the recycling technology suppliers. To answer the environmental impacts of recycling the carbon footprint of the recycling were calculated and finally compared with normal situation.

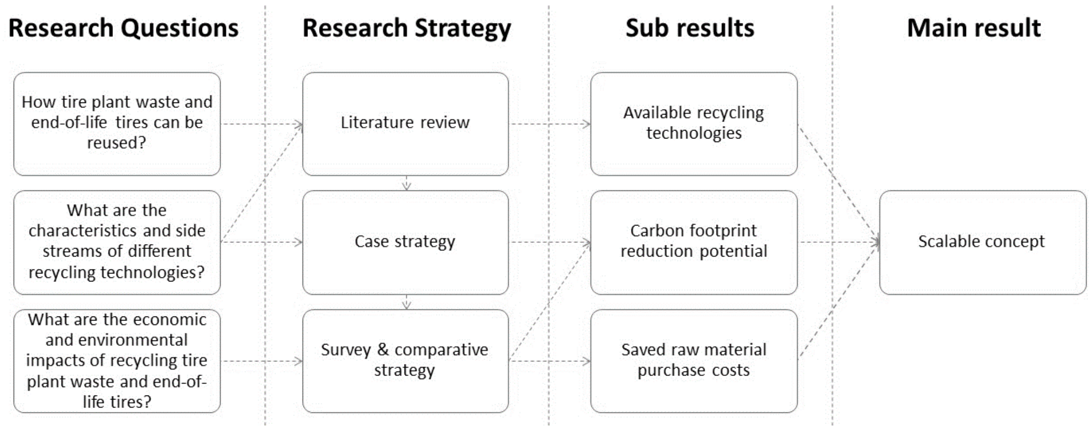

Figure 1. Research structure

Structure of research is presented in figure 1. From literature review possible recycling technologies are identified, characteristics and side streams are analyzed in more depth using case research strategy. Survey strategy is used to identify possible expenses relating to end-of-life tires. Economic and environmental impacts are analyzed by comparing the results to a normal tire plant.

Results from this paper are used to formulate the concept of a scalable recycling facility. A novelty in this study lies in the recycling facility location as the concept is planned to locate to the tire plant premises embedding it to the tire plant. Embedding recycling facility to the tire plant the amount of waste created outside the plant can be reduced or eliminated completely as the plant can handle the waste it generates. The aim of the concept is to enhance more environmentally friendly business and hence should be environmentally and economically viable.

2. THEORY

In this chapter theory behind material flow is presented consisting of tire structure, manufacturing, manufacturing waste, and used tires. How much used tires are generated, how they are collected, and recycling technologies of tires are discussed. The goal of the theory part is to present what is researched relating to the topic of this paper. After theory, material flows, and recycling technologies should be identified. End-of-life tires (EOLT) are commonly used as fuel in cement kilns or other energy recovery options mainly because tires have higher heating values than coal (Miranda et al. 2013; Williams 2013; Martínez, Murillo et al. 2013).

2.1 Material flow

Two main material flows have been identified for this paper i.e. end-of-life tires and factory waste. Factory waste can be divided into vulcanized and unvulcanized rubber. Before vulcanization rubber can be reused depending on the mixing state.

2.1.1 Tire Structure

Tire structure consists of eight key components as presented in figure 2. Components are in numerical order: inner liner, radial body plies, bead filler, bead, sidewall, steel belts, nylon overlay and tread (Tire Industry Project 2007). The tire structure can be dived into two levels macro level, which consists of eight key components presented, and micro-level which consist the parts in the rubber compound (Kohjiya & Ikeda 2014, p. 326).

Tire materials can be divided into two categories reinforcing system and rubber compounding. The reinforcing system contains steel and textile cords and is the primary load-carrying structure of the tire (Erman et al. 2013, p. 671). NR is used to improve tire's tackiness and green strength (Kohjiya & Ikeda 2014, p. 336). When protected by additives SBR has better the abrasion resistance and aging stability than other synthetic rubbers, highly resilient low-vinyl BR can also be blended to increase abrasion resistance of tire treads (Markovic & Visakh. 2017, p. 210; Gent 2012, p. 15).

Figure 2. Key tire components (Tire Industry Project 2007)

The inner line (1) is a butyl rubber layer designed to retain compressed air inside the tire, radial body plies (2) are textile or steel cords serving as primary reinforcing material in the tire. The bead is steel wire loop (4), which the anchor the plies and locks the tire onto the wheel, bead filler (3) protects wire bead and sidewall. Sidewall (5) controls ride characteristics by assisting in tread support. Steel belts (6) and nylon over lay (7) are designed to stiffen the casing and improve wear and damage resistance, steel belts are typically made of two cross plies. Tread (8) is in contact with the road surface and has the most performance requirements. (Erman et al. 2013, p. 657; De & White 2001, p. 353)

Typically, rubber compounds consist four basic components: polymers, filler system, vulcanization system and stabilizer system. The rubber compound of tire can contain up to 30 different types of synthetic rubber, 8 different natural rubbers (NR), a range of different fillers, and up to 40 different additive chemicals (Williams 2013). Most typical synthetic rubber types used are styrene-butadiene (SBR), copolymer, polybutadiene and butyl rubber (BR) (Erman et al. 2013, p. 684). Carbon black (CB), clays, and silica are used as filler components (Erman et al. 2013, p. 684). Two or more different raw rubbers are typically used to achieve best balance of properties (Dick 2009, p. 2). The stabilizer system consist, antiozonants are used to slow down the deterioration process and cracking, antioxidants are used to prevent oxidation. Plasticizers are used to improve mechanical – and low-temperature performance. The vulcanization system consists vulcanizing agent, typically sulfur. Accelerator and activator, without accelerator process could take 5-hours. (Fragassa & Ippoliti 2016)

Table 1, Sample recipe of tread rubber (Dick 2009, p. 5)

Ingredients	Parts per hundred rubber	Compound function
SBR 1502	80.0	Rubber
SMR 20 (NR)	20.0	Rubber
N299 (CB)	60.0	Reinforcing agent
Naphthenic oil	10.0	Processing oil
6PPD (phenylene diamine antiozonant)	3.0	Antidegradant
TMQ (antioxidant)	1.0	Antidegrandt
Wax blend	2.0	Antidegrandt
Stearic acid	1.0	Activator
Zinc oxide	4.0	Activator
TBBS	1.2	Accelerator
Sulfur	2.5	Vulcanizing agent

Table 1 shows an example recipe for tread compound where Standard Malaysian Rubber (SMR) is used as natural rubber quality. In the example recipe tread rubber is mostly synthetic rubber SBR 1502 and carbon black used as the reinforcing agent is 32.5 % of the compound.

2.1.2 Manufacturing

Tire manufacturing consists of six process steps: Compound mixing, calendering fabrics and steel cord, extruding different parts of the tire, tire assembly, curing and finishing, and inspection. Figure 3 presents a gate-to-gate approach, which only consists of manufacturing, of tire lifecycle. In figure 3 are feedstock for tire manufacturing, output wastes and finished tires are presented outside of the box, inside of the box are presented processes included in the manufacturing process. (Shanbag & Manjare 2020)

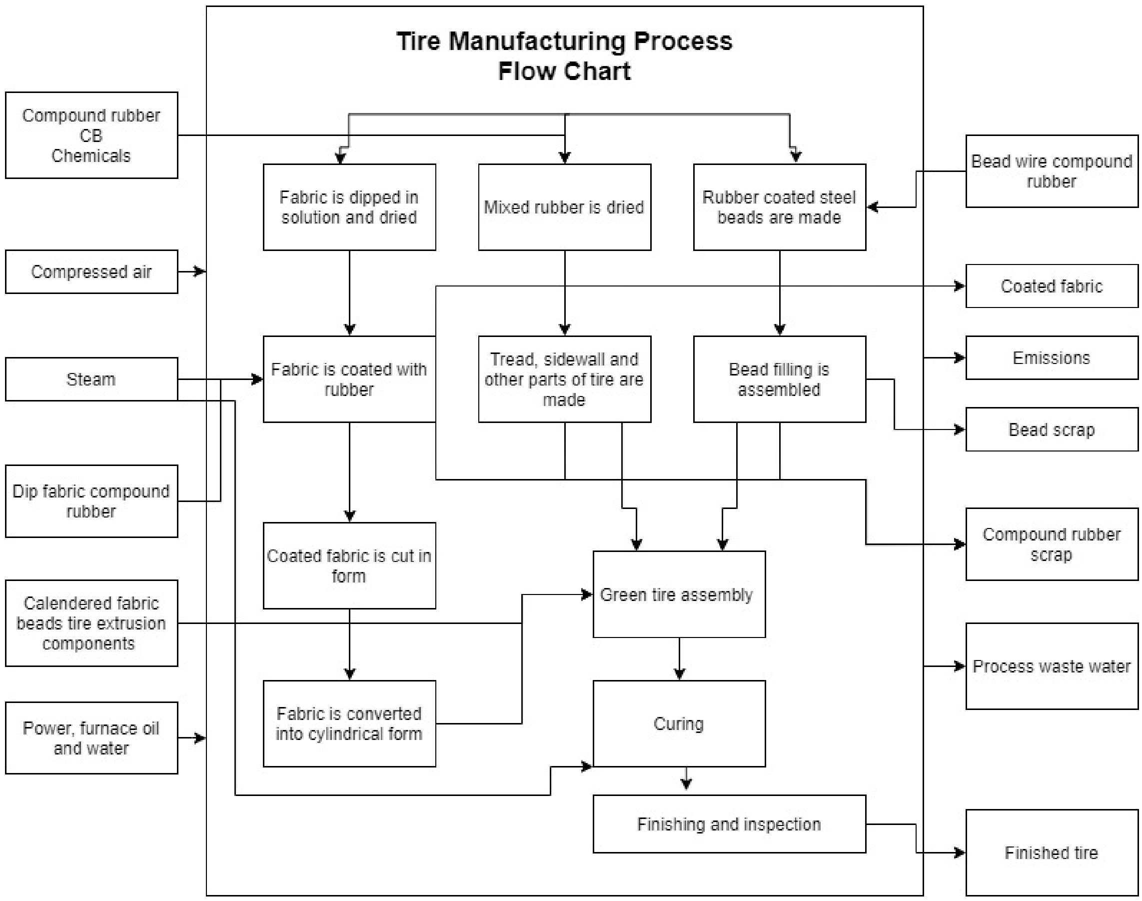

Figure 3. Gate-to-Gate approach of tire manufacturing process (Shanbag, Manjare 2020)

Rubber compounding can be summarized to three P's price i.e. process, and properties (Dick 2009, p. 1). In the compounding state polymers are broken down, so carbon black, rubber chemical, and oils can be mixed to complete the compound (Erman et al. 2013, p. 689). Mixing rubber compounds is typically done in batches using two roll mill or internal mixer, and requires three types of mixing: distributive mixing, dispersive mixing, and laminar mixing. Distributive mixing changes the particle positions, dispersive mixing uses shear stress and time to reduce particle sizes and increases the interfaces. (Limper 2012, p. 47-50, Dick 2009, p. 17) Mixing time, fill factor, rotor speed, and temperature effect on the dispersion quality are used to control the process (Limper 2012, p. 51-52). Poor controlling during rubber mixing can cause higher scrap rates, which increases internal and external failure costs and decreases productivity (Dick 2009, p. 21)

Different parts of the tire have different rubber compounds and therefore require also different grades of CB. Structure of CB is determined by the way it is produced, most of the CBs are produced by the oil furnace process, where natural gas generates a very hot zone in a furnace to which aromatic hydrocarbon feedstock is introduced and CB nuclei is produced. (De & White 2001, p. 133) CB aggregate performance when compounded in rubber is determined mostly by particle size and structure (De & White 2001, p. 138; Martínez et al. 2019). Reaction temperature effects oil consumption in CB production, finer particle size less oil is consumed since oil decreases reaction temperature (Donnet 2018). CBs are classified by American Society of Testing Material (ASTM) into two series N and S, where N comprises normal curing and S series are slow curing First digit after alphabet defines particle size. (De & White 2001, p. 141)

Natural rubber is commonly harvested from Hevea brasiliensis, the Para Rubber tree (Kohjiya & Ikeda 2014, p. 3). Two types of natural rubber are used in tires from Heavea brasiliens ripped smoked sheets (RSS) and technically specified rubber (TSR) (Kohjiya & Ikeda 2014, p. 349). RSS is a type of sheet rubber and is graded according to the green book and TSR according to the country of origin (IRQCP 1969). Over 90 % of Hevea brasiliensis is produced in south-east Asia, Africa produces less than 10 % and Latin America produces 1 – 2 % (Venkatachalam et al. 2013). Only two other species are identified that produce rubber with high molecular weight guayule and Russian dandelion (Venkatachalam et al. 2013). Natural rubber often require pretreatments since its Mooney viscosity has a tendency to increase during storage, viscosity can be decreased by mastication or stabilized by adding viscosity stabilizer into fresh NR (Kohjiya & Ikeda 2014, p. 335; Bei-Long et al. 2013; Ehabe et al. 2009)

Feedstock for synthetic rubbers are mainly petroleum, natural gas, and coal, alternative sources are also studied due to sustainability and price stability reasons (Akovalı 2012, p. 3; Qi et al. 2019). SBR is synthesized in water by free radical polymerization or anionically in solution. After polymerization SBR is completed emulsion is coagulated, with salt, dilute, sulfuric acid, or an alum. (Gent 2012, p. 14-15) Styrene affects the hardness of SBR rubber, so styrene-butadiene ratio is used to control SBR properties (Markovic &

Visakh. 2017, p. 211). BR is synthesized anionically like SBR or via Liegher-Natta catalysis. Amine or ether can be used as co-solvent in BR to increase vinyl content. (Gent 2012, p. 15)

Reinforcing fabric and rubber compound is combined by calendering, where rubber compound is applied below and above the fabric. (Erman et al. 2013, p. 691) Quality of rubber coating is controlled by rubber viscosity, speed of the rolls, friction ration, and gap of the nip. Calendering requires four roll arrangement to coat both sides on single run, rolls can be arranged in F, L, or Z shape. (Akovalı 2012, p. 219, 223) Using only three roll calendering arrangement can result in a bottleneck in the calendering station as studied by Krishnan et al. (2018). Rubber fiber result passes another roller to obtain mutual penetration and thickness. Steel wires are also combined by calendering, after wire clad in brass. (Fragassa & Ippoliti 2016) Finally, rubber-coated fabric and steel are cut to angle and width according to application (Bhatia & Goel 2019, p. 335).

The extruder is used when preparing tread, sidewall, and apex. Tread holds a significant proportion of total tire weight and therefore uniformity of defined cross-section is required. (Bhatia & Goel 2019, p. 335; Erman et al. 2013, p. 691) Extruders consist of feed barrel, screw, filter, and die. Screw length depends on the extruder type hot – or cold feed extruder. (Erman et al. 2013, p. 692) Cold feed extruder requires longer screw since heat and pressure must be generated in the extruder and therefore screw requires more energy. (Bhatia & Goel 2019, p. 335; Erman et al. 2013, p. 692)

Green tire assembly is typically done on a cylindrical drum starting from applying the inner liner to the drum. Followed by ply assembly and beads are assembled before ply is turned over them finally tread is assembled over the tire body. (Erman et al. 2013, p. 692) The radial tire belt does not extend in the circumferential direction and therefore belt and tread rubber are applied when tire is closed to the finished tire size. Inner line, ply, beads, and sidewall are laminated in flat drum, and sub-assembly is inflated for the belt and tread assembly. (Bhatia & Goel 2019, p. 337)

During vulcanization green tire is heated from both sides using steam and hot water. Steam is used to pressurize the tire in a way that it is pressed into the mold creating the desired tread pattern and desired sidewall thickness and markings. (Bhatia & Goel 2019, p. 337; Erman et al. 2013, p. 693) Radial tire molds are made of several parts, two elements for sidewall and between six to nine elements for tread, molds are equipped with single-use, semi-permanent, or permanent release agent system (Bhatia & Goel 2019,

p. 337; Fragassa & Ippoliti 2016). Tire molds consist several vents that are used to release air out of the mold, vents are filled during vulcanization with uncured rubber. Trimming uncured rubber from a single tire can produce 40 g of waste rubber. (Fragassa & Ippoliti 2016)

During the manufacturing process, it can be assumed that inefficiencies will occur and thus waste is created. Depending on the manufacturing stage, processes can be reversible or irreversible. (Gould & Colwill 2015) A fully reversible transformation may allow waste to be reused, and irreversible may result in not reusable or least limit the reuse potential. The vulcanization process, for example, is an irreversible process, since certain qualitative properties are destroyed upon cross-linking. (Gould & Colwill 2015)

2.1.3 End-of-life tires

Tire Industry Project (TIP) has been studying EOLT state of knowledge (2018) by studying EOLT management practices and data from 51 countries. TIP recognized three main EOLT management systems: extended producer responsibility (EPR), tax system, and free-market system. Figure 4 presents worldwide data of EOLT’s generated by weight and how they are managed in four categories, civil engineering, energy recovery, material recovery, and others, including landfill. Europe covers countries in European tyre & rubber manufacturers association (ETRMA) scope. (Tire Industry Project 2018) Members of the European union are free to choose the EOLT management system but are required to report to ETRMA (Campbell-Johnston et al. 2020). EOLT’s are generated from end of life vehicles or from replacing worn tire to a new one (Ramarad et al. 2015).

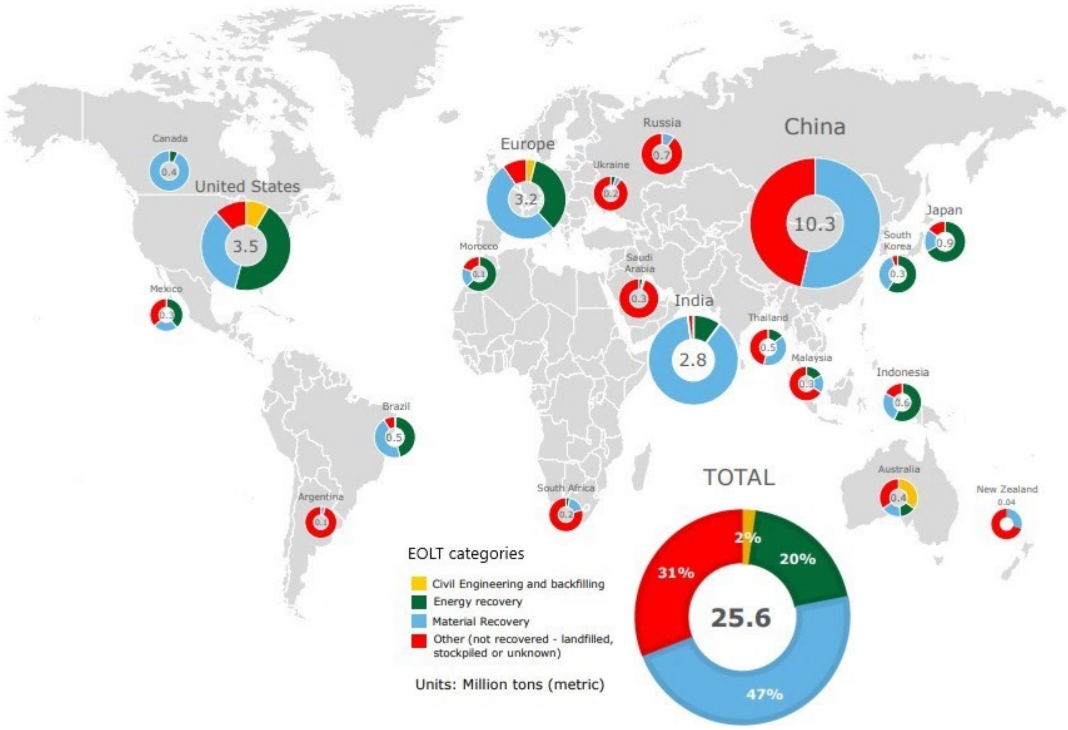

Figure 4. EOLT recovery management (Tire Industry Project 2018).

EPR system means that a producer’s responsibility is extended to the post-consumer state and the financial burden is aimed to the polluter (ETRMA 2020; Milanez & Bührs 2009). EPR system implementations vary between countries, mostly the EPR system is outsourced to third-party non-profit producer responsibility organizations, the amount of generated organizations depends on the legal framework. Two EOLT collection principles have been identified the “1-for-0” and “1-for-1”. In “1-for-0” waste tires are accepted even if new tires are not purchased and in the “1-for-1” principle new tires must be bought. (Winternitz et al. 2019) EPR system problems consists free riders, that are not participating in producer responsibility organization or individually taking responsibility, other problems are a financial burden for taxpayers and sustainability. Many EPR systems are not complete and some EOLT management fees are still collected from taxpayers and EPR systems have trouble fostering eco-design and thus reduce waste. (Winternitz et al. 2019; Campbell-Johnston et al. 2020)

In the tax system country is a responsible actor and the system is financed by taxes are collected from tire producers (ETRMA 2020). In Croatia, as an example of a tax system, tire producers or importers pay taxes to a public fund to cover EOLT management. EOLT processing companies report to public funds and are reimbursed according to reports. (Šandrk Nukic & Milicevic 2019) Problems for tax system is complex administration and fluctuations in availability weakens utilization of recycled resources, by demanding capital for EOLT processing companies (Šandrk Nukic & Milicevic 2019)

The free market system doesn't set a responsible actor, but legislation sets objectives that should be met (ETRMA 2020). The free market system assumes the profitability of EOLT recovery and recycling for the collectors (Sienkiewicz et al. 2012). In the free-market system collectors contract directly with collection points and thus can control collection price, compared to the EPR system where third-party organization contracts with collectors (Winternitz et al. 2019). Tax systems and free-market systems are not as common as the EPR system, even though they are more simple, reflecting that they are harder to control (Sienkiewicz et al. 2012).

Table 2, 10 value retention concepts in circular economy (Reike et al. 2018; Campbell-Johnston et al. 2020).

Strategies	Description	Tire
R0, Refuse	Refusing to consume or to use specific materials	Reducing tire consumption by using alternative transport modes
R1, Reduce	Reducing material per unit of production	Extend tire life cycle
R2, Reuse	Buying 2nd hand product that is working good as new	Reselling safe and functional tires
R3, Repair	Repairing product to work good as new by replacing broken parts	-
R4, Refurbish	Replaicing key modules or components when necessary	-
R5, Remanufacture	Use parts of discarded product in new with same function	Retreading functionally sound discarded tires
R6, Repurpose	Use discarded product or parts of it in new product with different function	New purpose without significant mechanical or chemical treatments
R7, Recycle	Process materials to obtain same or lower quality	Recycling rubber via devulcanization and grinding
R8, Recover	Energy recovery of material	Energy recovery via pyrolysis or incineration
R9, Re-mine	Reprosessing landfilled material	-

Table 2 presents ten circular economy strategies and reflects them to the tire industry (Reike et al. 2018; Campbell-Johnston et al. 2020). Circularity increases while the number after letter R decreases, while the consumer has the most influence in strategies R0-R2 (Kirchherr et al. 2017; Reike et al. 2018).

2.2 Recycling technologies

Tires can be recycled or reused. Recycling activities can be divided into four different categories: primary, secondary, tertiary, and quaternary. Primary and tertiary processes aim to produce new materials with high quality, secondary process creates new materials with reduced quality and quaternary aims to recover energy from used tires. (Martin 2014, p. 2) Reuse applications can be for example in civil engineering where their purpose change and mechanical properties are less demanding for example sports fields and playgrounds, roofing materials (Williams 2013). However, reusability of recycled rubber has been prime of interest in the scientific and technological domain as an alternative way to protect the environment, rethreading is also raised interest as a recycling method (Kim et al. 2019, p. 104). Figure 5 presents different utilization routes for used tires.

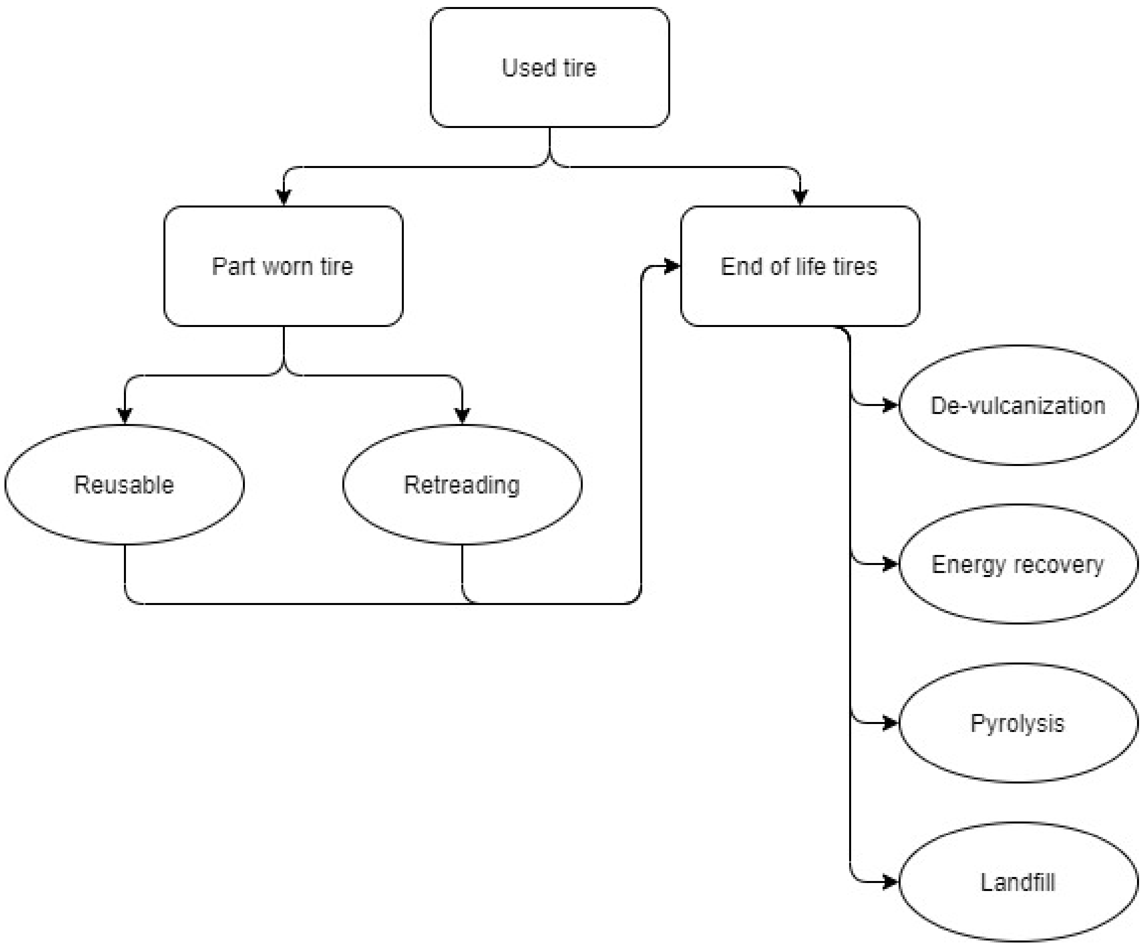

Figure 5. Flowchart of used tire utilization (Ramarad, Khalid et al. 2015).

Tire casing does not deteriorate much during the first life cycle of the tire and therefore tires can be reused by retreading old tire tread at least twice before classified as EOLT. Retreading can save approximately 57 l of oil compared to manufacturing a new truck tire. (Erman et al. 2013, p. 700; Kim et al. 2019, p. 104; Ramarad et al. 2015) Retreaded tires are the only recycling process that attempts to fully use the remaining value of EOLT and thus can save up to 70 % of material thanks to a longer lifecycle (Mugnier et al. 2016; Ferrer 1997). Two main tire retreading technologies are available, mold vulcanization and prevulcanization, mold vulcanization is a similar process as normal tire manufacturing and prevulcanization uses buffer rubber to bond carcass and prevulcanized tread rubber band (Qiang et al. 2020). Retreading can also be divided into three systems, by how much sidewall is retreaded, integral, semi-integral, and retreading only adhesion system (Kim et al. 2019, p. 700).

This paper focuses to identify primary and tertiary processes, and therefore landfill and energy recovery are not widely discussed. Before de-vulcanization or pyrolysis EOLTs are grinded to smaller crumb (Kim et al. 2019, p. 107).

2.2.1 Size reduction

Size reduction technologies are typically ambient or cryogenic. Ambient grinding is a multistep technology at normal room temperature. The cryogenic process freezes used tires to – 80 to – 120 °C. (Shulman 2004, p. 12) Other possible technologies are wet ambient, water jet, or Berstoff's method (Ramarad et al. 2015).

Ambient grinding technologies can be cracker mill, where two rollers counter-rotate and size of the particle size generated is controlled by the gap of the rollers (Martin 2014, p. 149). Fine rubber particles can be generated at ambient temperature by solid-state shear extrusion, where fine particle agglomerating is controlled by residence time in the pulverization section (Martin 2014, p. 152). Wet ambient technology uses grindstone for size reduction and water is used to cool rubber and grindstone, ambient grinding also requires cooling to prevent combustion. Both ambient grinding and wet ambient have a high surface area and volume ratio, but wet ambient decreases degradation compared to ambient grinding. (Ramarad et al. 2015)

Cryogenic size reduction takes used tire rubber below its glass transition temperature and after which it is fragmented at the mill into a final product (Ondrey 2012). Glassy state rubber can be grounded with impact force and high-shear tearing force isn't required (Martin 2014, p. 141). Cryogenic technologies can liberate steel and fiber easier resulting in a cleaner end product (Reschner 2008).

Both ambient and cryogenic technologies have their advantages and disadvantages, parameters used to compare technologies could be operating temperature, size reduction principle, particle morphology, particle size distribution, maintenance cost, electricity consumption, and LN2 consumption. Ambient particle morphology is rougher than cryogenic, but ambient size distribution is narrower. (Reschner 2008) Rubber blends containing size reduced recycled rubber typically have lower mechanical properties, since recycled rubber does not bond properly with virgin rubber. Bonding of recycled rubber can be improved by physical and chemical methods that aim to oxidize the surface of the recycled rubber. (Ramarad et al. 2015)

2.2.2 Pyrolysis

Pyrolysis is an endothermal process where organic material is degraded in the absence of oxidizing agents. The pyrolysis process is the sum of series of parallel and subsequent reactions, where organic material fed to the reactor undergoes a thermal cracking, by cleaving itself into a volatile fraction and a solid residue (Galvagno et al. 2002). The cracking process starts with C – C bonds since their dissociation energy is lower than in C – H (Xu et al. 2020). The decomposed solid residue from pyrolysis of EOLTs is char and the volatile fraction is oil and gas (Williams 2013; Martínez, Puy et al. 2013; Xu et al. 2020). Martínez, Puy et al. (2013) classified pyrolysis processes simply to slow and fast, where the objective of slow pyrolysis is char production and fast pyrolysis favors more formatting liquid products. Fast pyrolysis as the name states is faster but requires smaller particle sizes in the feedstock. Thus pyrolysis process should be selected according to the desired product (Xu et al. 2020).

Potential advantages of pyrolysis are a better option for CO2 capture and improved quality of solid residues. Drawbacks for pyrolysis are control compliancy, the temperature should be evenly distributed, and relatively homogeneous feedstock requirements Pyrolysis is classified as incineration in the EU, which creates a legislative barrier. (Christensen 2011, p. 503; Martínez, Puy et al. 2013)

Pyrolysis reactors that are commonly used are fixed-bed, screw kiln, rotary kiln, vacuum, and fluidized-bed, all the reactors except fixed-bed reactor are continuous reactors. Pyrolysis process yield and compositions depend on process parameters (Galvagno et al.

2002). Especially oils and gases vary between different reactors and operating conditions such as the volatiles residence time, temperature, and heating range. (Williams 2013; Martínez, Puy et al. 2013) Reaction times or residence times vary between reactor technology or particle size. Generally can be stated that larger particle sizes require longer residence time. (Martínez, Puy et al. 2013) Pyrolysis process temperatures affect decomposition. Decomposition starts at approximately 380 °C and is completed at approximately 550 °C (Fernández et al. 2012; Martínez, Puy et al. 2013).

Recycling EOLTs by pyrolysis is more attractive since it has minor environmental impacts and can recover solid and liquid material (Martínez, Puy et al. 2013; Galvagno et al. 2002). As mentioned, the pyrolysis process has three different products, char, oil, and gas. Char and oil can be recovered and used in other applications and thus effect the economic viability, but gas produced is usually used again in the pyrolysis process, since it has high a calorific value (Fernández et al. 2012). Martínez et al. (2013) reviewed several studies conducting that the pyrolysis process can be self-sufficient regarding energy needs. Using gas released during the pyrolysis process can significantly reduce emissions of the pyrolysis process.

Char produced in pyrolysis is often referred to as pyrolytic CB, since it consists mainly of carbon black and other inorganic fillers from the used tires (Xu et al. 2020; Martínez, Puy et al. 2013). Martínez et al. (2013) state that the amount is similar to the amount of original CB, but can be also higher due to secondary reactions formatting tar and char. If pyrolytic CB has commercial value it can have reducing effects on CO_2 emissions since new CB production would be redundant. Pyrolytic CB contains up to 10 – 15 % of ash and therefore cannot be directly reused especially in high-value products such as tires. (Martínez, Puy et al. 2013; Williams 2013) Many studies have been conducted to clarify pyrolysis process control and modify char to replace virgin CB with pyrolytic CB (Xu et al. 2020).

Surface area, structure, chemistry, and activity of pyrolytic CB are major effect to its reuse possibilities since these determine the strength of carbon black-rubber interaction. Pyrolytic CB has been used in active carbon production and some minor applications as reinforcing filler for low-value rubber goods. (Williams 2013; Martínez, Puy et al. 2013; Martínez et al. 2019; Xu et al. 2020) ASTM has created a committee to evaluate standards focusing on the pyrolytic char properties and quality (Enright 2017). However due to different raw materials and pyrolysis processed commonly accepted standards on evaluating which process achieves the best results are still undecided (Xu et al. 2020). Surface activity and morphology are decreased in pyrolytic CB due to carbonaceous deposits that are likely located in the void space between the primary particles of the CB aggregate blocking a portion of their surface (Martínez et al. 2019).

Oil produced in pyrolysis can reach an energy content of 44 MJ/kg. Pyrolysis oil has been researched to replace conventional liquid fuels. Although pyrolysis oil has properties like conventional liquid fuels it is observed that pyrolysis oil in injection engines produces higher CO, HC, SO_2, and smoke emissions. (Martínez, Puy et al. 2013; Williams 2013) Pyrolysis gas yields depend on the process temperature but have high enough energy content to produce electricity for the process. Pyrolysis gas has high methane content and is a proper fuel even though the content is lower than for natural gas, pyrolysis gas has large H_2S content which can oxides to SO_2 which creates an emission problem. (Czajczyńska et al. 2017)

2.2.3 Devulcanization

Devulcanization uses mechanical, thermal, chemical, microwave, ultrasonic, biological energy, or a combination of two technologies to convert vulcanized rubber into a state where it can be mixed, processed, and vulcanized again. The primary goal of devulcanization is to break down chemical sulfur bonds of rubber. (Kim et al. 2019, p. 108; Erman et al. 2013, p. 699; Martin 2014, p. 33) Devulcanizing rubber aims to attain plasticity to recycled rubber, however, as devulcanization aims to break sulfur – sulfur bonds and sulfur – carbon bonds, it is impossible to specifically target the cleavage of bonds. Thus, at some level cleavage of carbon – carbon occurs. (Ramarad et al. 2015) Different devulcanization methods are presented in table 3.

Table 3, De-vulcanization methods (Kim et al. 2019, p. 109)

De-vulcanization method	Basis of process	Rubbers
Thermal	Heat-induced cross-link scission	NR, SBR, BR
Thermal with chemicals	Targeted chemical reactions at elevated temperature	SBR, NR, BR
Mechanical	Shear-induced cross-link scission	NR, SBR, EPDM, IIR
Mechanical with chemicals	Shear/Chemical de-vulcanization	SBR, EPDM, SBR, NR
Thermo-mechanical with chemicals	Combination of heat, shear and chemical reactions to break cross links	EPDM, SBR, NR
Ultrasonic	Ultrasound energy used to break crosslinks	NR, SBR, IIR, BR
Microwave	Energy generated by microwaves	NR, SBR, BR
Microbiological	Microorganisms	NR, SBR, BR

Moulin et al. (2017) studied steam water thermolysis to recover CB from EOLTs. Steam water thermolysis is a thermochemical method and can be identified as a hybrid of pyrolysis and solvolysis. Besides of external heat process uses superheated steam in the process. A study conducted by Moulin et al. (2017) was carried in process temperatures of 450 °C to 500 °C and residence time of 30 mins or 60 mins. Steam water thermolysis process output is recovered CB similar to in pyrolysis.

The chemical method is the reclaiming process whose goal is to break C – S and S – S bonds by using chemicals, de-vulcanization leaves C – C intact. Drawbacks of the chemical method are slow to process time, solvent removal and additional waste are created. (Kim et al. 2019, p. 109; Erman et al. 2013, p. 703) Chemicals are used also on thermal devulcanization methods to assist the devulcanization at elevated temperatures. Thermochemical methods are usually small-scale batch processes and therefore inefficient. (Martin 2014, p. 40) Most devulcanizing agents are used to enhance process efficiency, devulcanizing agents are common: organic disulfides, mercaptans, aliphatic amines, trialkyl phosphates, and triphenylphosphine (Francis 2017, p. 145).

The most prominent devulcanization method is mechanical. The mechanical method takes place at ambient temperature and rubber is reclaimed using high-shear stress. The drawback for mechanical devulcanization is that high mechanical force can also break the main chain and might not break all the sulfur bonds which decreases the physical properties of reclaimed rubber. (Kim et al. 2019, p. 112; Francis 2017, p. 145) Some mechanical methods use supercritical fluids to swell the rubber and so facilitating devulcanization. However, maintaining fluid in a supercritical state is harder in mechanical methods compared to sealed vessels used in thermal methods. (Martin 2014, p. 45) Si, Chen et al. (2013) studied high shear stress effects on different ground tire rubbers using a twin-screw extruder. According to their findings, higher screw rotation decreases gel content and Mooney viscosity of devulcanized rubber.

The ultrasonic method is very fast, simple, efficient, solvent, and chemical-free widely accepted as a green de-vulcanization process that can be applied to a wide range of rubbers. The method creates a greater intensity of ultrasonic waves in the pressure and heat helping to breakdown a three-dimensional rubber network by generating cavitation. (Kim et al. 2019, p. 118; Erman et al. 2013, p. 710; Francis 2017, p. 147) Devulcanization degree can be controlled by ultrasound amplitude and the residence time. Two-phase material is generated fully devulcanized soluble portion and insoluble portion. (Francis 2017, p. 147)

The microwave method uses a controlled dose of microwave energy at a specific frequency and energy level is applied to break C – S and S – S bonds substantially but not C – C bonds, if the process can be controlled accurately enough. During microwave devulcanization, volatile organics with low molecular weight are released in form of sulfur dioxide due to breaking sulfur bonds. (Kim et al. 2019, p. 117; Martin 2014, p. 77) devulcanization can be improved by combining mechanical forces to process. Advantages of the microwave method are reduced process time, - energy, continuity, and handling. (Francis 2017, p. 146)

The biological method uses chemolithotrophic bacteria to selectively attack the sulfur crosslinks on the surface of waste rubber. Bacteria works primarily in surface phenomenon it requires finely ground rubber. (Martin 2014, p. 83) The biological method is uncomplicated, minimal equipment, no toxic chemicals, low energy consumption and no major damage to the C – C bonds since microorganisms can selectively break sulfur crosslinks. Therefore, the biological method is very promising for tire recycling due to efficient recycling, with technological and economic advantages. (Kim et al. 2019, p. 121; Francis 2017, p. 148)

2.3 Carbon Footprint Modelling

Wright, Kemp et al. (2011) reviewed studies to propose a sound and pragmatic definition of carbon footprint. They defined carbon footprint as: "*A measure of the total amount of CO_2 and CH_4 emissions of a defined population, system or activity, considering all relevant sources, sinks, and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as CO_2e using the relevant 100-year global warming potential (GWP100).*". Wiedmann and Minx (2008) defined carbon footprint (CF) as a total amount of both direct and indirect CO_2 emissions caused during the product life cycle. The latter definition is more cited in Google Scholar

GWP is used since all greenhouse gases (GHG) do not have equal capacity to cause warming. GWP considers both radiative forcing caused, and the average time molecule stays in the atmosphere. (Pandey et al. 2011) However, GWP has been criticized for being economically inefficient and inconsistent to stabilize GHG concentrations (Levasseur et al. 2016). Pandey, Agrawal et al. (2011) and Wiedmann (2009) also reviewed disagreements in the selection of GHGs in CF modeling, Pandey, Agrawal et al. (2011) pointed out also that set of GHGs covered depends on the followed guideline since different industries have different activities and thus emissions. Even though scientific literature has been able to inform about the implications, it's impossible to objectively determine which GHG metrics are best since it depends on the policy context and involves value judgments (Levasseur et al. 2016).

CF emissions are typically measured in one of three life cycle approaches environmental input-output analysis, process analysis, or hybrid environmental input-output life cycle analysis. Process analysis assesses process data, where environmental input-output analysis assesses sector-level data and hybrid environmental input-output lifecycle analysis assesses both levels. (Wright et al. 2011; Pandey et al. 2011) Differences in life cycle assessment methodologies are in the modeling approaches, midpoint, endpoint, and combined. The midpoint is useful when environmental effects are in interest, the endpoint is useful when final damages are in interest and the combined approach takes advantage of both approaches. (Shanbag & Manjare 2020) Midpoint approaches are more commonly used and thus more accurate since the endpoint approach is more complex (Levasseur et al. 2016).

Data for CF modeling can be collected directly on-site using measurement devices or through estimations based on emission factors and models, later being more commonly used, since direct measurements can be too expensive. GHG data is presented as CO_2 equivalent COe_2 which is calculated using conversion factors. (Pandey et al. 2011)

CF is seen as an easy to understand and a simplified process to obtain product CF helping to communicate and reduce emissions. Free methods and databases could improve CF strengths and transparency, independent audit agencies could improve the coherence of CF results. (Alvarez et al. 2016; Pandey et al. 2011) Accuracy and the narrow scope of environmental impacts are some of the CF weaknesses. Threats CF is facing are lack of system boundaries and lack of convergence between product CF and corporate CF, economic and financial crises also reduce investments to CF. (Alvarez et al. 2016)

2.3.1 Life Cycle Assessment

Life cycle assessment (LCA) investigates and evaluates the environmental impact of the given product caused by manufacturing, use, and disposal to identify various GHG emitted in stages and energy consumption (Trappey et al. 2012; Pandey et al. 2011). LCA encourages definition of very broad analytical goals by nature and might fall short on sharing responsibility and defining root causes (Löfgren et al. 2011). LCA techniques can be also implemented in gate-to-gate or cradle-to-gate studies with proper justification (ISO 2006). Narrowing studies to cradle-to-gate or gate-to-gate can be valuable when assessing manufacturing effects on the environment (Löfgren et al. 2011).

Process-based LCA specifies inputs and outputs for each process step and therefore results can be truncated and thus is only applicable for specific processes or products (Recker et al. 2011). Process-based life cycle inventory can be conducted by process flow diagram or matrix inversion, later being a more computational approach. Even though process-based approach data has low uncertainty, process-based analysis has high time- and labor intensity. (Suh & Huppes 2005)

Environmental input-output analysis is a top-down approach and thus scope of the sector can be economy-wide, and processes and products can be too heterogeneous. Process-based -LCA is a bottom-up approach and data is collected from the processes and thus data is more accurate, hybrid environmental input-output analysis combines the two approaches. (Kjaer et al. 2015; Wiedmann 2009) Environmental input-output analysis can provide an estimation of 100 % of the total carbon footprint and share responsibility between producers and consumers. Thus, environmental input-output analysis cannot specify process carbon footprints. (Wiedmann 2009) Triple bottom line concept has also been included to input-output LCA. Triple bottom line concept assesses three main pillars of sustainability which are environment, economy and society. (Onat et al. 2014)

Hybrid can refer either to hybrid data or hybrid analysis. Hybrid data uses physical data instead of monetary data and in hybrid analysis, both monetary and process data are combined. (Kjaer et al. 2015) Hybrid analysis can use accurate process data in an important process and cover less significant processes with environmental input-output data (Wiedmann 2009). Kjaer et al. (2015) studied three cases in Denmark and found that hybrid environmental input-output analysis provides a feasible analysis of the direct and indirect impacts in the supply chain, uncertainty was a major weakness revealed in the study. Uncertainty is generated if the data accuracy and modeling approach do not match.

2.3.2 Standards

International organization for standards (ISO) has published standard 14040 describing principles and framework of LCA and definition of goal scope (ISO 2006). ISO has also published three-part standard 14064 for reporting and verification of greenhouse gas emissions. The first part consists of organizational level quantification and reporting principles and requirements (ISO 2019a). The second part consists of project-level quantification, monitoring, and reporting principles and requirements (ISO 2019b). The scope of the third part is to specify principles and requirements for verifying and validating greenhouse gas statements (ISO 2019c). ISO 14067 covers quantification and reporting of product CF. The ISO 14060 family is made to provide clarity and consistency for quantifying, monitoring, reporting, and validating or verifying GHG emissions and removals. (ISO 2018)

Standards and guidelines are available to estimate GHGs using LCA (Pandey et al. 2011). World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) have conducted GHG protocol for quantifying GHGs tailored to serve business realities and to serve multiple business objectives. One part of GHG protocol is product standard which helps to quantify and report product-specific emissions. (WBCSD 2011) British standards institution (BSI) have conducted consistent method PAS2050 for quantifying life cycle GHGs for industries and communities by specifying GHG quantifying requirements. Requirements specified are system boundary, sources of GHG emissions that fall into system boundary, data, how to carry out the analysis and how to calculate the results. (BSI 2011) Japanese environmental management association for industry (JEMAI) have also published their CF standard (JEMAI 2013). The Japan automobile tyre manufacturers association, inc. (2012) have conducted guidelines for calculating GHG, for automobile tires, following ISO 14044, Japanese Carbon Footprint System, PAS2050, BPX30-323, and GHG protocol standards. GHG emissions covered in their guideline where: CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3.

ISO 16067, PAS2050, and GHG protocol are specific standards to calculate product CF. All three are based on the ISO 14044 LCA standard. (Garcia & Freire 2014) All processes should be included according to standards, but if some emissions are unused they should be insignificant and assessed properly (ISO 2018; BSI 2011; WBCSD 2011). Garcia and Freire (2014) studied differences between different protocols and conducted that carbon storage and delayed emissions should be included to enable comparability.

3. RESEARCH METHODS

A sequential exploratory mixed-method research design is used in this study. Where evaluative study is used to find out what are characteristics of pyrolysis or devulcanization yields (Saunders et al. 2019, p. 182) Evaluative study is also used to identify GHG emission impacts of the two technologies. The explanatory study is used to identify EOLT properties and finally to compare the two technologies against the normal tire plant. The evaluative research strategy used is case research and the explanatory research strategy is comparative research and survey research. (Saunders et al. 2019, p. 188)

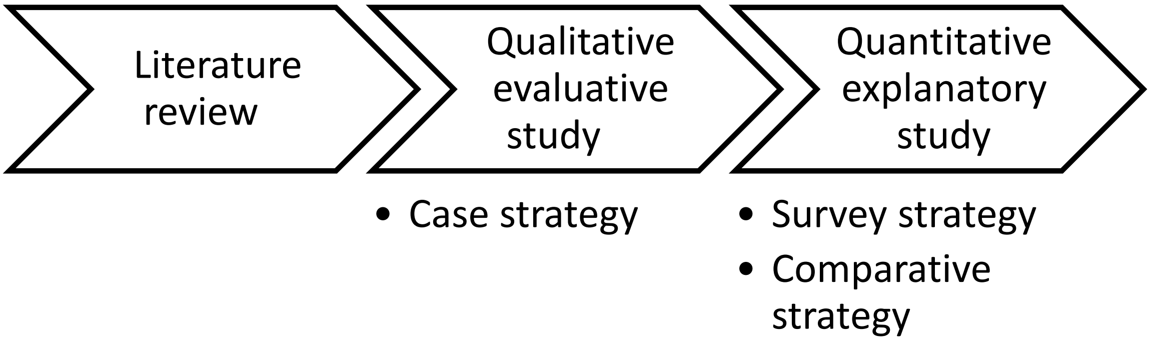

Figure 6. Research design

Figure 6 Illustrates the research design used in this study. A literature review is used to present the theory behind and present knowledge of recycling technologies. After theory case research is conducted to present recycling technologies and evaluate feasibility. Case study research is continued with a comparative research strategy which is used to compare the carbon footprint effects of the technologies. The feasibility of the case study recycling technologies is also compared. A survey strategy is used to study EOLT collection possibilities and properties.

3.1 Case research

Case research has often restricted scope or unit. The case research aims to provide detailed information from the chosen case topic. Case study research is often used as a strategy rather than method since the nature of the case study can vary significantly. Case topic choice usually follows replication logic to enable case comparison. (Mills et al. 2020)

Case study research studies a single case or limited entity. The case study does not define relations, hypotheses, or projections, the goal is to provide a detailed description of the case. (Saaranen-Kauppinen & Puusniekka 2006) Even though a case study can be either qualitative or quantitative, qualitative methods are more common. Since the case study aims to increase awareness of the phenomenon. (Saaranen-Kauppinen & Puusniekka 2006)

3.2 Comparative research

The goal of comparative research is to study similarities and differences between two entities that are under comparison. The comparison should be conducted to general processes under different conditions. (Given 2020, p. 100-101) One comparative research method is a comparative case study method, which studies two or more instances of a specific phenomenon. Comparative case study analysis is post hoc by nature since comparisons typically require final data from the cases. (Mills et al. 2020)

The analytical hierarchy process (AHP) has been generally applied to multi-objective environments AHP method has three decision-making steps: determine weights for each objective, determine weights for alternatives in respect to the objectives and determine final global weights (Forman & Gass 2001). Weights in the AHP method can be determined using linguistic pairwise comparisons, which are quantified, using a scale. Scale is commonly from 1 to 9 where, 1 refers to equally important and 9 is the highest possible importance, values can also be reciprocal if horizontal object or alternative has lower importance compared to vertical. (Triantaphyllou & Mann 1995) Finally, the order of the global weights determines the preferred order of the alternatives, where the most preferred alternative has the largest global weight (Forman & Gass 2001). Weights for each alternative are calculated by multiplying weight of the objective, with the alternatives weight regarding to the objective. Global weight is the sum of the weights per objective. (Triantaphyllou & Mann 1995)

AHP method has three functions i.e. complexity, measurement, and synthesis. Hierarchical structuring is found to be a natural way for humans to deal with complexity. (Forman & Gass 2001) Measurement has four scales nominal, ordinal, interval, and ratio, AHP method uses the ratio scale, because weights are determined by multiplying. The analytical part separates constituent elements of the entity which are analyzed. (Forman & Gass 2001)

3.3 Survey research

Survey research is often used to answer a question such as “how much” and it is therefore used in exploratory research. The survey strategy allows quantitative data analysis. (Saunders et al. 2019, p. 193) Survey research can be conducted using a questionnaire or interview, in both strategies the same set of questions is asked from each respondent. The questionnaire is a more effective way of conducting survey research since the researcher does not need to be presented during the research. (Saunders et al. 2019, p. 504)

A survey can be either researcher completed or self-completed where responders fill the answers to the survey and send it to the researcher. Researcher completed means that the researcher fills the answers to the survey, by questioning the responder face-to-face or via telephone. (Saunders et al. 2019, p. 506) In short, can be summarized that surveys have different attributes. Email surveys can be spread effectively to a global scale but have a rather low response rate of approximately 30 – 50 %, whereas face-to-face or telephone surveys have a higher response rate of approximately 50 – 70 % but demand more resources. (Saunders et al. 2019, p. 507)

Survey questions should be planned prior to data collection, by evaluating what data is required to collect with the survey. Understanding of organizational contexts is important when organizations are involved in surveys. To ensure all essential data is collected, nature of survey research should be identified and the accuracy level of the variables should be selected. (Saunders et al. 2019, p. 510, 514)

4. EMPIRICAL STUDY

In the empirical study, part case tire plant is presented and what technologies have currently commercial applications. Later feasibility of two technologies are studied in more detail under the triple bottom line scope. Legislations affecting tire recycling and reuse are also studied in European union scope since the scope is assumed to create a feasible framework for operations also in other parts of the world.

4.1 Current situation of tire recycling technologies

Three types of recycling technologies are currently used commercially. These include size reduction by cryogenic milling, carbon black recovery by pyrolysis, and devulcanization by carbon dioxide assisted thermomechanical process. Pyrolysis is a potential recycling method for tire recycling since char produced by pyrolysis can be used as a substitute for the carbon black, which is used as a filler. Reclaiming or devulcanizing rubber faces some challenges since compounds in EOLTs vary and thus reclaiming homogenous material can be challenging. Whereas pyrolysis breaks the chemical structure of the tire and reclaims only carbon black. Since tire structure contains a variety of CBs, reclaimed carbon black is a mix of these and therefore cannot substitute high-quality CBs.

Lehigh Technologies is USA based company that uses a cryogenic milling process to produce ultrafine rubber powder from 20 mesh to 300 mesh, that can be mixed back to tire rubber compound. (Lehigh Technologies 2020)

Tyromer Inc. is a Canadian based company which uses carbon dioxide assisted thermomechanical devulcanization process to produce a tire-derived polymer. They have two products one of which is produced from truck tire treads and another is produced from whole passenger tires, and thus their process requires sorted EOLT input. (Tyromer 2020)

Several companies have commercialized the pyrolysis process to process commercially applicable recovered CB. Swedish based Scandinavian Enviro Systems uses carbonization by forced convection system, which enables better temperature control than the typical pyrolysis process. Scandinavian Enviro Systems sells both recycled material and their recycling plants, the capacity of the plant can be controlled by the amount of their semi-batch reactors. (Scandinavian Enviro Systems 2020) German-based Pyrolyx produces commercially viable recovered CB by using batch reactors in its plants around the world (Pyrolyx 2020). USA-based Delta-Energy uses a continuous feed system in its DEPolymerization pyrolysis process, to produce over 350 grams of recovered CB from each kilogram of scrap tire. (Delta-Energy 2020)

Scandinavian Enviro System and Tyromer Inc. as other companies sell their recycled materials for tire manufacturers. However, Scandinavian Enviro Systems and Tyromer Inc. are interesting for the aim of this study, since both companies also license their technology. By licensing the recycling technology, it is possible to have its recycling facility impeded to the tire plant.

4.2 Legislation

According to the REACH chemical safety assessment, technical guidance document tire manufacturers are not required to register recovered substance use, but they are encouraged to include a statement of successful and safe uses. The main requirement in REACH legislation of the tire manufacturers is to provide risk management methods and operational conditions to control exposure during EOLT recycling. (ChemRisk 2009) According to the waste framework directive, EOLTs are waste until the recycling process is finished. Therefore, the waste life stage in REACH starts from EOLT collection and ends with recovered substance, which can be rubber crumb, carbon black, steel, or any other material reclaimed from EOLT. Tire manufacturers are not required to register the use of recovered substance according to REACH, since many recovered uses are similar to general rubber good exposures (ChemRisk 2009).

In table 4 European union directives that affect the different recycling methods of EOLTs are listed. OW refers to on waste and to directives 2006/12/EC and 2008/98/EC and provides a legal framework of treatment of waste and defines categories. IW refers to incineration of waste and to directive 2000/76/EC, its purpose is to limit the negative effect to the environment. LCP refers to large combustion plants and to directive 2001/80/EC and defines limits to emissions in large combustion plants. IPPC refers to integrated pollution prevention and control and to directives 1996/61/EC and 2008/1/EC, which require the best available techniques for industrial emissions. The environmental release category refers to REACH chapter R.18, which guides the waste life stage (ECHA 2012). The objective of the directives is simply to protect human health and the environment.

Table 4. Regulations and REACH categories of different recycling methods (ChemRisk 2009)

Waste treatment technique	Regulatory framework (EU directive)	Environmental Release Category (ERC)
Size reduction	OW	Formulation in materials
Pyrolysis	IW, OW, LCP, IPPC	Production of chemicals and formulation in materials
Devulcanization	OW, IPPC	Formulation in materials
Energy recovery	IW, OW, LCP, IPPC	Formulation in materials, Wide dispersive outdoor use of long-life articles with low release and emission guidance for incineration

Basel convention aims to control transboundary movements of hazardous wastes and their disposal however, tires are not included in the Basel convention since tires are not classified as hazardous (Basel Convention 2020). As technical guidelines on the identification and management of used tires created by Basel convention state that tires are stable (Basel Convention 2002). Since different components of rubber mixture are trapped in the polymer’s three-dimensional structure. Basel convention recognizes two potential environmental risks ecotoxicity and leaching, however, tests show no toxicity or contaminant leach in normal conditions. (Basel Convention 2002) As EOLTs export is possible, it can be seen from export data that countries with free-market system tend to export EOLTs to Asia, mostly to India (Chatham House 2018). As free-market system assumes that EOLTs have value and operators are willing to collect them and gain value from the EOLTs collection. Where countries with extended producer responsibility system tend to create domestic waste management systems.

Some countries are setting bans for waste exports, due to raising knowledge of environmental and health effects of poorly regulated waste management in low-income countries. For example, Australia is banning EOLTs export except for Bus, truck, and aviation tires for retreating purposes, with the call of facility verification (Ley Sussan 2020). China has also announced a ban on all solid waste imports to begin in 2021 (Cole 2020). Hence waste management strategy relying on export can be at risk if the importing country decides to ban or control waste imports, India in EOLTs case being the biggest importer.

4.3 Case tire plant

The case plant for which the recycling technology's feasibility is studied is tire plant in the ramp-up phase. After the ramp-up phase capacity should be 2 million radial passenger car tires (PCR) with unused land for planned capacity increase, by utilizing extra building to produce truck and bus tires (TBR). Eventually, capacity could be raised to produce 3,5 million PCR and half million TBR. Rubber mixture weight with reinforcement materials for the PCR can be approximated to 8,2 kg and for the TBR 56,2 kg and thus plant will produce approximately annually 56,7 million tons of rubber including reinforcement materials. Approximated tire mixtures and weights are used, since mixtures vary between different tire models, and thus more accurate production plan would be required to utilize more accurate mixture data. However, effect of more accurate tire mixture data is insignificant to the total amount of waste generated.

Waste rubber is produced in each step of tire production for example from poor control or trimming. However compound waste can be reused since no external materials than rubber compound is mixed to it, hence it is a reversible process. Fabric and bead coating are an irreversible process and waste cannot be directly reused since fabric or steel belts are already mixed. Green tire assembly and curing are other irreversible processes since multiple materials are installed which cannot be directly separated. Tires that fail at the quality control of these stages, must be recycled and have limited reuse properties. Waste amounts are estimated that coated fabric and bead waste is 0,5 % of the plant capacity, green tires are also 0,5 % of the plant capacity and waste vulcanized tires are 1 % of the production capacity. Estimates are made using data from existing tire plants that run in a normal capacity. The total waste amount is therefore 2 % of the total production volume in case plant this corresponds to 1134 tons of waste annually.

The most consumed utility in case plant is electricity from the local grit and natural gas is the second most-consumed utility purchased from the markets, which is used to fuel boilers. The case plant has two boilers to produce steam for the curing process, one boiler is in use and another one is for backup. Steam is generated at a steady rate since, steam consumption does not vary significantly whether PCR or TBR is cured, and thus natural gas consumption is also steady.

Raw materials are purchased from suppliers and mixed in batches at the factory's mixing station. Two materials carbon black and synthetic rubber are in focus in this study since these two are targeted to be replaced to the possible extend by reclaimed materials. CB purchasing expenses are expected to be around 1054 dollars per metric ton, which is equivalent to approximately 887 € per ton (Echemi 2020). Adding logistic costs and administrative costs kilogram of CB delivery is estimated to cost around 1,3 €. SBR is the most used synthetic rubber and thus can be used to estimate synthetic rubber costs. SBR ton cost approximately 1500 € and delivered price are likely close to 2000€, thus kg of SBR costs 2 €. With these price estimates annual purchasing expenses are 15,6 million € for CB and 19,5 million € for SBR.

4.4 Carbon emission impacts

Carbon emissions impacts are studied with environmental input-output analysis in cradle-to-gate scope. To identify impacts to regarding tire manufacturing, since 86.4 – 87.6 % of GHG emissions of tires are generated during the use phase (Kohjiya & Ikeda 2014, p. 333). Löfgren et al. (2011) studied that perspective is important when assessing the environmental performance of manufacturing sites. By narrowing the studied perspective to cover only manufacturing possible impacts of recycling are easier to identify. Carbon emission impacts are calculated according to ISO 14067 CF standard for products (ISO 2018).

The life cycle assessment method is used to calculate the carbon footprint. LCA contains four steps, goal and scope, inventory analysis, impact analysis, and interpretation. LCA assessment is conducted according to ISO 14040 standard and Carbon footprint is also calculated according to ISO 14067. However GHG protocol product standard is used also as a support at the CF calculations since it is based on ISO standards (GHG protocol 2011; Garcia & Freire 2014). Japanese automobile tyre manufacturer associations LCCO2 guidelines were also used to identify GHG emission factors and tire lifecycle system steps.

After identifying carbon emissions impacts in three cases, the first case is normal tire manufacturing process where CB is manufactured from fossil resources and all the required utilities are imported outside of the tire plant. Second is a case where recovered CB using pyrolysis is used in the rate where tire properties are not decreased due to the use of recovered CB. The third case is where the devulcanization method is used to recover tire delivered polymer, which is used to replace synthetic rubber. The comparative case study method is used to compare the effects of using reclaimed materials to the carbon footprint of a tire and tire plant.

4.4.1 Goal and scope

The goal is the intended application and reason for carrying out the study, goal also defines the intended audience and communication method if communication is applicable. (ISO 2006; ISO 2018) The scope of the LCA study should be consistent with the goal and present studied system and study boundaries, functional unit, data and its properties, assumptions, and allocation procedures (ISO 2018). Inventory quantifies inputs and outputs of LCA and includes data collection, data validation, system boundary refining, and allocation. Impact analysis analyses the magnitude and significance of impacts associated with the LCA. (ISO 2006) The interpretation phase evaluates relations between the previous three phases in order to reach conclusions and recommendations (ISO 2006).

The goal of this LCA is to identify the CF impacts of the tire manufacturing process. CF impacts are calculated for two scenarios. The first scenario uses completely virgin raw material and grid energy sources. The second scenario uses recycled CB from pyrolysis to a cautious extend. Results are, used to evaluate if pyrolysis can reduce CF of tire and tire plant, and presented in this study along with other results.

The functional unit used as a basis for comparison in this study is one passenger car tire, with an average weight of 8,2 kg. The scope of this study is cradle-to-gate. The life cycle system utilizing pyrolysis plant is presented in appendix A and appendix B utilizes devulcanization plant. The scope is presented as grey area. Raw material use, energy consumption, and direct emissions were calculated inside the system boundaries. Transportation of raw materials and other possible transportation phases were excluded from the calculations. Transportation was not included since this study is not a case study and results are not calculated to any specific tire plant hence transportation distances and routes are impossible to evaluate properly. Emissions to manufacture production machines were excluded, since their life cycle is long and thus has a small impact on overall emissions.

Primary data of the tire plant operations were collected from the plant capacity calculations and thus represent the normal operating conditions of the case plant. Present moment activity data was not collected since the factory is still in the ramp-up phase. Ramp up phase data was not seen as appropriate for this study since during ramp-up more waste is generated than in normal conditions.

4.4.2 Life cycle inventory analysis

GHG emission factors were collected mostly from Japanese automobile tyre manufacturers associations LCCO2 vol2 guide and Ecoinvent3 LCI database. Factors that were found from these sources were collected from peer-reviewed articles. Global warming potential values that are used to calculate GHG factors are from the year 2013.

GHG emission factors in table 5 were collected from Japanese automobile tyre manufacturers associations (JATMA) LCCO2 vol2 guide (JATMA 2012). GHG emissions are calculated as CO_2 equivalent per unit, which is one kg of raw material. These factors are then multiplied with activity data, which is collected, from the case factory capacity calculations. Calculations for case plant are used since current data does not represent normal conditions, and thus GHG results from the start-up phase are not sufficient in the long-term analysis. GHG factor for natural rubber is, likely for old rubber plantations, hence Jawjit et al. concluded (2010) that GHG emissions for natural rubber produced in new plantations are much higher, due to land conversion. (Jawjit et al. 2010)

Table 5. GHG emission factors for raw materials.

Material	Unit	GHG factor	Source
Synthetic rubber	kgCO_2e/kg	2,4	(JATMA 2012)
Natural rubber	kgCO_2e/kg	0,636	(JATMA 2012)
Carbon black	kgCO_2e/kg	3,2	(JATMA 2012)
Precipitated silica	kgCO_2e/kg	2,06	(JATMA 2012)
Sulfur compounds	kgCO_2e/kg	0,00709	(JATMA 2012)
zinc oxide	kgCO_2e/kg	2,01	(JATMA 2012)
Processed oil	kgCO_2e/kg	1,61	Ecoinvent 3.0
Steel wires	kgCO_2e/kg	2,46	(JATMA 2012)
Textiles	kgCO_2e/kg	6,37	(JATMA 2012)

GHG emission factors in table 6 for utilities were also collected from the JATMA LCCO2 guide. Some factors were not found from the guide and were collected from the Ecoinvent LCI database. Activity data for utilities are collected from case plant design calculations. Activity data thus do not represent the current situation of the case plant but represents estimations of consumption when the case plant operates in normal conditions.

Table 6. GHG emission factors for utilities.

Utility	Unit	GHG factor	Source
Electricity	kgCO2e/kWh	0,646	Ecoinvent 3.0
Natural gas	$kgCO_2e/m^3$	0,233	Ecoinvent 3.0

GHG emissions for pyrolysis were calculated for the self-sufficient pyrolysis process utilizing pyrolysis oil to generate electricity for heating. According to the supplier, the pyrolysis process consumes 250 kWh of electricity per ton of EOLT. Which can be used to calculate how much GHG gases are consumed per kilogram. Assuming that, pyrolysis oil, has similar emissions that diesel-electric generating set. Although as mentioned in the theory part, pyrolysis oil has higher emissions than normal liquid fuels, however how much higher emissions are is unknown, and thus not included in this study.

$$\text{Pyrolysis GHG factor} = \text{EC} \times \text{Diesel generator GHG factor} \times 10^3 \qquad (1)$$

Pyrolysis GHG factor was calculated using equation 1. Where EC is electric consumption of pyrolysis plant. GHG factors and allocated factors for pyrolysis yield are presented in table 7.

Table 7. GHG emission factors for pyrolysis process.

Utility/ Yield	Unit	GHG factor	Source
Diesel burned in generator	$kgCO_2e/kWh$	0,941	Ecoinvent3.0
Pyrolysis plant	$kgCO_2e/kg$	0,235	-
Pyrolysis oil	$kgCO_2e/kg$	0,094	-
Pyrolysis CB	$kgCO_2e/kg$	0,094	-
Pyrolysis gas	$kgCO_2e/kg$	0,012	-
Pyrolysis steel	$kgCO_2e/kg$	0,035	-

GHG emissions generated during pyrolysis were allocated for the output materials, using a physical allocation method. Allocation where done, since pyrolysis is a common process between pyrolytic oil, gas, and carbon, and GHG emissions cannot be directly assessed for each of the output materials.

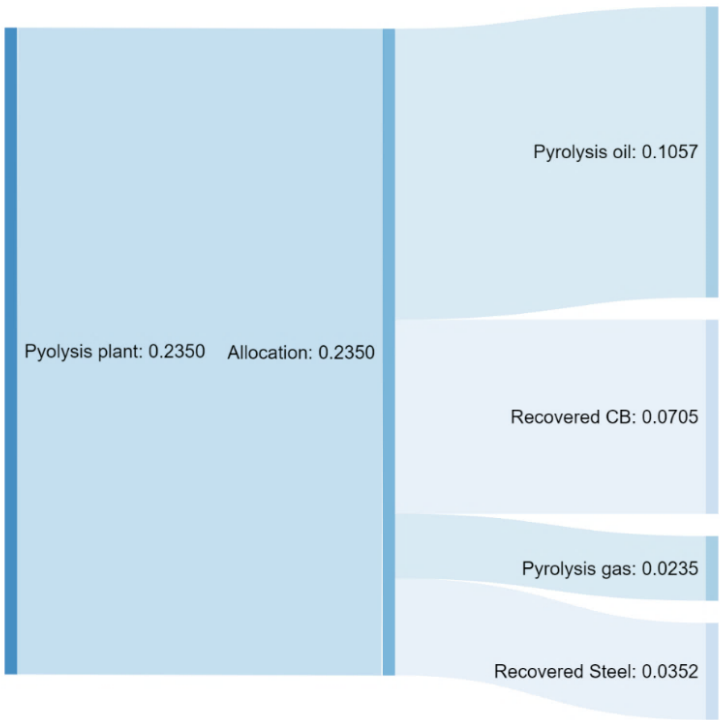

Figure 7. Pyrolysis GHG allocation

Figure 7 presents how GHG emissions were allocated between pyrolysis process outputs. Pyrolytic output yield for the allocation was assumed to be 45 % oil, 30 % rCB, 10 % gas and 15 % steel.

4.4.3 Life cycle impact analysis

Life cycle impacts are calculated using a single impact assessment method for 100-year global warming potential. According to ISO 14067 standard in the life cycle impact phase of CF study, each GHG and their potential impact in the product system is calculated. GHG are presented in a unit of CO_2e which means all emissions are calculated as equivalent to CO_2. GHG's are multiplied according to their global warming potential (GWP) with a 100-year time horizon given by the IPCC. GHG's covered in this study are emissions recognized in the Kyoto protocol. Kyoto protocol recognizes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Gases are converted to CO_2e so their comparability is possible.

4.4.4 Life cycle interpretation

As transportation is excluded from the study it is not fully complete and thus results are not absolute CF of the tire. The tire manufacturing process is also assumed to be static as in practice tire structures vary and the manufacturing line load varies slightly. However static assumption can be assumed to be sufficient since CF is calculated on an annual time period, and thus load variations should even. Major uncertainty from static assumption is from the assumption that PCR and TBR structures do not vary as in practice structures vary and thus raw material inputs vary.

The results can be identified that oil derived products such as synthetic rubber and carbon black presented a large quantity of the raw material stage. As synthetic rubber is assumed to be only SBR and CB qualities are not separated, hence this creates uncertainty to results. However, sources for GHG factors that would separate these were not found.

4.5 Survey research

The survey research method is used to collect data from different EOLT management organizations. The goal of the survey research is to identify how EOLTs can be recycled in a pyrolysis plant or devulcanization plant embedded in the tire plant. Pyrolysis plant requires EOLTs to operate in full capacity. EOLT rate differs in a relation of tire plant and pyrolysis plant capacity, if pyrolysis plant has small capacity and tire plant capacity is large then EOLT rate is smaller. The Devulcanization plant prefers sorted EOLTs since it can only process PCRs as a whole.

Data from survey research is used to identify three factors, the storage capacity required condition of EOLT and possible expenses. Since pyrolysis and devulcanization are continuous processes and EOLTs are received as batches from the collection facilities buffer storage is required. Storage capacity requirements are affected by how often EOLTs and in how large quantities EOLTs are available. EOLT condition affects the preprocessing of EOLT before pyrolysis especially grinding of waste tires. For example, if EOLT management organization processes EOLTs into smaller crumbs or whether truck and passenger tires are separated. Possible expenses are especially important to the economical operating conditions of the pyrolysis plant or devulcanization plant. Expenses could raise due to different EOLT management system, as a free-market system relies on to value which is stored to the EOLTs.

Survey research is conducted by an online survey, which is sent to different EOLT management organizations by email. Online survey via email can be targeted to the specific persons in the organization if email addresses are commonly available at the organization's web sites. In cases where email addresses for the right person are not available generic email was used. Survey questions were kept to a minimum and answers were in form of choice, aiming to keep the work required to answer the survey to the minimum.

4.6 Pyrolysis plant

The first recycling concept case utilizes a pyrolysis plant embedded in the tire plant. The benefits of pyrolysis technology are that it can process both vulcanized and unvulcanized rubber. Some commercial applications are already established using pyrolysis technology to process EOLTs. Other benefits are that all the outputs from the process can be utilized again char can be used as recovered CB, oil can be used in large diesel engines and gas can also be used in large gas burners to heat for example boilers.

The pyrolysis plant evaluated for this concept has shredding and screening units before the pyrolysis reactor. Pyrolysis reactor is continuous and available capacities are 0,6 tons of EOLT per hour up to 3 tons of EOLTs per hour and are operated and monitored by two operators. All the information about the plant is collected from the plant supplier. According to supplier output material collection can be arranged by the customers' requirements. In this case, the evaluation pyrolysis reactor is heated with electricity since heat can be controlled more precisely than by burning gas or oil to heat the reactor. Recovered CB is used in the rubber mixes, gas and extra oil are sold outside the plant. Output gas and oil are collected to oil tanks and recovered CB is collected into 1 metric ton bags, to allow easier logistics of the output material. Flowchart of the studied pyrolysis plant material flow is presented in figure 8.

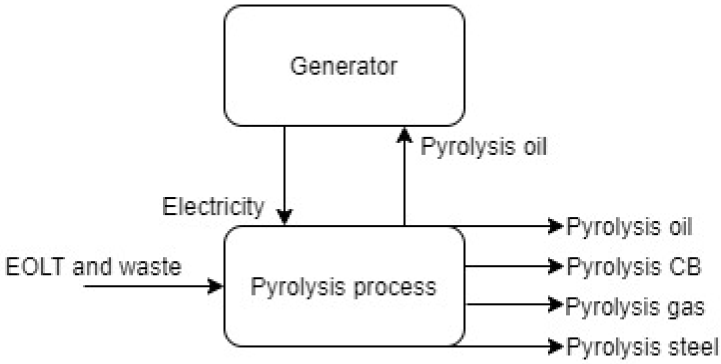

Figure 8. Material and utility flow in pyrolysis plant

Pyrolysis capacity depends on the amount of recovered CB that can be used in the tire manufacturing. Utilization rate depends on the quality of the recovered CB and of the tire in which it is utilized. Annual demand of the recovered CB (AD_{rCB}) can therefore be estimated by using plant capacity, CB rate of the tires and recovered CB utilization rate.

$$\mathrm{AD_{rCB}} = \left(\mathrm{PC_{PCR}} \times \mathrm{CB_{rate,PCR}} \times \mathrm{rCB_{rate,PCR)}}\right) + \left(\mathrm{PC_{TBR}} \times \mathrm{CB_{rate,TBR}} \times \mathrm{rCB_{rate,TBR}}\right) \quad (2)$$

Equation 2 can be used to estimate annual recovered CB demand. Capacity for both PCR and TBR are used to estimate demand, since recovered CB utilization rates for PCR ($rCB_{rate,\ PCR}$) and for TBR ($rCB_{rate,\ TBR}$) differ. Plant capacity (PC) is the mass produced annually. Virgin CB amounts also differ, and thus CB rates for PCR ($CB_{rate,\ PCR}$) and TBR ($CB_{rate,\ TBR}$) are used. Annual waste (AW) produced in the tire plant are planned to be processed in the tire plant. Equation 3 to is used to estimate annual waste amount.

$$\mathrm{AW} = (\mathrm{PC_{PCR}} + \mathrm{PC_{TBR}}) \times \mathrm{WR} \quad (3)$$

WR used in equation 3 is waste rate, which is estimated rate of waste from the total mass produced annually in the tire plant. EOLTs are used to fulfill the remaining capacity. EOLT demand is estimated using equation 4.

$$\mathrm{EOLT_{demand}} = \frac{(\mathrm{AD_{rCB}} - \mathrm{AW} \times \mathrm{rCB_{yield}})}{\mathrm{rCB_{yield}}} \quad (4)$$

rCB yield in the equation 4, is the yield rate of recovered CB from the pyrolysis plant. EOLTs are assumed to be relatively homogenous PCRs with same weight as the ones manufactured, but with 1,6 kg of tread wear. Thus, annual pyrolysis capacity is calculated using equation 5.

$$\text{Pyrolyzer}_{\text{capacity,annual}} = \frac{\text{AD}_{\text{rCB}}}{\text{rCB}_{\text{yield}}} \tag{5}$$

Pyrolysis plant capacity varies by multiple factors considering on the operating conditions. Variables that should be taken into consideration are, reactor capacity, operating hours which vary according to how many days pyrolysis plant is operated annually. During operating days, it should be considered in how many eight hour shifts the plant is operated.

$$\text{Pyrolyzer}_{\text{capacity,reactor}} = \frac{\text{Pyrolyzer}_{\text{capacity,annual}}}{\text{OD} \times 8 \times \text{NS}} \tag{6}$$

Equation 6 is used to calculate reactor size for pyrolysis plant. Tire plant is operating annually 345 days thus pyrolysis plant is assumed to operate also only for 49 weeks. OD in the equation is operating days per week and NS is number of shifts per day.

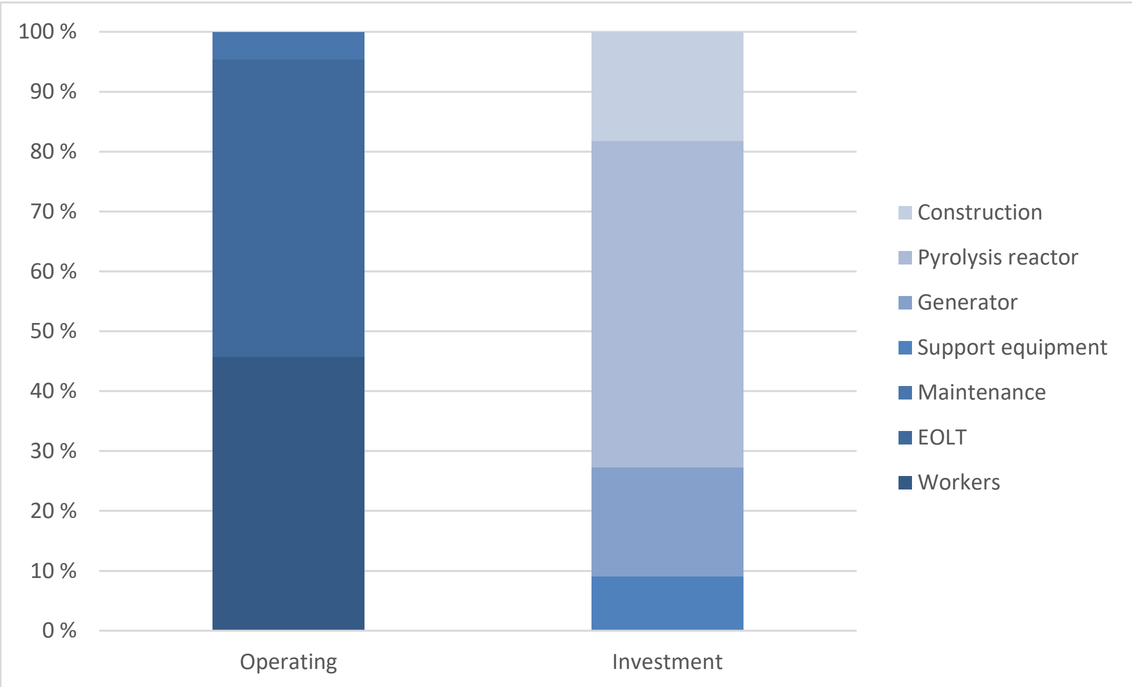

Figure 9. Costs structure of pyrolysis plant with 700 kg per h capacity

Pyrolysis plant investment costs can be divided into three factors pyrolysis reactor cost, generator, and support equipment cost as presented in figure 9. Pyrolysis reactors have fixed capacity and thus pyrolysis plant capacity is defined by the number of reactors. Therefore, reactor price can be identified as a cost factor. The second factor is support equipment which consists of all the other equipment which are used in the pyrolysis plant, such as control automation, shredding, and screening units, conveyor. Support equipment amount does not necessarily change if pyrolysis plant capacity is increased and thus their cost can be estimated to be fixed.

The generator can be either fuel or gas-powered, thus the pyrolysis process can be self-sustaining. A gas-powered generator will likely require a higher process temperature for a higher gas yield. Oil yield is enough to power generator and still, extra yield will occur, which can be sold outside. Fuel used in generator effects in the investment costs since gas-powered generators costs 4 – 5 times more than oil-powered.

Operating costs of the pyrolysis plant are the costs of EOLT collection, operator salaries, and maintenance costs as presented in figure 9. EOLT collection costs are depended on the EOLT management system of the country where the pyrolysis plant is used. Operator salaries also vary between countries. Maintenance costs of the pyrolysis plant are estimated to be 10 % of the total operating costs.

As presented earlier in this paper a lot of regulations affect to pyrolysis plant. Regulations that shall be considered when designing a pyrolysis plant are integrated pollution prevention and control, waste incineration, large combustion plant directive, and waste directives. Waste incineration directive requires an approved permit and established operating conditions that operate under air emission limits. Air emission limits are established in the large combustion plant directive. Integrated pollution prevention and control directives require the best available techniques to protect air, soil, and water. Waste directives, categorize wastes, disposal operations, and recovery operations. Large combustion plants and integrated pollution prevention and control directives consider only plants with an input of 50 MW or more.

A lot of directives affect the pyrolysis process since it is defined as an incineration process in the European Union. In this case, the legislation does not generate significant limits, since pyrolysis plant input does not exceed 50 MW and thus directives considering large combustion plants do not apply. As the pyrolysis process itself does not generate air emissions, pollution directives should be easy to fulfill. Emission limits might be an issue if pyrolytic oil quality creates higher emissions in the generator. Waste handling and operations should be operated according to the waste directive framework and measured according to directives.

4.7 Devulcanization plant

The second recycling technology studied is devulcanization technology. Devulcanization technologies have been studied and seen as very potential technology since the only output material from devulcanization is reclaimed rubber. Devulcanization technology studied for this concept is carbon dioxide assisted thermomechanical technology, which is already commercialized to some extent. Commercial applications of the studied technology utilize EOLT PCR or TBR treads as feed material, depending on the feed material two types of tire delivered polymer (TDP) is generated. The quality of the tire delivered polymer depends if the feed material is TBR tread or only PCR.

The Devulcanization plant layout consists of a shredding station and devulcanization line, figure 10. Devulcanization line is a continuous process. One devulcanization line capacity can process 700 kg of EOLT per hour and plant capacity can be increased by increasing the amount of devulcanization lines. The plant is operated by 12 workers in the plant and 4 administrative workers including lab workers. All the information about the plant is collected from the plant supplier. According to the supplier, tire delivered polymer can be collected to continuous strip, bales, pallets, or rolls. The most conventional collection is likely one with the most practical logistics and which is easiest to add to the masterbatch. Before EOLT can enter the devulcanization line all the fiber and metal must be severed from the rubber, and rubber must be milled to fine 20-40 mesh crumps.

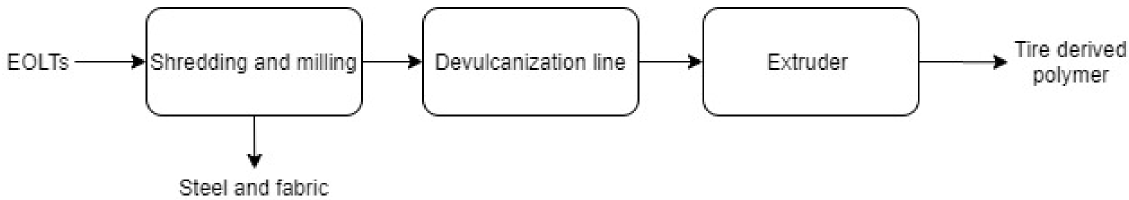

Figure 10. Devulcanization process material flow

Devulcanization plant capacity depends on the amount of TDP that can be utilized in the tire manufacturing. Utilization rate depends on the TDP quality and of the tire in which it is utilized. Annual TDP demand can therefore be estimated by using plant capacity, the amount of SBR used and TDP utilization rate.

$$\mathrm{AD}_{\mathrm{TDP}} = \left(\mathrm{PC}_{\mathrm{PCR}} \times \mathrm{SBR}_{\mathrm{rate,PCR}} \times \mathrm{TDP}_{\mathrm{rate,PCR)}}\right) + \left(\mathrm{PC}_{\mathrm{TBR}} \times \mathrm{SBR}_{\mathrm{rate,TBR}} \times \mathrm{TDP}_{\mathrm{rate,TBR}}\right) \quad (7)$$

PC in equation 7 is as in pyrolysis case the plant capacity, mass produced annually, for PCR or TBR. SBR rate is the total amount of SBR used in the given tire type as SBR is assumed to be replaced with TDP. Annual waste yield in devulcanization case does not differ from pyrolysis case and equation 3 can be used in both cases. EOLT demand which is used to fulfill remaining capacity can be estimated using equation 8.

$$\mathrm{EOLT_{demand}} = 100 \times \frac{(\mathrm{AD_{TDP}} - \mathrm{AW})}{82} \tag{8}$$

As devulcanization process is close to 100 % it is assumed that yield matches to the feed rubber quantity. EOLTs are assumed to be relatively homogeneous PCRs with same weight as the ones manufactured, nut with 1,6 kg tread wear. Fabric and steel are separated from the EOLT before entering to the devulcanization process and thus EOLT feed is assumed to be 82 % of the EOLT weight.

$$\mathrm{Devulcanization_{capacity,reactor}} = \frac{\mathrm{AD_{TDP}}}{49 \times \mathrm{OD} \times 8 \times \mathrm{NS}} \tag{9}$$

Devulcanization plant capacity varies by multiple factors considering on the operating conditions. Variables that should be taken into consideration are, reactor capacity, operating hours which vary according to how many days devulcanization plant is operated weekly. During operating days, it should be considered in how many eight hour shifts the plant is operated. Capacity of devulcanization reactor is estimated using equation 9.

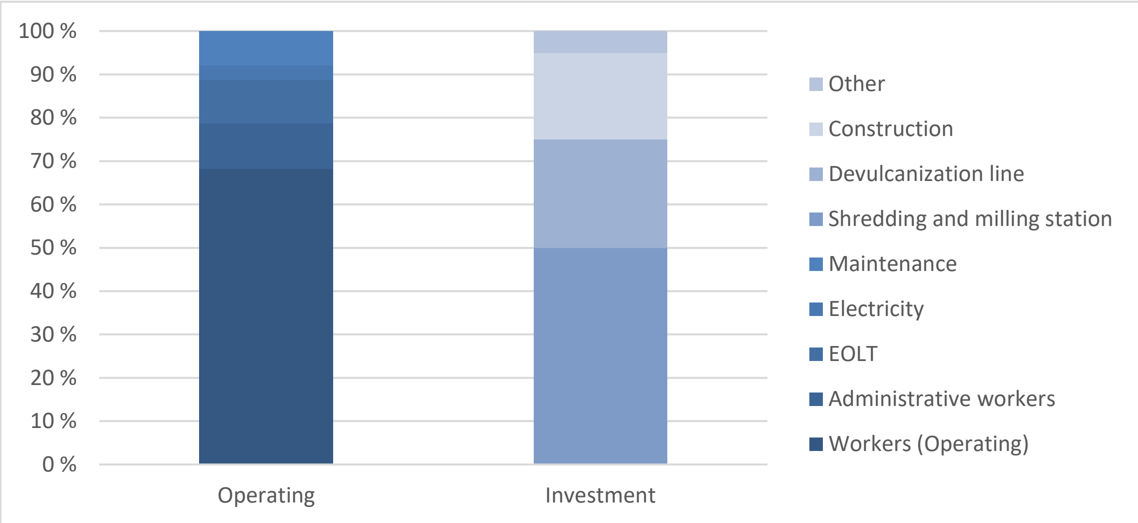

Figure 11. Devulcanization plant cost structure with one devulcanization line

Figure 11 presents cost structures of the devulcanization plant operation and investment, with one devulcanization line. Investment costs include shredding and milling station which can be assumed to be fixed cost since it has higher capacity than devulcanization line and thus can process EOLTs to fine crumbs for multiple devulcanization lines. Devulcanization line costs include the costs of manufacturing the line as well as the licensing fee. Other costs in the investment costs include all the required support equipment required for the devulcanization plant operations construction costs are also included to others. The operating cost structure includes the workers required to run the devulcanization plant, electricity purchased from outside the plant, maintenance, and costs from EOLTs, excluding logistic costs. Maintenance costs are assumed to be approximately 10 % of the operating costs, excluding costs from EOLTs.

Since the devulcanization process is not seen as an incineration process regulatory burden is smaller. Regulations considering waste, disposal operations, and recovery operations affect the devulcanization plant. Pollution prevention directive should also be considered when thermal input exceeds 50 MW. As thermal input does not exceed 50 MW in this case pollution prevention directive does not affect. In conclusion, regulations are fulfilled if proper measures are taken and operations are operated according to the framework presented in the waste directive.

5. ANALYSIS

In this chapter feasibility of the two different recycling cases are analyzed and finally compared. Technologies are first analyzed in the optimal situation before their feasibility to the case plant case is analyzed.

5.1 Pyrolysis plant analysis

The feasibility of the pyrolysis plant is analyzed under the triple bottom line: people, planet, and profit. People impacts that are accounted are waste pile degeneration and jobs created. Planet impact is presented using carbon footprint results, which are compared to the normal operating situation. Profit is presented by saving on the virgin raw material purchases and sales profit of the extra CB. After analyzing the pyrolysis plant under the triple bottom line, the feasibility of the plant to the case application is analyzed.

5.1.1 Pyrolysis plant impacts to community

In people aspect, pyrolysis plant offers a feasible process to mitigate EOLT landfill to valuable materials. EOLT landfilling is a significant issue even though no hazard leaches occur since even in controlled landfilling EOLTs offer a breeding ground for insects that are capable of transmitting diseases to humans. In the case of EOLT landfill fires, significant amounts of GHG are emitted into the air and pyrolytic oil can contaminate water sources. Varying by country, regulations on tire manufacturers or importers have responsibilities relating to EOLT management. Some countries might demand that manufacturer recycles a corresponding amount of EOLT as it has sold in the country.

From the social point of view, the pyrolysis plant creates direct jobs for the plant operators. As mentioned, the pyrolysis plant requires two operators, in the case of 24/7 running pyrolysis plant corresponds to eight to ten jobs for the operators. Indirect jobs occur from EOLT logistics and collection.

5.1.2 Pyrolysis plant carbon footprint

Impacts on the planet were calculated using ISO 14067 standard supported by GHG protocol and Jatma LCCO2 guidelines. Results were calculated for both situations for the tire plant, case where plant utilizes recovered CB in maximal extend. Transport emissions were excluded, from the calculations since transport routes can vary significantly for both EOLT and virgin CB and thus result in higher uncertainty. Tire plant emissions without recycling facility are presented in table 8.

Table 8. Annual case tire plant GHG emissions utilizing only virgin CB

Category	Raw material	Manufacturing
Annual GHG emissions ($tonCO_2e/year$)	134618,39	27206,21
Total ($tonCO_2e/year$)	161824,59	

Table 9. Annual case tire plant GHG emissions utilizing also recovered CB

Category	Raw material	Manufacturing
Annual GHG emissions ($tonCO_2e/year$)	133397,45	27233,13
Total ($tonCO_2e/year$)	160630,58	

In table 9 is presented case tire plants GHG emissions, with embedded pyrolysis plant. As presented in appendix A pyrolysis plant is in the manufacturing stage, and thus its emissions are also under manufacturing in table 9. As a result, manufacturing emissions, are higher for pyrolysis case, but raw material acquisition stage emissions are lower. Saved GHG emissions in raw material stage cover emission increase in the manufacturing stage and still decrease over all cradle-to-gate emissions.

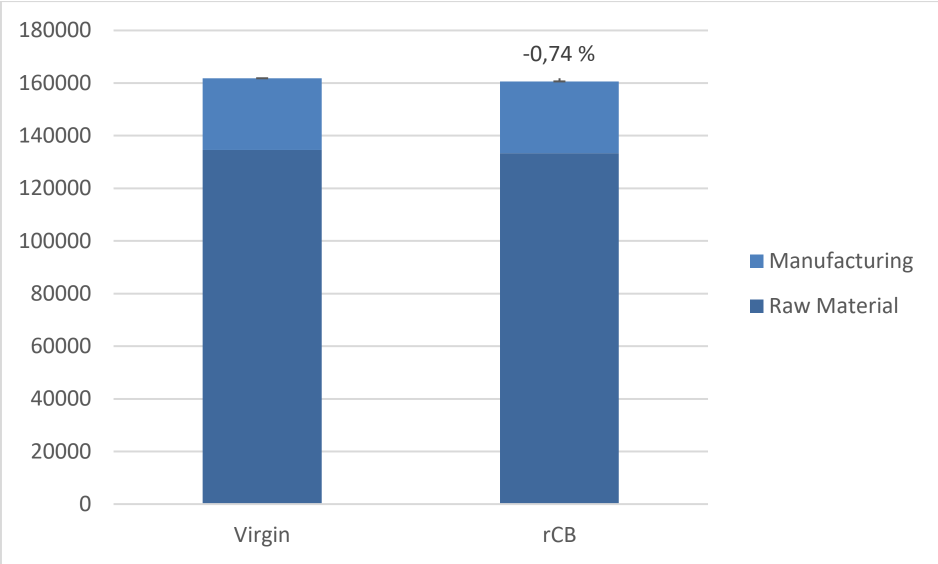

Figure 12. GHG emissions comparison of utilizing only virgin raw materials between utilizing also recovered CB

Figure 12 presents the total GHG emissions and visualizes how emissions are divided between raw material stage and manufacturing stage. From figure can be seen how much GHG emissions are reduced by only utilizing recovered CB from the pyrolysis.

5.1.3 Profit created by pyrolysis

The profit of the calculations is based on the average prices of the virgin CB. Sales profit from gas, oil, and steel are assumed to be low since neither of the materials is processed. Oil can be directly mixed in large diesel engines such as ship engines and steel can be sold to the construction industry, where it can be used as reinforcement material.

Total costs of the pyrolysis plant operations are as presented earlier, costs of EOLT collection, operator salaries, and maintenance costs. Case plant country does not have any identified EOLT management system, and thus the price of EOLT is assumed to be similar as in EPR system countries. Operator salaries were assumed since data of the case country's salary level was not available. The salary level was set to relatively high since the cost to the employer is usually higher than the actual salary. According to the plant supplier maintenance costs of the plant are 10 % of the operating costs and which was added to the calculated operating cost, without EOLT collection costs.

The cost of recovered CB is dependent on electricity, labor, and maintenance costs. As EOLT might have additional collection costs they also affect the costs of recovered CB. Costs per one kilogram of recovered CB are calculated using equation 10. EC is the hourly electricity costs, LC is hourly labor costs and EOLT cost is the hourly cost of consumed EOLTs.

$$\frac{(EC + LC) \times 1{,}1 + EOLT_{cost}}{rCB_{\frac{yield}{h}}} \tag{10}$$

Table 10 presents costs per kilogram of recovered CB in two cases first case utilizes only waste, and second is produced fully from EOLTs with 100 € collection costs per ton. Real price is likely in between of these as plant waste and EOLTs are used as a feed material in pyrolysis plant.

Table 10, recovered CB costs.

EOLT rate	recovered CB costs per kg
0 %	0,30 €
100 %	0,55 €

Total profit in the figure 13 payback time is the sum of saved purchase costs of carbon black or sales profit from spare recovered CB. Carbon black purchase costs savings are calculated using earlier virgin CB purchase costs of 1,3 € per kilogram. Pyrolysis process profitability could be increased by utilizing gas in the boiler to generate steam and thus reduce natural gas expenses. However, this would require extra piping in the plant and increases investment costs.

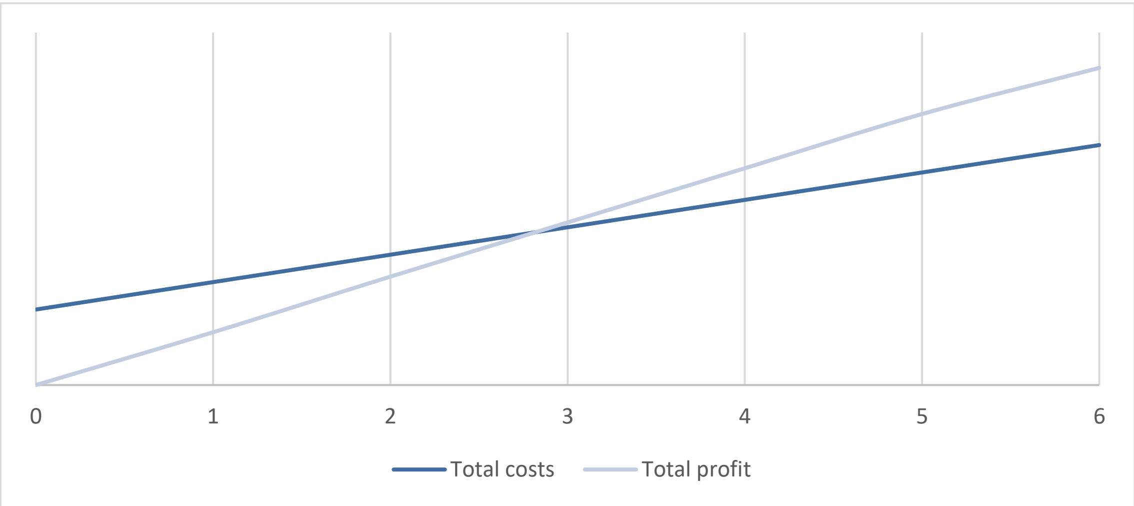

Figure 13, Pyrolysis plant payback time with 650 kg/h capacity

Payback time is calculated in optimal situation were pyrolysis plant is operated seven days a week in three shifts. Extra yield is sold with same price as is assumed to be saved in procurement expenses. Thus, payback time in figure 13, is the shortest possible payback time for pyrolysis plant, as profit decreases if plant is not operated continuously.

As mentioned, gas, oil, and steel profit are assumed to be low and thus sales profit for gas, oil and steel were excluded since they are likely sold with contract to outside the plant. The price is likely to be lower than market prices. Oil and steel profits present therefore only small rate of the total profit and can be excluded.

5.1.4 Pyrolysis plant feasibility

Feasibility of the pyrolysis plant in the case plant is analyzed in this chapter. As the recovered CB utilization rate is low, smallest commercially available pyrolysis line was analyzed. With the estimated utilization rate, plant waste can be used solely to process enough recovered CB. By processing annually all the generated plant waste with recovered CB yield of 30 % generates also yield which should be sold outside the plant or stored in buffer storage if the CB yield decreases due to feed material quality.

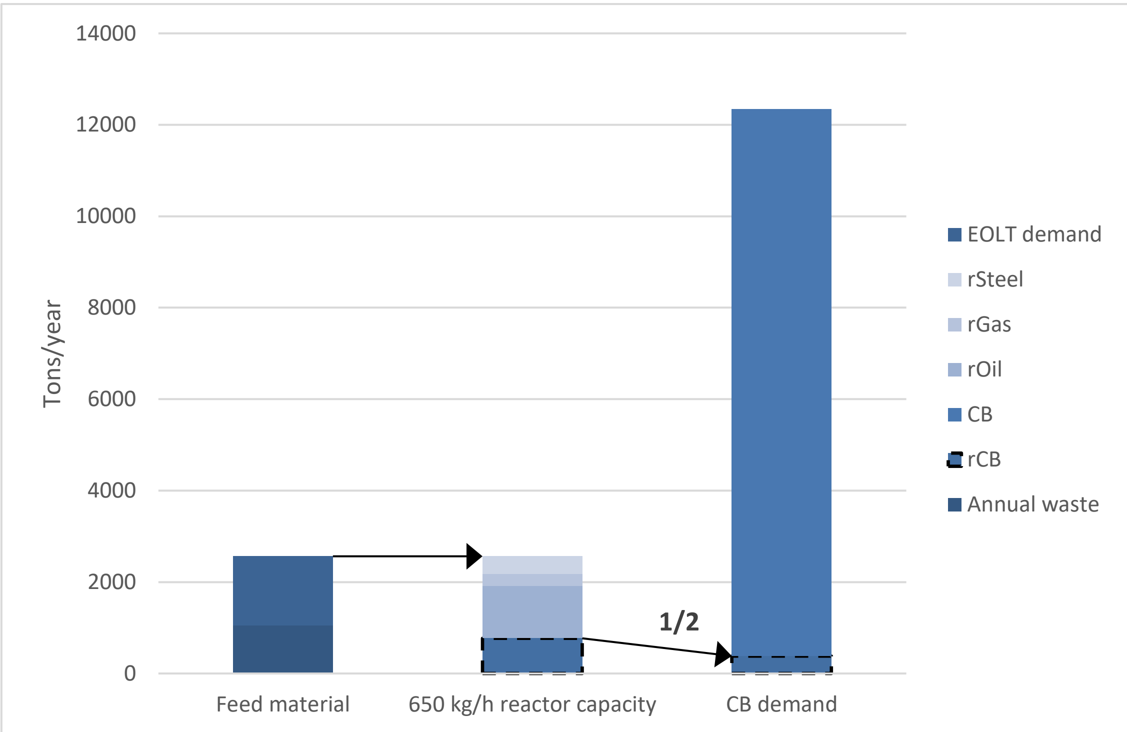

Figure 14. Annual pyrolysis capacity

Figure 14 presents the demanded annual capacity to produce recovered CB for the utilization rate presented earlier. The annual capacity of the pyrolysis line with 650 kg/h and feed materials are also presented. The pyrolysis line is estimated to operate 5 days a week in two shifts. Starting from the left is visualized how feed materials are dived between plant waste and EOLTs. The Middle column visualizes yields from the pyrolysis reactor and the right column visualizes the CB and recovered CB demand. From the figure can be seen that the recovered CB yield is 2 times higher than the demand.

5.2 Devulcanization plant analysis

Devulcanization plant feasibility is also studied under the triple bottom line. Community impacts are studied in the number of jobs created. Carbon footprint is used to evaluate the impacts on the planet. Profit from the devulcanization plant is calculated by counting the rubber purchase expenses saved by utilizing TDP.

5.2.1 Devulcanization plant impacts to community

Devulcanization also presents a feasible way to mitigate EOLT landfills, which might present fire hazards, as well as a breeding ground for insects that might spread diseases. The Devulcanization process itself creates dust, vibration, and smell emissions. Dust emissions created from the grinding can be solved by ventilation and filters. Vibration emissions and smell emissions are not significant issues if residential areas are not close by, as vibrations do not exceed the regulations and smell emissions don’t include any harmful substances.

From a social point-of-view devulcanization plant creates quite a significant amount of jobs for the community. As one shift requires 12 workers on the plant, which means approximately at least 50 workers for a 24/7 running plant. In addition to workers operating in the plant, 4 administrative workers are required to manage the plant and for the laboratory to oversee the quality of the TDP. Administrative workers amount was assumed to be lower than supplier presented since in this case plant is embedded to tire plant. Thus, for example, sales are not required for TDP and already existing administrative worker capacity was assumed to able to perform additional tasks from the devulcanization plant.

5.2.2 Devulcanization plant carbon footprint

Devulcanization plant carbon footprint was calculated according to ISO 14067 standard using GHG factors presented earlier. GHG factors for the plant not using TDP are the same as presented in the pyrolysis carbon footprint chapter, and thus not presented in this chapter. GHG factor for tire plant with embedded devulcanization plant is presented in table 11.

Table 11, Annual tire plant GHG emissions with embedded devulcanization plant.

Category	Raw material	Manufacturing
Annual GHG emissions ($tonCO_2e/year$)	126694,335	32062,63
Total	158756,96	

GHG emissions from the devulcanization are added to manufacturing, since emissions are created in the tire plant premises. Hence manufacturing emissions increase, but vice versa raw material emissions decrease by comparing to tire plant utilizing only virgin raw materials.

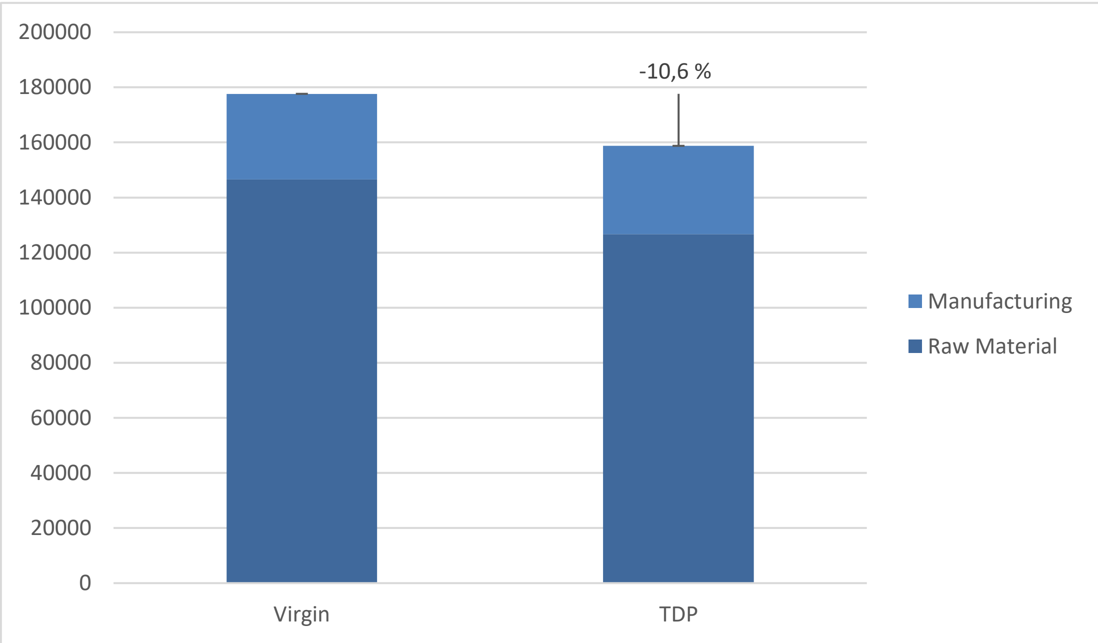

Figure 15. GHG emissions comparison of utilizing only virgin raw material between utilizing also TDP

Figure 15 visualizes how tire plant utilizing only virgin raw material compares to the tire plant embedded with the devulcanization plant. From figure 15 can be seen how much GHG emissions can be reduced from the raw material stage by utilizing TDP. Raw material stage reduction is enough to cover the increase in the manufacturing stage, and still decrease overall cradle-to-gate emissions by almost 20 million kilograms of GHG emissions annually.

5.2.3 Devulcanization plant profitability

Profit from the devulcanization plant comes only from the raw material purchase savings since the only yield material is TDP. TDP is assumed to replace the synthetic rubber part of the tire, as presented in table 1 in theory part PCR tread is mostly made of synthetic rubber. Synthetic rubber generates more emissions, and it has a higher price per kilogram. Therefore, by aiming to replace synthetic rubber instead of natural rubber, the profitability of TDP is higher as well as green impact.

Costs to produce TDP are varied by the feed material. Thus, costs are calculated for two feed material cases first uses only tire plant waste, and the second uses only EOLTs. Costs are calculated using equation 11.

$$\frac{(EC \times LC) \times 1{,}1 + EOLT_{costs}}{TDP_{\frac{yield}{h}}} \tag{11}$$

Electric costs are presented as EC, labor costs are presented as LC and EOLT collection costs are presented as $EOLT_{costs}$ in the equation 11. All the costs are per hour of operating and so by dividing costs by hourly yield costs per one kilogram are found out. Maintenance costs are 10 % of the operating costs and so operating costs are multiplied by 1,1.

Table 12, TDP costs

EOLT rate	TDP costs per kg
0 %	1,24 €
100 %	1,36 €

In table 12 costs per kilogram of TDP are calculated in two cases which are mentioned earlier. Real price is likely in between the values presented in the table 12 since feed material is likely a mix of EOLTs and plant waste.

Figure 16. Payback time of devulcanization plant with 700 kg per hour capacity

Payback time is calculated for the same case tire plant with the same operating conditions and thus, has the same assumptions as to the pyrolysis plant. Calculated payback time is in an optimal situation where the devulcanization plant is operated seven days a week in three shifts and extra yield is sold with the same price as assumed procurement saving. Thus, the payback time in figure 16 is the shortest possible payback time for the devulcanization plant. Devulcanization plant requires more labor, as presented in figure 11 significant amount, almost 80 %, of devulcanization plant operating costs are from operators and administrative workers. It can be seen in figure 16, that operating costs are not significantly lower than profit.

5.2.4 Devulcanization plant feasiblity

Feasibility of the devulcanization plant is analyzed in this chapter. The Devulcanization plant is assumed to have 82 % yield from EOLTs as fabric and steel are separated during the process and tread wear is considered. The analysis identifies that the devulcanization process is dependent on the EOLTs and TDP sales as tire plant cannot utilize all the produced TDP in the tire manufacturing.

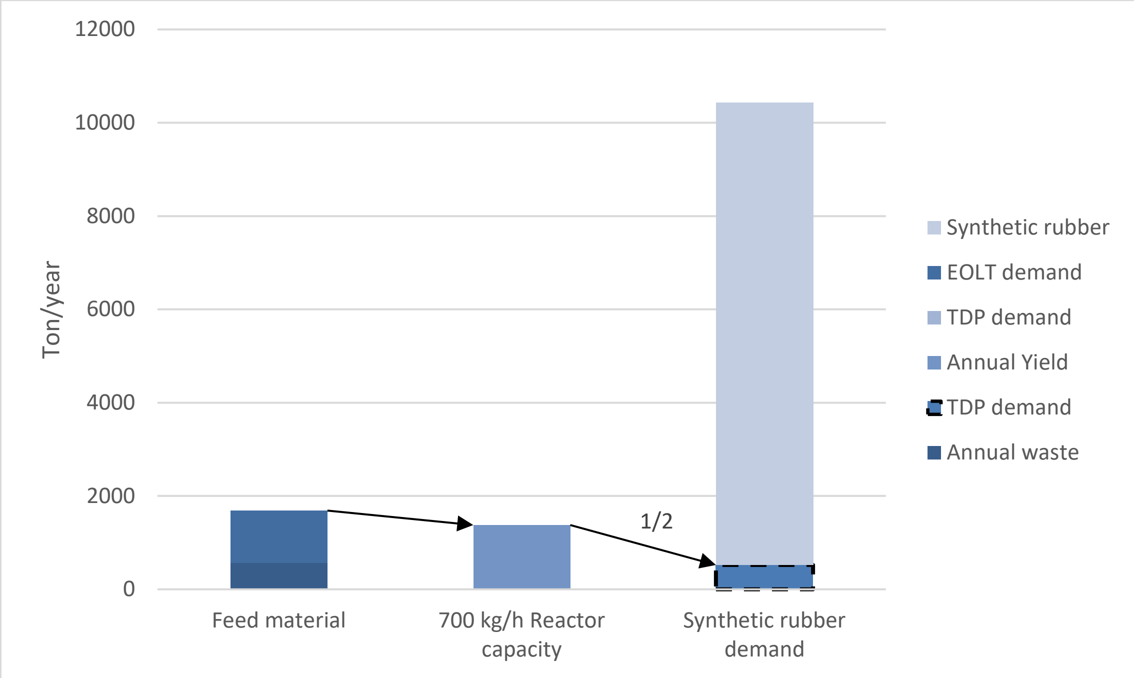

Figure 17. Annual devulcanization capacity

Figure 16 visualizes TDP demand with estimated utilization rates and how demanded capacity corresponds to reactor capacity. Starting from the left is visualized how feed materials are dived between plant waste and EOLTs. The Middle column visualizes yield from the devulcanization reactor, and the right column visualizes, from the figure can be seen that TDP yield is 2 times higher than demand. Devulcanization plant is operated 5 times a week in one shift, this way yield is sufficient and spare time is left for maintenance operations.

5.3 Comparison of the recycling technologies and normal tire plant

The comparison was made by utilizing the AHP method. AHP method is sufficient since it is an objective way to compare different alternatives between multiple objectives or factors. AHP method has been successfully used in selecting one alternative from many which is also the case in this study. The aim of the comparison is to compare two recycling cases and normal operations. Rates that were used vary between 1 and 9, where 9 is the highest importance and 1 is neutral.

Three alternatives were chosen for the comparison of normal tire plant without recycling facilities and tire plant with embedded pyrolysis plant or devulcanization plant. Factors that were chosen for the comparison are investment costs, profitability, feasibility, and GHG reduction. Investment costs are the amount invested in recycling technology. The profitability factor is the profit created by recycling, mostly from the saved raw material purchase costs. The feasibility factor defines, how well technology suits for needs of the tire plant. GHG factor measures the decrease of carbon footprint.

Table 13, Comparison matrix of evaluation factors.

	Invest-ment	Profitabil-ity	Feasibil-ity	GHG re-duction	$\sqrt{\Pi}$	Weights
Investment	1,00	1/2	1/2	1/2	0,35	0,07
Profitability	2,00	1,00	1/2	1	1,00	0,19
Feasibility	2,00	2	1,00	2	2,83	0,55
GHG re-duction	2,00	1	1/2	1,00	1	0,19

In table 13 comparison of evaluation factors is presented. Investment costs were evaluated to be insignificant since payback time for recycling technologies are reasonable. Profitability impacts payback time and finally to the tire plant profit, and therefore it was evaluated to be significant. Feasibility was evaluated to be the most significant factor since it represents how well technology suits the tire plant. GHG reduction was rated to be the second most important factor since the motive of the study is to reduce tire and tire plant emissions. Profitability was rated equally important as it effects to the payback time.

Table 14, Comparison matrix of investment factor among alternatives.

	Normal	Pyrolysis	Devulcanization	$\sqrt{\Pi}$	Weights
Normal	1,00	6,00	9,00	7,35	0,90
Pyrolysis	1/6	1,00	2	0,58	0,07
Devulcanization	1/9	1/2	1,00	0,24	0,03

Table 14 presents a comparison of the investment factor among the alternatives. The higher the factor fewer investments are required. Normal tire plant does not require any investments and hence pyrolysis and devulcanization plant have higher factors. Investment costs of pyrolysis plants are lower than for devulcanization plants and thus have a lower factor. A similar devulcanization plant is over 50 % more expensive and thus factor 2 is appropriate.

Table 15, Comparison matrix of profitability factor among alternatives.

	Normal	Pyrolysis	Devulcanization	$\sqrt{\prod}$	Weights
Normal	1,00	1/9	1/9	0,11	0,02
Pyrolysis	9,00	1,00	1/2	2,12	0,33
Devulcanization	9,00	2	1,00	4,24	0,66

Table 15 presents a comparison of the profitability factor among alternatives. Higher factor relates to higher profit created. Since a normal tire plant cannot handle tire plant waste, profitability was assumed to be very low. Tire plant could improve profitability by reducing the amount of waste created and reduce the amount of raw materials required. The waste amount can be reduced by improving process controls and reducing trimming needs. As the devulcanization process reclaims rubber, which is a more expensive raw material than carbon black profitability is higher. However annual profitability is only slightly higher and thus factor 2 is appropriate.

Table 16, Comparison matrix of feasibility matrix among alternatives.

	Normal	Pyrolysis	Devulcanization	$\sqrt{\prod}$	Weights
Normal	1,00	1/9	1/2	0,24	0,04
Pyrolysis	9,00	1,00	2,00	4,24	0,77
Devulcanization	2,00	1/2	1,00	1,00	0,18

Table 16 presents a comparison matrix of feasibility. The feasibility factor is used to evaluate how the recycling technology suits the need of the tire plant. As a normal tire plant does not have an embedded recycling facility and thus cannot handle waste generated from the manufacturing feasibility was assumed low. Pyrolysis can handle all the waste generated from the recycling facility. Since devulcanization technology can only handle vulcanized rubber waste and unvulcanized rubber, steel and fabric are not processed. Which represents 50 % of the waste, thus factor 1/2 was chosen. Compared to pyrolysis factor 2 was appropriate since pyrolysis can handle twice the amount of waste generated.

Table 17, Comparison matrix of GHG reduction among alternatives.

	Normal	Pyrolysis	Devulcanization	$\sqrt{\prod}$	Weights
Normal	1,00	1/9	1/9	0,11	0,02
Pyrolysis	9,00	1,00	1/3	1,73	0,25
Devulcanization	9,00	3,00	1,00	5,20	0,74

Table 17 presents a comparison matrix of GHG reduction. As in profitability, a normal tire plant can only reduce GHG emissions by reducing the amount of waste generated. Pyrolysis has the potential to reduce emissions, from raw material acquisition and steam generation. Devulcanization can replace a higher amount of virgin raw material with reclaimed material and thus has the highest potential, to reduce emissions. Since replacing part of the natural gas with pyrolytic gas is seen only as potential pyrolysis technology was evaluated to have a low factor.

6. RESULTS

In this chapter results from the survey and comparison are presented. Results are not analyzed deeply in this chapter. Further analysis and discussion are in the chapter 7.

6.1 Survey results

Answer rate of survey research was 38 % since 8 organizations replied to the survey. Two organizations replied with generic information documents and stated that they will not provide any other information, and thus did not reply to the survey. The survey aimed to identify how different countries manage EOLTS and how it affects storage capacity, condition of EOLT, and possible expenses. Organizations that replied are divided into three continents and at least one organization from the three EOLT management systems where represented.

Table 18. EOLT handling before recycling facility

ID	1	2	3	4	5	6	7	8	Percent-age
Are end-of-life tires treated in some way before sending to recycling facility?	Yes	No	Yes	No	No	Yes	Yes	No	50 %
Are end-of-life tires stored temporarily between collection and recycling facility?	Yes	No	Yes	No	Yes	Yes	Yes	Yes	75 %
Are passenger car tires, motorcycle tire and truck tires separated?	No	Yes	Yes	No	No	Yes	Yes	No	50 %

Table 18 presents answers replied by answerer regarding EOLT handling before, sending them to recycling-facility. Results show that 50 % of the collectors treat EOLTs before sending them to recycling-facility and most of the collectors have buffer storage for the collected EOLTs.

Figure 18 presents EOLT batch sizes and shipment intervals dived according to answers received from the EOLT collectors. Batch sizes are divided by European vehicle classes N1, N2, and N3, and to two typical container sizes in case that containers are used in

EOLT shipment. According to Monster Tyres (2020) one 40 ft. container can fit approximately 1500 tires.

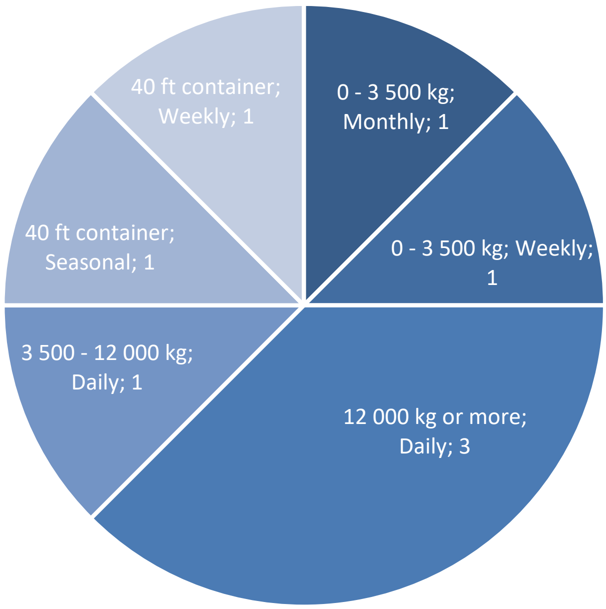

Figure 18, EOLT batch sizes and shipment interval

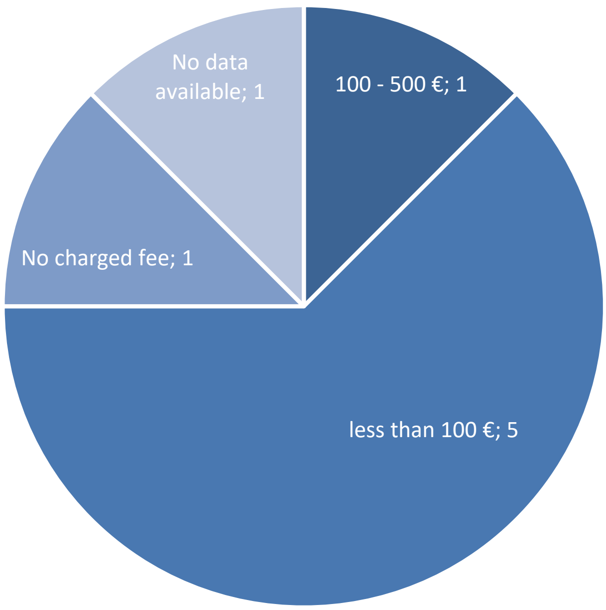

Figure 19, Fees collected from the recycler per EOLT ton

Figure 19 presents fee charged by ton of EOLTs. One replied that they could not answer the charged fee and it's presented in the figure as no data available. It is likely, that fee covers only the collection operations and administrative costs, thus logistic costs will increase the collection costs.

6.2 Analytical hierarchy process comparison results

Results of the analytical hierarchy process where calculated by using the factors presented earlier in the analysis chapter. Weights of the individual factors and how alternatives reflect are summarized in table 19.

Table 19, Summary of the weights.

	Investment	Profitability	Feasibility	GHG reduction
Weights	0,35	1,00	2,83	1
Normal	0,90	0,02	0,04	0,02
Pyrolysis	0,07	0,33	0,77	0,25
Devulcanization	0,03	0,66	0,18	0,74

Weights are multiplied with weight of each alternative which provides results which are presented in table 20. Global evaluation column is the sum of the results of the individual factors and thus is the result.

Table 20, Sum of alternatives.

	Investment	Profitability	Feasibility	GHG reduction	Global Evaluation
Normal	0,32	0,02	0,12	0,02	0,48
Pyrolysis	0,03	0,33	2,19	0,25	2,79
Devulcanization	0,01	0,65	0,52	0,74	1,92

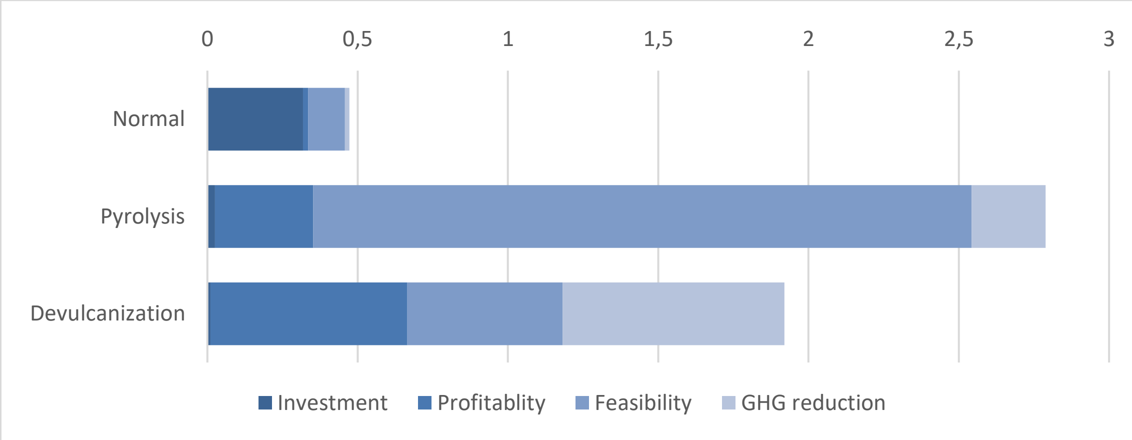

Figure 20, Results of the AHP comparison

Figure 20 visualizes the results from the AHP comparison and how weights are distributed by the factors. From the figure can be seen that pyrolysis is by far most feasible and devulcanization reduces GHG emissions the most. As could be assumed, that normal tire plant has best results only in the investment category. Since investment factor has lowest weight factor normal tire plant falls behind the comparison.

7. DISCUSSION

In this chapter relevance, reliability, and scalability of the results are discussed. Empirical research results are compared against previous results presented in the theory chapter. Pyrolysis and devulcanization technologies were chosen to case study comparison since they were the two most predominant technologies. Both technologies are available for tire plant's use by purchasing reactors and utilities or by licensing the technology. Cryogenic milling was excluded since it is not commercially available and utilizing micronized rubber powder requires more additives. Thus, the benefits of cryogenic milling technologies are already minor by a preliminary examination.

7.1 Pyrolysis plant relevance

As presented in theory part feasibility of pyrolysis plant is depended on the recovered CB yield. The value of the recovered oil or gas is minor compared to recovered CB. Transportation emissions or costs were excluded from the study thus they are likely to increase the feasibility of pyrolysis. Due to CB bulk density production facilities are located close to customers, hence recycling facilities should also be located close to tire manufacturing facilities. Bulk density favors the embedded concept of the recycling facility. By embedding the recycling facility with the tire plant, it is also possible to use gas yield from the pyrolysis in the steam boiler which was excluded in this study.

Utilizing the pyrolytic gas in steam production could also reduce GHG emission of the tire plant since pyrolytic gas has a smaller GHG factor than natural gas. As presented in theory gas can reduce pyrolysis process emissions significantly. Utilizing pyrolytic gas could also increase the profitability of the pyrolysis plant as it reduces natural gas purchase costs. However, in this case, the pyrolysis process itself does not generate any emissions since it is electrically heated. The electrically heated pyrolysis process has better controllability and efficiency.

GHG reduction properties are presented to be quite significant in the theory part, but as presented in theory recovered CB quality is lower than in virgin CB and thus cannot replace completely virgin CB. Due to quality reasons rate at which recovered CB can be utilized in tire manufacturing is assumed to be relatively low and thus overall GHG reduction rate is only marginal. GHG reduction potential is however significant since CB represents a large quantity of the tire's overall GHG emissions. Thus, if recovered CB quality can be increased to replace a larger quantity of virgin CB GHG emission reduction would increase.

Pyrolytic oil and gas have been studied in theory, and they have likely higher emissions than virgin oil or gas. Thus, their burning emissions should be studied if they are utilized in the tire plant. If emissions are higher and especially if emission limits are exceeded purification process is likely required, which effects the profitability of the plant.

From a circular economy point of view, pyrolysis is listed under the R8 recover strategy, even though it recycles CB and steel from EOLTs and plant waste. However over 50 % of the pyrolysis yield are fuels used to generate energy, hence this might be the reason why pyrolysis is listed under recover strategy. Thus, in practice pyrolysis in between R7 and R8 strategies as it recycles material and recovers energy.

7.2 Devulcanization plant relevance

Devulcanization plant utilizes carbon dioxide assisted thermo-mechanical method and does not create additional chemical waste. Additional chemical waste is identified as a drawback of the devulcanization method especially for chemical methods and has been a limiting factor of commercial use. The method in this study is particularly prominent as it does not create additional chemical waste. The tire-delivered polymer obtained from the devulcanization process has not the same mechanical properties as virgin synthetic rubber. As mentioned in the theory part mechanical devulcanization can break the main chain and might not break all the sulfur bonds. Thus, tire delivered polymer can only replace synthetic rubber to a certain extent, which limits the economical savings and GHG emissions reduction of tire delivered polymer.

Replacing synthetic rubber is in practice a simplified estimation. Utilizing devulcanized rubber, might also replace natural rubber or be an additive in the compound thus it would not replace rubber. As the rubber qualities vary in different compounds depending on the tires that are produced. Different compounds are used in PCRs and in TBRs, according to their target use and market area. Thus, more accurate data of the tires planned to be manufactured would be required to simulate more accurate demand for the devulcanized rubber.

Devulcanization plant is also assumed to only claim EOLT PCR tires where the collector would separate TBRs. As only 50 % of the collectors answered that EOLTs are separated this will increase the uncertainty of the feasibility, depending on the country in question. As devulcanization technology only can process vulcanized rubber further research should be aimed to study if the milling process could separate fabric or steel from unvulcanized rubber. Since the devulcanization plant has overcapacity in the shredding stage, it could be used to separate unvulcanized rubber from the fabric or steel. Thus, increase the amount of waste the devulcanization plant can handle. This would increase the feasibility of the devulcanization plant and therefore likely to be more sufficient compared to pyrolysis if all the generated waste could be processed in the devulcanization plant.

Devulcanization plant requires a large amount of manual labor, which increases the operating costs. In addition to the increased operating costs risks are also increased as profit is dependent on the rubber price, a small decrease in the rubber price can reduce the devulcanization plant profit. Utilizing more automation could be therefore appropriate research aiming to reduce operating costs. More automation would increase investment costs but reducing operating costs enough effects to payback time, which could optimally be reduced.

From a circular economy point of view, devulcanization is preferable as it is listed under R7 recycle strategy. Devulcanization yield is practically only recycled tire-delivered polymer and can be utilized in the largest quantity of recycled materials, thus material circularity is better.

7.3 Reliability and scalability

From the survey research can be identified as a possible misinterpretation regarding the availability of the EOLTs. As some countries have replied that EOLTs are available on 40 ft container seasonally or 3500 kg of EOLTs is available weekly. Comparing these results to EOLT generation presented in theory, significantly more EOLT should be available as for example Ukraine alone produces 0,2 million tons of EOLTs annually. Since the question is formed as typical batch size, answerers have likely answered to what size of batches is send. Thus, is likely that multiple batches would be available in the given time period that was answered. As EOLT availability is crucial in the recycling cases availability should be verified before investment in the recycling facility.

In both cases, EOLT material flow was assumed to be quite homogenous, as they were assumed to be PCRs with 1,6 kg of tread rubber wear. As EOLTs represent a significant part of the feed material in recycling plants their quality affects the yield in both cases. In practice, EOLT wear is likely higher or smaller depending on the country. In some countries, tires are used to the absolute maximum wear as in some countries, laws define maximum wear of tires. Especially in pyrolysis cases amount of wear affects the recovered CB yield. Other factors that affect the EOLT qualities that were not considered are winter tires, which also affect the yield of the reclaimed materials as the compound differs from summer tires. In more detailed research EOLT qualities should be simulated according to the tire use in specific countries.

The reliability of the payback times is affected by the price variations of the virgin raw materials as the payback times are dependent on the procurement saving. Hence both synthetic rubber and CB are oil-derived products and thus their price varies according to oil prices. Payback times can be therefore slightly longer or shorter. However, utilizing recycled materials can vice versa protect from the price fluctuations of the oil derived products. In the economic evaluation logistics costs should also be included to gain more reliable payback times as they will likely increase the costs. Payback times are also affected by the operating conditions of the recycling plant, mentioned presented payback times are the shortest possible times with current knowledge. If the recycling plant is not operated seven days a week in three shifts payback times are longer as profit yield is lower.

This study only relies on the existing knowledge of the reclaimed materials. It would be appropriate to study more of the qualities of the reclaimed materials and thus identify opportunities to improve the quality of the reclaimed materials. As mentioned in the theory part recovered CB requires further treatments. The amount of the utilization rate in this study is assumed to be relatively low for safety reasons as the quality is not ensured. The low utilization rate assumption is reasonable also since no further treatments are applied in the study. However, from the study materials can be realized that profit yield is significantly larger than expenses from the pyrolysis. Thus, it could be economically viable to also include after treatments to the pyrolysis plant to increase the utilization rate of the recover CB by increasing the quality of recovered CB.

Both recycling technologies that were studied, are easily scalable as the capacity is dependent on the reactor amount. However, in the tire plant case, both technologies are within the feasibility limit as recycling plants do not have to be operated around the clock to match demand. Thus, recycling capacity could also be scaled up by increasing operating shifts. Profit of the plant increases as the capacity increases if extra yield can be sold or utilization rate increased. GHG reduction is stable regardless of the recycling facility's capacity, hence GHG reduction is dependent on the rate at which reclaimed material can be utilized.

When scaling up, the reverse supply chain of EOLT should be considered carefully. Long logistic chains for EOLTs do not make economic or environmental sense. Thus, EOLT supply should be created relatively close to the tire plant. Logistic performance could be improved by improving EOLT bulk density, so longer logistic chains could be more feasible. Bulk density could be improved by shredding EOLTs already in the collection site since tire shape creates forcibly air slots in the carrier.

8. CONCLUSIONS

Significant amount of tire GHG emissions is generated during the raw material acquisition stage, in a cradle-to-gate life cycle scope. Thus, recycling is a sufficient method to reduce GHG emissions of the tire. As it reduces the amount of raw material required in tire manufacturing. RQ1 was answered already in the theory part as pyrolysis and devulcanization technologies where identified to be potential recycling technologies thus can reuse plant waste and EOLTs.

Case strategy was used to answer RQ2 considering characteristics and side streams. Devulcanization technology didn't have any identified side streams and pyrolysis side streams gas, oil and steel can be utilized in tire plant or in other purposes, hence no additional waste in generated in both cases. Pyrolysis was already seen as a potential way for tire recycling however drawback of pyrolysis is the quality of recovered CB. Devulcanizing EOLT or vulcanized waste can be utilized in larger quantities and thus have more impact on GHG emissions. In the end, however, pyrolysis was a more feasible option with current knowledge as it can process all the waste generated during tire manufacturing. Pyrolysis can also possibly reduce tire plant emissions, by reducing the amount of natural gas used in manufacturing.

Considering scalability, which was the goal of this study, of both recycling cases, it can be stated that both can be scaled for almost any given tire plant. The only limit in the scalability is that the tire plant should have enough capacity for feasible demand of the reclaimed material. As the motive for this study was to reduce tire and tire plant emissions, pyrolysis has the potential to reduce emissions in both. With current knowledge, it was assumed that pyrolysis gas was not utilized, and hence both compared technologies increased tire plant emissions. However, both compared technologies have the potential to reduce tire emissions enough to reduce overall cradle-to-gate emissions. To answer RQ3 recycling tire plant waste and EOLTs have a potential to reduce raw material purchase costs and reduce tire CF, depending of the utilization rate of reclaimed material.

The quality of reclaimed materials was unstudied, due to time limits, and hence utilization rates were based on estimations. Another limit in this study was the unavailability of real data from the case tire plant, as it is still in the ramp-up phase. Also, production plans were not available for this study, and thus created concept is more as a basis for practical recycling plant construction plans. More details of the production plans would allow more precise demand forecasts of the reclaimed material. As the case country does not have an identified EOLT management system EOLT quality could not be simulated or estimated in detail.

The aim of the study was to find a scalable concept that would be located embedded in the tire plant. Thus, the concept should be sufficient to handle, the tire plant waste. In the end, however, a more complete solution to reduce tire emissions is likely a solution combining both reclaimed materials. Where the pyrolysis plant is embedded in the tire plant and the devulcanization plant is independent of the tire plant and reclaimed rubber is delivered to the tire plant. Devulcanization plant can be large enough to fulfill the demand for multiple tire plants thus being as other raw material suppliers. This reduces tires CF by not increasing too much tire plants CF. By utilizing both reclaimed materials is also most suitable solution in circular economy point of view.

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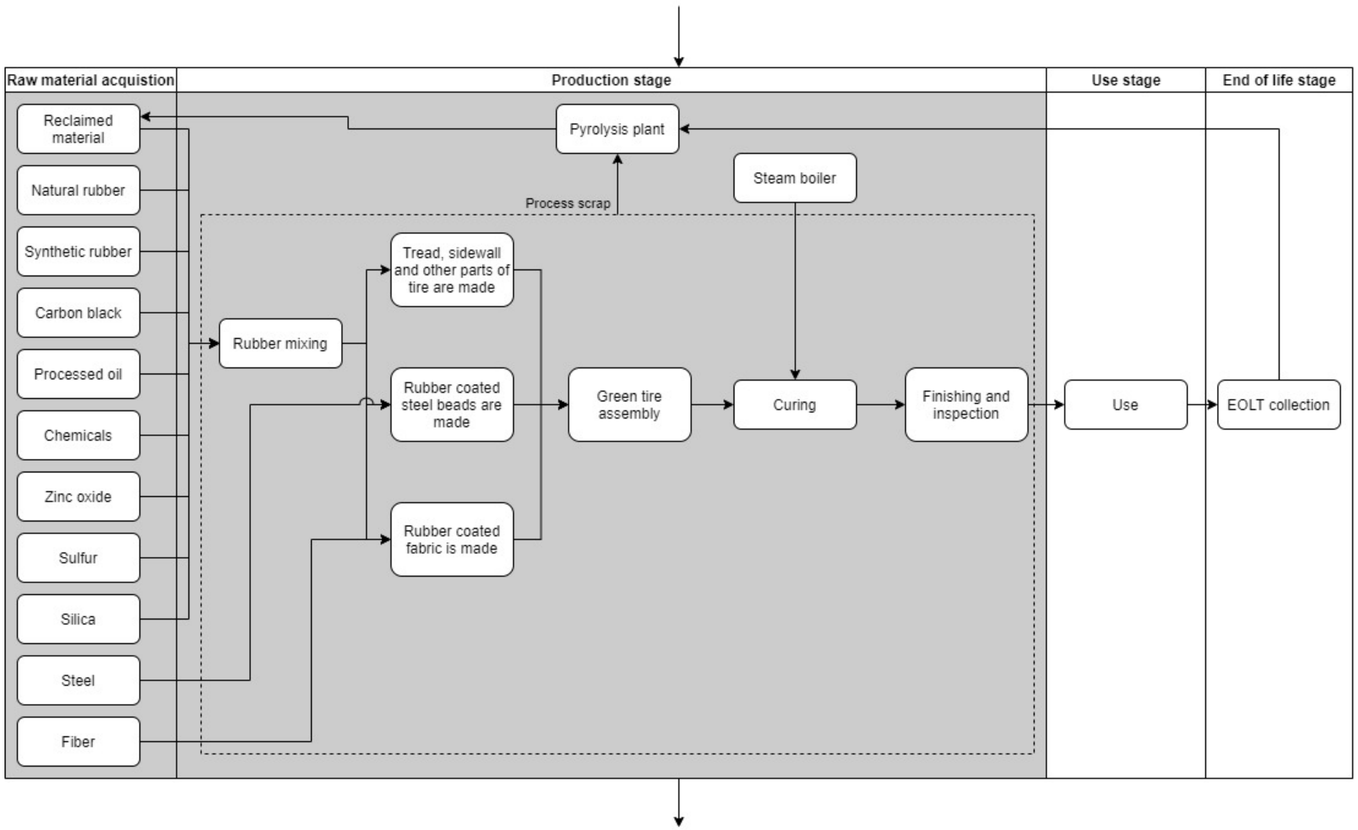
APPENDIX A: TIRE LIFECYCLE SYSTEM WITH PYROLYSIS PLANT

Input (electricity, natural gas)



Output (GHG emissions, extra pyrolysis oil and gas)

APPENDIX B: TIRE LIFE CYCLE SYSTEM WITH DEVULCANIZATION PLANT