Life Cycle Assessment of Coated White-Lined Chipboard

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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(Signature of candidate)

____03_____day of ________February_________2023

Executive Summary

South Africa is working towards creating a more sustainable and circular economy. As part of this goal, South Africa released the extended producer's responsibility to improve the effective management of products in the final waste streams by reducing the number of raw materials used in the product, minimizing waste and reducing the toxicity of the product in the final waste stream. This legislation applies to industries that produce products such as paper, plastic, biodegradable and compostable materials, glass, metal, and single-use packaging. According to the EPR legislation, white-lined chipboard (WLC) is considered a kraft/corrugated case product and is part of the paper and paper packaging class. The South African EPR requires an LCA for the products, however, South Africa does not have datasets for the pulp and paper industry that can be used to conduct the LCA. As a result, local LCAs have been conducted using international data. The results generated from these do not represent South Africa, its processes, infrastructure or its technologies and can therefore misinform industries, shareholders or management of the true impact of a process.

The objective of this work was to perform a cradle-to-gate LCA on WLC manufacturing in which the process of forestry, pulping, recycling and manufacturing was included. Data from local industries were used to conduct the LCA, thereby using data that only represent South Africa and eliminating the use of international data as much as possible. As part of the objective to create the South African LCA and South African datasets, process improvements, comparisons between international data and local data, and comparisons of life cycle impact methods were studied as well.

The life cycle assessment included a cradle-to-gate approach in which the environmental impact to produce a "1 kg coated white-lined chipboard" was studied. The LCA was conducted using SimaPro v9.3.0.3 simulation software and the impacts were determined using the ReCiPe 2016 v1.1 (H) impact method. The LCA included forestry and forestry operations, recycling, pulping and bleaching of virgin eucalyptus wood fibre, and WLC manufacturing. The LCA did not include the converting, use, or end-of-life phase. Data was collected from local industries, and most of the data was comprised of primary data, however, due to some data gaps, mass balances, energy balances and secondary data were used to calculate the missing values. The data collected was compiled into inventory lists for forestry, pulping and WLC manufacturing.

The environmental impact assessment of WLC production was conducted considering the following impact categories: global warming, freshwater ecotoxicity, terrestrial acidification, freshwater eutrophication, ozone formation and ozone depletion. The results indicated that the mill's use of electricity and energy (steam production) were the major contributors in all impact categories. The results indicated that it was because of South Africa's and the mill's reliance on fossil fuels, particularly coal, to produce electricity and energy.

A comparative LCA was conducted in which the South African WLC data was compared to a European dataset and a South African – European hybrid dataset. Due to South Africa's reliance on coal for most of its electricity and energy requirements, the South African datasets had a much higher impact in all the impact categories compared to the European dataset. The comparison to the hybrid dataset indicated that the hybrid dataset had a more accurate representation of the South African process. However, there was still variability in the results. It was expected that the environmental scores from the hybrid data analysis would be in between the South African and European scores, and for 4 out of the 6 categories it was. The comparisons favoured the use of South African data as it was more accurate and representative of the South African process and therefore more reliable, but the use of hybrid data could be beneficial if a quick LCA study needs to be conducted to obtain a general idea of the impact of a process or product comparison.

The uncertainty test was conducted using the Monte Carlo analysis with a 1000-interval run and a 95 % confidence interval. The uncertainty test conducted indicated that the use of different models could significantly change the outcome of the impact scores. Three factors could affect the outcome of the impact assessment, namely the uncertainty of the data in the inventory list, the inventory list of the impact methods and the characterisation factors used by the impact methods. To ensure that the uncertainty from the Monte Carlo analysis was because of the data in the inventory and not because of the impact method. The Monte Carlo analysis was conducted for three methods, the ReCiPe 2016, EF 3.0 and the TRACI 2.0 method. The error for global warming, acidification and ozone formation was small for all three impact categories, indicating that the uncertainty for the data was little. The error for freshwater ecotoxicity and ozone depletion was large for ReCiPe 2016, but small for EF 3.0 and TRACI 2.0, indicating that the uncertainty came from the ReCiPe method and not the data. Lastly, for freshwater eutrophication, the error for all three methods was large, indicating that the uncertainty came from the data used and therefore the data was less reliable.

As part of the LCA, possible process improvements were studied using comparative LCA. The first alternative studied was the use of alternative fuel sources for the boiler process. From the use of natural gas, coal and biomass it was found that both natural gas and biomass had an overall reduction in environmental impacts for all impact categories. Of the three fuels, biomass was the best alternative for global warming, but other than global warming, the environmental impact of both biomass and natural gas were similar. Although both options were more environmentally sustainable, limitations such as the capital required for boiler conversion/replacement, increased transport and transport costs (biomass), biomass availability, fluctuating currencies (imported natural gas) and the need to reduce fossil fuel reliance (natural gas), both alternatives could not yet be fully implemented.

Replacing electricity can only be achieved by considering alternative renewable electricity sources such as photovoltaic solar power (PV) and concentrated solar power (CSP). Of the two, PV solar power is the most accessible since it uses unusable space (rooftop) and is produced and installed by local companies. Sufficient roof space is available at the mill to substitute 11.6 % of the mill's electricity with PV solar electricity. The installation and purchasing of the panels would cost around ZAR 121 million (excluding storage systems). Based on the municipal electricity cost savings, the capital could be recovered in about 5 years. Running the comparative LCA with the PV solar system included, five of the six impact categories experienced a reduction, with global warming experiencing the lowest reduction of 5 % and ozone depletion experiencing the highest reduction of 7.8 %. The only impact category that worsened was freshwater ecotoxicity by 1.5 %, but this was due to the additional water required for PV maintenance and cleaning.

The last improvement studied was changing the production of the WLC, which consists of about 75 % recycled fibre and 25 % virgin fibre, to fully recycled fibre. A discussion with a food safety specialist indicated that doing the transition would require a completely new product development since a significant number of variables would change. These include mechanical properties; food safety requirements; changes in chemical requirements; increases in transport and energy; and changes to the production process as equipment would have to be altered or replaced. Conducting a theoretical comparative LCA, the fully recycled WLC had an overall lower environmental footprint compared to the original WLC. The largest difference was for ozone depletion at 6.4 % and the smallest was for global warming at 0.44 %. However, more research is required to accurately compare the two on a realistic basis as opposed to a theoretical basis.

Acknowledgements

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Nomenclature

adt	Air dry ton
CSP	Concentrated solar power
DAFF	Department of agriculture, forestry and fisheries
EU	Europe
EPR	Extended producers’ responsibility
ha	Hectare
kg	Kilogram
kg CFC11 eq	Kilogram trichlorofluoromethane equivalent
kg CO_2 eq	Kilogram carbon dioxide equivalent
kg 1,4-DCB eq	Kilogram 1,4-Dichlorobenzene equivalent
kg NO_x eq	Kilogram nitrogen oxide equivalent
kg P eq	Kilogram phosphourus equivalent
kg SO_2 eq	Kilogram sulfur equivalent
kJ	Kilojoule
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Megajoule
MW	Megawatt
NFSD	National Framework for Sustainable Development
NEMWA	National Environmental Management: Waste Act
NHV	Net heating value
PV	Photovoltaic
CPV	Concentrated photovoltaic
TRS	Total reduced sulfur
US	United States
USD	United States dollar
VOC	Volatile organic compounds
WLC	White-lined chipboard
ZAR	South African Rand

1. Introduction

1.1. Background

In 2008, the Cabinet approved the South African National Framework for Sustainable Development (NFSD). It is a proactive strategy that regards sustainable development as a long-term commitment, which combines environmental protection, social equity and economic efficiency with the vision and values of the country (Department of Forestry, Fisheries and the Environment, 2008). The goal of the NFSD was to guide South Africa to achieve more sustainable development and greater circular economy production.

To aid in the goal of achieving sustainability, the South African government published the extended producer's responsibility (EPR) regulations on November 5, 2020, under the National Environmental Management: Waste Act (NEMWA) (Act 59 of 2008). The regulation is intended to ensure the effective management of end-of-life products by minimising the amount sent to landfill, reducing the number of raw materials used in the product and reducing the product's toxicity in the final waste stream. This would be achieved by studying the entire value chain of the product, starting from raw material acquisition up to final product disposal. This is necessary to move South Africa into a more sustainable and environmentally friendly future. The EPR applies to package materials such as paper and paper packaging, plastic, biodegradable and compostable materials, glass, metal, and single-use packaging. White-lined chipboard (WLC) is categorised as a kraft/corrugated case product and therefore is part of the EPR.

Life Cycle Assessment is a method to assess the full environmental impact of a system (Muralikrishna & Manickam, 2017). It is a quantitative tool used to measure the environmental impacts of a product, all the processes and materials used, and the wastes produced during the production of the product. As such, an LCA is said to include the 'cradle-to-grave' impacts of the system, which start from resource extraction to post-consumer disposal. Life cycle assessment can be used to study a process and find possible solutions to improve the process (Muralikrishna & Manickam, 2017), by:

- reducing waste and resource consumption.
- implementing improved or newer technology.

- comparative studies amongst different products/processes; and
- influence business ideas and decisions

The life cycle assessment of white-lined chipboard was conducted for three value chains, namely forestry, pulping and manufacturing. The LCA was used for studying the environmental impacts of all three chains, but possible process improvements were only considered for the white-lined chipboard manufacturing mill. Because this is a cradle-to-gate study of WLC, the converting phase, use phase and end-of-life phase were not included in the research.

1.2. Problem Statement

LCAs are data-intensive, and a single project can at times contain hundreds (if not thousands) of data entries. Datasets can be obtained from many different sources such as EcoInvent, US LCA Digital Commons, the Brazilian LCA database, the European Life Cycle Database, IDEA, the Mexican LCI Database, France's IMPACTS database, and the Global Feed LCI institute (Life Cycle Initiative, 2021) of which EcoInvent has the largest database with thousands of datasets. The problem is not the lack of datasets available for the pulp and paper industry but that none are specific to South Africa (Karkour et al., 2021).

In addition, the data supplied by other countries represent different technologies, resources, and waste management techniques. Most datasets available are international, and the operations of international processes are significantly different to those of South African counterparts. These differences all contribute to the environmental impact of a process. Therefore, using international data will have a significantly different impact on the outcome of the LCA as opposed to using South African data.

However, despite the lack of datasets available and different technologies/processes, LCAs are still conducted locally with international datasets that do not represent South Africa. This affects the quality and validity of the results, leading to inaccuracies in conclusions and the information supplied to investors, corporate heads, and policymakers.

1.3. Research objective

The objective was to do a cradle-gate LCA on white-lined chipboard. This enabled the generation of LCA data that is specific to South African conditions and to identify the data gaps where additional information needed to be compiled. The outcomes of the project were:

1. Compile a life cycle inventory list.
2. Determine data gaps and suitable mechanisms to address the data gaps.
3. Submit datasets for incorporation into the EcoInvent database.
4. Life cycle impact assessment of white-lined chipboard.
5. Investigate alternative methods in the life cycle to reduce the environmental impact of the different processes.

The study was conducted following the four stages of LCA, which are goal and scope, inventory analysis, impact analysis and discussion of the results. The international standards for LCA, ISO 14040 and ISO 14044, were used to guide the study. The impact assessment was measured using simulations in SimaPro software, which was also used to conduct comparative LCAs in which different processes and technologies were studied to try and reduce the environmental impacts of the process of producing WLC.

1.4. Structure of the dissertation:

Chapter 1: Gives a brief description of the background of LCA in South Africa, the purpose for conducting the LCA and the objectives of the study.

Chapter 2: This is an overview of the unit operations involved in the production of white-lined chipboard which includes forestry, pulping and manufacturing of white-lined chipboard. The second part includes a description of LCA and how it has been applied in the pulp and paper industry.

Chapter 3 and Chapter 4: This is the goal and scope of the LCA and includes the creation of the system boundary and provides the inventory lists in which all mass and energy flow for WLC production, pulping and forestry are supplied.

Chapter 5: The results from the LCA simulation are presented and explained. The chapter includes the impact assessment and waste management analysis. The chapter also includes observations made concerning the influence of data and data types on the results and simulation software problems. Results and studies of possible process change to reduce the environmental impact of the process are also discussed and simulated.

Chapter 6 and Chapter 7: The main conclusions and recommendations reached by the LCA for WLC production.

2. Literature Review

2.1. Pulp and paper South Africa

2.1.1. History

The South African pulp and paper industry started in the 1920s, with the first mill built at Lip River producing wrapping and industrial papers (Association of Pulp; Paper and Board Manufacturers of South Africa, 1960). The South African paper and pulp industry has grown since then and is currently the 15th largest pulp-producing country (Fibre Processing and Manufacturing Sector Education and Training Authority, 2014) in the world. The paper and pulp industry has also expanded into several different branches of industry including multi-billion-rand commercial forestry, various types of packaging and boxing, tissue, and printed goods. In 2019 the entire forestry sector value chain contributed ZAR 24.3 billion to South Africa’s GDP with the paper and paperboard sector contributing ZAR 10.3 billion of this total value. The South African forestry and pulp sector exported ZAR 6.63 billion worth of pulp and imported ZAR 6.38 billion worth of paper and paperboard, resulting in a South African balance of trade of ZAR 0.25 billion for the entire sector (PAMSA, 2019).

2.2. Forestry

2.2.1. Background

The forestry sector contributes a significant amount to the South African economy. According to Forestry South Africa’s 2018 annual report (Godsmark & Oberholzer, 2019), the forestry sector employed around 59800 direct and 27500 indirect workers. Forestry contributed around ZAR 10.1 billion to the South African GDP and forestry-related products contributed ZAR 26.6 billion to the GDP. The industry exported ZAR 8.569 billion of forest products (excluding pulp and paper products) and had a balance of trade of ZAR 3.183 billion.

In South Africa, there are primarily three types of forests, namely indigenous forests, woodlands, and commercial forests. However, the focus on pulp and paper production makes commercial forests the main supplier of the wood fibre.

2.2.2. Forests

Indigenous Forests

Only about 0,5 % of South Africa's total land area is covered by natural forests (Department of Forestry Fisheries and the Environment, 2021). About half of the more than 1 700 indigenous tree and shrub species, representing some 530 000 ha of dense growth, grow along the south and east coasts and on the southern and south-eastern slopes of inland mountains (Department of Forestry Fisheries and the Environment, 2021). The other half is spread over the interior plateaux in isolated valleys and ravines.

Natural forests have continued playing a major role in the livelihoods and well-being of many rural communities. The use of natural forests as sources of building material, fuelwood, food, and income via tourism and medicine is increasing, with an estimated 80% of South Africa's population still using medicinal plants, most of which are sourced from natural forests

Woodlands

The woodlands, constitute a forest resource that is found within the central plateaux in the Limpopo, Kwazulu-Natal, and Mpumalanga regions. Woodlands collectively cover about 29 – 46 million ha of South Africa's surface. Woodlands are the most accessible forest resource for poor communities in South Africa. Resources gained from the woodlands can contribute around R2 000 to R5 000 to poor households annually (Department of Forestry Fisheries and the Environment, 2021). These resources can include wood as fuel and building material, craft timber, fruit, fodder, medicines, honey and meat. Rich biodiversity is found in the woodlands, comprising 5 900 plants, 540 bird species and 175 mammals (Department of Forestry Fisheries and the Environment, 2021), contributing to South Africa's tourism industry.

The National Forestry Action Programme of 1997 and the National Forests Act of 1998 are the two acts responsible for the protection and sustainable use of woodlands. Several specific woodland trees species, such as the camel thorn, leadwood, and silver tree, are also protected due to their low numbers (Maltitz & Mokoatsi, 2019). Guidelines have been set for licensing processes to assist with the control of their use.

Commercial forests

Commercial forestry occurs in South Africa with the silviculture of pine, eucalyptus and wattle. South Africa uses these sustainably farmed tree species because they are fast-growing (Molony,

2021) and because it conserves South Africa’s indigenous species. These exotic species are harvested and processed into pulp for the paper and packaging industries, sawn timber, furniture, shelving and flooring. Commercial forests account for around 1.19 million hectares (ha) of South Africa’s surface, of which 82 % of the land is privately owned (Forestry Economics Services CC, 2019a). According to Forestry South Africa (Godsmark & Oberholzer, 2019), wood cultivated in commercial forests is used for pulpwood production (56.6 %), sawlogs (37.7 %), mining timber (2.3 %), poles (2.6 %) and rest for other various purposes (0.8 %).

The forests are divided into hardwoods and softwoods. South African commercial softwoods consist of pine and make up 49.6 % of South Africa’s commercial forests. Hardwoods consist of eucalyptus and wattle, each contributing 43 % and 7 % respectively (Godsmark & Oberholzer, 2019). The trees take on average around 10 years to reach maturity, the point at which the tree becomes harvestable, however, the rotation period differs based on climate conditions and can range from 8 – 12 years. Eighty per cent of South Africa's commercial forests are FSC (Forest Stewardship Council) certified (Norris, 2017), which means that products come from responsibly managed forests which provide environmental, social and economic benefits to the surrounding communities and country.

2.2.3. Wood types and properties

The wood used in South African commercial forestry consists of softwoods and hardwoods. Both have different densities and properties that favour different characteristics in the products they are used in. The term softwood and hardwood does not refer to the physical properties of the wood, instead, it refers to the botanical structure of the tree, such as the presence of vessels/pores in the wood structure (Asif, 2009).

Softwoods

Softwoods are gymnosperms, meaning they are vascular plants that reproduce through an exposed seed or ovule (Mandal et al., 2021). Softwoods also have needle-like leaves and grow in a conical shape, such as pine trees. Softwood fibres contain tracheids, ray cells, ray tracheids, and extractives. Tracheids account for 90- 95 % of the timber volume and are aligned parallel (Figure 2-1) to the trunk of the tree, hence allowing for the vertical transportation of fluids and providing structural support (H. Chen, 2015).

Ray cells are in the radial–longitudinal plane and ensure radial movement of water and minerals between the tracheids and are also responsible for storing starchy material. Because most of the trees consist of a well-structured radial tracheid system, it has a more structured layout and is less complex and less dense than hardwood species. These properties make harvesting and processing of wood much easier.

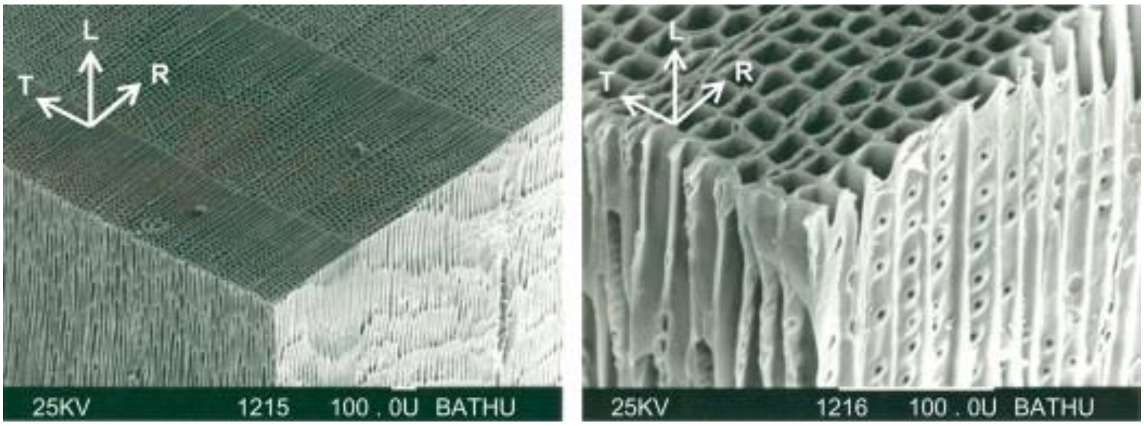

Figure 2-1: Well-structured and simple layout of the tracheid and ray cells of softwood species in the longitudinal and radial plane (Ansell, 2015)

Softwood fibres used for pulp are usually named long fibre pulp due to their longer average fibre lengths compared to hardwoods. Softwood fibre lengths range from 1.5 – 5.6 mm long, and have cell lumen with a ranging diameter of 30 – 75 µm and a cell wall thickness of 1 – 2 µm.

Softwood paper and paperboard products are categorized by good flexibility, high folding strength, good tensile strength, and increased printability (Adamopoulos, 2006) due to the longer and stronger fibres that are harvested from the softwood species (Johansson, 2011), which allow for stronger inter-fibre bonding during the mixing and forming stage of paper and paperboard manufacturing.

Hardwoods

Hardwood species are part of the angiosperm category and form part of the Dicotyledon family. They produce flowers and reproductive seeds through fruits and have ordinary flat-faced leaves. Their structure is more complex and less uniform than softwoods. In addition to the tracheids, ray cells, ray tracheids, and extractives, hardwoods also contain vessel pores (Wiedenhoeft, 2012). Vessels are the main conduits that transport water and sap from the roots of the tree to its leaves, unlike softwoods that solely rely on the tracheids. Vessels vary in size and are randomly located in the structure of the tree, thus resulting in a less uniform structure as can be seen in Figure 2-2.

Ray cells occupy a much larger volume in hardwoods, sometimes as high as 20 % (Bajpai, 2018b), but still perform the same role as in softwoods.

Hardwoods have shorter fibre lengths in a range of 0.8 – 1.6 mm and have thicker cell walls with a range of 3 – 7 µm. Hence hardwoods are classified as hardwood since they have shorter, thicker fibres and are therefore more closely packed, hence a denser wood species. This makes hardwoods more difficult to harvest and not preferred in mechanical pulping.

Hardwood species contain 21 – 31 % lignin, which is lower than the average lignin found in softwoods (27 – 32 %). The lower lignin content makes hardwood species easier to chemically pulp and requires less chemical treatment during the pulping phase compared to softwoods.

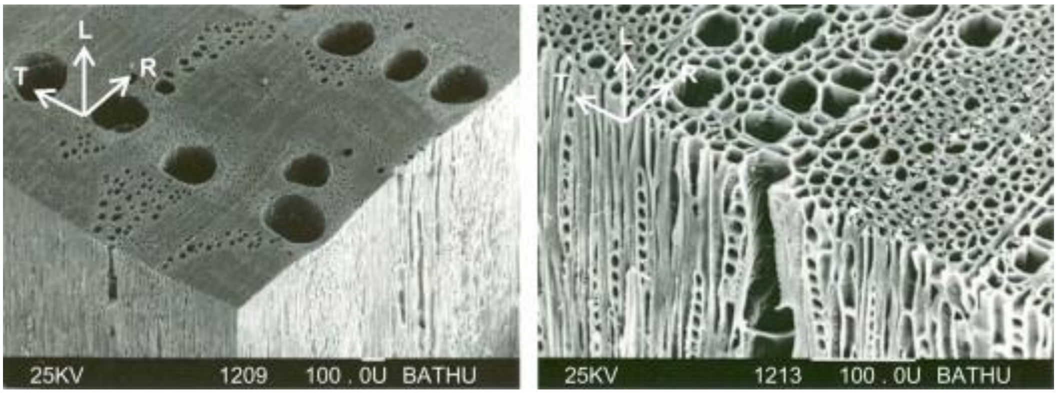

Figure 2-2: Complex structure of hardwood species with well-defined vessels (Ansell, 2015).

Hardwood paper and paperboard properties are characterized by strong absorptivity, high opacity, high thickness, and high stiffness (CNMB International, 2020). These properties are derived from the fact that the hardwoods consist of shorter, thinner fibres that allow for the improved formation of paper and paperboard products (Johansson, 2011).

Although both wood types have good paper and paperboard characteristics, they are often used together to allow the seemingly contradictory properties to amalgamate into one, thereby producing products with a balance of the desired properties.

2.2.4. Forestry wastes

According to Ximenes et al (2008), a tree can be divided into 4 above-ground biomass sections. These include the stump, debarked log, bark, and crown (foliage and branches) and the percentage attributed to each varies from species to species. Each part of the tree plays a specific role in the economy and as part of the waste cycle. However, according to Molony (2021), South African forestry already practised a circular economy even before the implementation of modern circular economic trends.

The crown of the tree refers to the canopy of the tree. This includes the leaves, twigs, and branches. The canopy is the part of the tree responsible for its survival. It absorbs light and converts it to food via photosynthesis, converts carbon dioxide to oxygen and provides food and shelter for wild animals. From the crown, the only real economic value lies in the logs, which could be sold as firewood. As for the rest, it remains on-site as debris that becomes a source of nutrients for the next generation of trees or is used as a biofuel for energy production.

The stump of the tree can follow two routes to its use, either it forms part of the coppice growth mechanism, or it becomes a waste. The term coppice means to cut back a tree or shrub to ground level to stimulate growth (Harmer, 2004), allowing the tree to regrow from its stump. If the second route is followed, the stump becomes part of the forest waste and is then either slash-and-burnt or mulched. Slash-and-burn is a method by which the harvested field is control-burnt to get rid of the remaining biomass waste and the remaining ash returns nutrients to the soil (Hauser & Norgrove, 2013). Apart from returning nutrients to the soil and reducing the organic load on the field, it can also prevent wildfires from occurring (National Geographic Society, 2022). Mulching the stumps and remaining waste also return the organic nutrient to the forest floor. However, mulching is more sustainable since it creates a bed of foliage in which micro-organisms that help breakdown the organic matter can grow, protect newly planted seeds, reduce soil erosion via wind and rain, and eliminate the combustion emissions from slashing (SA Forestry, 2018).

The bark is the rough exterior that surrounds the trunk and some branches of the tree. Depending on the harvesting technique, the bark could either end up as part of the forest's organic waste or as a fuel source for biomass energy. On-site debarking usually occurs via a single function unit, such as a flail de-barker, or by a multifunctional unit such as a cut-to-length (CTL) and a multi-stem system (Andie Immelman et al., 2004). In these scenarios, the bark ends up on the forest floor and becomes a source of nutrients for future crops. At mill debarking, the bark is removed by de-barkers and is used by the mill as a heat source for steam and/or electricity production.

2.3. Pulping

2.3.1. Background

In 2019, South Africa had 133 Roundwood processing plants in operation, of which there were 16 pulp and paper and chipping plants (Forestry Economics Services CC, 2019a). The pulp and paper industry provided around 13 200 direct and 11 000 indirect employment opportunities (Department of Forestry, Fisheries and the Environment, 2021).

2.3.2. Pulping

Pulping is the process whereby wood fibres (cellulose fibrils) are separated from each other by breaking the lignin and hemicellulose that bind them together (Davidsdottir, 2013). It forms the basis of all paper-related materials produced in South Africa; even if recycled fibre is used it still originated from wood fibres.

Wood chips and screening

The process of pulping starts with the receiving of wood from the forestry sector. This is usually done by long-haul trucks. Some mills cannot work with long logs and additional sawing units are also added to cut logs to the desired lengths. The logs can either contain bark or be debarked. As mentioned in forestry waste, if the bark is still on the log, the bark will be stripped on-site and fed to the boilers for steam and/or electricity production. It is essential to remove the bark as it contains very little wood fibre and thus does not add any value to the pulp. Instead, it leaves dark specks in the pulp, significantly reducing the mechanical properties of the pulp and waste processes chemicals (Tripathi et al., 2020). In most cases, some bark enters the pulping stream, however, a contamination tolerance of 0.3 – 0.5 % is permissible.

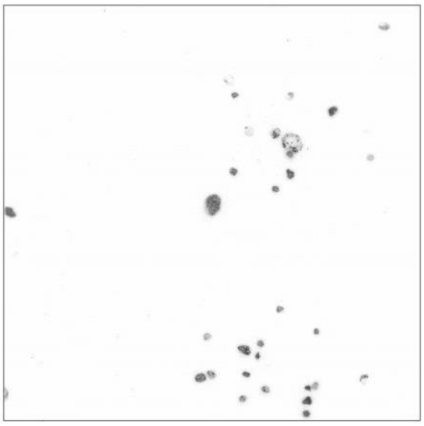

Figure 2-3: Specs of bark retained in the final paper product due to improper debarking (Reprinted by permission from Springer Nature, Strokina et al. (2011))

Once the wood is debarked, it is fed to a woodchipper, which mechanically disintegrates the wood into chips around 8 – 10 mm long along the grain and 3 – 6 mm thick (Biermann, 1997; Bajpai, 2018). The wood chips that are fed into the process need to be the same size. If the chips are too large, they exit the cooking process undercooked, leaving shives in the pulp which will affect any paper-making or drying process that follows. If the wood chips are too small, excess chemicals would be used for cooking; it will give weaker pulp due to overcooking and will clog the process's liquor circulation. To reduce the contaminations of dust and bark and to improve chip size homogeneity, the chips are screened. The screens separate overlong and over thick chips (> 45 mm), remove pin chips (< 7 mm) and fines (< 3 mm) from the acceptable wood chips (10 mm for softwood and 8 mm for hardwoods) (Bajpai, 2018a). The oversized chips are sent to re-chippers or sent to the boiler house as fuel wood. The fines consist of sand, wood fibres and small stones which are also discarded in landfills. This is the first line of screening that takes place in the pulping process. Wood chips are stored in cyclones or heaps in a stockyard.

Mechanical pulping

As the name suggests, mechanical pulping relies only on mechanical forces to separate wood fibres and make pulp. Softwood species are preferred, but some hardwoods are also used, like poplar and eucalyptus. Mechanical pulps are characterized by high yields (90 – 98 %), high bulk, high stiffness and low costs (Biermann, 1997; Gellerstedt, 2009). Mechanical pulps do not remove lignin, as such the lignin interferes with the hydrogen bonding between fibres when the paper products are made, thus giving mechanical fibre a weaker strength and a brown hue when exposed to air and light, which is commonly seen in newspapers. Because mechanical fibre is solely broken down by mechanical means, the wood chips (if not the stoneground wood pulp) need to be washed to remove any debris, such as stones, sand and tramp metals, since they can damage the refiners used to break down the wood. Mechanical pulping consists of stone groundwood (SGW), pressure groundwood (PGW), refiner mechanical pulp (RMP) and thermomechanical pulp (TMP). However, in the production of WLC, the stoneground mechanical pulp is used and will therefore be the focus of the four types.

Unlike the other three mechanical processes which use wood chips, SGW uses short logs also known as bolts. The bolts are fed into a grinder that contains grindstones made from segmented stone embedded with silicon carbide or aluminium dioxide (Bajpai, 2016). During the grinding process, water is used before and after grinding. Before as a mechanism to control the temperature of the process and after as a mechanism to move the fibres from the grinders. The stones can reach temperatures of 130 – 180 °C. The pulp that leaves the grinder has a 2 – 5 % pulp-to-water consistency.

The pulp consists of long fibres, short fibres, and fines. The long and short fibres provide strength and flexibility. The fines influence the smoothness and formation by filling the spaces between the long and short fibres. The fibres also provide a higher light scattering coefficient, increasing its opacity and allowing for better printability. After the grinding process, the pulp is sent through a bull screen. The bull screen is responsible for removing any knots and unground wood from the pump. The screen grid can vary from 3 – 5 mm in diameter (Biermann, 1997). Any wood fibres that do not pass through the screen are sent to refiners. The refiner further breakdown the wood fibres. The fibres are then sent through another screen and then recycled to the fine screens, which come directly after the bull screen. The fine screen has a mesh diameter of 1 – 1.6 mm (Pulp Paper Mill, 2015). As with the bull screen, any rejected fibres are sent back to the refiners, however, in this case, they are first dewatered. This results in less waste as the undesired pieces are recycled and used again as opposed to disposing of them.

Once the pulp has been screened, it is sent to a hydro-cyclone. The hydro-cyclone has a conical shape with no moving or rotating parts. Instead, it uses centrifugal forces by the swirling motion of the fluid to separate any impurities from the suspended fluid (Biermann, 1997). The impurities consist of sand, grit, stones, nuts, and bolts. After the cleaning process, the pulp is sent into a thickener (dewatering). Depending on the use of the pulp, it can either be stored or bleached and then stored. Once this process is complete, it is sent to a press section. In the press section, the pulp is rolled out onto sheets in which water is removed. The first section called the wet press removes water merely by gravity and compressive forces. The dry end is further dried by high-pressure steam, around 5 bar and 180 °C. Once this process is complete, the dried pulp is sent into a flash drier which then feeds the fibre to a baler. The baler compresses the pulp into rectangular prisms of around 200 kg per bale.

Chemical pulping (Kraft process)

Chemical pulping is a process in which chemicals are used to break down the wood structure by removing the lignin that bonds the wood fibres together. There are four types of chemical pulping, these include kraft, sulphite, neutral sulphite semi-chemical (NSSC), and soda. However, kraft pulp is used to produce WLC and so the focus will be on the kraft process. The Kraft process is divided into six main stages, namely: pulping, washing, evaporation, combustion, clarification, and causticizing.

To start the process, the wood chips are treated in a digester with a mixture of sodium sulphide (Na_2S), sodium hydroxide (NaOH) and water. The wood is charged to a large digester (either batch or continuous) that is operated at an elevated temperature and pressure (140 – 170 °C and 10 bar) and the wood chips are cooked for about 1.5 – 2 hours(Ahmad & Pant, 2018). After the cooking period is complete, the fluid that leaves the digester is called brown stock, which is a mixture of wood fibre, white stock and diluted black liquor. The brown stock is sent to a rotary knotter. The rotary knotter makes use of a course pressure screen to remove the remaining contaminants (Pulp Paper Mill, 2015). The contaminants can include knots, sand, grits, and stones. The screened pulp is then sent to the washers.

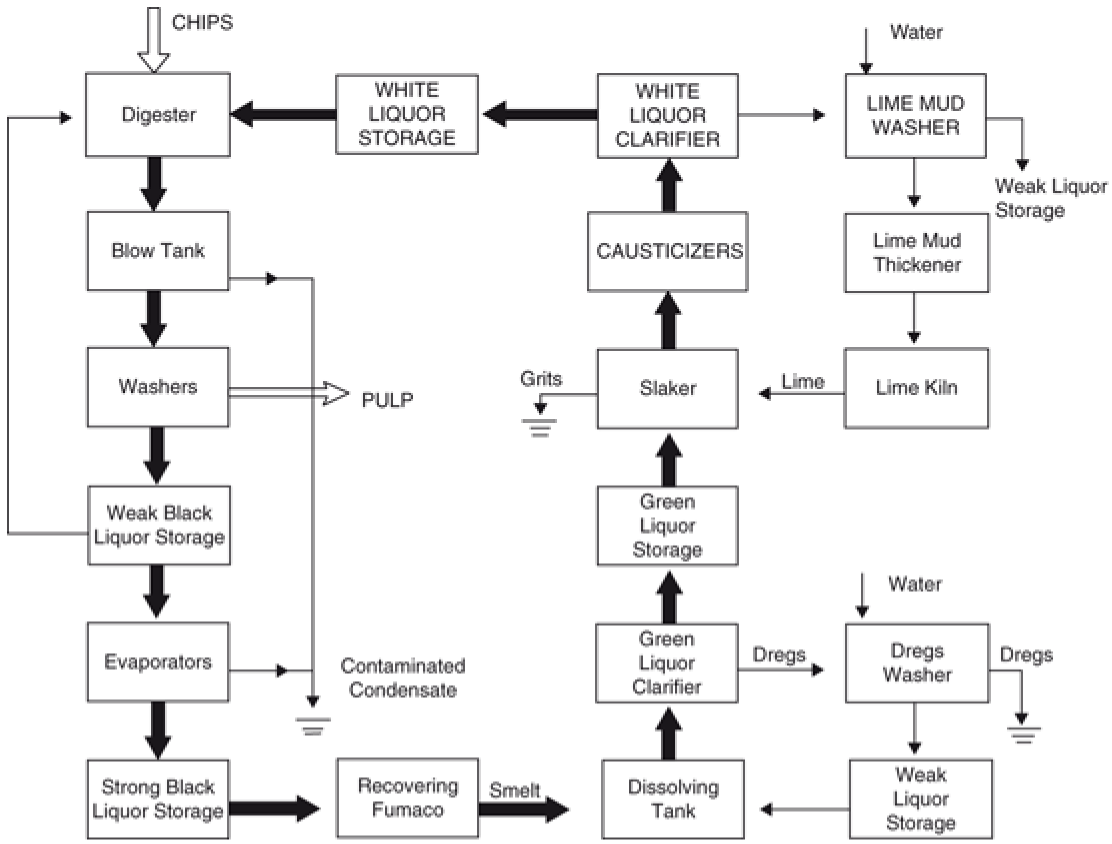

Figure 2-4: Simplified overview of Kraft process including recovery cycle (Reprinted by permission from Springer Nature, Badar & Farooqi (2012))

During washing, the brown stock is washed using water in a multistage counter-current sequence (Santos & Hart, 2014), where the cleanest water is added in the last stage and the resulting filtrate is used in the preceding stages. Several different washing mechanisms can be used, such as a vacuum drum washer, displacement washing and pulp press washing. Washing removes the black liquor and white liquor from the pulp. This is necessary for three reasons. The first reason is the expense of the inorganic chemicals used. The chemicals used in kraft pulping are expensive and for the process to be economically viable, washing is used to extract these chemicals for reuse (96 – 99 % recovery can take place). Secondly, it removes unwanted organic matter (dissolved lignin and carbohydrates), which will save costs during the bleaching and/or oxygen de-lignification processes. The organic matter will also react with the bleaching chemicals, thus increasing cost and reducing the quality of the pulp. The third reason is the removal of unwanted materials such as metals, pitch, and wood extractives. Wood extractives can accumulate in downstream processes and result in sticky deposits on equipment, which could result in the formation of spots, discolouration, and holes in the final products (Santos & Hart, 2014).

After washing the process flow splits into two, pulp and black liquor (organic and inorganic components). The pulp can undergo two processes. It can be bleached or remain unbleached. The bleaching process occurs in a multistage process which allows for the gradual whitening of the pulp, thus still achieving the objective without damaging the fibres. Chemicals such as chlorine gas, hydrogen peroxide and oxygen can be used. During each treatment and extraction stage, the pulp is washed to remove any impurities and is then heated via steam before entering the next stage of treatment (Loeschen, 2019). In some instances, depending on the downstream use of the pulp, fillers can be added. Fillers are used for altering the texture, opacity, brightness, basis weight, dimensional stability, ink absorbency and overall printability of the pulp (EU-MERCI, 2020). Some of the pulp (bleached and unbleached) is either stored, sold as the liquid slurry, or baled (as in Mechanical pulping).

Concerning the black liquor, the diluted black liquor is sent to the kraft recovery system. The kraft recovery system consists of several unit processes used to recover the inorganic chemicals. The weak black liquor is concentrated in a multi-effect evaporator to increase the ratio of the solid to a final 60 – 85 % solid-to-liquid ratio (Bonhivers & Stuart, 2013). The concentrated black liquor, consisting of organics and inorganics, is then sprayed into the lower part of the recovery boiler. The combustion takes place in oxygen-deficient conditions to form sodium sulphite (Na_2S). Only the organic chemicals are combusted. The extent of sulphide formed is dependent on the reduction efficiency which typically exceeds 90 %. The inorganic constituents are recovered as molten smelt and are emptied into a dissolving tank where it is mixed with water to form green liquor.

The smelt is composed of Na_2S and sodium carbonate (Na_2CO_3) (Badar & Farooqi, 2012). The green liquor is first passed through a clarification process, in which solid matter, known as dregs, is separated from the liquor. The green liquor is then sent to a causticizing plant where the sodium carbonate is reacted with lime (CaO) to produce sodium hydroxide. The efficiency of the reaction reaches 80 – 83 %. The products of the reaction consist of three inorganic chemicals, namely Na_2S, NaOH and $CaCO_3$ where the $CaCO_3$ precipitates as lime mud. The remaining liquid is then recovered as white liquor and recycled into the digester for the cooking process. The lime mud is extracted, washed, and sent to a lime kiln where it is heated to a high temperature to recover the lime. The use of recovered lime, coming from the lime kiln, is dissolved in water in a series of reactors, which is then recycled and used again during the causticizing reaction. During the lime cleaning stage, insoluble materials are removed from the process as solid waste known as grits (Biermann, 1997).

2.3.3. Wastes

During the many steps of pulp production, there are several points in the systems where solid, liquid, and gaseous wastes are produced. The way the waste is discarded is controlled by the Department of Forestry, Fisheries and Environment and by the Department of Water and Sanitation and the conditions as stipulated by the licenses.

Solids

Solid wastes consist of several organic and inorganic wastes produced at various stages in the pulping cycle. These wastes include treatment sludges, lime mud, grits, green liquor dregs, boiler and furnace ash and wood residues. Wastewater treatment sludges have higher environmental concerns since they could contain chlorinated compounds, which originate from the bleaching process of the plant (if chlorine-based chemicals are used for bleaching).

The grits originate from the white liquor slurry in the slacker by gravity and are classified as unreacted lime. Grit generation is approximately 5 kg adt^{-1} pulp produced (Torres et al., 2020). Grits are sandy in appearance and dark brown with a slightly grey hue. It consists of sand, gravel, limestone, impurities that concentrate the unreacted components from the process, and the remaining amounts of lime, calcium hydroxide, and sodium carbonate. Grits also contain several metal ions such as barium, chromium, copper, lead, nickel, and zinc. The source of the trace elements in the grits (and dregs) is associated with their absorption from the soil by tree roots and their fixation in the wood, chemicals used in the process of cooking the wood chips, the water used in the industrial process, and as a product of the corrosion of the equipment (Farage et al., 2020).

Green liquor dregs are generated during the clarification process of green liquor and have dark grey colour. During this process, all insoluble and additional impurities are removed. These include impurities such as pirssonite [$Na_2Ca(CO_3)_2.2H_2O$], hydroxides, metal sulphides and anionic metals suspensions such as sodium, potassium, manganese, magnesium, and zinc. The origin of the trace elements is the same as for the grits. The dregs have a high alkalinity pH of about 11 and a generation of up to 15 kg adt^{-1} of pulp produced (Torres et al., 2020).

Lime mud is produced as waste via a purge stream between the stage of white liquor recycling and the lime mud that is sent to the lime kiln. Lime mud has a light brown sandy-like appearance. It is purged to ensure that impurities do not build up in the process. The pH of the lime sludge has high alkalinity. Lime mud contains calcium carbonate as its main component, with other chemicals such as calcium hydroxide, lime and trace elements such as magnesium, potassium, sodium, chromium, manganese and iron. The trace element comes from the process (same as with grits and dregs) but can also come from the quicklime used to recover the sodium hydroxide. The quicklime is mined and can naturally contain trace elements such as chromium and magnesium. The amount of trace elements present is determined by the quality of the limestone and the manufacturing process (Schweiger, 2018).

Dregs, grits and lime mud are considered non-hazardous, with high alkalinities (>10) and high in nutrients and minerals. Several studies have found significant possible uses in the agricultural industry as soil fertilizers and land rehabilitation (Gaskin et al., 2009; Quina & Pinheiro, 2020; Ribeiro et al., 2010) and in soil-cement brick and various construction processes (Meyer, 2019; Siqueira & Holanda, 2013). However, in most cases, they are still disposed of in landfills.

Ash is generated in the largest amount at the boilers used for electricity and/or steam production. The ash generated come from coal and biomass combustion. The generated ash contains silica (SiO2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). Other metal oxides such as CaO, MgO, K_2O, Na_2O, TiO_2, and SO_3 are available in variable quantities, depending on the combustion temperature and the type of fuel used, whether biomass or coal, similarly trace metals such as As, Cd, Cr, Pb, Hg, Se, B, Cu, Ni, and Zn can also be present (Cherian & Siddiqua, 2019). Ash contains several different trace elements such as calcium, potassium, aluminium, magnesium, iron, phosphorus, manganese, nitrogen, and several other elements. In most cases the ash ends up being sent to a landfill, however, ash has seen some reuse in soil amendment in the agriculture and forestry operations, cement and construction industry, ceramics and geotechnical engineering applications (Cherian & Siddiqua, 2019).

Although the above solutions are used internationally, with the implementation of the "Exclusion Regulations" (National Environmental Management: Waste Act 2008 (Act 59: 2008), several other beneficiation projects have been implemented by the South African pulp and paper sector. These include using biomass for biofuel, composting, animal bedding, soil conditioning, fuel rods and landfill cover (Mondi, Sappi and Mpact); using ash for brick manufacturing, block manufacturing, landfill cover, cement making, soil amelioration and road construction and surfacing (Mondi, Mpact and Sappi); lastly, using gypsum as a soil conditioner and inert products (Mondi).

Wastewater (effluent)

Wastewater is generated from any of the drying, washing, concentrating, and pulping phases on the plant. Wastewater treatments consist of two stages, the primary clarification and the secondary clarification stages. Before the primary clarifier, acid and alkali streams are mixed in a chamber called the pre-neutralization chamber. The purpose of this chamber is to control the pH in the subsequent stages. The effluent then flows into the primary clarifiers which generate primary sludge. The remaining effluent is sent to a secondary treatment, which uses biological treatment to break down any remaining organic matter, thus, reducing the biochemical oxygen demand of the effluent water. Any other solid matter that passed through the primary clarifiers is removed by the secondary clarifier as secondary sludge. The treated effluent from these mills can be either disposed of into local municipal wastewater lines or into the ocean provided that strict quality demands are met as set out by the local governing body.

The primary sludge mainly consists of wood fibres and some filler chemicals, such as kaolin clay, calcium carbonate and titanium oxide, but can also contain potassium, magnesium, sodium and some toxic chemicals. Primary sludge also contains higher C/N ratios (150 – 250). Secondary sludge is composed of activated sludge. The sludge has a higher nutrient content compared to primary sludge, resulting in a lower C/N ratio (5 – 30) (Simão et al., 2018). Sludge is still mostly sent to landfills. There are other uses for the sludge, depending on its composition. Some sludges are used in land rehabilitation and agricultural fertiliser, some in construction such as brick production and mineral fillers (Meyer, 2019) and some sludge is used for biogas production via anaerobic digestion to produce electricity (Hagelqvist & Granstrom, 2013; Karlsson et al., 2011). For example, Bio2Watt is using pulp sludge as input for electricity generation via biogas combustion (Ndlovu et al., 2015). Air emissions

Air pollutants and gas emissions are one of the biggest concerns in the pulp and paper industry. The pulp and paper industry's emissions include water vapours, particulates, nitrogen oxides, volatile organic compounds (VOCs), sulfur oxides and total reduced sulfur compounds (TRS) (Ince et al., 2011), however, the air emissions are regulated by the license under the Air Quality Act 39 of 2004.

VOCs consist of turpentines, alcohols, phenols, and methanol. Acetone, chloroform, and methyl ethyl ketone. Digester cooking is the main source of VOC release. According to Kuenen et al. (2016), vapours from the blow tank may be vented to an accumulator or a vapour sphere for collection. The vapours may be incinerated, stripped, or recovered for resale as turpentine or tall oil. Other sources of VOC releases include the bleaching process, wastewater treatment, and evaporators for black liquor concentration.

The release of reduced sulfur compounds comes from the digester cooking process, the evaporators, strippers and the recovery furnace. TRS is characterised by strong odours at relatively low concentrations (Ince et al., 2011). TRSs include hydrogen sulphide, methyl mercaptan, dimethyl sulphide and dimethyl disulphide. Close evaluation of these gasses is necessary since some TRS are hazardous, such as hydrogen sulphide (H_2S). It is also associated with foul odours, such as the well-known rotting egg smell (Lin, 2007).

The remaining emissions, such as the SOx, NOx, particulates, trace elements and water vapours are released from the boilers, recovery furnaces, evaporators, and the lime kiln. These are general emissions that must meet the local emissions limits set by the government. Elemental trace elements would be lower when using alternative fuel sources such as biomass or biogas as fuel sources instead of coal.

2.4. Carton board (paperboard)

Carton board, also known as paperboard, is a multi-layered, wood fibre-based product. It consists of multiple layers (3 or more) that are combined in the wet state on a board machine and may consist of either virgin wood fibre (chemical or mechanical), recycled wood fibre or both (Marttila, 2012).

Paper-based products are only classified as carton board once their grammage exceeds 200 g / m^2 (ISO 536:2012) and has a thickness of 350 – 800 µm. However, some standards set by countries or organisations often consider a paper-based product a carton board once its grammage exceeds 225 g / m^2 (Confederation of European Paper Industries, 2021). In some instances, some products have been classified as carton boards, even though their grammage was 160 g / m^2. The standards used by the industry depend largely on local standards and the company's acceptance of international standards.

The Carton board is mechanically strong. Its stiffness, rigidity and toughness provide compression strength to protect products in distribution and use. It can be cut, creased, folded and glued, giving the structural designer scope to produce functional and creative packaging. The surface is usually white and smooth, with good ink retention, and can be printed on by all the main printing processes. Carton board can be embossed, and hot foil stamped. It can be laminated with aluminium foil, extrusion coated with plastics, such as PE, PP and PET, and given treatments that extend its range of appearance and performance properties

Carton board products can be divided into five grades namely folding boxboard (FBB), white-lined chipboard (WLC), liquid packaging board (LPB), solid bleached board (SBB), and solid unbleached board (SUB) (Marttila, 2012). Each grade has its unique use, quality, and characteristics; and is distinguished from one another by its fibre composition, physical properties, and chemical treatments. For the LCA, the focus would be on the manufacturing and waste production of white-line chipboard.

2.5. White-lined chipboard

White-lined chipboard is a carton board product that consists of several layers of recycled and virgin wood fibres, usually covered with a clay-based topcoat. White-lined chipboard has a grammage range of 200 – 500 g / m^2 and a thickness range of 350 – 600 μm. White-lined chipboard consists of a triple clay coat (pigment) and four fibre layers (depending on the company specifications and product use); topliner, underline, filler liner and bottom liner.

2.5.1. Layers

WLC consist of 6 layers, namely the triple clay topcoat, top liner, under liner, middle liner (filler), bottom liner and bottom coat (Figure 2-5). Starting from the top layer, the triple clay coat is a layer that coats the topliner. It serves two purposes for the product. The first is appearance and the second for protection. The clay coat is a bright white colour with added chemicals that help with ink absorption and rapid drying to prevent smudging. The second is for the protection of the product on the inside, the coat provides resistance against grease staining and increases the resistance to water absorption. The bottom coat serves a similar purpose and acts as a smell barrier preventing the odour of the paperboard from being absorbed by the food.

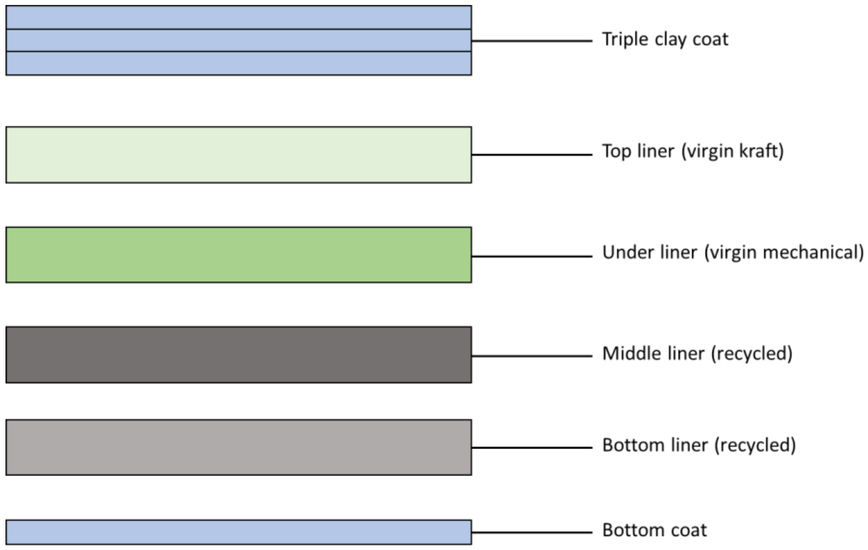

Figure 2-5: Different layers of WLC product.

The topliner is made from hardwood virgin bleached kraft pulp. Hardwoods have shorter fibre lengths and create a well, densely structured web of fibres. Because they are shorter, they lack the tensile strength of softwood pulp, but hardwood pulps have improved printability, sheet bulk, opacity, and surface smoothness (Fišerová & Gigac, 2011). Since marketing includes the use of vibrant and artistic methods to appeal to the consumer, using hardwood pulp as the topliner reduces the need for expensive specialised inks. The underline layer is either made of the same kraft pulp as the topliner or can be made from a less expensive bleached mechanical pulp. Either one is used to improve the stiffness of the products and to buffer the grey-blue hue of the recycled paper used in the filler layer. Using bleached pulp helps with the whitening of the product's surface, thereby requiring a thinner layer of coat.

The filler liner is usually made from mixed recycled fibres (newspapers and used printing paper) and recycled corrugated board. Due to the use of recycled material, the cost of the product is significantly reduced. However, every time paper-based products have been recycled the length of the fibres is reduced and the mechanical properties of the recycled fibre weaken. Hence, only certain grades of paper can be used for recycling. The bottom liner is also made from recycled material, but because this layer is more likely to contact food, it is made from a specially selected recycled corrugated board. This board comes directly from other companies and does not go through the 'consumer use phase', so contains few contaminants and microbes. The amount of recycled fibre used can vary from 80 – 100 % of the total product mass (Kirwan, 2011).

During the repulping process of the virgin and recycled fibres, several mineral additives, such as titanium dioxide (TiO) and precipitated calcium carbonate (PCC) is added to improve the optical properties of the final product, such as opacity and reduced show-through of ink during printing (Grönfors, 2010). In some instances, even dyes can be added to change the colour of the filler liner from a blue-grey hue (due to inks and prints of the various recycled materials) to a light brown colour. Some chemicals are also added to reduce foaming and decrease water retention for faster drying.

2.5.2. White-line chipboard uses

White-lined chipboard is primarily used as a secondary packaging material, especially for food products, and sometimes as primary packagings, such as for soaps and dishwashing powder. If WLC is used as secondary packaging, it means that the food is not in direct contact with the product, but rather with the primary packaging that holds the product, such as an aluminium bag, plastic bag or plastic tray. WLC is used in multiple industries for multiple purposes (Kirwan, 2011):

- Dry foods, such as cereal and tea containers
- Confectionary outers, icing sugar containers
- Personal hygiene, such as soap and toothpaste containers
- Cleaning agents, such as dishwashing powders
- Frozen and chilled foods

Due to the use of recycled corrugated board in the bottom liner, WLC is not used to package foods and materials that are sensitive to odours, such as cigarettes and chocolates. There are additional grades of white-lined chipboard and grades with special dyed liners, all depending on the purpose of the product.

2.5.3. White-lined chipboard manufacturing

The process at the South African WLC manufacturing mill starts with the collection of recycled fibres and the delivery/storage of virgin fibres and recycled fibres. Recycled fibres include newspapers, paperboard, and corrugated board. Since the paper is bought from recyclers, the selection and sorting stage is not included in the LCA. The information to follow pertains to the South African WLC manufacturing process.

<u>Repulping</u>

The recycled fibres are fed into a tank with water to fibre ratio of 98:2 wt % (Kirwan, 2011). Recycled fibres can make up 65 – 100 % of the WLC by mass, depending on its intended use (food packaging would have fewer recycled fibres for health reasons). This is part of the increased sustainability approach of the industry. Once the fibre and water are placed into the tank, the mixture is agitated (with a hydro pulper) to free the fibres from the paper, paperboard or corrugated network until a slurry is formed. Once the slurry is formed, it is fed through centrifugal screens (EU-MERCI, 2020). The screens remove any form of impurities, such as staples, paperclips, glass and metal shards, plastic, and sand. The virgin fibres go through the same process, except it is not screened since it is stored in warehouses and therefore have little contamination. All repulped fibres (recycled and virgin) are then treated in various ways to prepare them for use on the paper or paperboard machine.

During this mixing process, different properties of the pulp can be enhanced by additional refining or chemicals/mineral additives. Inter-fibre bonding can be increased by mechanical refining, in which the surface structure of the fibre is modified by swelling the fibre in water and increasing the surface area. The degree of refining, which also influences the drainage rate during the pressing section, is adjusted to suit the properties of the intended paperboard use. Additives, such as aluminium sulphate, calcium carbonate and synthetic resins, can be added to change certain characteristics of the pulp. For example, aluminium sulphate or synthetic resins can be used to increase the water-repellence of the fibres. Wet-strength resins can be added to increase the strength of the product when saturated with water. Fluorescent whitening agents (FWAs), also known as optical brightening agents (OBAs), can also be added to increase the whiteness and brightness of the pulp. Even dyes can be added to improve the colour of the recycled fibres, from their characteristic blue-grey hue to different shades of brown

<u>Sheet forming</u>

The slurry of pulps is fed into a headbox. The headbox is a piece of equipment that supplies the slurry stock onto the forming section evenly. By consisting of different sections, the triple or quadruple paperboard layers can be created by having the different pulps pumped into the different sections in the wet state, thereby allowing effective bonding of the different layers (Kirwan, 2011). The slurry is then formed in an even layer. This is achieved by depositing the suspension of fibre at a constant rate onto a moving plastic mesh, known as the wire. Forming results in a layer of entangled fibres from which water is then removed by drainage and pressing, which may be assisted by a vacuum. About 90 – 95 % of the water is removed during the forming section. Starting with a fibre-water ratio of about 1:50 and leaving the forming section with a fibre-water ratio of about 1:4 (Ajit K, 2011; Sjöstrand, 2017).

Once the sheet has been formed onto the mesh, the sheet enters the wet press section. Enough water has been removed so far by the previous section that the sheet can hold its weight. The sheet is then transferred to the press section. Here it is held on a fibrous mat and gently pressed using steel rolls, allowing for more water to be removed. At the end of the wet press section, the moisture retained in the fibre sheets is reduced by 60 – 65 %.

The drying section removes moisture by passing the sheets over steam-heated cylinders. During this process, heated steam is passed through the cylinder at 5 bar pressure and 180 °C. Heating the cylinders evaporates the remaining water in the fibre sheets, resulting in final moisture of about 4 – 8 % by mass. The thicker the grade of paper, the higher the remaining moisture will be. The high-pressure, high-temperature steam is also used as a sterilising agent, killing off bacteria. A starch solution is sometimes applied towards the end of the drying section to one or both sides of the sheet. This is known as surface sizing and is used to improve the strength and finish of the sheet. Surface sizing also firmly anchors the fibres in the sheet. Squeezing the sheets through a series of steel/composition rolls (which occurs in the wet-end and drying section) can enhance smoothness and thickness uniformity, this entire process is known as calendaring.

White pigmented coatings (the triple clay coat) are applied to the top side of the paperboard with three separate spray coaters. The coating can also be applied on the bottom side as a single layer depending on the use of the paperboard. The coatings consist of fine mineral pigments, such as kaolin clay, calcium carbonate, and synthetic binders (adhesives) dispersed in water. The coatings are dried by radiant heat (such as IR gas heating) and by steam-heated cylinders. Finally, once the paperboard is coated and dried one last time, it is reeled up into large jumbo reels, which have the same width as the paperboard machine.

Depending on customer requirements, the jumbo reels are slit into narrower reels of the same or smaller diameter. Sheets may be guillotined, pile turned, counted, ream wrapped, palletised, labelled and wrapped securely, usually with moisture-resistant material such as PE film, before being shipped out. The final moisture content of the reels varies between 4 – 6 % by mass.

2.5.4. Wastes

Solids

Several solid wastes are produced from the paperboard mill. These include boiler ash, sludge from water treatment, packaging material for all the chemicals used, plastics, metals, glass and sand.

The boiler ash comes from the combustion of coal to produce high-pressure and high-temperature steam. The ash makes up about 14 – 16 % of the coal (by mass) and consists of several metal oxides, with the highest concentrations being silicon dioxide (SiO_2) at 45 %, aluminium oxide (Al_2O_3) at 28.9 %, calcium oxide (CaO) at 9.83 %, sulfur trioxide (SO_3) at 5.91 % and many others including iron, magnesium, titanium (from report testing the ash content of the company understudy). The wastes can be disposed of in several ways such as in landfill, cement and construction industry, agriculture and land rehabilitation.

The second form of solid waste originates from the clarifiers as primary sludge. This consists of fibres, minerals, chemicals, inks and dyes, and small sand/grit particles. The clarifiers have a solids removal efficiency averaging around 85 – 95 %. Once the sludge has been removed from the underflow of the primary clarifiers, it is pumped to a sludge dewatering system where 55 % water is pressed from the sludge slurry and solid sludge is retrieved. The mill sends their sludge to landfills, but the sludge can also be beneficiated as agricultural fertiliser, land rehabilitation or used in aerobic digestion to produce biogas.

The last wastes are the chemical and materials packaging wastes and wastes retrieved from the centrifugal screens. When the recycled fibres are delivered to the mills, they are delivered in an uncleaned state. Thus, they contain contaminants such as sand, pebbles, plastics, metal and glass shards. The large bales are placed onto a conveyor belt, dropped into the repulping tanks and then screened. During this screening process, these contaminants are separated from the fibres and discarded in bins.

The contaminants are too small to separate from each other for recycling (glass from plastic from metal), thus it is landfilled. The packaging materials from the chemicals/minerals and general wastes are separated, placed into the appropriate bins and recycled accordingly, if this is not possible, then the wastes are landfilled, but only as a final resort. Wastes that cannot be reused or recycled, by either the mill or the suppliers, are disposed of in landfills.

Effluents

Liquid wastes include the water effluent from the water treatment plant and any leaks from the process, which could include water and/or chemicals. In most instances, the paperboard manufacturing plants have a water treatment system in which up to 80 % of the water can be recycled and reused, which all form part of the industry's sustainability movement. From the treatment plant, the products include sludge and final effluent. Sludge is treated as solid waste. The discharged effluent composition, depending on the mill's location and source of disposal (open water bodies, agriculture or municipal sewer lines), is governed by the license provided by the local authorities.

However, apart from some industries reusing the water, mill effluents have also found other uses in industry. A study conducted by Elsharkawy et al. (2020) found that treating mill effluent with combined dark and LED-mediated fermentation can produce hydrogen, which can be used as a clean fuel source for vehicles, ammonia synthesis and electricity production. A similar study conducted by Farghaly et al. (2015) found that using an anaerobic baffled reactor (ABR) could also successfully produce hydrogen from the mill effluents. A study conducted by Udayasoorian & Ponman (2009) found that using mill effluent significantly improved the soil health of a chilli and brinjal farm and increased the harvest yield by 20.9 % and 17.28 % respectively. Other studies were also conducted by Anushya et al. (2020); Prabakaran (2021) and many others found very similar results either seeing an increase in crop yield or improved soil quality.

Gaseous

Gaseous wastes can differ from mill to mill. Some paperboard mills are integrated with the pulping mills meaning their emissions are based on the same fuel sources as the pulp mills, such as biomass, black liquor, and gas. Some mills are self-standing, and their gaseous emissions come from biomass, gas, and/or coal. In the mill under study, both coal and gas are used. From these fuel sources, the major emissions include carbon dioxide, nitrogen oxides, sulfur oxides, methane and several trace elements. These emissions are controlled by local air emissions licenses provided by the Air Quality Act 39 of 2004.

The best way to control emissions is to use cleaner fuel sources, such as biomass or gas instead of coal. Using biomass is considered a closed-loop system because the trees are harvested from sustainable forests (renewable energy sources), which means the carbon released during combustion is again absorbed by the newly planted trees. However, this only applies to biogenic CO_2 released during the combustion of the biomass.

2.6. Life cycle assessment (LCA)

2.6.1. LCA and LCA modelling

Life Cycle Assessment is a method to assess the full environmental impacts of a system, product, process or service by evaluating the effects that it has on the environment, including extraction, processing, manufacture, transport, distribution, use, reuse, maintenance, recycling, and final disposal (Muralikrishna & Manickam, 2017). As such, an LCA is said to include the 'cradle-to-grave' impacts of the system or product. Obtaining this data may be difficult due to the quantity of data required, the difficulty in measurement of the data and the sensitivity of the data (confidentiality of processes and materials). Due to the high data volumes, manipulation is often done using specialised software, such as SimaPro, GaBi or others. This allows for easier data manipulation, faster calculation and standardisation (which also allows for data transfer across databases). To standardise studies, LCAs are performed according to the ISO 14040 and ISO 14044 standards.

Before an LCA can be conducted, it is important to first decide what type of model (attributional or consequential) will be used to conduct the LCA and how far the system boundary will extent (scope). The type of model used to conduct the LCA depends on the goal of the study and the end objective. The definition of the two models by Finnveden et al. (2009) states that "Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from life cycle and its subsystems" and "Consequential LCA is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions." In other words, attributional LCA looks at the environmental impact of a process or product as it presently stands based on past and present data and therefore includes the entire unit operation. The data used in attributional modelling usually requires averaged data since it is measurable and based on real operational conditions, such as the average electricity consumption of a mill for the last five years. Consequential LCA studies the possible changes that could occur in the environmental impact of a product or process if changes were to be made to the present process or product. Consequential LCA therefore only includes the processes that change in its system boundary and can include the entire unit operation or only a unit process. Consequential LCA, therefore, relies more on marginal data since it uses proposed data (not currently present in operation) to model possible future changes to the environmental impact of a product or process if changes are made to the current process or product. For example, if a pulping mill decided to switch from coal to natural gas boiler, only the environmental consequence of the boiler (and affected processes) can be studied and not the entire pulping process. If the change occurs in the mill's feed line, such as using recycled fibre, then the entire unit operation is affected since this change will affect the volume of chemicals used, quality of effluent, energy demand, etc. and now the entire unit operation needs to be included. There is a lot of argument that surround the use of attributional and consequential LCA and when which model is appropriate, but from the research of Finnveden et al. (2009), the general trend shows that consequential LCA is more appropriate for decision-making and attributional LCA can be used to identify key problems and environmental hot spots in an LCA.

The second decision in LCA relates to how much of the product's or process's value chain will be included in the scope. A full cradle-to-grave LCA (from raw materials extraction to final product disposal) can be broken down into separate unit operations if the full LCA is not necessary, as in Figure 2-6. Considering the process of making paperboard, its value chain can be divided into different segments, such as forestry, recycling, pulping and manufacturing. Based on the goal of the study, it can be segmented to become a cradle-to-gate study, where only forestry is considered. The study would include cultivation, planting/sowing, growing, trimming, irrigation, applying pesticides/fungicides/herbicides, harvesting and waste management. A gate-to-gate study, in which only pulping is considered would include the receiving of the wood from forestry, debarking, chipping, de-lignification, bleaching, baling, material recovery, water treatment, washing and energy production. Even a gate-to-grave study can be conducted in which the use phase and waste disposal of the final product can be studied.

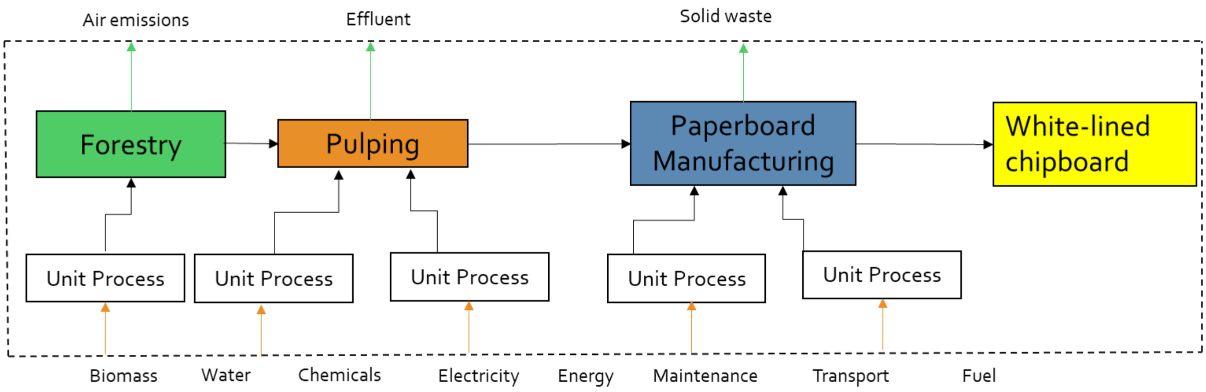

Figure 2-6:Unit operations involved in producing WLC.

LCAs can also be used to isolate the individual processes of a system, such as transport, energy production via boilers, recycling and so on to evaluate the separate impacts of these processes. This could allow for a more detailed study since the volume of information is less, allowing for more focus on all the information related to the selected process. For example, in researching the impact of kraft pulp production, the chemicals used to treat the boiler water to prevent foaming and scale build-up are often excluded. This is because the anti-foaming chemical's contribution by mass is insignificant to the overall LCA, therefore, to save time, it is excluded (cut off). Conducting an LCA specifically for the boiler system would allow the anti-foaming agent to be included in the LCA since the study would be less data-intensive, allowing for a more thorough analysis.

LCAs can be conducted to study the broader geographical influence of a set of systems representing a country, continent or world, such as conducting an LCA for all coal-fired power stations in South Africa, thereby generating results that are specific to South Africa, instead of the results being specific to a single process or company.

All these aspects associated with LCAs allow them to be used for several purposes, such as sustainable development, informing public policy, optimising process flow, reducing waste, changing to cleaner energy sources, finding alternative waste management strategies and even product comparisons, in which the product with the lowest production impact can be used in the process/service (Algren et al., 2021).

One of the most important aspects of an LCA is that it is a quantitative process. The results from an LCA are therefore reproducible, thereby enhancing credibility. It is for this reason that the ISO 14044 standards strictly specify that all assumptions, calculations, estimations and data validation must be given in an LCA report as this would aid in the recreation of the study and would allow an external viewer to identify errors and incorrect calculations.

2.6.2. Conducting an LCA according to ISO standards

According to the ISO standards that govern Life Cycle Assessment (ISO 14040 and ISO 14044), an LCA is made up of 4 stages, namely: goal and scope, inventory analysis, impact assessment and interpretation.

<u>Goal and scope definition</u>

The goal and scope define what is to be investigated in the LCA and indicate how it should be done even before data gathering starts taking place (Curran, 2016). This step ensures that the LCA is performed consistently and in line with the intended outcome in mind. It is responsible for defining the function and the functional unit. The goal and scope are also used to define a system boundary. The system boundary establishes all the unit processes included in the system. The extent to which the system boundary is established depends on the goal of the study, its intended application, its audience, the assumptions made, data and cost constraints, and cut-off criteria (International Organization for Standardization, 2022).

The goal of the LCA defines what is to be studied, defines the type of LCA that will be conducted (reason for the LCA) and indicates the application of the LCA. Types of LCAs include strength and weakness analysis, product comparison, product improvement, environmental impact assessment of a product/process, water/carbon footprint study and so on.

The scope defines the extent to which the LCA will be conducted. It is responsible for defining the functional unit, which is a quantified description of the function of a product that serves as the reference basis for all calculations regarding the impact assessment (Arzoumanidis et al., 2020). This is the reference product to which all mass and energy flows must be related, for example, kg of chemical per kg functional unit or MJ of steam per kg functional unit. The functional unit is extremely important as it allows for the study to be replicated and allows for comparisons to other similar products on an equal basis.

The scope is also responsible for defining the scale of the project. This means that the scope would define the:

1. the system boundary

2. the information included in the study,
3. information excluded (cut-offs)
4. allocations used (if any)
5. impact categories to be studied, and
6. assumptions and limitations.

<u>Inventory analysis</u>

The second step of an LCA is inventory analysis. An inventory analysis can be seen in engineering terms as a mass and energy balance. Inputs and outputs, including the economic (services and goods) as well as environmental values (resources and emissions), are needed to construct the list. In the inventory analysis, data collection and calculation procedures are done on all the inputs and outputs associated with the product or service. This requires that the full flowsheet, including all processes required in the manufacturing, use, and final disposal are known.

The process of conducting an inventory analysis is iterative (H. Chen & Wang, 2017). As data is collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures (Figure 2-7). This is important as it will allow for the objective of the study to remain valid. The entire life cycle implies that the flowsheet starts with the raw material acquisition (such as mining and forestry) and ends with final use or disposal (process waste and public waste).

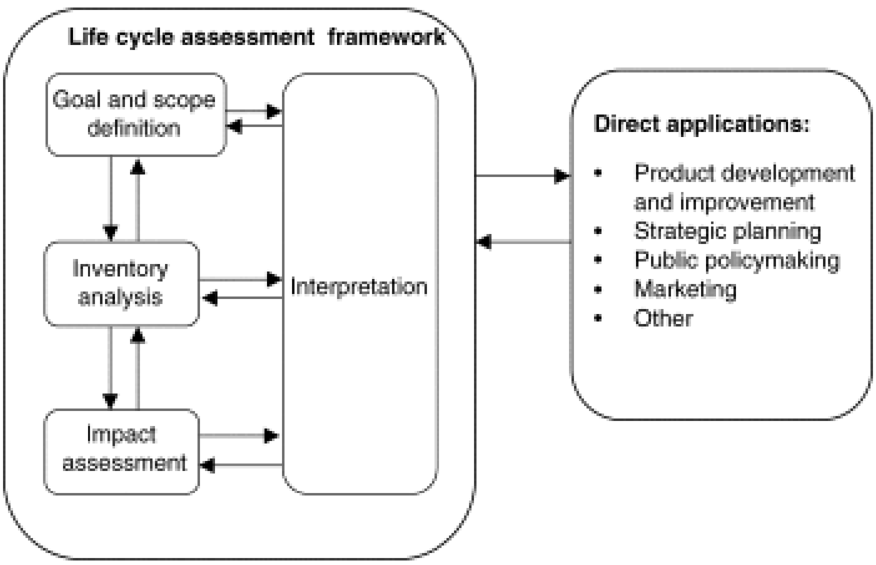

Figure 2-7: Iterative nature associated with conducting LCAs (Nieuwlaar, 2004).

Inventory lists can consist of two data types. Data that are directly calculated or measured for the specific study are known as foreground processes. This data comes directly from the process and can be measured on-site, also known as primary data. Secondary data include data collected from secondary sources, such as research and databases, and are known as background processes (Life Cycle Initiative, 2020). Any information that is missing, needs to be identified and calculated if it was not excluded from the scope of the study. The missing data can be calculated by using mass and energy values obtained from the foreground and background data.

The final step in the inventory analysis is to construct an inventory table. This involves converting all the material and energy values across the flowsheet into values relative to the functional unit.

Impact Assessment

The impact assessment phase of LCA is used to evaluate the significance of the environmental impacts of the product or service by using the inventory results (International Organization for Standardization, 2022). This process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The impact assessment may include an iterative process in which the goal and scope of the LCA are reviewed to determine whether the objectives of the study have been met, or to modify the current goal and scope of the assessment if the results indicate that they cannot be met. Problems related to situations such as choice, modelling, and evaluation of impact categories can introduce subjectivity into the LCIA phase (International Organization for Standardization, 2022). Therefore, it is important to ensure that the choice of variables, boundaries, and assumptions are clearly stated.

To understand the impact of the product or service, three steps must be followed, namely classification, characterisation, and valuation.

Each of the inventory table data values is classified (classification) according to an environmental impact category. The categories can include issues such as global warming, ozone depletion, water eutrophication, human toxicity, photochemical oxidation, natural resource depletion, and more (Goedkoop et al, 2016). Each data value in the inventory has an impact on the environment, such as emissions to air, effluent to water sources and solid wastes to landfill. These wastes contribute to one or more environmental problems. For example, carbon dioxide (CO_2) contributes to global warming, sulfur dioxide (SO_2) contributes to terrestrial acidification via acid rain, and methane (CH_4) contributes to both global warming and ozone (smog) formation. Classification is therefore responsible for taking wastes and assigning them to different environmental impact categories based on the effect they have on the environment.

The characterisation step is the process of multiplying all substances by a factor that reflects their relative contribution to each classified impact category (Golsteijn, 2014). A category contains several hundreds of emissions and all of them have different units. However, these cannot be summed together because they do not share the same unit, for example, kg CO_2 cannot be summed together with kg CH_4 (methane) or kg N_2O (nitrous oxide) because they are different. To solve this, all emissions associated with an impact category should be converted to an equivalent unit, which will then allow for the different emissions now with the same unit to be summed into a single value that represents the respective impact category. The conversion to an equivalent unit is obtained by multiplying each chemical in a category by a factor that represents its relative contribution to that category. Once all the materials from the inventory table have been classified into a category, each is multiplied by its respective weighting factor to become an equivalent value. For example, in the global warming impact category, carbon dioxide was chosen as the reference chemical to represent all emissions classified in the global warming category. Considering three emissions, 1 kg of CO_2 has the same impact as 1 kg CO_2 eq, hence its conversion factor is 1 kg CO_2 eq per kg CO_2. For methane, 1 kg of methane has an impact on global warming potential that is 28 times more than 1 kg of CO_2, hence methane's global warming factor is 28 kg CO_2 eq per kg CH_4. Similarly, 1 kg nitrous oxide has a global warming potential that is 298 times more than 1 kg CO_2, hence nitrous oxide's global warming factor is 298 kg CO_2 eq per kg N_2O (Greenhouse Gas Protocol, 2014). In this way, different emissions can be converted to a single equivalent unit, which can be summed together to reach a single value that represents the collective impact of all the emissions in that category.

Summing all the equivalent contributions will give a final LCA score for each selected impact category (Goedkoop *et al*, 2016). Values from characterisation are often meaningless when taken as is. They are more meaningful either when used as a comparison to a similar product/process or during an improvement assessment, or when the assessment is broken down to show the contributions of individual parts, for example, the contribution of individual processes such as transport, heat production, use phase and disposal.

A further way to make sense of the numbers from characterisation is when many LCAs have been performed and a comparison can be made from these studies. This is termed Normalisation. Normalisation involves comparing the size of your contribution versus. the total contribution to the problem over one year. The most common normalisation approach is the average environmental impact of a citizen, for example, the ReCiPe method uses the impact of an average world citizen and CML-IA uses the impact of an average European citizen in one year (Golsteijn, 2014). However, the reference may be chosen freely, such as an environmental load of lighting a 60W bulb for one hour, 100 km of transport by car or 1 litre of milk (PRé, 2020).

The final step in the quantification procedure in an LCA is the valuation step. This is the conversion of characterisation scores to a single value. Each characterisation value is given a weighting and all values are added to give a single score, such as a human health impact score, environmental impact score and so on. While valuation and single scores are still used, they are not required by the ISO 14040 regulations.

The classification and characterisation steps are calculated by simulation software, such as Gabi and SimaPro. The software uses impact models that have a dataset of substances (models such as ReCiPe 2016, EF 3.0 TRACI, BEES+), if the substance occurs in the inventory table, the model will classify, characterise and weigh the substances. This means that in an LCA study, the only work done is collecting, calculating and composing the inventory table. Entering the data into the software and then simulating the processes, results in a table or figure representing the final impact categories with their respective equivalent values ready for interpretation. The software allows a researcher to change the weight and characterisation of a substance if desired. It also allows the researcher to isolate and study the impact of a specific substance and its contribution to each (if more than one) impact category.

Interpretation

LCA is designed to be questioned at each stage of the process. This is the role of the interpretation phase, to make sense of what the numbers represent. According to ISO 14044, there are several ways in which the results could be analysed, and the validity of the result be tested, such as uncertainty tests, sensitivity analysis, and contribution analysis.

The contribution analysis is the process where a single impact category is isolated and evaluated on a process/substance-specific level. This will indicate which processes in the LCA contributed most to the impact category. For example, on a mill, the global warming category can indicate that electricity use was the highest contributor to global warming, followed by steam generation, then transport, and so on. The same can be done for substances, in which the substance responsible for the highest global warming count can be evaluated, for the same example, CO_2 could contribute the most, followed by methane, and so on.

The sensitivity analysis is used for two reasons, firstly to study how sensitive the results are to a change in mass of an inventory substance. Secondly, to test for any exclusions and assumptions made and whether the decision to exclude the processes significantly affects the outcome. If it does, then the goal and scope would have to be reconsidered. The uncertainty test is used to study the error of the results based on the uncertainty in the inventory table and based on the uncertainty of the impact model chosen (inherently included in the simulation software (Goedkoop et al., 2016).

2.6.3. LCA alternatives

If conducted correctly, LCAs have many applications that can greatly benefit sustainable development and improve circular economy operations, however, it also has limitations (Envirotrain, 2018; James & Morrison, 2022; van der Meer, 2018), such as:

- Being dependent on assumptions and scenarios.

LCA attempts to numerically present the environmental impact of a real-world process or product. This is an extremely challenging and time-consuming task, and in most cases, not even possible. As a result, the real-world process is simplified with assumptions and scenarios and as a result, valuable information can be lost.

- Using generalised and /or averaged data

LCAs make use of average and generalised datasets. For average data, any outliers or abnormal circumstances that occurred during the selected period are "lost" and the impact of the deviations is not seen in the LCA results. Generalised data apply more to secondary data that is taken from life cycle inventory databases such as Ecoinvent. Ecoinvent (and all other LCI databases) models the datasets they receive to represent a country or region. This means that the finer details of a process or product are lost, and the accuracy of the data is reduced, hence the reliability of the LCA results is also affected.

- LCAs differ in scope, even for the same products, resulting in different outcomes.

The biggest problem in LCA is that the scope of the study is determined by the researcher, which in the worst-case scenario, could lead to biased modelling or omission of significant data. This could mean that several LCAs for the same product could all have different outcomes, which could lead to inaccurate conclusions and inaccurate information supplied to stakeholders, investors and corporate heads

- LCA studies are data intensive and often require sensitive data.

Data collection is time-consuming, and it can take several months before a reasonable inventory list is created. On top of this, LCAs also require sensitive data that relate to product formulations and intricate operational procedures. Companies are reluctant to supply this information and as a result, inventory lists can often be incomplete. To account for this, secondary and generic data are used to fill the missing data gaps, which further reduces the accuracy and quality of the LCA as the information is no longer valid to the process, geographical boundary and temporal boundary. Although this can be accounted for by reliability matrices supplied by simulation software and databases, it still does not truly represent the current process.

- Comparative LCAs, although useful, are not always reliable and do not always lead to decisive conclusions.

As with the "LCA scope" problem, LCAs are conducted and modelled based on the knowledge, timeframe and experience of the researcher. Often, when considering product comparisons, the detail of the LCA is also depicted by the researcher's knowledge of the products or processes being compared. All these facts affect how accurate the comparison will be. Even if the comparison is conducted accurately, the results could still not give a decisive conclusion. However, comparative LCA can be used to support other economic, environmental and social research to help an organisation make a more informed decision.

- LCA only considers environmental impacts and does not consider economic and social sustainability.

LCAs are conducted to address the environmental concerns of a process, service or product and neglect to address social and economic sustainability. Making a product that is more environmentally sustainable but has a much higher operational and resource cost could be economically unsustainable. The cost of the service or product would become proportionally more expensive, which would decrease demand and eventually lead to the financial downfall of the organisation. Similarly, if a product or process change is more environmentally sustainable but results in the mass retrenchment of employees or large business loss to supporting companies, the decision is not socially sustainable as many families and social structures would buckle under the change. As a result, LCA must always be used in conjunction with economic and social sustainability research to ensure that complete sustainability is reached.

There are several more intricate limitations of LCA relating to allocation, temporal and spatial boundary problems, linearly modelling non-linear systems, uncertainty in product comparisons, and several others; but the above-mentioned are the more general limitations.

Alternatives to LCA include Environmental Product Declarations (EPD) and Environmental Impact Assessments (EIA). Environmental Product Declarations are standardised documents that provide information on the product's environmental and human health impact to stakeholders (Liebsch, 2019). The goal of an EPD is to encourage the demand and supply of products that have lower negative impacts on the environment. It proves that a product is sustainable, and the information can be used for commercial applications, such as eco-labelling. Inherently EPDs require the results from life cycle assessment. However, EPDs are produced based on specific product category rules (PCR) (Ibáñez-Forés et al., 2016; Minkov et al., 2015). These are a set of instructions that provide calculation rules and guidelines to ensure that all EPDs for the same product category report the same type of information. This prevents biased modelling and allows for more accurate product comparisons. One benefit of EPDs, unlike LCAs, is that they do not require sensitive product information, such as bill-of-materials. This means that the results of the EPD can be communicated to stakeholders without the fear of disclosing sensitive information. Another benefit EPDs is the independent third-party verification process (Ibáñez-Forés et al., 2016). Because EPDs are used to certify the environmental sustainability of a product, third-party verification is important to ensure that the information supplied, and the results generated are accurate and follow the LCA and PCR guidelines. Thus, preventing miscommunication among stakeholders and unfair trade in the marketplace. Environmental Product declarations, therefore, serve as a solution to most of the limitations found in the LCA methodology. Allowing for reliable and accurate results communicated to both stakeholders and the product/service consumer.

An Environmental Impact Assessment (EIA) is a process in which the likely environmental impacts, good and bad, of a proposed project, are evaluated. EIA does not only consider the natural environment but also takes into account inter-related socio-economic, cultural and human-health impacts (Convention on Biological Diversity, 2022), which is not covered by LCA. Environmental impact assessment aims to predict the impact that a new process will have on the environment before it is started. This way the information gained from the EIA can be used to solve potential problems, optimise the construction and operational process, and inform stakeholders of changes to come. By using EIA both environmental and economic benefits can be achieved, such as reduced cost and time of project implementation and design, avoided treatment/clean-up costs and impacts of laws and regulations (Manuilova et al., 2009). Although EIA does not rely on LCA to conduct the environmental assessment, EIA could greatly benefit from its inclusion. LCA may be useful in strategic and project EIAs since LCA can do environmental comparisons of processes which would allow for alternative operations to reduce the environmental impact. LCA also allows the inclusion of all upstream and downstream processes, thus, taking into account all impacts along the different value chains, which would allow for a more accurate comparison of different process alternatives (Manuilova et al., 2009).

There are several environmental assessment methods (alternatively to LCA) available that can be used to study the impact of a process/product on the environment. However, more and more of these environmental methods are starting to see the value of LCA and are including it in their methodology. Therefore, the question should not be whether there is a better alternative to LCA, but should rather focus on creating a more robust way of conducting LCAs so that the results they produce are more reliable.

2.7. LCA studies within the pulp and paper sector

Many LCA studies have been conducted on the paper and pulp industry in which the cradle-to-grave approach was used to study all aspects of the production of paper and related products. All the studies point to the fact that the pulp and paper industry is a resource-intensive and energy-intensive operation (Ince et al, 2011; Poopak and Agamuthu, 2011; Wang et al, 2005)., However, there have been significant improvements in the industries' increasing sustainability and closed-loop economy. This includes producing their energy and electricity via biomass waste instead of fossil fuels, recycling process water, increasing recycling of paper and paper-related products instead of landfilling/incineration, sustainable forest management, changing the mechanisms of bleaching fibres (virgin and recycled) and effluent water treatment via primary and secondary treatment plants.

The pulp and paper industry is a field well-established in LCA research. Although major countries such as Europe and America have been using LCA for a long time, it is still a new concept in South Africa, only recently gaining more ground, especially after the implementation of the EPR regulations. LCAs in South Africa span several industries, but to date, there are no LCA datasets available for the South African pulp, paper and paperboard industries (Harding et al., 2021; Karkour et al., 2021). For this reason, since the production of WLC is similar to the other paperboard processes in terms of the milling operations, LCAs found for any of these processes were also considered. The process of producing WLC can be divided into three categories namely 'raw material collection', 'production', and 'distribution and disposal', LCAs within these categories will also be studied and related to WLC production.

2.7.1. LCA in WLC and related industries

Folding boxboard - Finland

A study by Goyal (2021) studied the impact of production and waste scenarios of folding boxboards (FBB) in Finland. The folding boxboard consists of layers of virgin mechanical fibres sandwiched between two layers of virgin kraft fibre. Although FBB has different fibre content, its milling operation and process layout are the same as that of WLC which is why its LCA was considered.

The research examined the cradle-to-grave processes that included raw material extraction, the manufacturing process, consumption, and end-of-life. Because of limited data, the study did not include any fibre additives and the coating was assumed to be plastic-free for all FBB produced.

In the study, five different impact categories were considered, namely goal warming, acidification, human toxicity, ozone depletion and photochemical potential. The major contributor to all the chosen impact categories was found to be the various forms of transportation, diesel production and electricity.

Finland’s FBB production has an extensive international trading route which requires a lot of transport, but the overlying problem as discovered by the LCA is the reliance on fossil-based fuels, such as the diesel used in the transportation process. Therefore, diesel production and consumption were the largest contributors to all the impact categories.

Electricity also played a role in the impact, but because of the lower fossil-dependent electric grid supply i.e. 25 % oil, 30 % biofuels and waste, 2 % wind and solar, 5 % hydro, 20 % nuclear, 8 % natural gas and 10 % coal (IEA, 2020), its overall impact was smaller. However, they did a comparison in which electricity was supplied by biogas instead of relying on the electric grid and the kg CO_2 eq per 378 kg FBB produced decreased by 21.4 %, which showed the benefit of moving away from fossil fuels.

In this study, it was concluded that the best way to reduce the environmental impact would be to reduce the reliance on fossil fuels and move to cleaner sources of energy.

Corrugated board – Thailand

An LCA conducted by Ongmongkolkul et al. (2001) studied the environmental impact of the production of corrugated paperboard. The product consisted of about 85 % recycled fibre and 15 % virgin kraft pulp (WLC contains about 20 % virgin fibres). Even though the product is slightly different in structure and additives, the methods of waste collection, repulping, cleaning, and milling operation is similar.

The research studied cradle-to-grave corrugated paperboard production. The impact categories included global warming potential, acidification, eutrophication, photochemical ozone formation, smog formation, and solid waste generation. According to the impact analysis from the study, ‘landfilling’ was the major contributor to global warming (32 %), acidification (41 %), eutrophication (20 %) and smog formation (27 %). The follow-up was ‘Other processes’ (electricity and energy) accounting for global warming (26 %), acidification (32 %), eutrophication (30 %) and smog formation (38 %) and energy use (27 %). The last major contributor to energy use was the ‘paper pre-drying process accounting for 27 % of the total energy used. This study shows that how waste is controlled and managed in paperboard mills has a significant impact on the environment.

In the LCA, the authors looked at ways to reduce the impact of landfilling and ended up with the following, firstly to collect the emitted gasses, such as methane, from the landfills and use them as fuel sources; to encourage recycling and reusing of the material, and to upgrade the technology on the mill's processing line to increase the mill's efficiency.

They concluded that to reduce the impact of the product, they would have to improve on site-generated solid waste management; and secondly, the use of renewable and cleaner energy sources needs to be implemented in the industry.

Corrugated board – America

The LCA conducted by Gaudreault et al. (2017) studied the production and use of corrugated boards in a cradle-to-grave study, starting from forestry to consumer use and end-of-life. The corrugated board is also made from recycled fibre (52 %) and a mixture of virgin kraft fibre and semi-mechanical pulp.

The impact categories investigated included global warming, ozone depletion, photochemical oxidation, acidification, eutrophication, respiratory effects and fossil fuel depletion. The LCIA was conducted by focusing both on the entire process, but also on the different industries and use phases, namely, 'pulp and papermaking (from forestry to linerboard manufacturing)', 'converting', 'use phase' and 'end-of-life', indicating the impact contribution for each impact category.

Due to the large percentage of virgin fibres used, the results indicate that the highest process contributor to all the impact categories is the 'pulping and papermaking" process. The pulping and papermaking process contributes on average more than 68 % to the impact score of each impact category, with the largest in the 'ozone depletion' category reaching 90.3 % contribution.

When considering the release of biogenic carbon dioxide, the 'pulp and paper making process' contributes the largest to the global warming potential, however, in the study they considered the fact that the biogenic CO_2 released during combustion is re-absorbed by the replenished trees from the sustainable forest management. Thus, the only part of the study where 'pulp and papermaking' had the lowest impact percentage of 3.6 % was in the global warming potential category because of the 'flow accounting approach' for the biogenic CO_2 released.

Similar to the other studies, it is also noted that the major contributors to the other impact categories, such as ozone depletion, photochemical oxidation, acidification, eutrophication, respiratory effects and fossil fuel depletion come from the presence of the pulp and papermaking process and the combustion of different fuel sources to meet the industries energy demands.

Impact assessments

From several paperboard and cardboard LCA studies, there are similar trends that can be followed, especially related to the impact categories and conclusions related to the industry. Only the top five categories are evaluated but the different impact categories used in the studies are represented in Table 2-1.

The first impact category is the process concerning global warming (measured as global warming and climate change). This could be for two reasons, namely the global goal of reducing greenhouse gas emissions and because the pulping and manufacturing processes release significant amounts of greenhouse gasses. The process of producing pulp, paper, and paperboard is energy-intensive (both as electricity and energy for power and/or heat) irrespective of the source of fuels. However, with the increase in environmental sustainability awareness, many mills have moved away from fossil fuels (coal) to burning biomass (or a mixture of biomass and fossil fuels). Although this still releases greenhouse gasses, the cleaner biomass reduces the overall score of the impact category and relates to the circular uptake of biogenic CO_2 from sustainable forest management, reducing the net amount of CO_2eq released. However, as the study by Ongmongkolkul et al. (2001) and Gaudreault et al. (2017) indicates that the use of energy and electricity is becoming more environmentally sustainable since cleaner fuel sources and alternative green energies (solar power) are used, hence the impact of the waste streams and end-of-life processes are becoming more noticeable. As indicated by PE-Americas & Five Winds International (2010), if the corrugated product was landfilled instead of recycled, the current global warming potential would have increased from the 1.04 kg CO_2eq to 2.0 kg CO_2eq, indicating the significance of the end-of-life of the product. However, pulping and manufacturing stages in the LCA remain the highest contributors to global warming due to their energy and electricity demands.

The second most observed contributor was acidification. The main contributors to acidification were NO_x and SO_2, although other gasses also contribute to acidification, these were the highest. The largest process responsible for this, even in the mills that use larger volumes of cleaner fuel sources, is the production of energy from both purchased and self-produced electricity and energy and the chemicals used in the processes. This was similar to all the studies, where energy and electricity contributed the most to acidification. In the papers by John (2007) and Iosip et al. (2010), they found that the chemicals used in the process of pulping had quite a significant contribution, however, they failed to explain how these contributed to the acidification potential, but it was assumed that the acidification occurred during its production. The study by Ongmongkolkul et al. (2001) found the results swayed more toward landfilling being the largest contributor to acidification. They found that ammonia (NH_3) and methane were the largest gasses released from the landfill, and a kg of NH_3 is equivalent to 1.8 kg of SO_2, which is why the contribution was so much higher. However, it does seem steep, especially since they included virgin pulp manufacturing and recycling. The study done by all of the other papers also included the end-of-life, such as landfilling and energy production via incineration and despite this inclusion, its effect on the acidification potential was negligible, which questions why landfilling had such a large impact on the Ongmongkolkul et al. (2001) study.

Table 2-1: Most used impact categories in LCAs conducted for the pulp and paper industry

Product	Location	Model	Impact Categories											Reference
			GW	AC	CC	NCC	RE	EU	OD	EY	Smog	FFD	Other	
FBB	Finland													Goyal (2021)
CB	Thailand													Ongmongkolkul et al. (2001)
CB	America	TRACI												Gaudreault et al. (2017)
CB	Europe	CML												Iosip et al. (2010)
CB	America	TRACI												PE-Americas & and Five Winds International, (2010)
Paperboard	America	TRACI												Montalbo (2020)
Paperboard	Europe	TRACI												
CB	America	TRACI												Thorbecke et al. (2019)
Linerboard	South Africa	Eco-Indicator 95												John (2007)
Linerboard	South Africa	CML												Mokebe (2008)

FBB – folding box board, CB – Containerboard, PB – Paperboard, GW – Global warming, AC – acidification, CC – carcinogenic, NCC – non-carcinogenic, RE - respiratory effects, EU – eutrophication, OD – ozone depletion, EY – ecotoxicity, FFD – fossil fuel depletion

The third major impact category included in all the studies was smog formation (photo-oxidant formation). The emissions such as NO_x, SO_2, and NMVOC are the major contributors, and there are a few other minor emissions. In all the case studies, the largest process contributing to smog was energy and electricity production. In Ongmongkolkul et al. (2001) research, it was found that landfilling was again one of the biggest contributors to smog. However, for the rest of the studies, smog formation was mainly due to electricity, energy production and transport. For the process of WLC production, this could be a potential impact category since the process is known to be energy and electricity-intensive, but also because the South African electricity grid relies on coal as a fuel source, which is used to produce 85 % of the country's electricity.

The fourth major impact category was eutrophication. Depending on the methods used in the different studies, the sources for eutrophication included NO_x, nitrogen in the water, phosphorous in water, and several other minor substances (related to BOD and COD). The sources of eutrophication were split between the production process and end-of-life in all the papers. However, eutrophication from the production process (pulping and papermaking) was the dominating source of eutrophication. In the LCA by Gaudreault et al. (2017) they tested the difference between the Traci and CML methods and found that when using CML, emissions to air were not considered as eutrophication agents, whereas Traci saw both emissions and effluents as eutrophication agents. Similar to the Traci method, Eco Indicator 95, used by John (2007), also considers both emissions and effluents, but also included solid pollutants to be contributors to eutrophication. In both Traci and Eco Indicator 95, effluents have higher priority over air emissions. Again, the pulping, papermaking and paperboard manufacturing processes have the highest contribution to the environmental impacts, with end-of-life being the runner-up process. The study by Ongmongkolkul et al. (2001) found that energy and electricity production were the major contributors, at 30 % influence, followed by landfilling at 20 %, similarly, the study by Iosip et al. (2010) found that the milling process the highest contribution at 44 % followed by the chemicals used at 38 %, again it was assumed that this contribution was due to the production of the chemicals. Because the studies do not trace back to individual processes, the information supplied represents entire processes. Being able to identify which unit processes contributed to eutrophication was not possible for all the studies, however, process emissions and effluents were the main sources of eutrophication, such as the study by John (2007), which found that the effluent contributed 99.9 % to eutrophication.

The fifth and last category is ozone depletion. Ozone depletion includes emissions such as chloromethane, methyl bromide, halon 1211, 1,1,1 - trichloroethane and several other substances. The main contributor to these was the energy and electricity production/purchase in the pulping, papermaking, and paperboard manufacturing processes. Depending on how the pulp was bleached, a study by ENVIRON (2012) indicated that a 27 % contribution to ozone depletion was accounted for by the production of chlorine dioxide via sodium chlorate, followed by natural gas combustion at 26 %.

3. Method: Goal and scope

3.1. Goal

The goal of the LCA was to study the impact of the production of white-lined chipboard jumbo reels across its entire value chain. The data used covered 3 years starting from 2018 – 2020. The assessment started from South African forestry, all the way down to the final cut and wrapped jumbo reels of WLC leaving the mills and process waste management. In this LCA the converting phase, consumer phase and WLC disposal as consumer waste was not studied since the jumbo reel production was not the final phase in the value chain.

The primary audience for this study would be PAMSA members and the industries for which the LCAs were completed. The information generated in this LCA could be used to evaluate and change/improve the current technology, processes and materials used thus reducing the overall environmental impact scores and creating a more circular economy. The primary raw data will not be disclosed to the public.

3.2. Scope

3.2.1. Function, functional unit, and reference flow.

The function of the product system (collection of product systems) is to produce white-lined chipboard from recycled and virgin fibres, which is treated, coated, rolled up into jumbo reels, cut, wrapped and ready for transport to clients. The functional unit is "one kg of white-lined chipboard produced", with the reference flow being all inputs and outputs divided by the functional unit.

3.2.2. Product system and System Boundary

The WLC jumbo reel product system was investigated in this LCA. The system boundary (Figure 3-1). was modelled to represent the cradle-to-gate process. The cradle-to-gate process represents the following product systems:

1. Raw material acquisition from forestry and recycled papers.
2. Pulping of virgin wood fibre

3. Converting of fibres to WLC jumbo reels

The mill in this study is non-integrated, meaning that the pulp bales used in the production of the WLC are produced and transported from a pulping mill to the WLC manufacturing mill.

The process starts with the acquisition of hardwood eucalyptus from local commercial forests. The wood is harvested, cut to size and transported to the pulping mill. At the mill, the wood is debarked chipped, cooked, cleaned, bleached, dried and baled into rectangular virgin fibre bales which are then transported to the WLC mill. The process of recycled fibre collection starts with the collection of recycled paper products (from industries, schools, etc), transportation to the sorting and baling plants, and then transportation to the WLC manufacturing mill. Once all the recycled and virgin fibres are received at the WLC manufacturing mill, the fibres are repulped, cleaned, dried, coated and rolled resulting in the final WLC reels. The reels are then cut, wrapped and transported to the clients.

3.2.2. Inclusion in system boundary

Table 3-1: Materials included and excluded from the WLC system boundary.

Products system/unit process	Included	Excluded
	Raw material acquisition	
Forestry	Intermediate and long-haul transport; equipment fuel and emissions; land use, carbon absorption, and bio waste left on-site and used in industries.	Fertiliser, pesticides and herbicides, water use, capital equipment and human activities.
Fibre (recycled)	Collection and transportation of paper products, sorting and baling, and waste handling.	Capital equipment and human activities.
Chemicals and fuels	Production and/or acquisition of fuels and chemicals (all local but used international datasets) and transport.	Capital equipment and human activities.
Electricity	Purchased and included pre- and post-combustion activities. Also includes on-site production.	Capital equipment and human activities.

Pulping of virgin wood fibre		
Pulping & baling	On-site chipping, pulping, converting, steam production, on-site chemical production, on-site waste management and recovery, transportation from upstream life cycle stages and intermediary transportation, on-site water treatment, on-site electricity generation	Capital equipment and maintenance, human activities, on-site spills and leaks, dust and particulate matter from wood yard operations, and emissions from the recovery process.
Manufacturing		
WLC production	Manufacturing operations, transportation to clients, on-site energy production (steam), on-site water treatment, chemicals, and on-site transportation.	Capital equipment, construction, maintenance, human activities, leaks and spills, land use, operational dust and particulate matter.

3.2.3. Exclusion from system boundary

- **Capital equipment and maintenance**: Capital goods were excluded from the system boundary because most (if not all) of the capital goods have a use phase that exceeds 5 years, thereby falling outside of the 3-year temporal boundary. Also, capital goods such as buildings have been in operation for periods exceeding 20 years. To include its impact, the initial materials and services required would have to be divided by the accumulated production volumes from the point of operation to the 2020 boundary year, which would make the impact insignificant. Maintenance of capital goods such as the building was excluded since it did not directly involve the process. Maintenance of the machinery was also excluded since the information mostly included human services, which is challenging to present numerically. Cleaning maintenance, such as process lye wash, was included since the number and amount of chemicals used to maintain the equipment and the frequency with which it was done are known. Also, maintenance of vehicles is already included in the South African transportation datasets supplied in SimaPro.
- **Human activities:** These were excluded because it forms part of social LCA and because the information required to capture this is resource-intensive and the time frame of the project could not accommodate this.

- **Fertilisers, pesticides, and herbicides**: The average growing time of the wood species averages around 9 years. During this period, fungicides, herbicides and fertilisers were applied at the time of planting and their continuous application is based on their need, meaning that if its application is not necessary, it will not be applied. Also, pesticides are area and pest dependent and thereby can be applied once in a tree's lifetime or several times. The uncertainty and variability of the application make modelling difficult and creates high uncertainty, and as a result, it was excluded. These exclusions are tested in the “Sensitivity and error analysis” section but are based on general industry data, not data specific to the forestry company that supplied the inventory data.
- **Spills and leaks**: Any spills and leaks that might occur were excluded since it was assumed that any amount of product lost in spills or leaks was small considering the annual production volume of WLC and cleaned (no environmental contamination), which makes its impact on the overall process insignificant.
- **Dust and particulate matter**: During the process of chipping wood and transporting it on-site, dust and particulate matter are created. This was excluded since measuring the amount was not possible and because it was assumed that the amount released was insignificant.

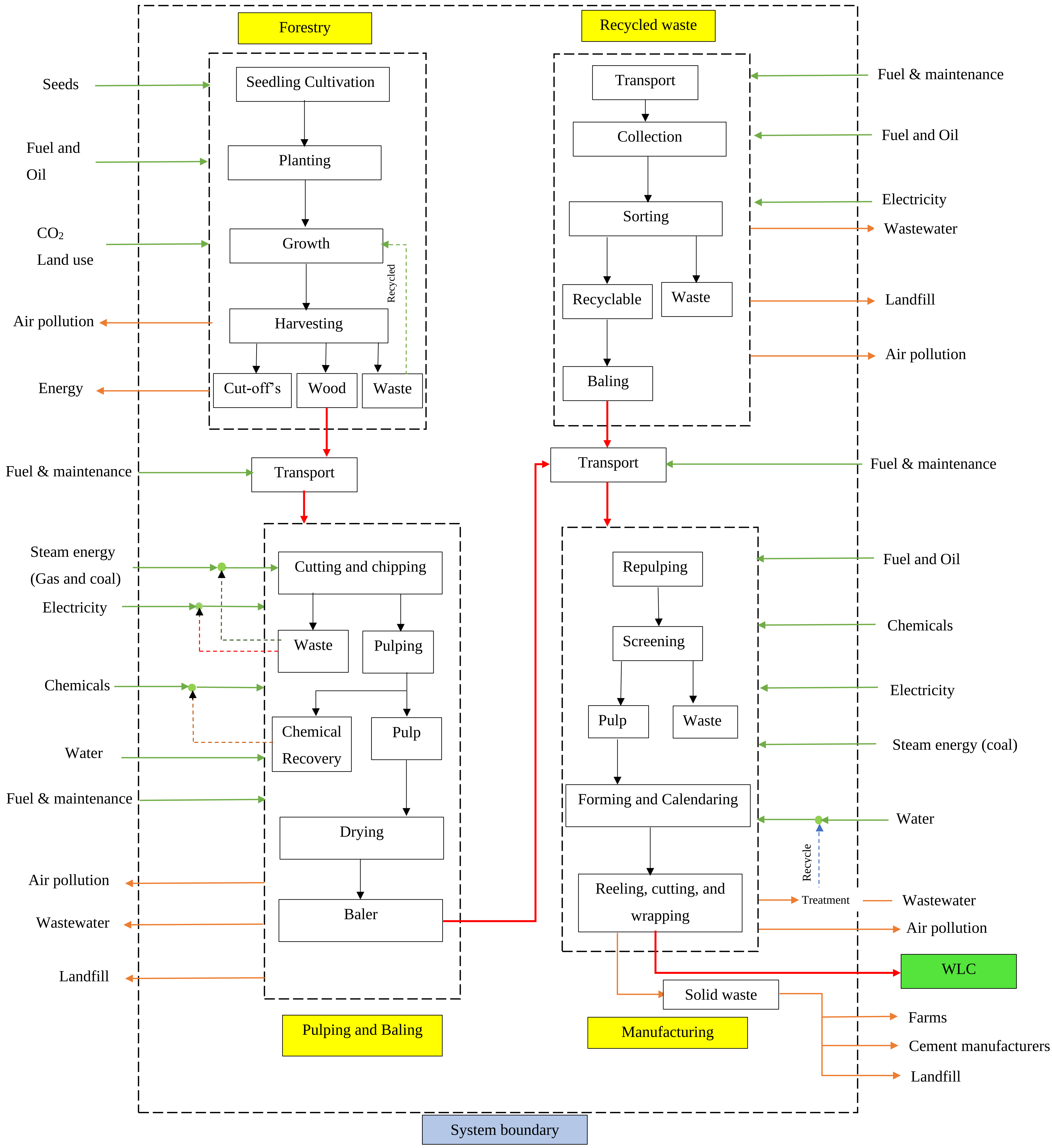

Figure 3-1: System boundary for all unit operations involved in the production of WLC, from raw material acquisition to WLC jumbo reels produced.

3.2.4. Assessment criteria

The ReCiPe 2016 Midpoint impact method has 18 impact categories (Table 3-2), but from the literature review, in the "LCA studies within the pulp and paper sector ", global warming, acidification, photochemical oxidant formation (smog), eutrophication and ozone depletion were the 5 most studied impact categories for the pulp and paper/paperboard industry. Also, as South Africa is a semi-arid country, its water reserves are not as abundant as some of the countries in the studies, therefore, along with those 5 categories, freshwater ecotoxicity was also added. The impact categories studied in this LCA were global warming, freshwater ecotoxicity, acidification, eutrophication, ozone formation (smog) and ozone depletion.

Table 3-2: ReCiPe 2016 Midpoint impact categories (PRé Sustainability, 2020).

Category
Climate change
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, human health
Fine particulate matter formation
Ozone formation, terrestrial ecosystems
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water use

3.2.5. Allocation choices

White-lined chipboard manufacturing does not contain any other co-product production. The company produces several paperboard/kraft grades per day on the same processing line, which includes WLC and several other kinds of paperboard, but it is all produced at different time intervals. Thus, there are several inputs (fibres, chemicals, electricity, steam, etc.) and outputs (wastewater, mechanical wastes, emissions, etc.) that should be fractioned to match the production rate of WLC. In most instances, mass fractioning was used since the actual production of the wastes and intermediate products are simply fractioned based on their production volumes.

However, in certain scenarios, economic allocations would be necessary. Physical allocation can be unfair when working with lower-valued by-products with larger significant masses, hence economic allocation is more appropriate. Economic allocation played a bigger role in forestry. In integrated forestry, a tree is used for both sawlogs and pulp logs, however, the sawlogs are the main drivers for harvest. Sawlogs, however, make up less by volume but is much more economically valuable, hence economic allocation is used. The forestry operations used in the context of this LCA are non-integrated, meaning it is solely grown for pulp production.

Once the wood is harvested for pulp production, several by-products are produced. These include bark, stump and crown (branches, twigs and leaves). The debarked logs have the highest value per ton as opposed to the other products and the logs constitute about 45 % – 66 % of the tree (Huynh et al., 2022; Pagano, 2011). It also requires the most work to extract and clean, whereby the bark, stumps and crown (in most cases) are usually considered low-valued products or even wastes. As a result (for this LCA) the complete economic consideration of the bark, stump and crown was excluded and the whole impact of forestry was solely attributed to the pulp logs.

3.2.6. Data and data quality requirements

The data collected covered the years 2018, 2019, and 2020, taken as an average yearly value for all flows involved in the process. Since the data for this study will be new, most of the information concerning flows into and out of the system boundary would be primary data, thereby ensuring more exact results for each of the processes. Primary data will be used as much as possible. However, when there are gaps or shortcomings in the data, calculations using primary data will be used to fill in the missing information. If this is not possible, secondary data sources such as other research projects and estimations will be used. The data quality of the secondary data and their influence on the results will be accounted for based on the data quality pedigree as presented by SimaPro. The quality as generated by the matrix would then be added to the standard deviation of the data to account for uncertainty in the data, which will be especially important when using secondary data.

Once the data is collected, sensitivity analysis would be conducted to study the influence of the assumptions and estimations on the impact of the LCA. Similarly, the Monte Carlo analysis will also be used to study the probability of the influence of different outcomes on the impact of WLC production.

4. Method: Inventory analysis

4.1. Eucalyptus forestry process

Eucalyptus forestry is the process in which eucalyptus, the main raw material input for virgin fibre production, is planted, grown, and harvested. In South Africa, the eucalyptus seedlings are grown in glasshouses for three months before being planted by hand. Once planted, the trees grow for 7 —12 years before being harvested, with an average growing period of 8.5 – 9 years.

The datasets were supplied by South African industries. Because of the nature of forestry data, it is challenging to find a process by which the data can be validated, by either mass or energy balances, especially since the trees (from the same species and area) have different widths, heights, crown sizes and bark coverage (by mass). The use of fertilisers, pesticides, herbicides, fungicides and the occasional irrigation was excluded from the LCA because its application only occurred when and if necessary and varied from one plantation to another.

Forestry was modelled as one product system. For this reason, all inputs and outputs were modelled to a functional unit of “1 m^3 of Roundwood harvested”.

Table 4-1: Inputs and outputs associated with South African eucalyptus forestry

Product	Value	Unit	Source	Note
Wood under bark	1	m^3		Reference product
		Resources		
Carbon dioxide	898	kg	Secondary	Absorbed from environment
Energy (Biomass)	12939	MJ	Secondary	
Wood	1	m^3	Primary	Harvested
Forest land occupied	567	m^2a	Primary	Land area used for a period of tree growth
Rail/road embankment land occupied	17.0	m^2a	Secondary	Land used for rail and road during the period of tree growth
Land transformed into forestry	0.21	m^2	Secondary	Afforestation
Land transformed from forestry	2.5	m^2	Secondary	Deforestation
Land transformed from traffic area, rail/road embankment	0.075	m^2	Secondary	Roads removed during deforestation
Land transformed into a traffic area, rail/road embankment	0.0063	m^2	Secondary	Roads built during afforestation

Product	Value	Unit	Source	Note
Materials/fuels				
Harvesting, forestry harvester	0.03	hr	Secondary	Machinery used to harvest trees
Forwarding, forwarder	0,038	hr	Secondary	
Skidding, skidder	0,077	hr	Secondary	
Power sawing, without a catalytic converter	0.25	hr	Secondary	
Gravel, crushed	20.0	kg	Secondary	Road construction and maintenance
Lubricating oil	0.3	kg	Secondary	Maintenance
Electricity/heat				
Diesel	78	MJ	Secondary	Fuels used in machinery

4.2. Virgin fibre kraft pulping process

Pulping (kraft) is the process in which the wood from the forestry sector is cleaned, chipped and delignified in a digester using chemicals such as sodium hydroxide (NaOH) and sodium sulphate (Na_2SO_4) which break down the lignocellulosic material that binds the wood fibres together. The fibres are then screened to remove any large unbroken chips and other impurities. It is then washed, bleached, dried and sold as bales of pulp.

The datasets were supplied by South African industries. Since the data was supplied on an annual basis, there was no way to validate the data by mass balances. To validate the data, the data was compared to an existing European kraft pulping dataset with similar operating conditions.

The kraft pulping dataset was modelled as one product system. For this reason, all inputs and outputs were modelled to a functional unit of “1 kg of baled pulp produced”.

Table 4-2: Inputs and outputs associated with South African eucalyptus kraft pulping.

Product/Process	Value	Standard deviation	Unit	Source	Notes
		Materials/fuels			
Delignification & bleaching	0.011	0.0039	kg	Primary	Chemicals
pH control	0.008	0.0002	kg	Primary	Chemicals
Heavy fuel oil	0.14	0.071	MJ	Primary	Used for drying and electricity production
Heat (biomass)	0.77	0.028	MJ	Primary	Used for drying and electricity production
Disinfectant	9.3×10^{-5}	2.1×10^{-5}	kg	Primary	Chemicals
Starch	0.0019	6.8×10^{-4}	kg	Primary	Chemicals
Other fillers and additives	0.019	0.0057	kg	Primary	Chemicals
Sizing agent	0.00014	3.0×10^{-5}	kg	Primary	Chemicals
Pitch control	0.00022	8.4×10^{-5}	kg	Primary	Chemicals
Eucalyptus (wood under bark)	0.0031	-	m3	Primary	From forests
Water	25	1.3	kg	Primary	Surface water source
		Electricity/heat			
Electricity, natural gas	0.11	0.008	kWh	Primary	On-site
Electricity, wood bark	0.039	0.0028	kWh	Primary	On-site
Electricity, coal	0.19	0.014	kWh	Primary	On-site
Electricity, coal	0.034	0.0053	kWh	Primary	Municipality
Heat, black liquor	6.1	0.32	MJ	Primary	On-site
Transport from forests (40- ton truck)	100	-	kgkm	Primary	

Product/Process	Value	Standard deviation	Unit	Source	Notes
Emissions to water					
COD	0.00068	2.9×10^{-4}	kg	Primary	
Suspended solids	0.00020	8.6×10^{-5}	kg	Primary	To the ocean,
Nitrogen	7.9×10^{-7}	2.8×10^{-7}	kg	Primary	after treatment
Phosphorus	1.1×10^{-6}	7.3×10^{-7}	kg	Primary	
Waste to treatment					
Wood ash mixture	0.00011	5.3×10^{-5}	kg	Primary	Landfill
Hard coal ash	0.00055	2.6×10^{-4}	kg	Primary	Landfill
Municipal solid waste	0.001	3.7×10^{-4}	kg	Primary	Landfill
Hazardous waste	2.3×10^{-5}	2.1×10^{-5}	kg	Primary	Incineration
Green liquor dregs	0.00077	2.2×10^{-4}	kg	Primary	Landfill
Sludge	0.004	-	kg	Primary	Landfill

4.3. WLC manufacturing process

As mentioned in the goal of the study, the main objective is to study the impact of the production of WLC. The mill is divided into three main sections, namely energy production, water treatment and the production line.

4.3.1. Production line

The process starts with the receiving of the raw materials. This will include recycled wood fibre (newspaper, paperboard and cardboard) and virgin wood fibre (eucalyptus – chemical and mechanical baled pulp). These are stored in a stockyard and taken to the loading station by forklifts. Once loaded, the material is fed into a pulper (4 separate pulpers) where the pulp is mixed with water up to a 2 % fibre by mass ratio. During this process, all wood fibres are beaten, and chemicals are added to the mixture. The recycled fibres are fed through screens to remove any impurities such as paperclips, plastics, glass, metal shards, sand, and stones. This is removed and disposed of in container bins which are transported to landfills.

Once the fibres have been cleaned, they are fed into a headbox. The headbox is used to layer the four different fibre layers on top of each other, which is then gently rolled between two cylinders. This is known as the forming process and most of the water is removed during this process. The layered material is then fed into the calendaring section. The calendaring section consists of two steps. The wet press section is where gravity and the pressing of metal rolls remove water from the layers (up to 65 % moisture removed). The drying section makes the second step, where steam at around 5 MPa and 158 °C is fed through similar metal cylinders as in the wet press section, except now it is simultaneously pressing the sheets and evaporating the remaining moisture. The moisture that remains in the sheet after drying varies between 4 – 8 % by mass (depending on the grammage produced). The sheet is fed to a coating section where it is triple clay coated on the top side and single-coated on the bottom side. The coated sheet is then dried by a gas-fuelled IR heater.

The final coated material, now termed WLC, is reeled onto a cardboard core. The jumbo reel is cut to requirement and then wrapped, marked, and loaded onto trucks using forklifts. The mill has an average annual production volume of 66 270 tons of WLC.

4.3.2. Water treatment

The water treatment process consists of the treatment of water removed during the forming and calendaring section of the process. Some of the water can also come from the boiler house during the cleaning of the water softening process and purge streams from the recycled condensed vapour water. The water is received and fed into buffer tanks where biocides are added. From the buffer tanks, the water is moved to the clarifier. Coagulants and flocculants are added before the water enters the clarifier. From the clarifiers, two streams rise namely sludge and overflow. The sludge is removed from the bottom of the clarifier and fed to a sludge tank. The sludge is then fed onto a belt press where 40 – 45 % moisture is removed and emptied into a skip. The sludge is transported to farms for use as fertilizer. The water from the sludge press is recycled back into the buffer tanks. The clarifier overflow water is fed to clear water tanks, The water is then split and either reused in the process as filtered water or discarded as effluent to the municipal sewer. The process can recycle on average about 80 % of water, discharging only 20 % of water as effluent.

4.3.3. Energy production

Energy production includes the generation of steam via coal combustion in boilers. The coal is received by truck, stored and fed into the boilers using conveyor systems. The coal quality consists of bituminous coal with a higher heating value (HHV) of 26.56 MJ kg^{-1} and carbon content of 54.4 wt %. The energy produced is used to produce steam at 10 MPa and 180 °C.

Most of the water vapour is condensed and reused. Some of the water is lost through purge streams and leaks, so when new water is pumped into the system it is first softened by the addition of chemicals and then used. Once the coal is combusted, the ash is removed and transported to cement-producing companies. The air emissions have been accounted for; however, the mill's boiler is characterised as a small boiler under Section 21 of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004), as a result, an air quality license is not required and the only emission limits apply to particulate matter and sulfur dioxide. The mill's readings supplied by their stack tests are for CO_2, CO, SO_2, NO_x and PM. The rest of the emissions were extrapolated and adapted from a boiler dataset in EcoInvent.

4.3.4. Allocation calculation

During the LCA study, some of the information available represented the unit process and the materials, requiring no further calculations. For example, the amount of fibre and chemicals used in the production of WLC was known. However, as the mill consists of several production lines and different processes, not all measurements from the site only represented WLC production. Some represented the production line on which WLC was produced, "PL 1", and some information represented the entire mill.

PL 1 produces different paperboard materials at different time intervals. Some readings, such as the water readings are taken every day for the entire production line, and therefore, represent the water used for all the paperboard products produced on PL 1. To solve this problem, the mass allocation method was used. Since the annual production volume of PL 1, and the annual production of each product produced on PL 1 was known, it was possible to determine the annual mass fraction of WLC produced (Equation (1)) on PL 1. Dividing the two by each other results in,

$$\frac{WLC\ produced}{\text{PL 1}\ Production\ volume} = \frac{66270.51\ ton}{101064.8\ ton} = 0.656 = 65.6\ wt\% \qquad (1)$$

This means that WLC accounts for 65.6 wt% of the annual production volume and resource consumption of PL 1.

In some instances, such as electricity, the reading was taken for the entire mill. This means that the electricity used by all production lines and processes was included in the reading. However, not all the production volumes of the different processing lines were known. The entire mill has an average annual production capacity of about 137 000 tons, but this is not the actual value. Therefore, to try and determine the mass fraction of WLC produced for the entire mill an alternative approach was used. However, using this 137 000 tons value, the potential mass fraction of WLC produced for the entire mill (Equation (2)) could be calculated.

$$\frac{WLC\ produced}{Total\ mill\ production\ average} = \frac{66270.51\ ton}{137000\ ton} = 0.484 = 48.4\ wt\% \tag{2}$$

Staff on site said that PL 1 accounted for about 75 – 80 % of the mill's average annual production volume. The standard fibre-to-water ratio when mixing fibre is 2 % fibre-to-water. Assuming that it remains the same for all the process lines, taking the amount of water fed to PL 1 and dividing it by the total water fed to all production lines would then closely represent the actual production value. The average water fed to PL 1 to the total water fed to all the production lines came to,

$$\frac{PL\ 1\ water}{Water\ fed\ to\ all\ production\ lines} = \frac{721884\ kL}{915954\ kL} = 0.788 = 78.8\ wt\% \tag{3}$$

This means that the entire production volume of PL 1 accounts for 78.8 % of all flows into/exiting the mill. Multiplying Equation (3) by Equation (1) to represent the value in terms of WLC produced,

$$\frac{WLC\ produced}{Total\ mill\ production} = 0.788 \times 0.656 = 0.517 = 51.7\ \% \tag{4}$$

This is close to the value obtained in Equation (2). To check Equation (3), when dividing the PL 1 total production volume by the mill's average possible annual production, the fraction is quite similar,

$$\frac{\text{PL 1}\ Production\ volume}{Total\ mill\ prodcution\ average} = \frac{101064.8\ ton}{137000\ ton} = 0.738 = 73.8\ wt\% \tag{5}$$

Therefore, in the calculations to follow, if data was specific to PL 1 production, Equation (1) would be used to determine the fraction associated with WLC production. If data was specific to the entire mill, Equation (4) would be used to determine the fraction associated with WLC production.

4.3.5. Inputs and outputs

The information supplied represents three years (2018 – 2020) on a month-to-month basis. The values were averaged across the same months (average for January 2018, 2019, and 2020) and then summed to give an average annual production volume. The values as measured/calculated were taken and divided by the annual average production volume of WLC to calculate the values in terms of the functional unit. Therefore, all the data represented below are already based on the functional unit, unless specified otherwise.

Methods used to calculate the values obtained and validation of the data by mass balances, energy balances and secondary sources are explained in Appendix A – C (pg. 143 – 165)

Inputs - raw materials

These inputs refer to raw materials used to produce WLC, which includes fibre and water, but excludes energy fuel sources.

Table 4-3: Input of raw materials to produce WLC

Product	Value	Standard deviation	Unit	Source	Note
Manufacturing line					
Virgin kraft fibre	0.19	0.0052	kg	Primary data	-
Virgin mechanical fibre	0.06	0.0017	kg	Primary data	-
Common mixed waste	0.36	0.04	kg	Primary data	Consists of newspaper and paperboard
K3 (recycled fibre)	0.1	0.0093	kg	Primary data	Pre-consumer corrugated material
K4 (recycled fibre)	0.27	0.016	kg	Primary data	Post-consumer corrugated material
Own broke	0.07	0.0034	kg	Primary data	Recycled own material from the process line breaks
Freshwater - pulping	7.2	0.43	L	Calculate from primary data	Water from municipality
Freshwater - domestic	0.25	0.1	L	Primary data	Water used onsite
Water treatment					
Water received from the process line	40	-	L	Primary data	This is the total water sent to the treatment plant, 81.97 % is recycled.

Product	Value	Standard deviation	Unit	Source	Note
Energy production					
Freshwater - boiler	1.4	0.15	L	Primary data	Water from municipality
Oxygen	0.86	-	kg	Calculated from secondary data	Oxygen required for combustion

Inputs – Energy and electricity

The primary source of energy required to operate the mill comes from electricity. The electricity runs all machinery and equipment on site. Electricity is purchased from the local municipality. The second major energy source is coal-fired boilers. They are responsible for producing the high-pressure and high-temperature steam used during the drying phase of the fibre sheets. The last two sources of energy required are natural gas for IR heating, used to dry the coat sprayed onto the rolled fibre sheets, and diesel used to fuel on-site vehicles such as forklifts.

Table 4-4: Energy requirements to produce WLC

Product	Value	Standard deviation	Unit	Source	Note
Manufacturing line					
Electricity	1.1	0.065	kWh	Primary data	Represents the entire mill
Natural gas	0.76	0.12	MJ	Primary data	Infrared gas (IR) heater. Used to dry clay coat on WLC.
Diesel	0.13	-	MJ	Primary data and Secondary	Represents all forklifts on site
Energy production					
Coal	0.36	0.026	kg	Primary data	Used in the on-site boiler

Inputs – Chemicals

The chemical inputs represent all the chemicals used in the three processes, these include water treatment, water softening, fillers, coatings, and cleaning materials. Most of the chemicals used in the mill were given by market names and because many of the suppliers of the chemicals want to keep their formulas confidential, the exact chemical compositions were unknown (not for all the chemicals). To account for the unknown chemicals, the MSDSs were used to determine their composition. In most cases, the MSDS would only supply some of the information about the chemical’s composition. In this instance, the chemical would be represented by the most abundant chemical present in the formulation (excluding water). This means that if a mixture of water, alcohol, and oil was 50:40:10 (assuming oils were unknown), the entire chemical's mass would be represented by the alcohol. This was accounted for in the uncertainty matrix in SimaPro.

To prevent exposing confidential information concerning the chemicals used in the process of producing WLC, the chemicals in Table 4-5 are represented by their market names or functions, such as defoamer, or by their "chemical family group" or "functional group", such as carboxylic acids. Secondly, the chemicals with the same "functional groups" were aggregated. This means that a single name in the table could represent 1 – 5 (max) chemicals. However, the simulations were conducted using the individual chemicals as supplied by the mill, therefore still representing the actual process.

Table 4-5: Chemicals required to produce WLC

Product	Value	Standard deviation	Unit	Source	Notes
Manufacturing line					
Binding agents	0.0198	0.00051	kg	Primary data	Chemicals used in WLC manufacturing and process cleaning.
Aluminium sulphate	0.0021	0.00078	kg	Primary data	
Starches	0.018	0.00028	kg	Primary data	
Biocide	0.00089	2.6×10^{-5}	kg	Primary data	
Carboxylate salts	0.000287	2.4×10^{-5}	kg	Primary data	
Ethanolamine's	0.00013	1.2×10^{-5}	kg	Primary data	
Sodium hydroxide	0.0012	3.3×10^{-5}	kg	Primary data	
Defoamers	0.00027	7.8×10^{-6}	kg	Primary data	
Sizing agents	0.0004	0.00016	kg	Primary data	
Perlites	0.00014	6.4×10^{-6}	kg	Primary data	
Carboxymethyl cellulose	0.00068	2.5×10^{-6}	kg	Primary data	
Glyoxal	0.00072	2.1×10^{-5}	kg	Primary data	
Kaolin	0.025	0.00074	kg	Primary data	
Carbonate minerals	0.046	0.0013	kg	Primary data	
Optical brighteners	0.00015	4.2×10^{-6}	kg	Primary data	
Polyacrylamides	0.0031	0.00011	kg	Primary data	
Organic halogen compounds	0.0003	7.8×10^{-6}	kg	Primary data	
Sodium salts	2.2×10^{-6}	7.7×10^{-8}	kg	Primary data	

Product	Value	Standard deviation	Unit	Source	Notes
		Water treatment			
Flocculant	3.9×10^{-5}	2.2×10^{-5}	kg	Primary data	
Coagulant	0.00017	5.6×10^{-5}	kg	Primary data	
Biocides	0.0002	6.6×10^{-5}	kg	Primary data	Used in the water treatment process.
Hypochlorite's	1×10^{-4}	1×10^{-4}	kg	Primary data	
Defoamers	9.9×10^{-6}	9.6×10^{-6}	kg	Primary data	
Oxygen	0.00019	5×10^{-5}	kg	Primary data	
		Energy production			
Sodium hydrogen sulphites	5.6×10^{-5}	7.3×10^{-6}	kg	Primary data	
Sodium hydroxide	2.5×10^{-5}	3.3×10^{-6}	kg	Primary data	Boiler water softening.
Morpholine	1.3×10^{-5}	1.6×10^{-6}	kg	Primary data	
Salt	0.00032	4.2×10^{-5}	kg	Primary data	

<u>Inputs – Transport</u>

The transport represents all transport from and to the mill and includes the delivery of chemicals and raw materials, the delivery of the WLC jumbo rolls to clients, and the disposal of materials at farms, cement manufacturers and landfill. All distances are supplied as kgkm. This means that the mass of products transported was multiplied by the distance travelled to the site.

Table 4-6: Transport requirements to and from the mill

Product	Value	Standard deviation	Unit	Source	Note
			To WLC mill		
Mechanical pulp - International – by truck	6.5	0.18	kgkm	Primary and estimated	International - mill to port
Mechanical pulp – International – by ship	849	24	kgkm	Primary and estimated	International by seaport to SA port
Mechanical pulp - truck	39	1.1	kgkm	Primary and estimated	From SA port to WLC mill
Chemical pulp - truck	106	3.1	kgkm	Primary	National truck transport
Recycled fibres - truck	74	3.7	kgkm	Primary and estimated	National truck transport
Chemicals - trucks	12	0.33	kgkm	Primary and estimated	National truck transport
Diesel purchased - truck	1.3	0.02	kgkm	Primary and estimated	National truck transport
Coal - truck	51	4.3	kgkm	Primary	National truck transport

Product	Value	Standard deviation	Unit	Source	Note
			From WLC mill		
WLC to clients - truck	404	36	kgkm	Primary and estimated	Product transport to client
Sludge - truck	5.2	1.7	kgkm	Primary and estimated	To farmers
Ash - truck	8.6	1.8	kgkm	Primary and estimated	To cement manufacturers
Reject plastics - truck	1.7	0.34	kgkm	Primary and estimated	Landfill
General waste - truck	0.063	0.035	kgkm	Primary and estimated	Landfill

<u>Outputs</u>

The outputs include the final product, intermediate products and wastes from the company. All the outputs, by volume and mass, were supplied by the company. The emissions not measured by the mill were adapted from an existing boiler dataset supplied by EcoInvent, in which the data was adjusted and extrapolated to match the quality of the coal used by the mill.

Table 4-7: Solid and liquid outputs generated by the production of WLC

Product	Value	Unit	Standard deviation	Source	Note
			Manufacturing line		
Jumbo reels	1	kg	NA	Functional unit	Product to client
Screened waste	0.0762	kg	0.016	Primary	To landfill
General waste	0.0067	kg	0.0022	Primary	To landfill
			Water treatment		
Effluent	5.7	L	0.41	Primary	Discharge into municipal wastewater lines
Sludge	0.048	kg	0.0083	Primary	To farmers as agricultural fertiliser
			Energy production		
Ash	0.085	kg	0.018	Primary	To cement manufacturers

Table 4-8: Air emissions generated from the production of WLC

Product	Value	Standard deviation	Unit	Source	Note
Manufacturing line					
Water lost as steam during drying	1.49	-	L	Calculated from primary data	To environment
Energy production					
Carbon dioxide, fossil	0.6	-	kg	Primary	
Carbon monoxide, fossil	1.5×10^{-3}	-	kg	Primary	
Methane, fossil	1.0×10^{-4}	-	kg	Extrapolated from EcoInvent	
Nitrogen oxides	1.2×10^{-3}	-	kg	Primary	
Particulates, < 2.5 um	4.0×10^{-4}	-	kg	Primary	
Particulates, > 10 um	2.0×10^{-4}	-	kg	Primary	
Particulates, > 2.5 um, and < 10um	4.0×10^{-4}	-	kg	Primary	To environment
NMVOC, non-methane volatile organic compounds	1.8×10^{-3}	-	kg	Extrapolated from EcoInvent	
Sulfur dioxide	1.9×10^{-3}	-	kg	Primary	
Metals	0.0027	-	kg	Extrapolated from EcoInvent	
Inorganics	4.2×10^{-4}	-	kg	Extrapolated from EcoInvent	
Organics	1.7×10^{-4}	-	kg	Extrapolated from EcoInvent	

5. Results and discussion

5.1. Impact assessment

5.1.1. Impact value ranges

In the results, only a single value for the impact of each process was given although the inventory tables indicated that there was a range of possible values for each process and product. In the SimaPro software, it is possible to study the effect that these ranges/deviations have on the environmental impact, as in the "Uncertainty analysis" section, however, the SimaPro software can only study the effects of the deviations on the results in total and not for the individual processes or products. Therefore, the results to follow were based on the single-valued averages.

5.1.2. Global warming

Global warming is the steady rise in the earth's average temperature. Global warming does occur naturally but human activities have increased the rate of warming. The release of greenhouse gases into the atmosphere creates a blanket-like effect, preventing reflected sunlight from escaping into space. This is because the rate of generation of greenhouse gasses is outweighed by the rate of its absorption by natural plant life. Secondly, the combustion of fossil fuels is not sustainable and does not form part of the carbon-neutral cycle since it comes from matter that lived millions of years ago. As a result, the remaining emissions stay trapped in the atmosphere. Thirdly, the Holocene extinction (the extinction of the earth's flora and fauna) also slows down the rate of greenhouse gas absorption, thus further increasing its presence in the atmosphere. Lastly, human structures such as roads and buildings, with more reflective surfaces, reflect more sunlight into the atmosphere when compared to the earth's natural surface, which absorbs more sunlight. The process of global warming occurs when the reflected sunlight from the earth's surface gets trapped in the atmosphere. Naturally, some reflected sunlight will remain in the atmosphere and some will escape to space. However, because of the greenhouse effect, the reduced fauna and flora and increased reflection of the sun's rays from the earth's surface, more reflected sunlight remains trapped in the atmosphere and less escapes to space, hence heating the atmosphere and resulting in global warming. With the new global initiative to reduce global warming and push back against fossil-fuel use, such as coal, global warming is a good impact category to study to see which processes contribute the most to it.

The use of electricity and energy generation from the boiler were the two highest contributors to the global warming impact category, outweighing the other processes by a significant amount (Figure 5-1). Table 5-1 shows which global warming substances contributed the most to the impact category. The substances classified as “Remaining” include emissions such as biogenic methane, sulfur hexafluoride, nitrogen fluoride and several other fluoro-, chloro- and bromo- alkanes.

Table 5-1: Substances responsible for global warming

Substance	Value (kg CO_2 eq)	Contribution (%)
Carbon dioxide, fossil	2.2	91
Methane, fossil	0.14	5.8
Dinitrogen monoxide	0.033	1.4
Methane, biogenic	0.029	1.2
Remaining	0.007	0.29
Total	2.41	99.7

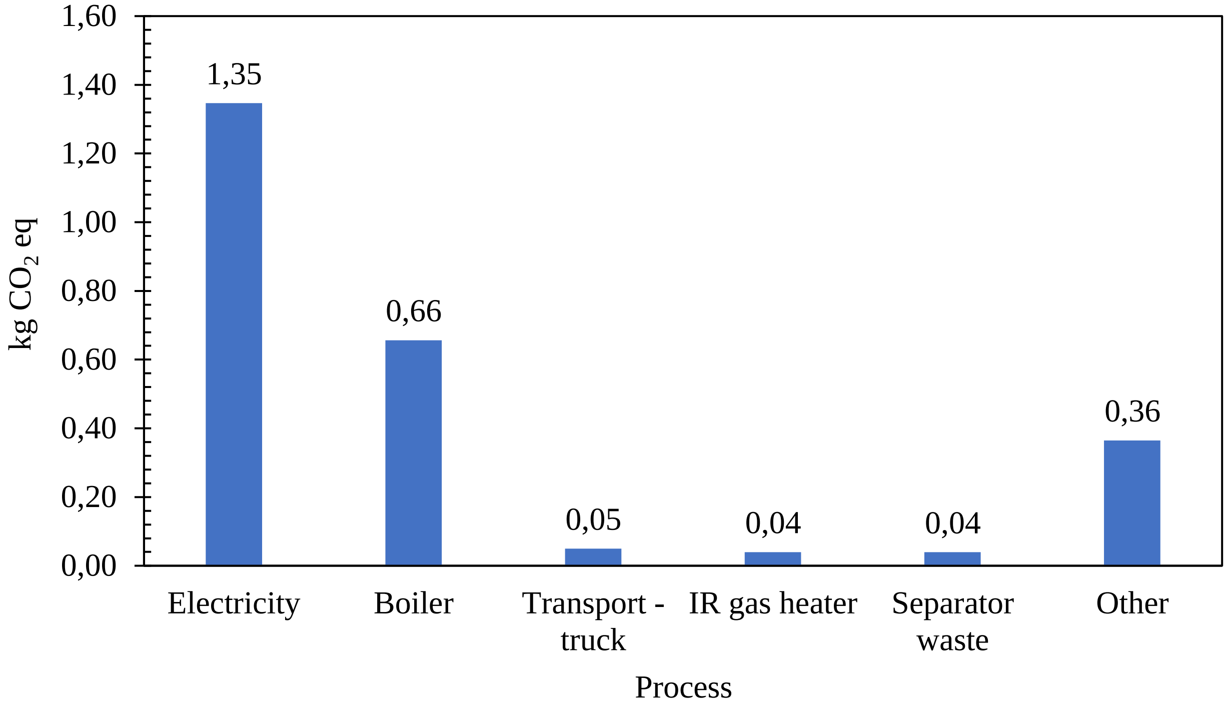

Figure 5-1: Top five contributors to the global warming impact category

The total global warming impact for WLC production came to a final value of 2.45 kg CO_2 eq. The carbon dioxide released (kg CO_2) contributed to 95.9 % of the total emissions responsible for global warming (Table 5-1). Of this total value, electricity end energy generation was the highest contributor, at 44 % and 38 % respectively. Electricity and energy production has a large impact on the category because of the use of coal as the primary fuel source. The South African electricity grid relies on coal for 83 % of its electricity (Department of Energy, 2019) and the boiler on-site used for energy production solely uses coal as a fuel source. Thus, to see a major reduction in the global warming impact category, a change in fuel source would be necessary.

The major contribution from transportation was also carbon dioxide at 98.5 %, methane at 1.12 % and the remaining at 0.38 %. Emissions are generated from diesel combustion, again indicating that the reliance of industry on fossil fuel-based fuel sources is a major concern.

The IR gas heater is used to dry the coat that is applied onto the rolled paperboard after the drying section of the calendaring process. It uses natural gas as a fuel source, and as a result, releases carbon dioxide (92.9 %) into the atmosphere along with methane gas (6.8 %) and other gasses (0.7 %) such as dinitrogen monoxide, biogenic methane, sulfur hexafluoride and several other fluoro-, chloro- and bromo- alkanes.

Separator waste refers to landfilled waste material removed after the recycled pulp has been repulped and screened. This waste includes waste plastic, wood fibre, metal shards and glass shards. Because the material is too fine to recycle, all of it is sent to landfill. The landfilled organic wood fibre decomposes releasing methane into the atmosphere. Methane has a global warming potential that is 28 times greater than CO_2, which means a small amount released can have a significant effect on the environment (Greenhouse Gas Protocol, 2014).

5.1.3. Freshwater ecotoxicity

Freshwater ecotoxicity occurs when chemicals and substances are released into freshwater sources via air, water and soil wastes and are measured as kg 1,4-dichlorobenzene (kg 1.4-DCB). From the results to follow, the process of producing WLC does not contribute directly to this impact category. Rather, the impacts are due to the processes involved in acquiring the raw materials used to produce WLC, of which electricity was the highest contributor. Figure 5-2 indicates the five highest contributing processes to freshwater ecotoxicity. The 1,4-DCB (1,4-Dichlorobenzene) is the reference chemical used to characterise the substances responsible for freshwater ecotoxicity. The 1,4-DCB is a raw material extensively used in industry to produce insecticides, deodorants, pigments and solvents (Motejlová & Kočí, 2011). Its widespread usage leads to an increased concentration in the environment, and since it is environmentally hazardous, it is used as the reference measure for ecotoxicity.

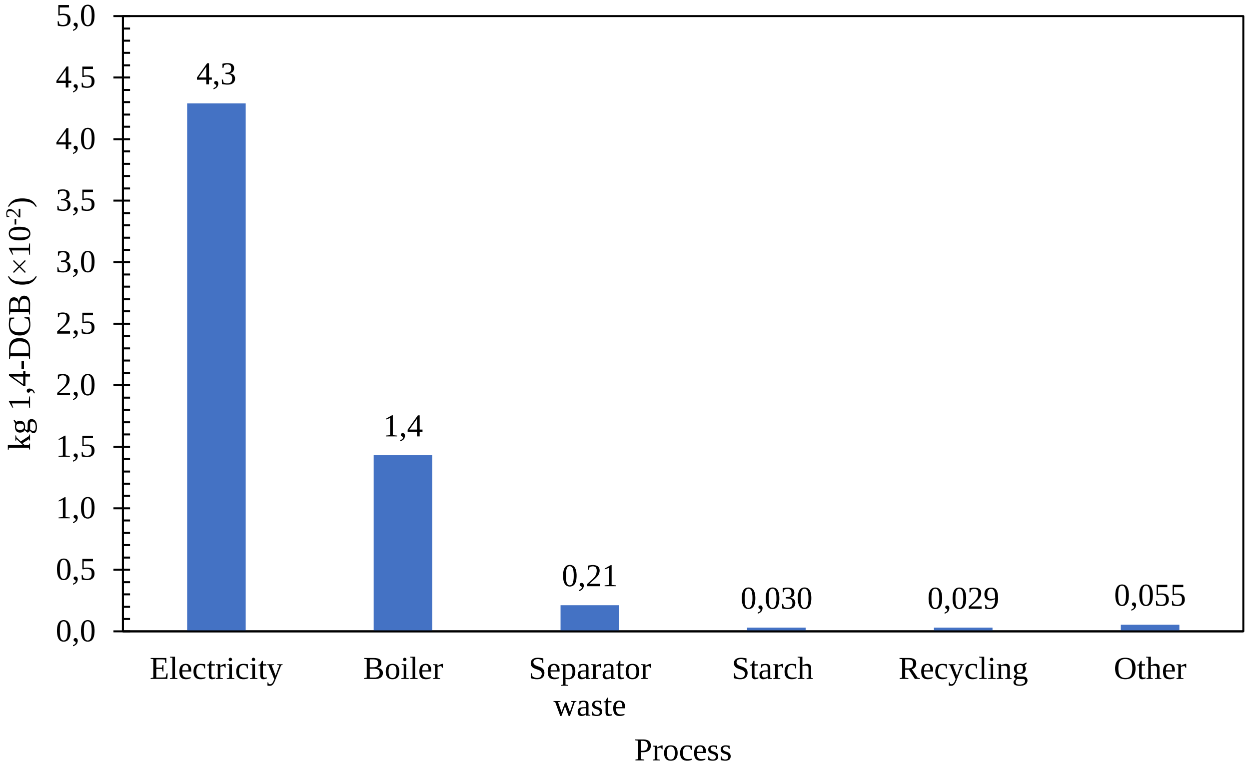

Figure 5-2: Top five contributors to the freshwater ecotoxicity impact category

Table 5-2 shows the five main substances responsible for causing freshwater ecotoxicity and their contribution to the impact category. All five of the substances in the table indicate freshwater ecotoxicity via wastewater, with the highest pollutant being metallic in origin.

Table 5-2: Chemicals responsible for the toxification of freshwater sources

Substance	Value (kg 1,4-DCB)	Contribution (%)
Zinc	0.031	51.4
Copper	0.015	24.7
Vanadium	0.006	9.8
Nickel	0.005	8.5
Chromium VI	0.002	2.5
Remaining	0.002	3.0
Total	0.061	99.9

From Figure 5-2, electricity is the major contributing factor to freshwater ecotoxicity. Electricity generation does not contribute directly to freshwater ecotoxicity but is more related to the processes involved in acquiring raw materials and maintenance. Hard coal mining spoil which occurs for both the electricity and boiler processes is the major contributor. Spoil is the overlying material that is removed during mining and set aside in heaps (X. Li et al., 2014). Trace elements contained in the spoil are washed into the surface and underground water sources by rain seeping through the spoil and by surface run-off. The coal mining dataset in SimaPro defined hard coal mining spoil impacts as; "short and long-term emissions to groundwater from rainfall infiltration and leaching." This means that the trace element pollution that occurred via wastewater was the leaching of the metals and minerals into groundwater sources.

Hard coal ash is another major problem. Coal can on average contain about 10 – 20 % ash by mass. The mill relies heavily on electricity and energy generation via coal, which in turn produces a lot of ash. The effect of the ash on the environment depends on the disposal method. All the ash produced from the mill's boilers is sent to cement and concrete manufacturing companies, which is why it has no impact in this category. However, Eskom produces about 34.4 million tons of ash a year (Funston et al., 2021) of which about 1.2 million tons are sold to the cement and brick industry (Ndou et al., 2021). This means that there are still 33.2 million tons that need to be disposed of. The ash is considered hazardous waste and is disposed of in ash dams and dumps lined with Class C liners beneath (Ndou et al., 2021; Reynolds-Clausen & Singh, 2016) to help reduce leachate. The dataset for electricity production (South African data) considers the pollution generated from the "landfilled" ash as both short-term leachates contaminating surface water and long-term leachate contaminating groundwater as the main sources of freshwater toxicity. As in the hard coal spoil, the landfilled ash included the leaching of heavy metals and minerals into the water sources.

As part of the electricity and boiler dataset, sulfidic tailings from mining activities also affect freshwater systems. Sulfidic tailings are waste materials that remain after the ore (coal, limestone, copper, kaolin clay, etc.) has been processed (Everaert et al., 2020). The mining spoils and tailings can cause acid mine drainage when in contact with water and can cause trace elements and minerals to seep into water sources. The dataset used in SimaPro also indicates that the impoundment leachates' effect on the environment and water sources is measured as short-term and long-term pollution.

Scrap copper represents any material from the electricity production plant that was disposed of due to maintenance and repairs. The Eskom waste management standard report indicates 4 main sources of copper waste, namely, stores, substations and construction camps, dismantling of disused lines and reconducting projects (Ndou et al., 2021). The scrap copper is either recycled, reused, or landfilled, but the percentage of each end-of-life possibility was not indicated in the report. For this reason, the dataset was used as-is.

The separator waste (3.5 %) and recycling waste (0.43 %) refer to the material sent to landfill. Like mining wastes, surface runoff via rain can cause trace elements and chemicals to wash into surface water sources and/or seep into underground water sources. Although the landfills in South Africa are lined to prevent leachate, the dataset considers the fact that some contamination could occur and therefore these two datasets are included.

The starch production (0.5 %) refers to the contamination of water sources by production effluent, which, although treated, still contains minerals, nitrogenous pollutants, organic acids, and a small amount of oil and fat (Cai et al., 2019; Neogi et al., 2018). The organics can ferment and cause water toxification and the mineral material either release trace elements into the water or are themselves the trace elements.

5.1.4. Terrestrial Acidification

Terrestrial acidification is the process by which the accumulation of soluble inorganic and organic acids occurs at a faster rate than they can be naturally neutralized (Freedman, 1995). Acid rain is measured as SO_2 eq. According to Farinha et al. (2021) the sulfur compounds deposit within 2–4 days after emission, therefore, it affects areas close to the emission source and as a result, acidification is quantified by SO_2 eq as it is a faster acidifying compound. Acidification can occur via acid rain, the process where gaseous emissions react with water molecules in clouds to form their acidic counterpart. The acid is then precipitated onto terrestrial surfaces thereby acidifying the surface. Another way in which this can occur is via acid mine drainage or leaching of water through soils and waste, reacting with acid potential chemicals. Using the ReCiPe 2016 method, terrestrial acidification is only accounted for by the emissions of inorganic compounds (ammonia, nitrogen oxides, sulfur oxides and sulfuric acid) that reacts with moisture in the air and then acidifies the soil via precipitation and condensation.

Figure 5-3 shows the five highest contributors to the terrestrial acidification impact category. The highest contributors again are the use of electricity and energy generation from the boiler process.

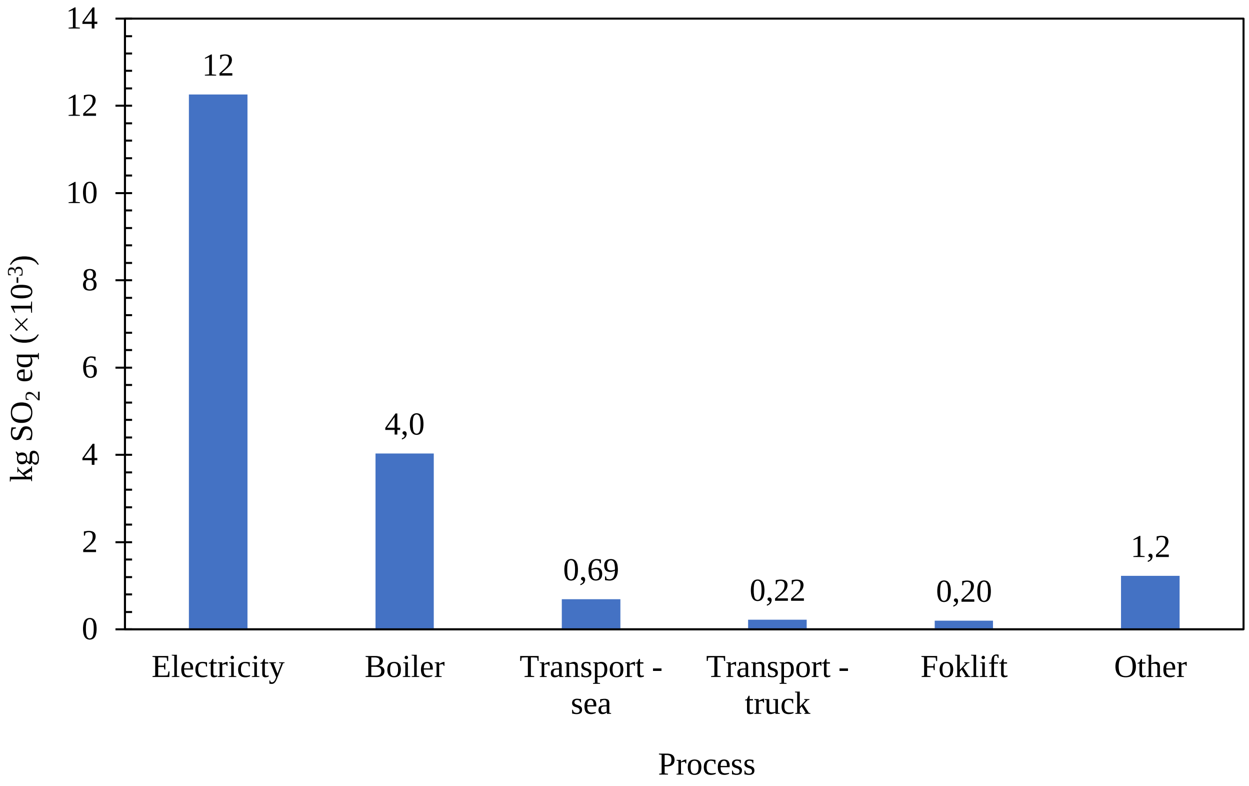

Figure 5-3: Terrestrial acidification and the five highest contributors to the category.

Table 5-3 below shows the three substances that contributed the most to terrestrial acidification.

Table 5-3: Substances responsible for terrestrial acidification

Substance	Value (kg SO_2 eq)	Contribution (%)
Sulfur dioxide	0.0149	80.1
Nitrogen oxides	0.0033	17.9
Ammonia	0.00036	1.9
Remaining	8.27E-7	0.01
Total	0.0186	99.91

As highlighted in the global warming impacts, the mill requires a lot of electricity and energy. South Africa's coal forms part of the bituminous coal reserve and contains around 1.1 – 1.8 % sulfur (Jeffrey, 2005). This means that for high electrical demand, the sulfur oxides released during combustion can amount to significant numbers, which is why electricity generation is the major contributor to terrestrial acidification. Similarly, energy production at the mill for steam generation also uses coal. The coal used in the mill has a lower sulfur content ranging from 0.7 – 0.9 %, making it cleaner coal. The nitrogen oxides originate from both the coal containing nitrogen-based substances and the atmospheric nitrogen that oxidises in the combustion chambers of the boilers and transport vehicles.

As with freshwater ecotoxicity, not all the acidification potential originates from combustion, but from mining activities as well. For example, the blasting process refers to coal mining operations in which explosives are used to break mineral-bearing materials (Adams, 2021). According to Lashgari et al. (2013), in the process of surface coal mining several physical and chemical processes are involved to retrieve the coal, such as drilling, blasting, loading and haulage. Various of this mining equipment and blasting agents are a dominant source of NO_x emissions. The same conclusions were reached by Attalla et al. (2008), who also found that NO_x was the main source of emissions during the blasting process.

Transportation occurs via sea and land, but also includes on-site material movement by forklifts. Sea transport mainly occurs because of the importation of materials required in the process. Transportation on land occurs because of the transportation of raw materials and chemicals, transport of waste to end-of-life locations (for reuse, recycling or landfilling), and transport of the final product to the clients. The database in SimaPro indicates that the main fuel source for sea, truck and forklift was heavy fuel oil (ship) and diesel (truck and forklift). From both these fuel sources, NO_x and SO_2 were the primary emissions responsible for terrestrial acidification.

5.1.5. Ozone formation

Ozone formation occurs via the reactions between NO_x and non-methane volatile organic compounds (NMVOC) in the presence of sunlight, which is why the effects of ozone are also more prominent in summertime (Huijbregts et al., 2016). Ozone is also one of the main components responsible for the formation of smog. Although ozone formation occurs via the reaction between NO_x and NMVOC, the ReCiPe 2016 method measures ozone formation via NO_x release.

In this impact category, electricity and the boiler process were still the highest, but not so much that the other processes became negligible (Figure 5-4).

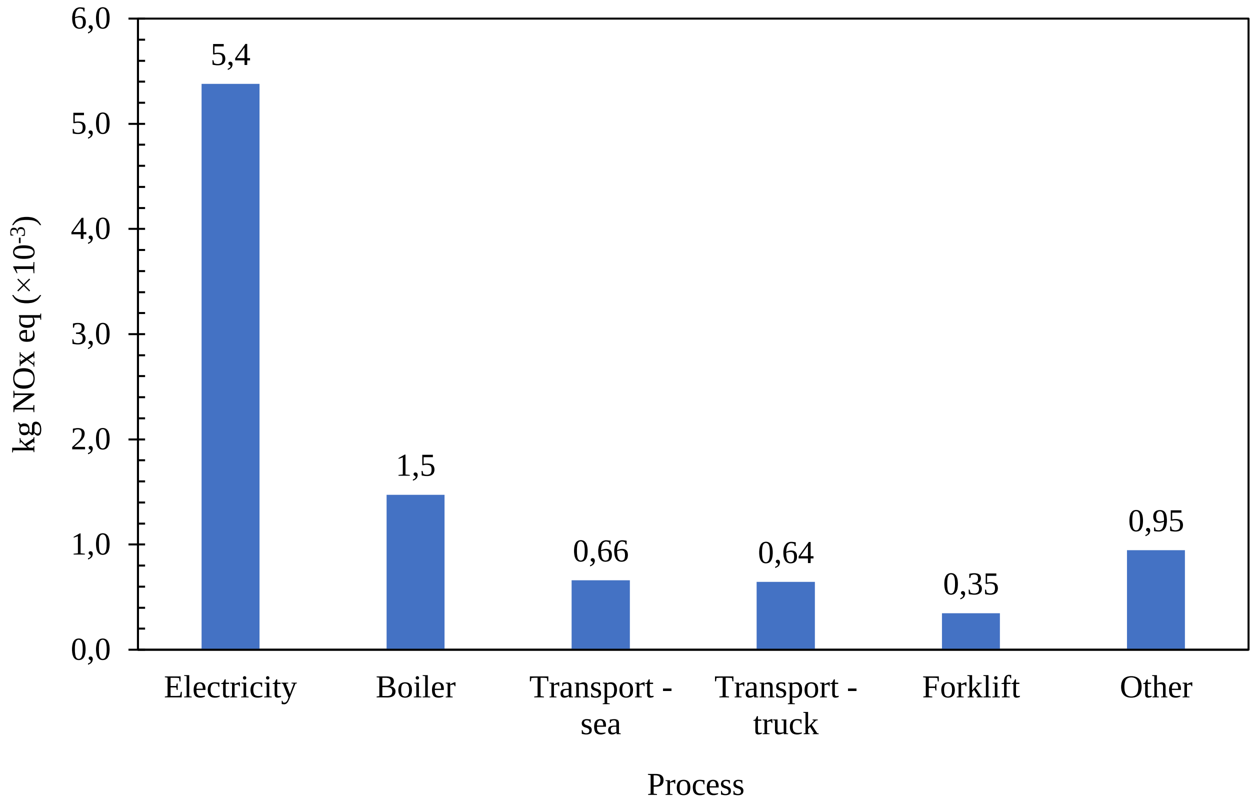

Figure 5-4: Ozone formation impact category and the five highest contributors

Similar to global warming and terrestrial acidification, due to the high demand for electricity and energy, the amount of NO_x and NMVOCs released during combustion is also high. The amount of nitrogen oxides released from coal combustion is generally lower than the sulfur oxides by about 40 – 60 %, depending on the quality of the coal and also on the efficiency of the combustion process (Marcy, 2018). Despite the smaller amount released, the effects it has on the environment are still severe and even a small value becomes large when a significant amount of coal is combusted. Therefore, the two leading impact processes are electricity generation and energy production. As with acidification, mining processes such as blasting also contribute to ozone formation.

The ozone formation originating from vehicles, ships and forklifts occurs not because heavy fuel oil and diesel inherently contain nitrogen-based compounds, but because of the nitrogen in the atmosphere. The atmospheric nitrogen is sucked in with oxygen into the combustion chamber where the fuel is ignited and oxidized along with the nitrogen, producing NO_x (Ramalingam & Rajendran, 2019). As indicated in the inventory analysis, there are several trucks used for transporting raw materials and chemicals, and the transport of products to clients and wastes to end-of-life sites. The ships are responsible for carrying imported pulp.

5.1.6. Freshwater eutrophication

Eutrophication occurs due to the discharge of nutrients (such as nitrates and phosphates) into water sources, which causes a rise in nutrient levels. Eutrophication is measured as kg phosphorous equivalent (kg P eq) and only includes phosphorous and phosphate-containing compounds. Since phosphorous is the reference element, all phosphorous-containing compounds have a contribution value of 1 to the impact category. All phosphate-containing compounds have a 0.33 contribution factor to the impact category. This increase in nutrients causes a rise in the nutrient uptake by autotrophic organisms such as cyanobacteria and algae, which can take over the entire water body (algal bloom) and use all dissolved oxygen and block out sunlight, essentially leading to the death of aquatic species (Huijbregts et al., 2016).

In this instance, electricity and energy production again dominates the impact category, but not so much that the other processes become negligible (Figure 5-5).

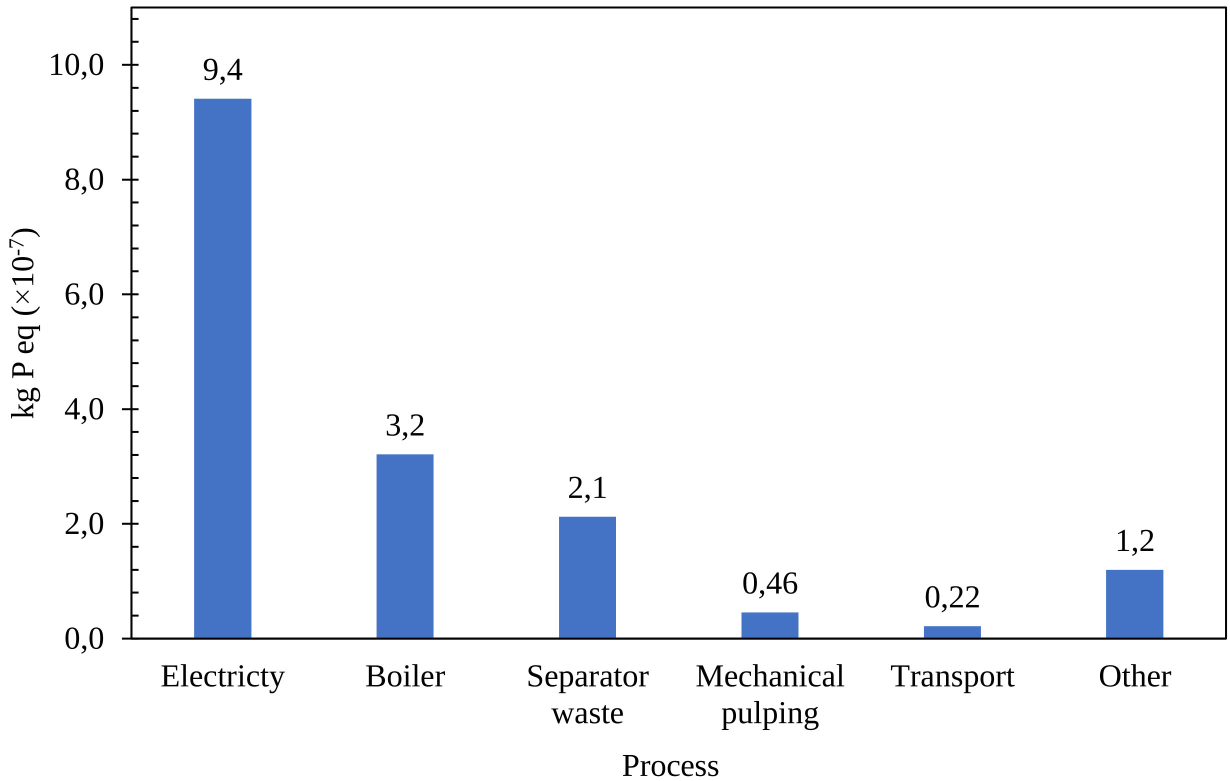

Figure 5-5: Freshwater eutrophication impact category with the five highest contributors

For the electricity and boiler processes, combustion is not the source of eutrophication, but the processes involved in acquiring the coal are. The spoil from mining activities consists of topsoil and some organic matter, which contains phosphorous and phosphates. When it rains, minerals from the spoil are washed out and accumulate in freshwater bodies, essentially causing eutrophication. Soil compaction in mining also plays a role in eutrophication. The soil is compressed by machinery and vehicles to a point where the water can no longer be absorbed by the soil. Water then flows on top of the soil increasing the leaching of nitrates, phosphates and other minerals into the water sources. Naturally, minerals will flow into water sources, however, due to the increased concentration of minerals at a single point (spoil) and the hardened ground, mineral pollution happens faster and is more concentrated than the water source can manage, causing eutrophication. The same applies to sulfidic tailings. The concentration of minerals in a single area makes it easier for the rain to seep through and deposit the mineral-rich rainwater into water sources.

Related to electricity production, Eskom disposes of most of its ash in ash ponds/dams. Although these sites are lined, some leaching still occurs carrying the minerals to surface water sources (short-term) and underground water sources (long-term), causing eutrophication.

The organic and mineral content of the separator waste is disposed of in a landfill. Similar to the ash, the landfill sites are lined, but it is assumed that some leaching still occurs, carrying the nutrients into water sources. Mechanical pulping contributed to this dataset via effluent. Although the effluent is treated before it is disposed into water sources, it still contains organic material. The effluent which is discharged into either surface water sources or the ocean carries this organic material and could cause eutrophication.

Transportation contributed by 1 %, not by combustion but by fuel production via crude oil extraction and follows a similar process to the acquisition of coal from the mine. Soil that is disturbed and heaped during the start-up and expansion of the mining operation can release nutrients into the water sources causing eutrophication.

5.1.7. Ozone depletion

Ozone depletion is the process by which emissions react with ozone in the stratosphere, essentially breaking the O_3 oxygen bond and decreasing the overall ozone concertation. The reduction of atmospheric ozone increases the inlet of solar radiation, particularly UVB (Huijbregts et al., 2016). Chemicals responsible for ozone depletion mostly contain fluor-, bromo- and chloro- compounds, hence, ozone depletion is measured as kg Trichlorofluoromethane eq (kg CFC eq) and the characterisation factors for the other substances can be found in the ReCiPe 2016 v1.1 guide (Huijbregts et al.;2016).

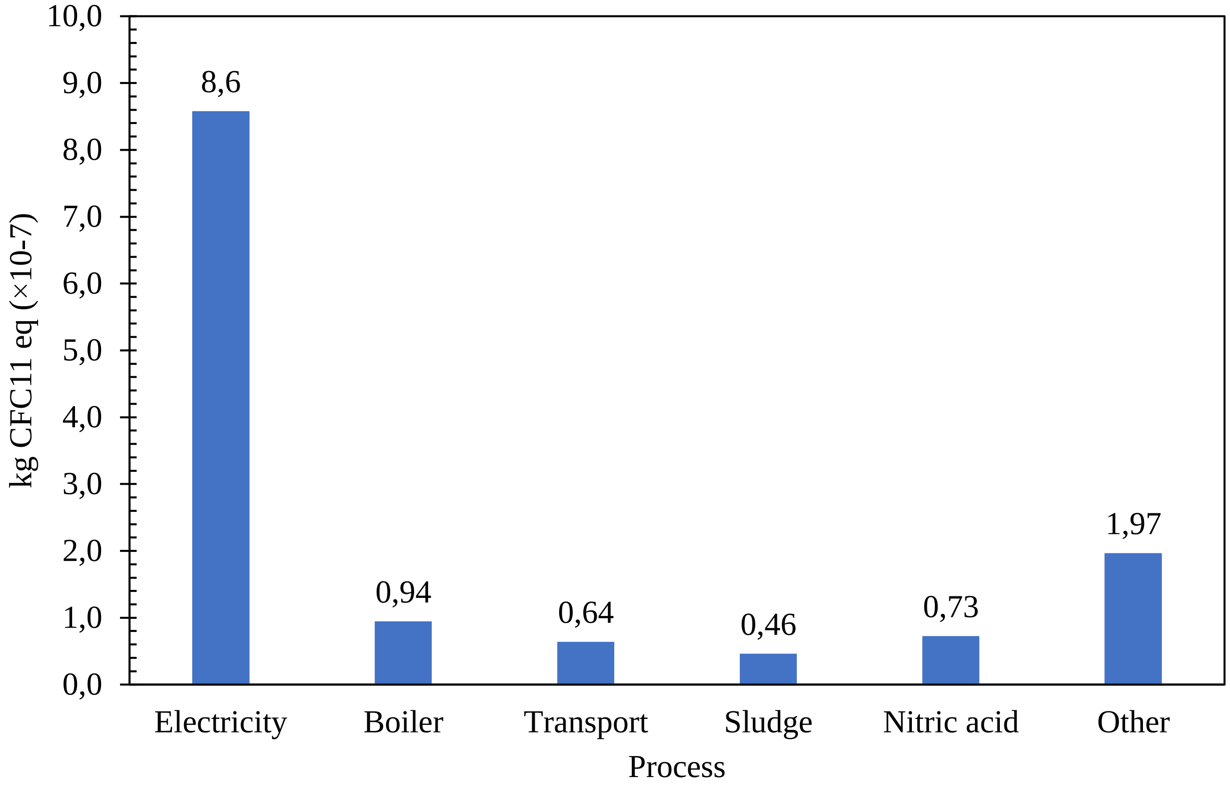

Figure 5-6: Ozone depletion impact category with the five highest contributors

Electricity production is the dominating source of ozone depletion (Figure 5-6). The release of ozone depletion substances from the electricity, boiler, and transport processes originates from the coal and fuel combustion processes. The emissions consist mainly of chloro-, bromo- and fluoro-containing methane and ethane substances.

The sludge consists of settled fibres and chemicals from the clarifier. The sludge is transported and spread across fields as agricultural fertiliser. Nitrous oxide (N_2O) is a greenhouse gas that comes from agricultural fertiliser, decomposing organic matter (including sludge) and animal excreta as anthropogenic N_2O emissions (Rousset et al., 2020). Nitrous oxide is released into the atmosphere during the denitrification of anaerobic bacteria in soil or by bacterial decomposition of fertilizer, biomass burning, livestock manure, sewage treatment, combustion and other industrial processes (Purkayastha, 2021). The released nitrous oxide reacts with elemental oxygen generated by photolysis in the stratosphere to produce nitric oxide, which then reacts with ozone in the upper stratosphere producing nitrogen dioxide (Crutzen & Ehhalt, 1977).

During the production of nitric acid, there are several chemical reactions performed. In the final reaction, nitrogen dioxide is reacted with water to form nitric acid and nitric oxide. The nitric oxide is further oxidised during the reaction by a secondary air stream, but some of it remains unoxidized (Speight, 2017). As with the decomposition of the sludge, nitric oxide reacts with ozone in the upper stratosphere, resulting in ozone depletion.

5.2. Waste management scenarios

During the production of WLC jumbo reels, several waste streams originate. This includes waste from separators, wastewater, emissions to air, process breaks, sludge, and ash. Due to the nature of each waste, the mill either treats, reuses, recycles, landfills or does a mixture of these for the same waste.

5.2.1. Waste from separators/screens

The waste from the separators is the only waste that the mill sends to landfill (apart from general waste). The waste consists of sand, grit, plastic, glass, metals and some fibres with the majority being sand and grit. Unfortunately due to the nature of this waste (very small shards of plastic, glass and metal), it is not possible to separate it into recyclable and non-recyclable (landfill) groups and as a result, the waste is sent to a landfill. Table 5-4 indicates the impact of the process.

Table 5-4: Environmental impact associated with the landfilling of screened waste

Impact category	Unit	WLC Production	Waste landfill	Contribution (%)
Global warming	kg CO_2 eq	2.5	0.028	1.1
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	2.4×10^{-10}	0.018
Ozone formation	kg NO_x eq	0.0093	3.4×10^{-6}	0.037
Terrestrial acidification	kg SO_2 eq	0.017	2.5×10^{-6}	0.015
Freshwater eutrophication	kg P eq	0.0017	3.6×10^{-8}	0.0022
Freshwater ecotoxicity	kg 1,4-DCB	0.061	0.0017	2.8

Initially, the contribution seems low, but this is simply because the electricity and the boiler operations have such a large influence on the process. However, when discussing possible process improvements in the sections to follow, landfilling could become more prominent as cleaner alternative fuel sources for electricity and energy production are considered.

5.2.2. Wastewater

Wastewater on the mill is divided into two sections, the water that is effluent discharged to the municipal sewer system and the second which is cleaned and recycled on-site.

<u>Wastewater - effluent</u>

The wastewater generated in the process is any water that comes from the mill, which includes purged condensed steam, water from the calendaring section and water from overfill tanks. The water is first treated on-site to meet the requirements set by the local municipal wastewater by-laws. The impact of the wastewater effluent discharged to the municipal wastewater treatment works was not included in the dataset. This is because the effluent discharge from the mill does not flow into underground water sources or rivers/dams/oceans, but is sent to the municipal wastewater treatment works for treatment and “reuse”, and is therefore not considered a waste in the modelling of the process. The process and chemicals used by the municipalities to treat the water are included in the “freshwater” dataset, which represents the process of treating the water and the energy required to pump the water.

<u>Wastewater – on-site treatment and recycling</u>

The mill has an on-site wastewater treatment facility, where the water coming from the process is treated. The treated water is then split into two streams: around 80 % is reused in the mill in the pulping process and the other 20 % is discharged to the municipal sewer as effluent. As the recycled water is reused in the same system boundary as the mill, it is not modelled because it creates a closed-loop system. However, all the chemicals used to treat the water have been included in the model since they are used every day (Table 5-5).

Table 5-5: Environmental impact of chemicals used to treat wastewater from the process line

Impact category	Unit	WLC Production	Chemicals	Contribution (%)
Global warming	kg CO_2 eq	2.5	2.7×10^{-10}	1.1×10^{-8}
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	4.7×10^{-15}	3.4×10^{-7}
Ozone formation	kg NO_x eq	0.0093	5.4×10^{-13}	5.7×10^{-9}
Terrestrial acidification	kg SO_2 eq	0.017	8.4×10^{-13}	4.9×10^{-9}
Freshwater eutrophication	kg P eq	0.0017	7.8×10^{-14}	4.7×10^{-9}
Freshwater ecotoxicity	kg 1,4-DCB	0.061	9.9×10^{-12}	1.6×10^{-8}

5.2.3. Emissions to air (generated on-site)

These emissions include the emissions from the boiler, the emissions from the infrared (IR) gas heater, the forklifts and the steam evaporated during the drying section of the calendaring process, however, the steam is added to the boiler process (Table 5-6).

Table 5-6: Contribution of onsite emissions to the overall environmental impact

Impact category	Unit	WLC Production	Boiler (% Contribution)	Forklift (% Contribution)	IR Gas (% Contribution)
Global warming	kg CO_2 eq	2.5	31	0.31	0.71
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	11	0.23	0.25
Ozone formation	kg NO_x eq	0.0093	21	1.2	0.13
Terrestrial acidification	kg SO_2 eq	0.017	20	0.23	0.026
Freshwater eutrophication	kg P eq	0.0017	20	0	0
Freshwater ecotoxicity	kg 1,4-DCB	0.061	17	6.4×10^{-5}	3.1×10^{-6}

Of the three processes, the boiler's overall contribution is the highest. Unfortunately due to the nature of the processes, the only way to reduce the impact of the categories is to either find a way to increase the efficiency of the process or change to an alternative, cleaner fuel source. This is further discussed in the "Recommendations and improvements" section (pg 103).

5.2.4. Process breaks (material removed due to faults in the process line)

Sometimes when the process is in operation, a snag could occur in the process line which causes the paperboard to break. This is what is referred to by the phrase "paperboard from process faults". Since the mill already uses recycled material to produce the WLC jumbo reels, the break-offs are simply recycled back to the pulpers as feed for the next batch of product, thus creating a closed-loop and therefore not adding to the overall environmental load of the process. The break-offs were therefore not modelled.

5.2.5. Wastewater treatment sludge

The sludge is the fibrous waste removed from the settling tank in the on-site wastewater treatment plant. Sludge is generally managed in three ways, it is either landfilled, dried and incinerated as fuel, or is sent to landfarming. The mill being studied sends all their sludge to be used in land farming as an agricultural fertiliser. The wet sludge is first pressed to remove around 55 % of the water before being transported. The water is recycled back into the wastewater treatment process. So far this is the most efficient and clean way to manage the sludge (Table 5-7), however, landfilling is also an option. The difference between landfarming and landfilling is the nitrous oxide released, with landfarming contributing 1.82×10^{-4} kg per kg sludge and landfilling, $6,54\times10^{-5}$ kg per kg sludge. As discussed in the ozone depletion impact category, nitrous oxide reacts with oxygen to produce nitric oxide, which then reacts with ozone to produce nitrogen dioxide. The difference between landfarming and landfilling indicates that the landfarming method has the lowest impact on the environment.

Table 5-7: Wastewater sludge waste management scenarios - landfarming

Impact category	Unit	WLC Production	Landfarming	Contribution (%)	Landfill	Contribution (%)
Global warming	kg CO_2 eq	2.5	0.0025	0.10	0.032	1.3
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	4.6×10^{-8}	3.4	1.78×10^{-8}	1.3
Ozone formation	kg NO_x eq	0.0093	1.6×10^{-6}	0.017	1.3×10^{-5}	0.14
Terrestrial acidification	kg SO_2 eq	0.017	1.2×10^{-5}	0.071	1.9×10^{-5}	0.11
Freshwater eutrophication	kg P eq	0.0017	2.6×10^{-6}	0.16	6.6×10^{-6}	0.40
Freshwater ecotoxicity	kg 1,4-DCB	0.061	7.4×10^{-6}	0.012	0.001	1.7

5.2.6. Ash

Similar to sludge, the ash from the coal-fired boiler can either be landfilled or reused in the cement industry. The mill sends all its ash to a cement manufacturing company and as a result, it has no environmental impact (Table 5-8) since it is never released into the environment, hence it does not contaminate air, soil or water. Unlike sludge, which is re-purposed and released into the environment, thereby bearing an environmental load.

The ash can also be landfilled, which means it is released into the environment and will therefore have an environmental impact. From the comparison, using ash in cement manufacturing, which is the mill's current management method, is much cleaner than landfilling the ash.

Table 5-8: Environmental impact of reusing ash in cement manufacturing.

Impact category	Unit	WLC Production	Cement production	Contribution (%)	Landfill	Contribution (%)
Global warming	kg CO_2 eq	2.5	0	0	0.0081	0.33
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	0	0	6.2×10^{-10}	0.046
Ozone formation	kg NO_x eq	0.0093	0	0	7.5×10^{-6}	0.08
Terrestrial acidification	kg SO_2 eq	0.017	0	0	5.2×10^{-6}	0.03
Freshwater eutrophication	kg P eq	0.0017	0	0	8.6×10^{-7}	0.052
Freshwater ecotoxicity	kg 1,4-DCB	0.061	0	0	0.013	21.0

5.3. Sensitivity and error analysis

5.3.1. Temporal observations and validation

The mill supplied the data monthly for the years 2018, 2019 and 2020. This allowed for the data to be average for three months instead of for three years. This means that data would be more accurately represented if done monthly instead of annually since the effect of outliers and anomalies are less hidden in the data. However, considering the small difference between the monthly averages to the total annual average, using either the monthly or yearly approach makes little difference (Figure 5-7).

Temporal boundaries are important to consider if a process experiences significant changes due to seasonal weather changes, such as winter vs summer. In this scenario, taking data based on average monthly readings instead of average annual readings could significantly alter the results since the annual average would hide seasonal effects. In the case of the mill understudy, seasonal effects are not that significant since the only variable that changes based on seasonal weather conditions is the boiler process, which only contributes around 30 % to the total impact, and because seasonal temperature changes do not vary significantly from winter to summer

Secondly, during the inventory analysis, data validation was done (Appendix A – C, pg. 143 – 165). Validation was the process in which mass/energy balances and secondary data sources were used to validate the accuracy of the data provided/calculated and to prevent double counting, identifying missing data and several other possible errors. One way to also check the accuracy of the data supplied (validate the data) was to observe how the seasonal changes affected the energy requirements of the process. This validates the calculations as energy loss is greater in colder weather due to a higher temperature gradient between the boiler and the environment. For this reason, the energy produced should be higher in the winter months, which can be seen by the steady rise and fall of energy produced from month to month, with a single outlier in August (Figure 5-7). This outlier exists because of an unexpected mill shutdown that occurred.

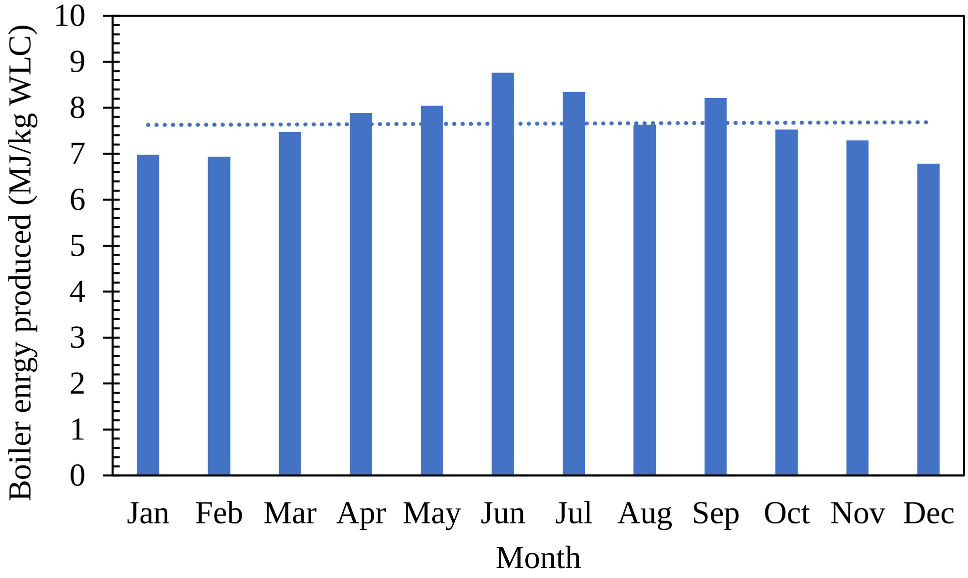

Figure 5-7: Temporal changes in energy demands for the different months of the year.

5.3.2. Sensitivity analysis

The sensitivity analysis was conducted to address any issue where several assumptions were made to obtain a numerical value, for data with the most uncertainty and to compare the sensitivity of the LCA to changes in the largest contributing processes. In the sensitivity analysis, the data values were increased by a certain % to identify the impact that the assumptions had on the environmental impact score and to see whether any additional research had to be done to address significant changes observed because of the assumptions made.

Sensitivity of largest contributors

From the impact assessment, it was possible to see that the highest contributor to all impact categories was the use of electricity, followed by the coal-fired boiler. Figure 5-8 and Figure 5-9 were generated to observe the change in the increase (and subsequent decrease) of the use of electricity (kWh) and energy production (MJ). The values were increased by 20, 40, 60, 80, and 100 % for both processes. In both instances, a straight-line correlation was established between the increase in the source load and its resulting impact on the environment. SimaPro uses linear transformations to characterise substances into impact categories and because only numerical values can be used for process inputs, the results will also have a linear correlation.

However, the relationship between the specified increase (and subsequent decrease) and the environmental impact change that occurred was not proportional to either the electricity or the boiler. As in freshwater ecotoxicity, for example, an increase of 20 % in consumption/use for both electricity and the boiler process only increased the environmental impact by 11 % and 4 %, respectively. This applies to the subsequent decreases as well, which indicates that changes to individual processes have smaller effects on the environmental impact of the overall process since the process only contributes a fraction to the overall impact.

Electricity, compared to the coal-fired boiler, has a larger impact on the environmental score of WLC production in total. Therefore, changes made to the use of electricity would have a larger impact on the final environmental impact score. If the purpose is to reduce the impact of global warming, changing either one of the two would suffice since both processes carry equal weight for this category. However, for all other categories, electricity had a 3 – 6 times higher impact with each change, the highest being ozone depletion at 5.82 times larger (480 % greater) than the coal-fired boiler impact.

The sensitivity test indicates that the LCA is more sensitive to changes in electricity. If the mill wants to change the overall environmental impact of the production of WLC, the best place to start would be to address electricity use and find possible alternative electricity sources. If the only concern is global warming, then either the electricity or the boiler system (alternative fuel sources) could be addressed to observe equal change.

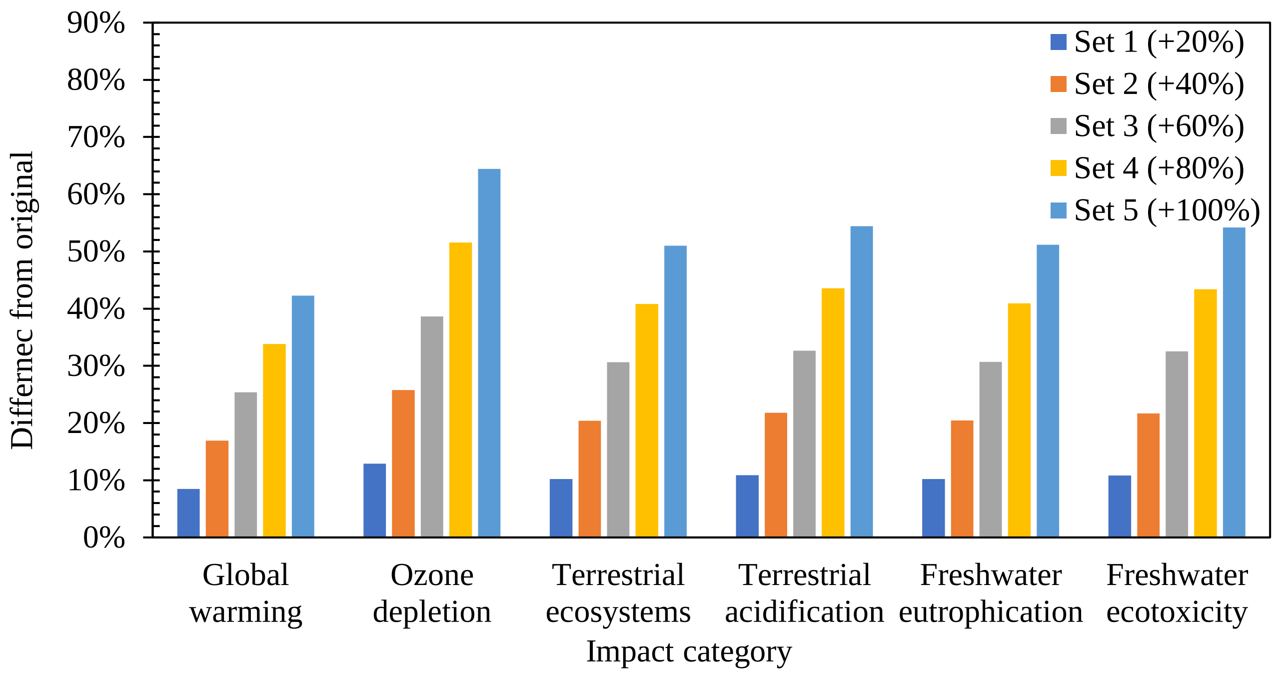

Figure 5-8: Sensitivity of the LCIA when changes to electricity use are applied.

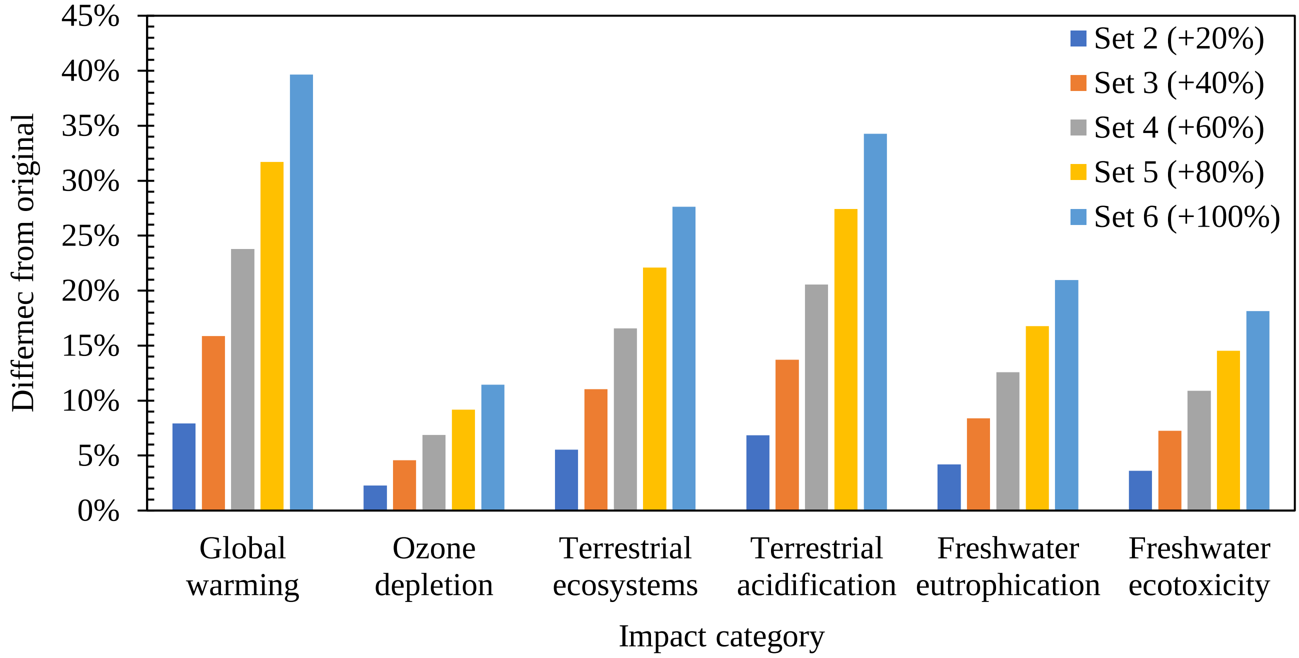

Figure 5-9: Sensitivity of the LCIA when changes to the coal-fired boiler are applied.

Sensitivity analysis of assumptions made for transportation

Transport was divided and aggregated into two sections, namely “known” and “unknown” transport. The unknown transport was where the mass carried (mass of chemicals, fibres and wastes) was known but the distances travelled were unknown. This included transport to clients, mechanical pulp transport from the ports to the mill, recycled fibre collection, chemicals, purchased diesel, and waste transport for sludge and ash. To address these, several assumptions were made to account for the missing distances (WLC – Transport). Since the same method of transport was used for all the products (assumed 40-ton truck) the sensitivity analysis was conducted based on the aggregated transport.

The transport was increased from the aggregated 664 kg.km starting at a 20 % increase up to a 100 % increase by increments of 20 % (Figure 5-10). The results indicate the percentage change of the impact categories concerning the original 664 kg.km value. The results indicate that the highest increase was observed when the “unknown transport” was increased by 100 %, resulting in a 6.5 % increase in the “Ozone formation” impact category. This indicates that the transport had a low influence on the system and that a significant error in the assumptions had to be made for the transport process to have a significant influence on the results of the LCA. However, considering the results from the “Impact assessment” section, the large contribution of the electricity and coal-fired boiler processes to the environmental impact is causing the transport to appear less significant in comparison, but once these two processes are addressed and reduced, transport would have to be re-evaluated to ensure that the assumptions are still valid.

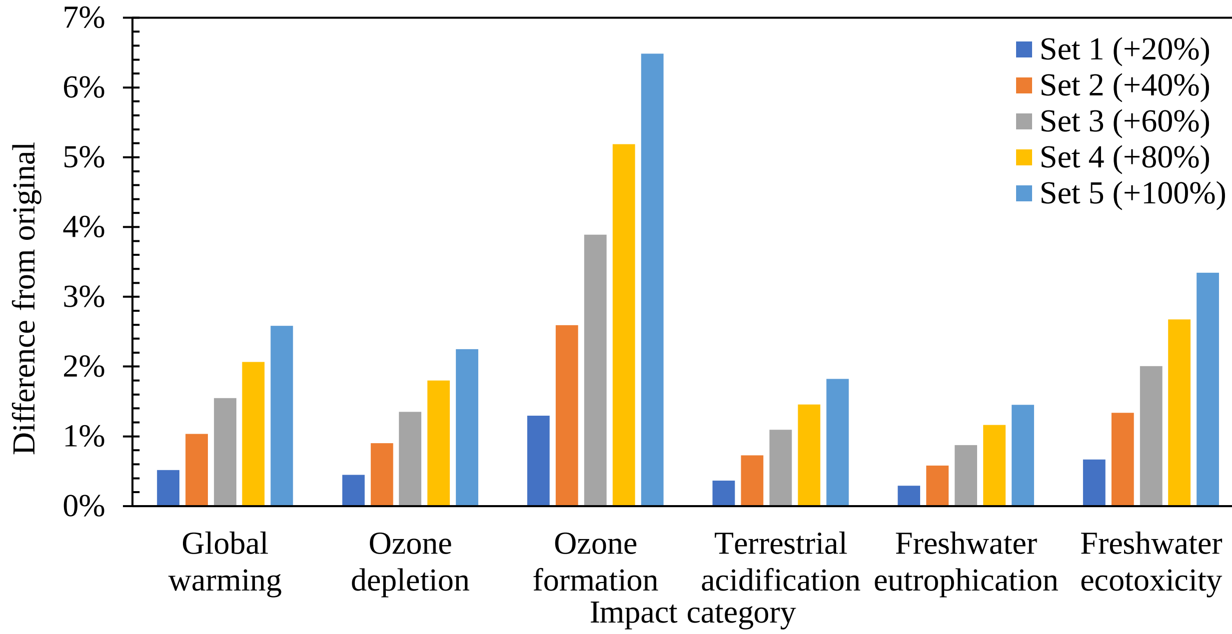

Figure 5-10: Changes to "unknown distance" transportation, testing the influence of the assumptions made on the impact categories.

<u>Sensitivity analysis of assumptions made for forestry operations</u>

In the "Scope" section, it was decided to exclude fertilizers, pesticides and herbicides due to the inconsistency in the application of the chemicals and the temporal boundary defined in the goal. Under further investigation, it was established that the assumption to exclude these could change the outcome of the study. The inclusion of these variables is based on industry norms and does not represent the process or materials used by the company that supplied the forestry data.

It was found that fertilizers are only applied in South African silviculture operations at the time the seedling is planted and in low enough concentrations to only provide localised nutrition (Crous et al., 2022). The report also indicated that fertiliser supplied is dependent on the organic carbon in the topsoil, it was assumed that the organic loading was greater than three per cent and as a result a fertiliser with an N:P:K of 8:12:8 ratio (gram per tree) was used. Based on the information supplied in the "Eucalyptus forestry" methodology section, the land occupied for the 9-year growing period is 567 m^2a, which is equivalent to 63 m^2 of land harvested per year per m^3 of wood harvested. According to Forestry Economics Services CC, (2019), a total of 449509 ha of land was used for eucalyptus pulpwood and 6323734 tons of eucalyptus was harvested for pulping operations. Based on the report, a 9-year rotation period is used before the trees are harvested, this means that 49945.4 ha yr^{-1} of land is harvested. Dividing the harvested area by the volume of wood harvested, a total of 83.2 m^2 m^{-3} of wood is harvested each year. The conversions are 1 m^3 of pulpwood to 1.05 tons of pulpwood and 1 ha is equivalent to 10000 m^2. Using the report by Crous et al., (2022), trees are planted with a spacing of 3 m by 2.2 m (assuming the largest spacing), thus the number of trees in the 83.2 m^2 area is 12.6 trees. Thus the 63 m^2 area harvested contains 9.6 trees and the fertiliser applied is 269 grams of nitrogen, phosphorous and potassium.

Using the number of trees, specifications for the nursery could be determined. It is assumed that the seedling will be planted in the fields during summertime, hence wet soils and therefore no "water on planting" would need to be considered. Due to summer planting, the seedlings are kept in the nursery for 3 – 5 months (SA Forestry Online, 2010b), but an average of 4 months will be used (seed germination period). This means that the resources required to grow the 9.6 tree seedlings for 4 months need to be included. The seedlings are grown in 128 deep containers (110 cm^3) using coco-peat, thus a total of 1056 cm^3 of soil is required. Secondly, according to SA Forestry Online (2010a), at least 3 L of water is required per seedling per day, thus 9.6 seedlings for 4 months require 3456 L of water. Herbicides are used before the planting of the seedlings, thus it was assumed that glyphosate was used (for broadleaf weeds and grasses) at 130 L ha^{-1} (Minogue & Osiecka, 2015) which is equivalent to 0.819 L for the 63 m^2 area. The energy required to mechanically prepare the land (tillage) is also included, but SimaPro allowed the calculation based on the area of land prepared, thus fuel and emissions were calculated by the programme. Based on these new values, the difference in the impact of forestry excluding and including the nursery is quite extensive (Table 5-9).

Table 5-9: Impact on the forestry dataset when forestry assumptions are re-evaluated

Impact category	Unit	Forest (With exclusions)	Forestry (original)	Difference (% larger)
Global warming	kg CO_2 eq	42	29	42%
Ozone depletion	kg CFC11 eq	2.7×10^{-5}	1.8×10^{-5}	56%
Ozone formation	kg NO_x eq	0.30	0.27	12%
Terrestrial acidification	kg SO_2 eq	0.18	0.13	40%
Freshwater eutrophication	kg P eq	0.021	0.0060	255%
Freshwater ecotoxicity	kg 1,4-DCB	0.95	0.39	146%

However, when the impact of the nursery data is considered in the WLC dataset, the impact is negligible (Table 5-10).

Table 5-10: Impact on white-lined chipboard dataset with re-evaluated forestry assumptions

Impact category	Unit	WLC - Nursery	WLC - No Nursery	Difference (%)
Global warming	kg CO_2 eq	2.5	2.4	0.28
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	1.4×10^{-6}	0.40
Ozone formation	kg NO_x eq	0.0094	0.0094	0.20
Terrestrial acidification	kg SO_2 eq	0.017	0.017	0.17
Freshwater eutrophication	kg P eq	0.0017	0.0017	0.52
Freshwater ecotoxicity	kg 1,4-DCB	0.061	0.061	0.52

The results indicate that if the LCA was meant to study the impact of forestry, then the inclusion of the nursery data would have been an important dataset.The inclusion or exclusion of the nursery data in the impact assessment of of WLC production made no noticeable difference in the results, and as such, excluding the data was acceptable.

5.3.3. Uncertainty analysis

The uncertainty analysis was conducted using a Monte Carlo analysis simulation in SimaPro, with 1000 fixed runs and a 95 % confidence interval. The results vary from category to category, but overall, the error associated with the ReCiPe 2016 method for the analysis is small for global warming, ozone formation and terrestrial acidification. The error for freshwater ecotoxicity, freshwater eutrophication and ozone depletion are much larger (Figure 5-11).

The size of the error can vary for several reasons. A study by Chen et al. (2021) indicated that there are uncertainties caused by selecting and using different impact methods. Their study indicated that discrepancies in the total impact results were caused by differences in the:

1. total emission values included in the inventory;
2. coverages of substances in methods (impact method inventory), and
3. differences in the characterisation factor values of the substances

From their analysis, they found that significant uncertainty existed for all impact categories, except for global warming. This indicates that the uncertainty in an LCA links both to the uncertainty in the inventory and the uncertainty in the impact model chosen. Similar conclusions were made by Alyaseri & Zhou (2019) who also indicated that uncertainty in the results is a result of deviations in the inventory lists used and in the impact model chosen to conduct the impact assessment.

To investigate whether the errors were because of the inventory list or because of the impact method selected, the Monte Carlo analysis was also conducted using the EF 3.0 and TRACI 2.0 impact methods (Figure 5-11).

When entering the data from the WLC inventory table into SimaPro, an uncertainty matrix was completed for each substance. This matrix is used to indicate any uncertainty regarding the quality of the data and define a standard deviation for the average value entry. This is the reference made to uncertainty in the inventory list. The uncertainty values defined by the matrix are however small since the data used was mostly primary data, with a few exceptions such as for transport, forestry and some of the emissions values. However, it was proved that the overall impact of these processes was negligible and so the uncertainties were not a concern. Despite this, each process/substance has uncertainty and each process/substance used in the production/operation of these also have uncertainty. This means that in the end, there could be several thousand substances/processes, directly and indirectly, involved in the production of WLC. For the WLC dataset, we could define the uncertainty of the data that we calculated/supplied, but for the EcoInvent datasets used, the uncertainties were already defined.

For SimaPro to account for these uncertainties (deviations) from the mean value, the characterisation factor would be multiplied by the mean, the upper and lower deviation values and several values in between the highest and lowest deviations, based on the number of intervals specified in the Monte Carlo analysis. This is where the 2nd and 3rd observations made by Chen et al. (2021) start to apply. Multiplying by the characterisation factors associated with a specific emitted substance differs from impact method to impact method. For a well-defined and developed impact category, such as global warming, there is little uncertainty in the estimated impacts of emissions, and as a result, classification and characterisation would be the same (very similar) for all three impact methods used. In other words, the amount and type of substances included in the inventory of each impact method, and the characterisation factors used by each impact method to convert the substances in the inventory into equivalent units would be more accurately determined and would also be similar for all thee impact methods.

The opposite is true for impact categories that do not have well-defined impact parameters, such as ozone depletion. For the developers of an impact method to classify a waste substance as ozone-depleting and to assign it a numerical value that can be used to characterise it, a lot more estimations and assumptions have to be made. This is because the ozone depletion potential of the substance is unknown, its reactivity with ozone could be unknown and its retention time in the atmosphere is also unknown. This results in more uncertainty associated with the characterisation factor and also causes greater differences in the final impact value between the different impact categories. The probability and distribution figures from the Monte Carlo simulation for the six impact categories can be seen in Appendix E (pg. 167)

Based on this, it can be seen that, firstly, for the ReCiPe 2016 method the error span from the average value for global warming, acidification and ozone formation is small, indicating that the data supplied in the inventory list is reliable. The same is observed for the other two impact methods, EF 3.0 and TRACI 2.0. The distribution of the results for the ReCiPe 2016 impact method followed a bell-shaped curve for all three impact categories, indicating that the results are evenly distributed and that the uncertainty does not significantly influence the results.

For freshwater ecotoxicity and ozone depletion, the impact associated with the ReCiPe 2016 method was much higher for both the average value and the error distributions when compared to EF 3.0 and TRACI 2.0 methods. The results indicate that the error is not based on the uncertainty of the data entered in the inventory list, but based on the classification of substances and the characterisation values used by the ReCiPe 2016 impact method. Therefore, the data supplied in the inventory list is reliable but does not appear to be because of the impact method. The distribution of the results for the ReCiPe 2016 method is right-skewed, indicating that the uncertainty of the impact method has a large influence on the LCIA results.

Lastly, for the freshwater eutrophication impact category, all three impact methods have similar impact equivalent averages and the data error distribution is also similar. This means that the problem is with the data supplied in the inventory list and not with the impact method chosen. Therefore, the results indicate that the data supplied in the inventory list that represent freshwater eutrophication is unreliable. The distribution of the results for the ReCiPe 2016 method is right-skewed, indicating that the uncertainty has a large influence on the LCIA results

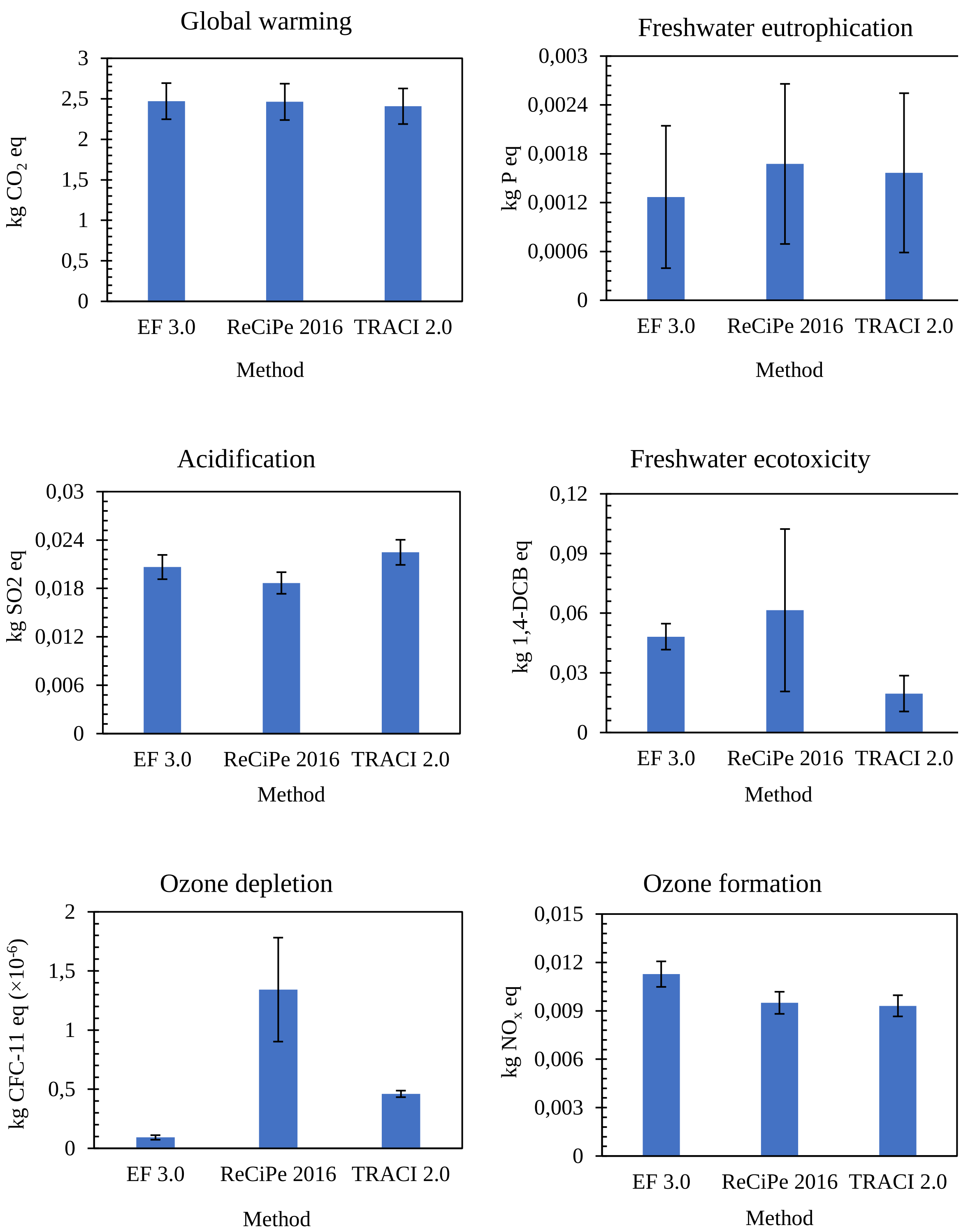

Figure 5-11: Uncertainty analysis for the six different impact categories compared to the uncertainty associated with two other impact methods.

5.4. International dataset comparison

As mentioned before, South Africa has no datasets in databases for the forestry, pulping, and paper/paperboard industry, as a result, researchers would use international datasets to conduct LCAs. Using international datasets can change the outcome of the results of a study since each dataset is representative of its country and its processes (Ciroth et al., 2019). Also, the information gathered for each dataset and the timeframe of the project is determined by the individual/organisation who collects it, which in turn affects the type, quality and quantity of data collected.

As an alternative, some researchers would use international datasets and change some of the international data to South African data, such as electricity, transport, water and several others, thereby creating a hybrid South African/international dataset. Although this does aid in creating a more South African representative dataset, it still does not truly model the actual South African process. However, due to problems associated with sensitive data and data gaps, it is not possible to create 100 % South African datasets and as a result, the hybrid dataset would usually be used.

In the SimaPro simulation software, there is a European dataset for white-lined chipboard. The system boundary is similar and includes transport, electricity and energy generation, waste disposal and water clarification. Figure 5-12 indicates the differences between the South African dataset, the European dataset and a hybrid South African/European dataset. In the hybrid dataset, the electricity, water, transport, coal and landfilling scenarios were changed to South African data.

There is a clear distinction in the results for each dataset (Figure 5-12). If a researcher used the European dataset to represent a South African process, the impact of the process would be significantly smaller in all impact categories, thereby underestimating the overall impact of the process. The major difference between the European dataset and the South African dataset is that energy and electricity co-generation of the European mill occurs on an integrated mill and all sources of fuel are biomass. Biomass is a significantly cleaner and renewable fuel source, which makes its overall contribution to the impact load significantly smaller. Also, the electricity grid relies on cleaner fuel sources, with 60 % of their electricity demands met by renewable energy, which is significantly different to South Africa's electricity grid. This indicates how country-specific data can influence the outcome of an LCA.

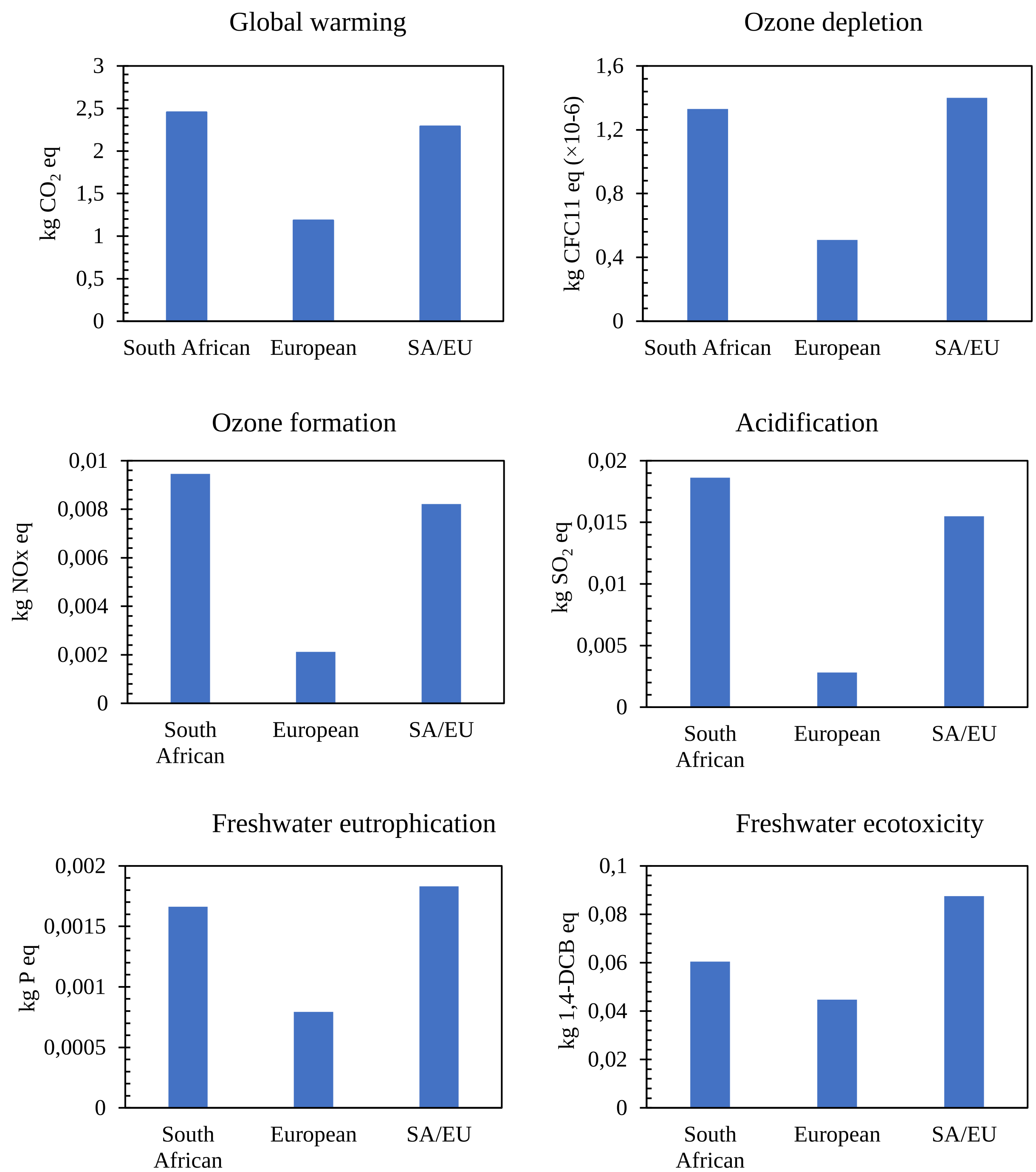

Figure 5-12: Impact of WLC using South African, European and hybrid SA/EU datasets.

Using the SA/EU hybrid dataset is more representative of the South African process, but still creates some variations. If a researcher was doing a carbon footprint balance of the process, they would be looking at the global warming impact category. Using the hybrid SA/EU process would underestimate the impact of the carbon footprint by a small amount. However, if the researcher used the hybrid dataset for a water footprint study, the opposite would be true, and an overestimation would be concluded for the water impact categories. Although the hybrid is more representative of the country for which it is hybridized, it still does not truly represent the process on a country-specific level and can still misrepresent the environmental impact of the process/product. However, if a quick LCA must be conducted to study the impact of changing a process or product, hybridization would save a lot of time and still be able to give a general idea of the environmental impact before a full investigation is launched. Thereby saving time and money that would have been spent studying a process with no possible/significant improvement potential.

Thus, it is best to use datasets as follows. The first option would be to use a local dataset or to create one, if there are no local datasets available or creating one is not possible, the second option would be to use the hybrid dataset, but to apply with caution. If either of the first two options is not available, then the final resort would be to use an international dataset of a region/country with a similar process and similar infrastructure and technology.

5.5. Impact of international datasets on downstream processes

From the information supplied in the “International dataset” section, sometimes changing every single dataset to a hybrid version can be time-consuming and can increase the probability of errors. For example, if in a dataset a natural gas-fuelled boiler is used and the emissions from this boiler are also included in the dataset, then only changing the fuel input from natural gas to coal would be incorrect. The change in fuel source would require a change in the emissions to air, an additional waste scenario for the ash and transport of the coal to the site and the transport of ash to a landfill. The problem is that not all the data is available to fully represent the change, which means that the international dataset must be used.

If the international data used has a limited role in the process and is high up the value chain, the impact of the process becomes less significant. For example, in the LCA for WLC jumbo reels, a South African dataset was created for the forestry operation of eucalyptus. It includes the harvesting and planting process, carbon dioxide absorption, transport and land use. The only other dataset available in SimaPro was the eucalyptus forestry of Thailand, which means that either the South African or the Thailand dataset could have been used. Simulating the environmental impact of each (Figure 5-13) based on 1 m^3 of wood harvested (reference flow of dataset), the difference between the two can be seen.

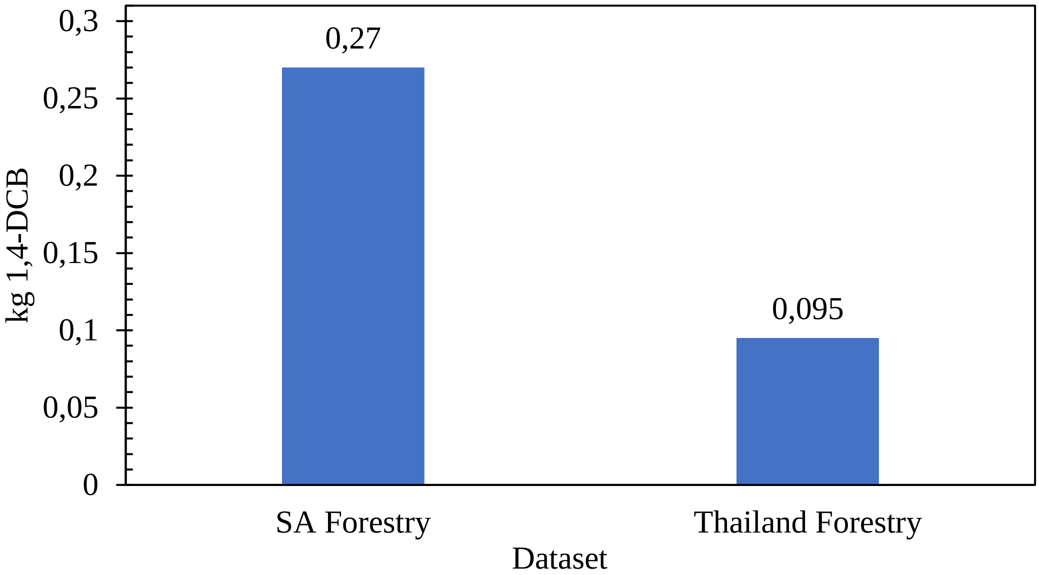

Figure 5-13: Freshwater ecotoxicity of South African eucalyptus forestry compared to Thailand eucalyptus forestry.

The impact of South African eucalyptus forestry, concerning the freshwater ecotoxicity impact category, was 64.8 % higher compared to the Thailand eucalyptus forestry dataset. Indicating that Thailand's eucalyptus forestry operations had a smaller impact on the quality of surface and underground water sources.

In the South African pulping datasets, only a fraction of the 1 m^3 harvested wood is used, about 0.0031 m^3 wood per kg pulp. To test the influence of using either the South African forestry dataset or the Thailand forestry dataset in downstream processes, two LCA simulations for the South African pulping dataset were run, one using SA forestry and the other using Thailand forestry (Figure 5-14). The results indicate that the significance of using the Thailand dataset becomes smaller in the downstream processes.

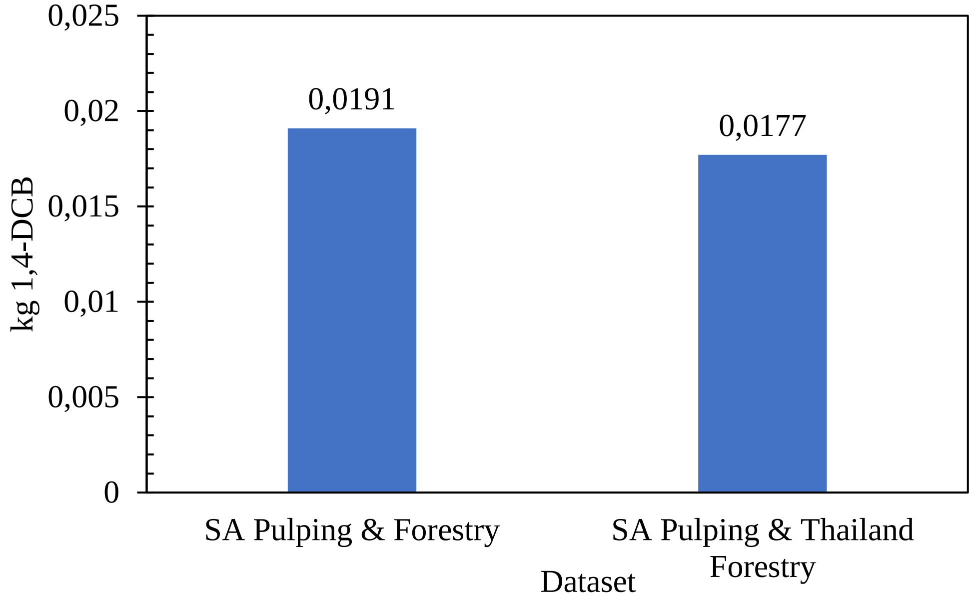

Figure 5-14: Freshwater ecotoxicity of SA pulping process using SA eucalyptus forestry (left) and Thailand eucalyptus forestry (right) datasets

The difference in the freshwater ecotoxicity impact category between the South African pulping dataset containing South African forestry and the South African pulping dataset containing Thailand forestry is 7.41 %, which is much smaller than the first difference of 64.8 %. To test the influence of both pulping datasets on downstream processes, both datasets were used in a comparative simulation for WLC production. The results represent South African-produced WLC using South African-produced pulp which makes use of either South African eucalyptus forestry or Thailand eucalyptus forestry. The results indicate that the use of the different forestry datasets becomes negligible in the WLC impact assessment (Figure 5-15),

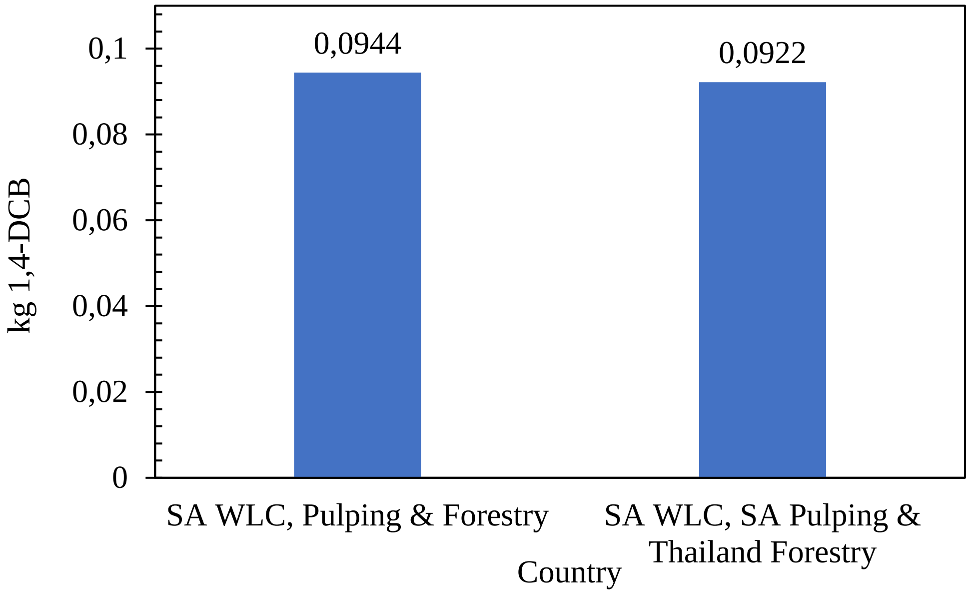

Figure 5-15: Freshwater ecotoxicity of WLC manufacturing using SA eucalyptus forestry (left) and Thailand eucalyptus forestry (right) datasets.

The final difference for the freshwater impact category between the full South African WLC dataset and the South African WLC dataset containing Thailand forestry is 0.27 %. This shows that if a chemical, substance or process is included in a dataset and is used high up in the value chain of the final product, the effects of that substance become less prominent further down the value chain. This is because each time a dataset is called into a process, only a fraction of the dataset is used. For example, in the final WLC dataset, only 0.18 kg of eucalyptus kraft pulp was required to produce 1 kg of WLC, but the pulp dataset was modelled with a reference flow of 1 kg of pulp produced. The same with forestry, in the pulp dataset only 0.0031 m^3 of roundwood was required to produce 1 kg of pulp, but it was initially modelled as 1 m^3 of roundwood harvested. This observation is also dependent on the scenario. For example, if the dataset was for the construction of a log cabin then about 4 m^3 of Roundwood would be required and the difference between Thailand and South African datasets would have been a lot more prominent.

The same applies when a chemical, substance or process adds very little by mass, volume or energy to the final product dataset. This is why cut-offs are specified in the scope of an LCA study so that more time is spent on larger contributing processes, chemicals or substances instead of on those that have a negligible contribution.

5.6. Process improvements

One of the requirements of the EPR is using LCA as a tool to:

I. Minimise the material used in the identified product.
II. Design of the product to facilitate reuse; recycling or recovery, without compromising the functionality of the product; and
III. Reduction of environmental toxicity of the resulting post-consumer waste stream.

By using LCA these objectives can be reached by studying and possibly implementing process and product improvements that would aid in establishing a more sustainable environment and circular economy.

For this reason, the following processes were studied:

1. Replacing the onsite boiler's fuel source from coal to biomass
2. Replacing municipal-supplied electricity with solar power
3. Replacing the virgin fibre content with 100 % recycled fibre

5.6.1. Fuel sources (energy)

As established in the "Impact assessment" section, the use of coal for energy and electricity generation was the highest source of pollution in all the studied impact categories. The onsite coal-fired boiler uses 100 % coal to generate high-pressure steam that is used to dry the WLC sheets. To try and reduce the environmental impact of the coal-fired boiler, a comparative LCA was conducted to study the environmental impact associated with the use of either biomass or natural gas as potential fuel sources for steam energy production.

Natural gas was chosen since the mill already uses natural gas in the IR gas heater process used to dry the triple-layer clay coat. This means that the existing pipelines can be adapted (for more gas supply), extended and integrated into the new natural gas-fired boiler system. Biomass was chosen as the second fuel source since it is a renewable and carbon-neutral (if sustainably sourced) alternative that could aid in establishing a more circular economy and because South Africa has a strong supply of biomass via its silviculture industry. Using the created dataset for WLC South Africa and replacing the coal-fired boiler dataset with either a biomass-fired boiler or a natural gas-fired boiler, a comparative assessment could be conducted (Table 5-11).

The results indicate that the use of biomass and natural gas in the boiler had an overall lower environmental footprint for all impact categories. The largest differences were observed for the global warming impact category, with biomass and natural gas contributing 51 % and 10.6 % less to global warming, respectively. The results also indicate that the differences between biomass and natural gas for the remaining impact categories are small. Indicating that global warming is the main environmental concern that could determine the change from coal to either natural gas or biomass when solely considering environmental aspects.

The only downfall of using biomass as opposed to natural gas is the ash generated after combustion and the transport required to collect and deliver the biomass and ash. However, if the ash is treated the same way that the mill treats their coal ash, by sending it to cement manufacturing companies, the impact of the ash will be zero, as indicated in the "Ash" section of "Waste management scenarios". Secondly, even having included the transport associated with biomass in the comparative assessment (Table 5-11), the results still indicate that the overall impact of biomass is lower than natural gas, however, transport would be an additional operational cost for the mill.

Table 5-11: Environmental impact of each impact category when using coal, biomass and gas-fired boilers in WLC production.

Impact category	Unit	Coal	Biomass	Gas
Global warming	kg CO_2 eq	2.5	1.2	2.2
Ozone depletion	kg CFC11 eq	1.4E-06	1.23E-06	1.3E-06
Ozone formation	kg NO_x eq	0.0094	0.0076	0.0077
Terrestrial acidification	kg SO_2 eq	0.017	0.014	0.014
Freshwater eutrophication	kg P eq	0.0017	0.0013	0.0013
Freshwater ecotoxicity	kg 1,4-DCB	0.061	0.051	0.051

Green – smallest environmental impact, red – largest environmental impact

The greatest underlying factor that would affect the successful change from coal to either biomass or natural gas would be the capital required to change the current coal-fired boiler to a biomass or natural gas-firing boiler. This could mean that the entire existing boiler system would need to be replaced, or that alterations to the existing boilers need to be made to integrate the new fuel source, which would be expensive and result in a mill shutdown, resulting in a loss of revenue. Additionally, changes to the mill's existing air quality license would need to be made to accommodate the new emissions spectra associated with the new fuel source.

Biomass

Considering biomass, South Africa has no forests specifically grown to supply biomass as fuel for energy. South Africa's current forestry crops (eucalyptus, pine and wattle) are not quick-growing crops (8 – 10+ -year rotation period) and water licenses are required to start the silviculture projects, which are costly and can take some time to acquire.

An approach to solve this shortcoming could be to switch to short-rotation coppice (SRC) crops, such as poplar or willow. A few of South Africa's plantations grow poplar but in very small numbers compared to South Africa's growth of eucalyptus and pine (Forestry Economics Services CC, 2019a) and the poplar is not being used for energy generation. Poplar hybrid species have been recorded to have a rotation period of 3 – 5 years (An et al., 2021). These trees are perennial species and are characterised by rapid growth and high productivity, it does not require a large amount of care/work (tillage and planting, fertilizer, herbicides, and pesticides) (An et al., 2021). This means that it is possible to use them in South African landscapes where the soil is poor, such as areas affected by desertification or potentially even in rehabilitated mining grounds, thereby also restoring South Africa's natural landscape. However, An et al. (2021) also found that the yield of biomass from the poplar and willow trees is controlled by genetic variation, local environment, and climatic conditions which means its potential as an energy crop would first need to be evaluated before large silviculture projects can be put into operation. Another concern is that the willow and poplar species are already considered invasive in the South African fauna and flora landscape, therefore acquiring legal approval to use these trees in large-scale silviculture would pose a challenge and possibly delay (if not stop) its use in South Africa.

The only currently available source of biomass would be forest floor residues (bark, twigs, leaves) or the canopy left after harvest (branches, twigs, leaves and bark). However, this could also cause other problems since forest residues are considered wastes according to the Waste Act (59 of 2008) and by the Department of Forestry, Fisheries and Environment. To have access to, and use the residue, the mill would require a waste license or apply to have the residue excluded as a waste stream through the waste exclusion regulation.

Secondly, even if biomass is excluded as a waste stream or the waste license has been acquired, another variable that would affect the use of biomass would be the location of the biomass fuel sources relative to the source of coal. The coal purchased for the coal-fired boiler is within a 150 km radius of the mill. Commercial forests that could potentially supply biomass residue are a minimum of 270 km away (up to 750 km and more), thereby significantly increasing the transportation cost and environmental impact associated with transport. Commercial forests are also large and are divided into blocks/grids. These grids can span several hundred thousand meters. Since most forest residue would be available after harvest (some during pruning) and certain blocks are harvested every 8 – 10 years, it means that the source of forest residue could move around by several hundred kilometres each year, making biomass supply and transport costs uncertain and irregular, which is not suitable for stable mill operation.

Biomass also has a lower net calorific value compared to coal, which means more biomass (by mass) would be required to meet the mill's energy demands, thus further increasing the cost of transport (based on mass) and the impact of transport on the environment. According to Orémusová et al. (2014), the highest gross calorific values amongst four species of trees namely pine, spruce, beech and maple, were the needles of pine wood at 21.32 MJ kg^{-1}, the bark of spruce wood at 21.21 MJ kg^{-1}, leaves of beech wood at 20.44 MJ kg^{-1} and inner wood of spruce tree 20,54 MJ kg^{-1}. The net calorific values of *Eucalyptus globulus*, according to Telmo & Lousada (2011) were around 14.4 MJ kg^{-1}, *Pinus pinaster* at 16.9 MJ kg^{-1} and according to Marsoem & Irawati (2016), wattle (acacia) tree has a net calorific value at 17.1 MJ kg^{-1}. All the species have net calorific values lower than that of the coal currently used at the mill, with a net calorific value of 26.5 MJ kg^{-1}, which indicates that the mill would require +/- 30 % more biomass by mass to meet their energy demands.

Co-combustion of coal and biomass is also an option, thereby adding biomass to the coal feed. This option would still reduce the environmental footprint of WLC production and offset some of the problems associated with the purchase of biomass and problems associated with coal combustion. As mentioned above, biomass has different properties and combustion kinetics. Research by Guo & Zhong, 2018; H. Li et al., 2021; Xinjie et al., 2021 and Yuan et al., 2021 found that the inclusion of biomass in the coal reduced the ignition temperature, increased the rate of combustion and reduced emissions. However, the biomass ratios should remain less than 40 % as the studies by Kanwal et al., 2021; H. Li et al., 2021 and Yuan et al., 2021 found that the combustion efficiency was at its highest when biomass made up 20 – 40 % of the fuel mixture. This is also good for the mill since the National Environmental Management Act: Air Quality Act, 2004 (Act No. 39 Of 2004), Gazette no. 36973, stipulates that "co-feeding" (co-combustion) is permitted, but that the emission limits of the main fuel source need to be adhered to. Since biomass is a cleaner fuel source, it will reduce the emissions of particulate matter and sulfur dioxide making it easier for the mill to comply with the emission limits. Considering the economic application of this, the study by Akinbami et al. (2021) stated that co-combustion technology is a relatively developed technology and requires only some alterations to the existing coal boiler to accommodate the mixed feed and has been used in Canada, several European and Mediterranean countries. Alterations to the current boiler system to allow co-combustion would result in much lower capital investment as the original infrastructure is already present. Hence, co-combustion seems to be the best economic, technological and environmental option for the mill. Particularly with the threat of unsustained biomass supply, if biomass supply changes, the boiler can still run on coal until supply is restored.

There is also a possibility for parallel combustion. Generally, parallel combustion refers to the construction of a biomass boiler that feeds steam into the coal steam line. Since the mill has several boilers, some of the boilers could run on biomass and some on coal. This would still allow the mill to improve its environmental sustainability without the threat of an unsustained biomass supply. This would also carry a lower economic cost as the same alterations for co-combustion would suffice (Akinbami et al., 2021). However, according to Sahu et al. (2014), biomass combustion has some operational pitfalls, such as unsustained availability of biomass, and higher risks of slagging, fouling and equipment corrosion problems (Ma et al., 2022), which would increase the cost of repairs and maintenance.

According to Sahu et al.(2014), the cost of retrofitting coal boilers for co-combustion technologies can range from ZAR 8000 kW^{-1} for co-feed boilers, ZAR 14300 kW^{-1} for separate feed boilers (parallel) and ZAR 60300 kW^{-1} for indirect co-firing (converted from the dollar, ZAR 17.22 per USD), which is still cheaper than the construction of a new biomass boiler plant. The other problem apart from the capital investment is the cost of biomass. A study by Visser et al. (2019) tried to estimate the cost of electricity produced by biomass based on an international context. They studied the cost of supplying energy using biomass in three cases, looking at the worst case (WC), most likely case (MLC) and the best case (BC) possible, provided that the cost includes the construction, operation and decommissioning of the plant. The results they found indicated that in each case the approximate cost of electricity was

ZAR 3.4 kW^{-1} (WC), ZAR 1.3 kW^{-1} (MLC) and 0.78 kW^{-1} (BC), compared to the cost of coal-based electricity at ZAR 2.8 kW^{-1}. Of these totals, the biomass cost contributed 32.1 %, 42 % and 34.2 %, respectively, to the total cost, which, firstly is expensive, but also shows that the cost of biomass remained almost constant (proportionally) even though the cost of electricity decreased. The research, therefore, shows that one of the limiting factors, if the mill decides to switch to biomass, would be related to the price of biomass. Secondly, in the study, they assumed that the plant would be close to the biomass sources, but this is not true for the mill, and hence the cost of biomass would be even higher due to increased transport. The best approach would be for the mill to either source biomass locally, from private residents and agricultural waste, for which supply would be less stable, or to have an agreement with forestry companies for a reduced cost and more stable supply, but increased transportation cost.

Other countries have also taken advantage of alternative fuels to reduce their dependence on fossil fuels. A paper mill in Ontario, Canada combusts 100 000 tons of paper mill sludge to produce steam, which eliminates the cost of sludge disposal to landfill and reduces their reliance on fossil fuels (Redling, 2018). In a discussion with the mill's energy expert, it was said that the use of sludge was a feasible option. However, because the mill produces little sludge (in comparison to the Canadian mill), and the necessary resources and space required to dry the sludge to a usable state were not available, the initial capital investment required to get the sludge to a point where it was combustible (even in co-combustion) was impractical for the mill understudy. Visy pulp and paper mill in Tumut, New South Wales, is using biomass resources to produce 30 MW of electricity, which supplies 40 % of the mill's annual electricity demand. The biomass sources include woodyard bark, screen fines, forest residue and sawmill residues (Martin & Cameron, 2017). Swedish and Finnish pulp and paper mills also use pulp residues as biomass for energy production, with their integrated kraft mills contributing 86 % and 91 % of all electricity produced in the Finnish and Swedish pulp and paper industry, respectively (Lipiäinen et al., 2022). Like the mill understudy, the Finnish non-integrated paper mills (stand-alone mills) still need to produce their energy, and as a result, rely on fossil fuels. Showing that it is more difficult for non-integrated mills to benefit from the biomass availability that integrated -mills have. Integrated mills are mills that do pulp wood (roundwood) processing, pulping and paper /paperboard manufacturing and are generally situated near forests and sawmills, which means sawmill residue, pulp mill residue and forest residues are readily available, as opposed to mills in industrial areas far away from forests.

Natural gas

Other than the capital required to convert the mill's existing coal-fired boiler to a natural gas boiler, natural gas also has a limited supply in South Africa, with most of the natural gas imported either by gas pipeline or imported via sea. Gas piped imports are facing constraints because of the depleting gas fields in Mozambique, even with the Rovuma Basin reserve in northern Mozambique, the gas supply is still under serious threat (Halsey et al., 2022). Secondly, natural gas imported from international countries has its risks, such as exchange rate fluctuations and global LNG prices that could significantly affect the use of natural gas and its economic impact on the mill (Halsey et al., 2022). With the mill's desire to reduce its reliance on fossil fuel, reduce its GHG emissions and the variability of natural gas supply, the change to natural gas might not be the best solution for the mill in the long run.

However, with the introduction of the carbon tax and carbon budgets, companies would have to move towards lower carbon fuel sources. Thus, the use of biomass, and possibly natural gas, could become more necessary, irrespective of the additional costs involved.

5.6.2. Solar solutions

Electricity is currently supplied by the local municipality and the South African government will not be able to successfully switch from coal to alternative energies, such as solar, wind or biomass in the short term. However, many companies are using solar panels to generate their electricity, and those that generate energy in the form of heat for steam use the same processes for energy and power co-generation.

PV solar panels

The best option for the mill is to move to solar power-based electricity production. The mill uses about 13 000 000 kWh of electricity per month, which includes all the process lines and all the building, machinery, lighting, etc. This, assuming a 30-day month, come to around 433 333 kWh per day. The mill operates 24 hours a day, but the solar panels will only generate max electricity for 6 hours a day. To save costs, the use of batteries for power storage was not included in the calculations.

In the calculations (Appendix F – PV solar power calculations), 400-Watt PV panels were used. A single 400-Watt panel covers a 2 m^2 area. Solar power cells also have an efficiency of around

80 %, accounting for dust and other electricity-generating inhibiting variables. It was assumed that the ratio of direct current (DC) produced by the solar panels to alternating current (AC) required by the mill was a 1.1 DC: 1 AC conversion. By using Google Earth, a total roof surface area of 57551 m^2 was available. Using an average of 6 hours of peak sunshine, a total of 50225 kWh per day could be generated.

The Mall of Africa in Midrand has installed a 4755 kWh PV solar system for R 50 million (Cokayne, 2018). If it is assumed that the ZAR kWh^{-1} scales proportionally to the larger power supply for the mill and that the solar panel prices are charged per kWh (excluding efficiency loss), then it would cost the mill +/- ZAR 121 million to purchase and install the panels. If the power supply is substituted by 11.6 %, then 1508 MWh per month is saved, which is equivalent to saving around ZAR 2 million per month on their municipal electric bill. This means that the solar panels would be paid off in 5 – 6 years (5 years and 1 month).

Conducting the new LCA (by including 11.6 % PV solar power), there was an overall decrease in the impact of WLC production for all impact categories (Table 5-12). The only exception was for freshwater ecotoxicity in which the impact increased by 1.5 %. The increase observed was due to annual maintenance, in which water is used to wash the panels to remove dirt and dust, thus improving the efficiency of the panels allowing for higher energy output and ensuring a longer lifespan. There are additional costs involved with PV that were also not included in the cost calculation. Maintenance is one of the costs, but also replacing broken and old panels, and structural alterations required to the existing infrastructure to support the weight of the panels. This means that the initial ZAR 121 million capital investment would be higher and that additional maintenance and operational costs would be incurred.

Table 5-12: WLC production impact for replacing 11.6 % municipal power with PV power

Impact category	Unit	Electricity	Electricity and solar power	Impact reduction (%)
Global warming	kg CO_2 eq	2.45	2.32	5.3
Ozone depletion	kg CFC11 eq	1.36×10^{-6}	1.27×10^{-6}	6.6
Ozone formation	kg NO_x eq	0.00935	0.00877	6.2
Terrestrial acidification	kg SO_2 eq	0.0172	0.0159	7.6
Freshwater eutrophication	kg P eq	0.00166	0.00157	5.4
Freshwater ecotoxicity	kg 1,4-DCB	0.0605	0.0613	-1.3

Green – smallest environmental impact, red – largest environmental impact

Concentrated solar power

Concentrated solar power works differently from PV solar panels. Photovoltaic power panels generate electricity via the displacement of electrons whereas CSP concentrates the sun's rays to a central point using a reflective surface, heating fluid or gas which then heats a water stream producing steam. CSP energy production can be used to produce thermal energy and/or electricity. In South Africa, several solar power plants use CSP to produce electricity (Table 5-13).

Table 5-13: CSP power plants installed in South Africa (NREL, 2022)

Power Station	Location	CSP type	Power	Commission date
Bokpoort CSP	Groblershoop	Parabolic Trough	50 MW	2016
Ilanga I CSP Project	Upington	Parabolic Trough	100 MW	2018
Kathu Solar Park	Kathu	Parabolic Trough	100 MW	2019
KaXu Solar One	Pofadder	Parabolic Trough	100 MW	2015
Khi Solar One	Upington	Power Tower	50 MW	2016
Xina Solar One	Pofadder	Parabolic Trough	100 MW	2018
Redstone	Postmasburg	Power Tower	100 MW	2023, 4^{th} Q

CSP plants are often built for large-scale energy production that feeds into the national grid, however, smaller off-grid plants for industrial use are also possible. Several small-scale plants, < 5 MW_e power, have been constructed using different CSP technologies. The CSP technology is used to produce electricity, however, it can also be used to generate thermal energy.

The mill is built in an industrial area surrounded by other factories, warehouses and buildings. Like PV power, concentrated solar power (micro CSP) units have been installed on rooftops but these are used for refrigeration and air conditioning systems. Small-scale CSP systems are therefore used for their thermal applications but not for electricity production (Cabrera et al., 2013). This means that the use of CSP and CSP-hybrid systems is not only limited by capital cost and the availability of the appropriate technology in South Africa, but also by space. Based on this information, smaller CSP and CSP-hybrid systems were researched to ensure that the land space required is kept to a minimum.

A small-scale CSP tower design has been implemented in Spain and Israel, with the capacity to generate 100 kWh using gas turbines (Kopilovsky, 2012). The area spans only 2300 m^2, equivalent to a 50 by 50 m lot. The 50 reflectors on the ground reflect the sun's rays onto a receiver at the top of the tower (bulb of the tower), where it heats air to around 1000 °C. Fitted in the bulb of the receiver is a 100-kW gas turbine that then takes the thermal energy and converts it to electricity. The process is also designed to operate using liquid and gas-based fuel sources, such as diesel and natural gas, allowing energy to be generated at night and on days with low solar radiation. The Israeli system only generates 100 kW of electricity, but the Spanish plant can generate 100 kW of electricity and 170 kW of thermal power, which can be used for heating purposes. As in the “PV solar panels”, the mill requires on average 433 333 kW of electricity per day. The process can only generate 100 kW, including solar and fuel, which means in 24 hours 2400 kW of electricity can be produced per day. However, when considering the mill’s daily electricity consumption, only 0.55 % of the monthly electricity will be replaced by a cleaner system. The capital cost for the 100 kW plant (2400 kWh/day) is 550 000 USD (Lombardo, 2015), which converts to about ZAR 8.35 million assuming linear scaling of USDD per kWh from large to smaller plants and using a ZAR to the USD exchange rate of ZAR 15.18 per USD. This option, therefore, has no economic feasibility or even process feasibility since a large sum of capital is required to produce a small amount of electricity.

Another study by Camerada et al. (2015) studied the expected performance of a pilot solar power plant under construction in Ottana, Italy commissioned in 2017. The plant can generate 1 MW_e using both CSP and CPV (concentrated photovoltaic energy), with the Fresnel-based CSP contributing 600 kWe and the CPV contributing around 400 kWe. The solar field uses a 10 000 m^2 solar area (100 by 100 m) and the cost of construction was around ZAR 97.7 million (European Commission, 2020) using a ZAR to the USD exchange rate of ZAR 15.18 per USD. This included all costs, the CSP system, CPV system, heat exchangers, turbine system, thermal energy storage units (CSP), an electrochemical storage system (CPV), regenerator and all other minor equipment. The thermal storage unit can run the process for another 5 hours and the electrochemical storage facility can run the process for 1.4 hours. The total run time of the plant is presented Table 5-14, assuming a solar time of 8 hours.

The 11430 kWh per day only covers 2.6 % of the electricity required per day for a total investment cost of ZAR 97.7 million. This indicates that the use of CPV and CSP Fresnel design has a higher energy production than the small-scale CSP tower design. However, the initial capital cost and power output make it economically unfeasible, provided the CPV panels are not available in South Africa and must be imported. The CSP is available locally, with a

CSP trough system built in Lesotho, and the heat collecting element (HCE) manufactured to obtain a 250 °C exiting temperature of the heating fluid with 65 % sunlight absorption efficiency (as opposed to the 300 °C exiting temperature at 70 % efficiency from imported material) (Orosz et al., 2016). This indicates that the CSP trough, and probably the CSP Fresnel design can be produced from local equipment, reducing the cost and time associated with importing materials.

Table 5-14: Power output and storage potential of the Ottana CSP power plant

Power supply	Time (hr)	Power (kWh per day)
CSP	8	4800
CPV	8	3200
CSP storage	5	3000
CPV storage	1.4	430
Total	NA	11430

Another small-scale CSP plant was built in Arizona in 2005. The Saguaro power plant, can generate 1 MWe from a 13 500 m^2 plot of parabolic trough collectors and does not contain an energy storage unit (Canada, 2006). The total capital cost was 6 million USD (ZAR 92 million) (Kryzanowski, 2007). Assuming an 8-hour effective sunshine period, 8 MW of electricity can be produced per day. This meets 1.8 % of the daily electricity demand.

Another option is CSP-hybrid systems (such as the small-scale CSP tower design). This process operates by supplying solar power during the day by using CSP (no thermal storage) and biomass combustion at night (also for periods of lower solar radiation). An example of this is the thermo-solar Borges CSP-biomass power plant in Spain, producing 22.5 MWe (Power Technology, 2013). Both the CSP and biomass sections supply enough energy to supply the mill independently from each other., which means if no solar energy is produced, the biomass boilers would be able to carry the load for the entire day. Some of the CSP-biomass hybrid plants are used for the co-generation of thermal energy and electricity. For the mill understudy, this solution is not viable since the land for the solar section is not available and using biomass is not yet a consistently available fuel source in South Africa. However, this is an interesting potential approach for South Africa to generate electricity. Currently, South Africa has several CSP plants that use thermal storage for periods of low or no solar radiation. Replacing the thermal storage units with coal boilers could supply hybrid electricity for 24 hours a day, therefore, reducing the reliance on coal for electricity production by substituting part of it with solar.

These examples indicate that although the CSP and CSP-hybrid energy solutions show the potential to transition the mill from its reliance on fossil fuel for electricity and heat, the limiting factor is the initial investment cost, availability of fuel sources (biomass and natural gas), availability of land and the limited electricity produced from the CSP plants (considering power output per m^2 of land). However, a positive from these results indicate that the construction of the CSP power units (parabolic troughs and Fresnel reflectors) can be built using local materials, which could reduce the cost and time associated with importing materials.

5.6.3. Producing WLC with fully recycled fibre

The mill uses a mixture of recycled and virgin fibre, with the top liner and underliner consisting of virgin kraft and virgin mechanical (respectively) fibre, and the filler (middle liner) and bottom liner consisting of different grades of recycled fibres. As part of the objective to reduce the use of natural resources by increasing recycling and achieving a more circular economy, a comparative assessment was done to study the impact of changing the two virgin layers with recycled fibre layers.

It is important to note that when changing WLC from a mixed fibre product to a fully recycled fibre product that there are many properties of the product that could potentially change, such as food safety properties, mechanical properties, product weight and several others. These changes need to be considered to ensure that the new product is still “fit for purpose”. For example, WLC is used in food packaging (secondary and direct contact), therefore, potential changes to its food safety properties need to be considered and tested to ensure that the new WLC product meets food safety standards.

Due to the complexities of these properties and the unknown effect they could have on the final WLC product (further discussed after the theoretical comparison section), they could not accurately be modelled in the comparative LCA. The effect of these changes was estimated as discussed below.

Theoretical comparison

Replacing virgin fibre with recycled fibre is not a 1: 1 change. An article by Czene & Koltai (2020) found that the mass differences between a fully recycled paperboard product and the virgin paperboard product required a 24 % increase in mass for recycled fibre. However, because WLC consists of 75 % recycled fibre and 25 % virgin fibre, 24 % was only applied to the virgin fibre sections. The 24 % is derived from the specific volume difference in the study, where the specific volume of the recycled product was 1.54 $cm^3\ g^{-1}$ and the virgin product was 1.24 $cm^3\ g^{-1}$, indicating a 24 % difference in the specific volume.

Taking the mass of virgin fibre and increasing it by 24 % meant that the mass of the new 100 % recycled fibre product could be determined.

$$Recycled_{Fibre,Full} = Recycled_{Fibre} + (Virgin_{Fibre} \times 1.24)_{Recycled\ fibre,New} \qquad (6)$$

$$Recycled_{Fibre,Full} = 0.7572 + 0.2428 \times 1.24 = 1.058\ kg\ WLC_{Recycled} \qquad (7)$$

By taking the new mass of the 100 % recycled product and dividing it by the mass of the original product, all the additional chemicals and processes required to work with the new recycled fibre could be accounted for in the simulation.

$$Ratio = \frac{Recycled_{Fibre,Full}}{Mixed_{Fibre,Full}} = \frac{1.058}{0.996} = 1.06 \qquad (8)$$

This means that all chemicals for fillers and coating, transport, sludge, steam energy, screened waste and forklift fuel consumption were increased by 1.06 to account for the increased product mass. The comparative assessment was conducted based on these measurements. The results from the simulation indicated that there was an overall reduction in the environmental footprint of the product (Table 5-15), however, the differences were very small.

Table 5-15: Environmental impacts of the original WLC product compared to a WLC product made from 100 % recycled fibre

Impact category	Unit	WLC original	WLC fully recycled	Impact reduction (%)
Global warming	kg CO_2 eq	2.5	2.4	1.6
Ozone depletion	kg CFC11 eq	1.4×10^{-6}	1.3×10^{-6}	6.6
Ozone formation	kg NO_x eq	0.0094	0.0088	5.7
Terrestrial acidification	kg SO_2 eq	0.017	0.017	3.5
Freshwater eutrophication	kg P eq	0.0017	0.0017	0.6
Freshwater ecotoxicity	kg 1,4-DCB	0.061	0.059	2.3

Green – smallest environmental impact, red – largest environmental impact

The results indicate that there is an overall decrease in all impact categories when switching to 100 % recycled fibre. However, after having a conversation with a specialist that works for the milling company, the specialist highlighted that the results, although showing that the recycled WLC product is more environmentally sustainable, exclude many factors that could impact the change to fully recycled fibre (further discussed below), such as additional capital investment for process changes, increased operational costs and the possible changes in the products "purpose". These problems related to :

1. Which grade of recycled fibre to use,
2. Would the product still be food safe
3. Whether the mechanical strength of the product would be sufficient for its use
4. Product density changes and how this affects the manufacturing process,
5. Would changes in the barrier coating composition be required, and
6. How does this affect the optical properties?

<u>Grade of recycled paper</u>

There are many grades of recycled wood fibre products to choose from (Fibre Circle, 2020). A food safety specialist working for the milling company indicated that it is difficult to select a specific grade as a replacement for virgin fibre since the properties that the recycled fibre could add or remove from the final WLC product are unknown. For example, the food safety specialist stated that the use of newsprint is good for multi-ply products since it gives bulk and good mechanical properties. However, the recycled materials (predominantly due to the inks) used in food-grade packaging could be a source of mineral oils and contaminants that can evaporate from the recycled material and seep into the food products, making the packaging product unsafe (Fiack & Wittkowski, 2017; Spack et al., 2017). This could mean that using 100 % recycled fibre would either narrow down the market for WLC to a few non-food-based products or additional processes, such as de-inking, could be required in the manufacturing line to remove these inks and dyes, thereby removing mineral oils and other contaminants. Common deinking processes include adsorption deinking, flotation deinking, enzymatic deinking and wash deinking (Jamnicki et al., 2015; Lee et al., 2013), however, de-inking usually only removes between 60 – 80 % of inks and minerals depending on the type and grade of inks used, thus additional measures such as using a more functional bottom coat or improved primary packaging would need to be added to mitigate the contamination of the food product (Spack et al., 2017).

The first option (non-food-based products) would result in a loss of revenue, and the second option (deinking) would result in major adaptations of the manufacturing process requiring additional capital investment, process shutdown for installation, increased cost of chemicals for de-inking the products and increased cost of chemicals used for treating the wastewater to comply with the South African industrial effluent guidelines. An additional benefit of de-inking is the removal of impurities which in turn increases the tensile strength, and burst strength and reduces shrinkage of the products during drying (Ahmed & Mohammed, 2014), thereby improving the overall mechanical quality of the WLC product.

The grade of recycled paper used can also influence the mechanical and physical properties of the final WLC product. The extent to which the mechanical properties could change would first need to be evaluated. However, if they are weaker, polymers, adhesives and fillers can be added to the product which will help to improve its mechanical properties. This could create downstream problems since adding more chemicals and fillers contaminates the recycling stream making the paper waste less recyclable and resulting in more fibre loss during the repulping and screening stage. Similarly, if excess adhesive and polymers are used and insufficient cleaning occurs during the repulping and screening stage of a milling operation, the adhesives and polymers could accumulate downstream of the manufacturing process and result in sticky deposits on equipment, which could result in the formation of spots, discolouration, and holes in the final products (Confederation of Paper Industries, 2019; Santos & Hart, 2014) and increased cost related to cleaning of equipment.

For the mechanical properties of the new product, the magnitude of the change associated with the replacement of virgin fibre with recycled fibre is unknown. The effect of this change needs to be tested to ensure that the product remains fit for purpose.

Food safety

There are many paper-based packaging products made from 100 % recycled fibre that is used in food packaging and food contact applications, but all of these have been tested for food safety and comply with food safety standards, such as the ISO22000:2005, British Retail Consortium and the German Federal Institute of Risk Assessment.

Replacing the virgin fibre in WLC with recycled fibre could change the food safety quality of the product, but the extent of this change is unknown. Each grade of recycled fibre contains different inks, dyes, adhesives and fillers; not all of these were intended for food contact and are therefore not food-safe (Fiack & Wittkowski, 2017; Spack et al., 2017). The impact these chemicals could have on the food safety of the final WLC product would need to be tested, for example, maybe during the cleaning processes most of these inks, dyes, etc are removed and their presence in the final WLC product is low enough to meet food safety standards; maybe they are low enough to only require a barrier coating to prevent the chemicals from migrating to the food, or if it is too high in general, another recycled fibre grade could be used or an additional cleaning stage could be considered, such as a de-inking tank, where most of the dyes and inks could then be removed.

Mechanical properties

Another important factor to consider when switching to fully recycled fibre is the change in the physical and mechanical properties of the product. A study by Czene & Koltai (2020) studied the mechanical properties of dried paper that consisted of pure virgin fibre, pure recycled fibre and a 94 %, 88 %, and 85 % recycled to virgin blend. The objective of the research was to study the change in mechanical properties between the different blends and to observe any correlation between the mechanical properties and the addition of virgin fibre. From their results they found that there was a distinct change in the tensile strength, bursting strength and tear force. The recycle-virgin blends gained higher tensile and bursting strength when compared to the 100 % recycled product and obtained a stronger tearing strength when compared to both the 100 % recycled and 100 % virgin products.

The different strength properties observed are due to the changes in fibre strength, fibre length, and fibre bonding capabilities when the paper is recycled and processed. Every time fibre is recycled, the length of the fibre decrease and the physical properties attained by the length of the fibre start to decrease as well, hence a decrease in the flexibility of the product, folding strength and tensile strength. A longer fibre can have more fibre joints and therefore create stronger inter-fibre bonds (Johansson, 2011; Minor & Atalla, 1992). For this reason, products made from recycled fibre could require more chemicals and additives to help them regain these lost properties (Hamzeh et al., 2013).

The results from the study indicate that the addition of virgin fibre to a recycled product significantly improves the mechanical properties. Using purely recycled fibre could impede the function of the product and to regain the lost properties more fillers would need to be used. However, the extent of the loss of mechanical properties differs based on the grades of recycled fibre used and therefore needs to be tested before adding fillers. This is to ensure that the product remains fit for purpose and to prevent the overdesign of the product.

Density

A change in the density of the product can also occur when it is recycled (Czene & Koltai, 2020; Obradovic & Mishra, 2020). The apparent density is a scale of the elasticity of the pulp. A resilient pulp has a higher apparent density as its fibres are more lightly compressed into the holes of the paper sheet. Due to the shorter fibre lengths in recycled pulp, the product becomes more inflexible and less compressible. Considering a constant surface area, the only way to make up for the mass associated with the reduced density of the recycled product would be to make it thicker. To attain the same physical properties, an additional amount of chemicals and fillers might be needed, and the mass of the product would also have to be increased by thickening the product with more recycled fibres. This means that less water could be removed during the forming stage of the process, and therefore more steam energy would be required during the drying phase of the calendaring section to remove any remaining moisture. Thereby increasing the impact of the boiler system.

Coating for protection

The specialist also indicated that recycled fibre is more prone to weakening when in the presence of moisture as opposed to virgin fibre. This is proven by Czene & Koltai (2020) who found that capillary rise in recycled paper was 12 mm higher than in virgin paper. This is because fluid transport in the paper depends on fibre types, level of refinement, and the other materials used in the paper (filers, sizing materials). As recycled paper products contain more fillers and chemicals and the material is more closely packed, the potential for water absorption is increased. Similar results were found by Navaranjan et al. (2013) who studied the change in mechanical properties of fully recycled corrugated board and standard corrugated board (mix of virgin and recycled fibre) exposed to 50 % and 90 % relative humidity under constant pressure loads. They found that the standard corrugated board (mixed virgin and recycled fibres) performed better in compressive performance than the fully recycled corrugated board in both directions and at both relative humidities. The combination of relative humidity and compression resulted in local buckling of both boards. However, the elastic performance of the recycled corrugated board was found to be lower than that of the standard corrugated board at both relative humidity conditions. This indicates that both are susceptible to failure when exposed to moisture, but the standard corrugated board (virgin and recycled fibre mix) is stronger than the recycled corrugated board.

Since moisture might not be a problem for most WLC packaging applications, addressing this problem will not be necessary. But since the effect of moisture on the new 100 % recycled WLC product is unknown, it would still have to be tested. If it is a problem, there are several ways to address this, such as increasing the thickness of the currently used barrier layer or changing the composition of the barrier layer formula. For example, a study by Marzbani et al. (2021) found that adding a polyethylene wax (PE wax) to their coating formula improved water vapour permeability (WVP), surface wettability, and water resistance and also increased the compressive strength of the product. Making these changes (similar changes) could result in additional costs incurred by the mill to purchase the extra chemicals for the additional barrier protection and therefore this also needs to be considered before changing to 100 % recycled fibre use.

Coating for optical properties

Making white-lined paper products from recycled fibre can be difficult. The "whiteness" of the repulped recycled fibre varies from grade to grade. For example, if heavy letter one (HL 1) recycled fibre (consisting of office paper with little printing and water soluble adhesives) is used, the need for de-inking could be unnecessary or very little since the product would already be quite white. Comparing this to the common mixed waste (CMW) recycled fibre (consisting of various grades of paper and board), the CMW grade could require an entire de-inking process to effectively remove the ink and create a whiter pulp since it consists of heavily inked and dyed paper products.

Even if the grade of recycled fibre is considered, de-inking recycled fibre creates whiter products but the pulp could still have a light grey/blue hue, as opposed to the bleached virgin fibre which has high whiteness and opacity. If this is a problem, it could be addressed by the addition of a bleaching process or by changing the surface coat applied to the finished sheet.

Bleaching is an effective way to improve the brightness of recycled pulp, but there are some limitations. A study by Y. Chen et al. (2015) indicated that bleaching, although whitening the product, comes at a cost of product loss. They found that as they increased the feed of the bleaching compound (hydrogen peroxide) the brightness of the product increased but at the cost of reducing the yield of the fibre. The yield decreased because of fibre loss during rinsing, removal of chromophores during bleaching and the dissolution of other pulp components. Some other property changes were also observed, such as reduced fibre length, increased fibre strength, and a few others. Fibre length is shortened due to the additional working of the fibres. Fibre strength increased in the final sheets, because the bleaching occurred on the fibre surface, releasing fibrils which increased the roughness of the surface of the fibre, resulting in better interfiber bonding. This study by Y. Chen et al. (2015) specifically studied the bleaching of newsprint, but these properties could also change based on the grade of recycled fibre used and the type of bleaching chemical used.

The whiteness of the product could also possibly be increased by changing/adjusting the formula of the coat applied on the surface of the final WLC product, thereby hiding the blue/grey hue. If the current coat used by the mill cannot properly cover this, the formula of the coating can be changed to adjust for the whiteness, since coatings, based on the chemicals used, can offer different levels of smoothness, gloss, brightness, and opacity to the base paper/product (El-Sherif et al., 2017).

It is also important to consider the costs associated with improving the optical properties. High capital investment is required to construct and connect the bleaching processes, the additional operational costs and chemical costs (bleaching chemicals can be expensive), and the additional chemical cost that might be required to treat the effluent before discharge. The cost involved for the coat could be for product redevelopment and the chemicals required to make the new coating, but based on the redevelopment, the cost of the new coat could be cheaper. Thus, the cost of either option (bleaching or new coating), if both are not required, will be based on the grade of recycled fibre used.

6. Conclusion

With the supplied data and mass/energy balances, it was possible to conduct the LCA and validate the mill's data, identify data gaps and calculate the missing values and create and compile a complete inventory list for WLC manufacturing, kraft pulping and eucalyptus forestry. This inventory list was used to conduct the life cycle impact assessment for 1 kg WLC, in which the five highest contributors to the six different impact categories, namely: global warming, ozone formation, ozone depletion, terrestrial acidification, freshwater eutrophication, and freshwater ecotoxicity could be determined and evaluated. The inventory list was used to successfully create an EcoInvent dataset. This dataset was submitted to Ecoinvent and is in the process of being incorporated into their database, thereby creating a dataset for WLC manufacturing that not only represents South Africa but will also allow for any future LCA studies to be conducted using local data.

6.1. Impact assessment

The life cycle impact assessment of the white-lined chipboard indicated that the highest contributors for all six impact categories were the use of electricity and energy generation. The results indicated that this was due to the mill's reliance on coal for its energy supply with 100 % of the mill's steam coming from coal combustion, as well as South Africa's reliance on coal for electricity generation, with more than 80 % of the national grid relying on coal

Although the combustion of coal had the highest impact on global warming, the coal mining processes also had significant contributions to the other impact categories. Due to this large contribution from electricity and onsite energy generation, the impact of any other processes became overshadowed.

The results indicated that South Africa's current state of electricity generation and the mill's reliance on fossil fuels for energy generation has a significant impact on the environment, especially when compared to cleaner alternative fuels (such as biomass and natural gas) used by other countries.

6.2. Waste treatment

The mill produces several wastes, which included air emissions from the boiler and forklifts, liquid emissions from the clarification process and several solid wastes from different processes on the mill, which included sludge, general waste, screened waste and ash. Although the air emissions can only be changed by considering alternative fuel sources for the boiler process, how the mill manages its solid and liquid wastes are environmentally sustainable and are the best solution currently available, only using landfill as a final option.

6.3. International data

The EcoInvent database includes some South African datasets, including electricity, transport, water, mining, and agricultural but no datasets for the South African pulp and paper industry. As a result, local studies within this industry have been conducted using international datasets.

The results showed that using international datasets was not a problem if the process, input or output contributes < 5 % by mass/energy, and if it was process-specific and not country-specific, such as electricity. If international data that is country-specific is used to represent a South African process, it can significantly change the outcome of the LCA, overestimating or underestimating its environmental impact.

The results also showed that creating and using a hybrid dataset is an effective way to conduct an LCA to obtain a general idea of the impact of a process or to quickly compare products/processes. However, it is best to still conduct LCAs with original, real-time data that is more representative of the process/product and location.

6.4. Sensitivity and uncertainty tests

The results from the sensitivity analysis indicated that the major contributors to the environmental impact of WLC were electricity and steam generation. The results indicated that an increase/decrease in the load does not return the same magnitude of change in the results of the LCA.

The sensitivity analysis testing the impact of the exclusion of the nursery phase data of forestry, forestry fertilising, irrigation and herbicide application in the LCA, indicated that the assumption made to exclude these was acceptable since they had minimal impact on the outcome.

The Monte Carlo uncertainty analysis indicated that the data supplied in the inventory results were reliable. There was little error in the results for global warming, ozone formation and terrestrial acidification and this was consistent for all three impact methods studied. For freshwater ecotoxicity and ozone depletion, the results for the ReCiPe 2016 method indicated that the effect of the uncertainty in the data was large. However, the same data simulated with the EF 3.0 and TRACI 2.0 method showed that the error was very small (small standard deviation), which therefore indicates that the error was not based on the uncertainty of the inventory data, but based on the inventory included in the ReCiPe 2016 method. Lastly, for freshwater eutrophication, the mean value for all three impact methods was the same and the error for all three was large, indicating that the reliability of the data representing freshwater eutrophication was low.

6.5. Alternative solutions

The use of biomass as a substitute for coal has a lower environmental impact across all impact categories, even with the additional transport and ash production. The largest difference was observed for global warming, reducing the impact by 52 %, but an overall reduction was observed for biomass use, indicating that biomass is the more sustainable option. However, though biomass is a cleaner fuel source, the capital required to replace/alter the existing technology, additional costs involved in transportation, problems associated with laws governing its use, and the uncertainty of supply and transport distance make the transition difficult.

In solar solutions three technologies were discussed, namely, photovoltaic power (PV), concentrated solar power (CSP) and CSP – biomass hybrid power. Concerning PV power, based on the available roof surface area, a total of 50225 kWh of AC electricity could be produced per day which could substitute municipal electricity by 11.6 %, thereby reducing the environmental impact of WLC production by 8 %. This was by far the most effective and most feasible of all the solar solutions since it uses unusable space, and can be produced and installed locally. CSP systems and CSP-biomass hybrid energy solutions are effective in allowing the mill to generate steam energy and electricity, but the limiting factors included the initial investment cost, availability of biomass and availability of space/land to construct the system.

Using fully recycled fibre to produce WLC is a possibility, but due to the limitations associated with the changeover, such as loss of mechanical strength, food safety concerns, milling operation changes, and operational and capital costs, the implementation of this change is not yet feasible and would require more research. However, based on the theoretical study, the results showed that using 100 % recycled fibre could lead to a reduced environmental impact.

7. Recommendations

7.1. Future work

Based on the results generated by the uncertainty analysis, the impact method chosen can significantly alter the outcome of an LCA. Therefore, it would be beneficial to do a more thorough investigation of the different impact methods to determine how each method categorises, classifies and weighs each of the pollutants produced. From this, the method with the lowest uncertainty and best data coverage can be chosen to model future LCAs, ensuring that the results from the LCAs are as accurate as possible.

Due to the significant influence of electricity and energy production on the overall impact of the LCA, they overshadow the other processes. To improve the study, it would be good to conduct the LCA excluding electricity and energy generation. This would allow for a better investigation of the influence of the other processes involved in WLC manufacturing, and allow for process improvements on a smaller, more feasible scale as opposed to the large projects required to reduce the environmental footprint of electricity and energy production.

7.2. Current process improvements

From the process improvements available, the best and most feasible process that can be implemented with few problems would be the PV solar power solutions. Solar power is a power source readily available in South Africa with many companies providing services related to supply, installations, maintenance, and repairs and is currently the most cost-effective form of self-power generation.

As for steam generation, although biomass is an effective alternative fuel source, there are several problems associated with its use as the only fuel source for energy generation. The co-combustion scenario seems to be the most feasible at this point since only 20 –40 % of coal needs to be substituted by biomass, which means that coal is still the primary fuel source and that uncertainty associated with biomass supply will not be a problem. Secondly, no major alterations need to be made to the existing boilers as the current boiler set-up could still run the mixed fuel source. Thirdly, there will still be a reduction in emissions, reducing the environmental footprint of WLC production.

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Appendix A – Data validation (WLC Inputs)

In this section, the mass and energy flows that enter the mill are validated by using mass and energy balances from the primary data collected onsite or from secondary data sources. This was done to ensure that there were no:

1. Double counting of the data,
2. Missing data
3. Calculations and readings were correct.

A1. WLC – Raw materials

A1.1. Virgin and recycled fibres

<u>Calculation</u>: The mass of fibres of both recycled and virgin origin were given.

<u>Validation</u>: The final WLC product had the following compositions (Table A-1),

Table A-1: Final composition of WLC.

Material	Mass (kg)
Fibre	0.894
Coating	0.039
Filler	0.018
Moisture	0.05

The total Fibre fed consisted of:

$$W_{Fiber,T} = W_{Kraft} + W_{Mechanical} + W_{CMW} + W_{K3} + W_{K4} + W_{OB} \qquad (9)$$

$$W_{Fiber,T} = 0.1914 + 0.05984 + 0.3601 + 0.1043 + 0.2717 + 0.0702 \qquad (10)$$

$$W_{Fiber,T} = 1.061\ kg \qquad (11)$$

However, the common mixed waste and Kraft 4 waste still contains impurities (it was assumed that Kraft 3 had no impurities as it is composed of unused corrugated boxboard). To account for the impurities removed after repulping, the mass of screened waste had to be subtracted as well. This means that Equation (9) above becomes,

$$W_{Fiber,T} = W_{KF} + W_{MF} + (W_{CMW} + W_{K3} - W_{Waste}) + W_{K4} + W_{OB} \tag{12}$$

$$W_{Fiber,T} = 0.1914 + 0.05984 + (0.3601 + 0.1043 - 0.07665) + 0.2717 + 0.0702 \tag{13}$$

$$W_{Fiber,T} = 0.98035\ kg \tag{14}$$

From this, about 6 % is lost due to process line breaks (recycled back as Fibre feed, but not in the same production batch) and 2.34 % is lost as fibre in sludge. This means that the Fibre fed is higher than the actual mass of Fibre in the final WLC product. Taking the value from Equation ((14)) and subtracting the 6 % and 2 % lost to process breaks and sludge, the difference between final and fed (minus losses) came to,

$$Fibre\ mass\ after\ loss = (0.98035 \times 97.7\%) \times 94\% \tag{15}$$

$$Mass\ after\ loss = 0.9003\ kg \tag{16}$$

$$\%\ difference = \frac{0.9003 - 0.894}{0.9003} \times 100\% = 0.7\% \tag{17}$$

The difference could result in rounding during the calculation steps and the 6 % loss as process breaks is an average value used by the industry (varies from month to month but the value is not known). It can also be because of the unaccounted moisture in the Fibres fed, giving it a higher wet mass.

A1.2. Freshwater – pulping

Calculation: The freshwater for "PL 1" was not directly supplied. Instead, the total freshwater supplied to the mill was given, from which the flow of freshwater to "PL 1" could be calculated by subtracting the flow of water to the boilers, for domestic use and the freshwater supply to the other processing lines. Each one of these processes had a meter to measure their water intake, so by default, the difference would be the intake into "PL 1" as calculated by the company. The values were given as actual flows just to show how it was related to the functional unit.

$$W_{PL1} = W_{Fresh} - W_{PL-other} - W_{Boiler} - W_{Domestic} \tag{18}$$

$$W_{PL1} = 1111020 - 183115 - 173156 - 32866 \tag{19}$$

$$W_{PL1} = 721884\ kL \tag{20}$$

Multiplying W_{PL1} by the allocation ratio in Equation 1, the water supplied to W_{PL1} for WLC production was

$$W_{WLC} = W_{PL1} \times 65.6\% \tag{21}$$

$$W_{WLC} = 473555.904\ kL \tag{22}$$

Taking Equation (22) and dividing it by the production volume of WLC, the flow of freshwater could be determined per functional unit,

$$W_{WLC,FU} = \frac{W_{WLC}}{PV_{WLC}} = \frac{473555.904\ kL}{66270\ ton} = 7.15\ \frac{L}{kg} \tag{23}$$

Validation: As mentioned, the amount of freshwater sent to "PL 1" is not measurable on the site. There is another way to validate the value obtained in Equation (23) by taking a total water balance across the process line,

$$In = Out \tag{24}$$

$$W_{Fresh} + W_{filtered} = W_{filtered} + W_{Effluent} + W_{evaporated} \tag{25}$$

The $W_{evaporated}$ is explained in Appendix B6 but is essentially the water that evaporates from the fibre sheets during the drying section of calendaring. Since the $W_{Filtered}$ forms are part of a closed-loop (via reuse), it subtracts from each other resulting in the following equation,

$$W_{Fresh} = W_{Effluent} + W_{evaporated} \tag{26}$$

$$W_{Fresh} = 5.867 + 1.381 \tag{27}$$

$$W_{Fresh} = 7.248\ \frac{L}{kg} \tag{28}$$

Therefore, the difference becomes

$$\%\ difference = \frac{7.248 - 7.15}{7.248} \times 100\% = 1.35\% \tag{29}$$

This shows that a very similar value was obtained by considering only the flows of fresh water fed to the mill and by considering only water exiting from the mill.

A1.3. Boiler water

Calculation: The water flow supplied to the boiler was a measure for the entire mill. To determine the boiler water flow for WLC the following calculations were done,

$$W_{Boiler,WLC} = W_{Boiler} \times 51.7\ \% \tag{30}$$

$$W_{Boiler,WLC} = \ 89522\ kL \tag{31}$$

$$W_{Boiler,WLC,FU} = \frac{89522\ kL}{66270\ ton} = 1.35\ \frac{L}{kg} \tag{32}$$

A1.4. Domestic water: Followed the same steps as with “Boiler water” above.

A1.5. Oxygen:

Calculation: The calculation of the oxygen was done by only considering the oxygen required to produce CO_2 and CO. The total CO_2 and CO produced were 0.945 kg and 0.001035 kg respectively. Calculating the oxygen required came to**,**

$$C + O_2 = CO_2 \tag{33}$$

$$nCO_2 = \frac{0.6\ kg}{(12 + 16 \times 2)\ \frac{kg}{kmol}} \tag{34}$$

$$O_2 = (2 \times 16) \times nCO_2 = (2 \times 16) \times \frac{0.6\ kg}{(12 + 16 \times 2)\ \frac{kg}{kmol}} \tag{35}$$

$$O_2 = 0.436\ \frac{kg}{kg\ WLC} \tag{36}$$

For CO the mass of oxygen required was calculated as,

$$C + \frac{1}{2} O_2 = CO \tag{37}$$

$$O_2 = (16) \times nCO = (16) \times \frac{0.001521\ kg}{(12 + 16)\ \frac{kg}{kmol}} \tag{38}$$

$$O_2 = 8.69 \times 10^{-4}\ \frac{kg}{kg\ WLC} \tag{39}$$

Validation: Based on the emissions report supplied by the mill, the average O_2 fed to the boiler was 0.862 kg. Summing Equation (36) and Equation (39), the total oxygen required was.

A2. WLC – Energy and electricity

A2.1. Electricity

Calculation: Initially the data was supplied by the company. Due to the nature of the electricity readings, they represented the electricity used by the entire mill. Thus, to obtain the electricity consumption for WLC, allocation as in Equation (4) was used.

$$E_{WLC} = E_{Mill} \times 51.7\% \tag{40}$$

$$E_{WLC,FU} = \frac{(137193086{,}3 \times 51.7\%)}{66270000} \tag{41}$$

$$E_{WLC,FU} = 1.07\ \frac{kWh}{kg} \tag{42}$$

Validation: Initially there is no way to mathematically determine whether the calculation is valid. However, the electrical engineer working on-site said that, on average, "PL 1" consumes about 82 % of the electricity consumed by the mill. Using this information and Equation (2), the electricity consumed becomes,

$$E_{WLC} = \frac{(137193086{,}3 \times 82\% \times 65.6\%)}{66270000} \tag{43}$$

$$E_{WLC,FU} = 1.114\ \frac{kWh}{kg} \tag{44}$$

With a difference of,

$$\%\, difference = \frac{1.114 - 1.07}{1.07} \times 100\% = 4.11\% \tag{45}$$

A2.2. Natural gas

Calculation: The amount of natural gas used was supplied by the mill and was supplied as an energy value. The information was only supplied for four months (Table A-2). These values were divided by the total "PL 1" production value for that month, averaged and then extrapolated to the other months based on the average production volume for each month, assuming the production volume had a direct relationship to the amount of gas required to dry the coating.

Table A-2: Natural gas used for drying coating on paperboard.

Month	Energy (GJ)	PL 1 production volume (ton)	Ratio (GJ ton^{-1})
Month 1	6716	9284,6	0,7233
Month 2	5288	7506,9	0,7044
Month 3	7404	9660,0	0,7665
Month 4	6327	7046,2	0,8979
Average			0.773

Therefore, the new value for months 5 to 12 would be,

$$M_5 = PV_{5,average} \times 0.773 \tag{46}$$

$$M_5 = 8927 \times 0.773 \tag{47}$$

$$M_5 = 6901\ GJ \tag{48}$$

This process was repeated up to month 12 and each energy value represents the total GJ of gas combusted in that month. The total energies for each month were summed to a final yearly value of,

$$E_{Gas,PL\ 1} = 78127\ \frac{GJ}{yr} \tag{49}$$

Then to covert from GJ for "PL 1" to GJ for WLC produced, the value is multiplied by Equation (1),

$$E_{Gas,WLC} = E_{Gas,PL\ 1} \times 65.6\% \tag{50}$$

$$E_{Gas,WLC} = 78127\ \times 65.6\% \tag{51}$$

$$E_{Gas,WLC} = 51253\ \frac{GJ}{yr} \tag{52}$$

Then to get this value in terms of the functional unit,

$$E_{Gas,WLC,FU} = \frac{E_{Gas,WLC}}{PV_{WLC}} \tag{53}$$

$$E_{Gas,WLC,FU} = \frac{51253\ GJ}{66270\ ton} \tag{54}$$

$$E_{Gas,WLC,FU} = 0.773\ \frac{MJ}{kg} \quad (55)$$

Validation: No validation was possible since this is the only point where gas was used. Validation via secondary sources was not possible either since the thickness and composition of the coats vary from company to company and from product to product, changing the heating requirements.

A2.3. Diesel

Calculation: The diesel was calculated based on the number of times the tank is filled each month. Which would represent how much fuel is used. Because there is no forklift dataset in SimaPro, it was suggested by an EcoInvent employee that it be presented as diesel burnt in a machine, which is why the value was given as an energy value instead of a volume value. The mass was calculated by multiplying the volume of diesel used by its density. This mass value was then multiplied by the HHV of diesel to calculate the energy output. On-site, there are about 16 forklifts, consisting of 5 tonners and 2.5 tonners. The forklifts operate for about 16 hours a day. According to Hinz (2021), the fuel consumption of a forklift with a load capacity of 2.5 – 3.5 tons can on average consume 2.7 – 3.6 L of diesel per hour (unloaded), similar results were found by Pashkevich et al. (2019) and All Lift (2021). According to information received from the staff, the maximum load carried per 5-ton forklift is about 2.8 tons and per 2.5-ton forklift was about 1.5 tons. The number of the different forklifts used was unknown, thus all 16 of the forklifts were modelled as 3.5 tonners (average between the two sizes). Also, the number of times the forklift loads material is unknown, therefore calculating the loaded fuel use was not possible. However, the forklifts do not operate at a constant load for the 16 hours of work time, thus, to account for the loaded portions, the higher fuel consumption value of 3.6 L hr^{-1} was used. To calculate the fuel consumed per month, the following values were used as in Table A-3.

Table A-3: Assumed values used to determine the forklift fuel used

Fuel consumption (L hr^{-1})	Operation (hr day^{-1} $forklift^{-1}$)	Days in month	Forklifts	Volume used (L $month^{-1}$)
3.6	16	30	16	27648
3.6	16	31	16	28569.6

The volume obtained was then summed for the years, averaged and multiplied by the allocation fraction for WLC for the entire mill as in Equation (4), and then lastly divided by the annual WLC production volume. The volume answer (in litres) was then multiplied by the density of diesel, 0.85 kg L^{-1}, and then multiplied by the HHV of 45.5 MJ kg^{-1}. This came to,

$$\text{Annual fuel consumption} = 336384\ \text{L} \tag{56}$$

$$\text{Annual WLC fuel consumption volume} = 336384\ \text{L} \times 51.7\% = 173911\ \text{L} \tag{57}$$

$$\text{Annual WLC fuel consumption mass} = 173911\ \text{L} \times 0.85\ \frac{kg}{L} = 147824\ \text{kg} \tag{58}$$

$$\text{Annual WLC fuel consumption energy} = 147824\ \text{kg} \times 45.5\ \frac{\text{MJ}}{kg} = 6740772\ \text{MJ} \tag{59}$$

Dividing the energy value by the annual production volume to obtain the energy in terms of the functional unit,

$$\text{Energy}_{Forklift,FU} = \frac{6740772\ \text{MJ}}{66270000\ kg} = 0{,}101716796\ \frac{MJ}{kg} \tag{60}$$

Validation: None since secondary data sources were used to calculate the consumption of the fuel.

A2.4. Coal

Calculation: The value for coal as supplied by the company represents the actual amount of coal used for the entire mill. This means that Equation (4) would have to be multiplied by the initial coal value. When supplying the data to EcoInvent, the value of coal was given as kg. In the SimaPro simulations, the value was given as MJ, since the energy dataset was created based on every MJ of energy produced. However, in the end, the results are the same. The calculation for coal was,

$$W_{coal,WLC} = W_{coal,Mill} \times 51.7\% \tag{61}$$

$$W_{coal,WLC} = 45387\ ton \times 51.7\% \tag{62}$$

$$W_{coal,WLC} = 23465\ ton \tag{63}$$

$$W_{coal,WLC,FU} = \frac{23465\ ton}{66270\ ton} = 0.354\ \frac{kg}{kg} \tag{64}$$

And the process of calculating the energy it was assumed that the boiler had an 80 % efficiency. The HHV value was supplied by the company that tests the coal burnt in the boiler.

$$E_{coal,WLC} = W_{coal,WLC} \times HHV \times 80\% \tag{65}$$

$$E_{coal,WLC} = 23465000\ kg \times 26.55\ \frac{MJ}{kg} \times 80\% \tag{66}$$

$$E_{coal,WLC} = 498396600\ MJ \tag{67}$$

$$E_{coal,WLC,FU} = \frac{498396600\ MJ}{66270000\ kg} = 7.52\ MJ \tag{68}$$

Validation: The mill produces around 371829 tons of steam in a year. The production of WLC uses about 192235 tons of steam per year. Using the mass of steam produced and knowing that the water enters the boiler at 50 °C, the energy required to produce steam can be calculated and then converted to kg of coal.

$$Q = m(C_{p,liquid}dT + H_{vap} + C_{p,vapour}dT) \tag{69}$$

$$C_{p,liquid} = 4.186\ \frac{kJ}{kgK} \tag{70}$$

$$H_{vap} = 2260\ \frac{KJ}{kg} \tag{71}$$

$$C_{p,vapour} = 1.872\ \frac{KJ}{kgK} \tag{72}$$

$$Q = [192235 \times 1000][4.186(100 - 50) + 2260 + 1.872(180 - 100)] \tag{73}$$

$$Q = 5{,}0492 \times 10^{11}\ kJ \tag{74}$$

The coal used had an average HHV value of 26.55 MJ kg^{-1}, this was then used to calculate the mass of coal required.

$$M_{coal} = \frac{\frac{Q}{\%\ Efficiency}}{HHV} \tag{75}$$

$$M_{coal} = \frac{\frac{5{,}0492 \times 10^{8}\ MJ}{80\ \%}}{26.55\ \frac{MJ}{kg}} \tag{76}$$

$$M_{coal} = 23772\ ton\ coal \tag{77}$$

This results in a difference of,

$$\% \, Difference = \frac{M_{coal} - W_{coal,WLC}}{W_{coal,WLC}} \times 100 \tag{78}$$

$$\% \, Difference = \frac{23772 - 23465}{23465} \times 100 \tag{79}$$

$$\% \, Difference = 1.3 \, \% \tag{80}$$

A3. WLC – Chemicals

A3.1 Mill processing line

Calculation: Like the fibres, the compositions were given specifically to the grade of WLC produced. Therefore, the chemicals %'s were multiplied by the production volume of each grade of WLC for the month, averaged, summed and then divided by the annual production volume of WLC on process line "PL 1" to obtain the masses per functional unit.

Validation: The chemicals used by mills across the world is significantly different and the compositions used, even of the most common chemicals, are based on the thickness of the grades produced, the thickness of the coats and the percentage of recycled fibre used. Validation was not as easy to perform even when using secondary sources. For example, this mill uses bleached mechanical fibre, which generally has high opacity and good printability and covers the recycled fibre, hiding even more of its grey hue. A European dataset supplied by EcoInvent uses no mechanical pulp, which means the only coat covering the recycled fibre is the sulphate pulp layer (which has a lower opacity) and it also means that more fillers and binders need to be used. By doing this alone, the coat on the European product would be thicker since the coat would need to cover the stronger grey undertone of the recycled fibre. Therefore, comparing datasets to validate the SA results would result in significant differences.

A3.2 Water treatment:

Calculation: The chemicals used to treat the water were based on the flow rate of the incoming water from all the processing lines on the mill. The masses of the chemicals were supplied as is by the company and represented the entire mill. Therefore, the masses of chemicals used were multiplied by Equation (4) to obtain the mass used per kg WLC produced, which was then divided by the annual production volume of WLC to get the values in terms of the functional unit.

Validation: No validation was done since the chemicals used added very little value by mass.

A3.3 Energy production - Water softening:

Calculation: The masses of chemicals used to soften the freshwater entering the boiler were given as is by the company.

Validation: No validation was done to check the values since their overall contribution to the mass balance was small.

A4. WLC – Transport

A4.1 Known distances:

Calculation: The distances of travel were known for the mechanical pulp – SA truck, chemical pulp, coal, reject plastics, and general waste. The information on the locations was supplied by the company. To calculate the kgkm mass distance, the mass of the product or waste was taken and divided by the annual production volume of WLC, which was then multiplied by the distance of the delivery.

A4.2 Unknown distances:

Calculation: For the other distances, assumptions had to be made to obtain a distance because of client–company confidentiality agreements. For mechanical pulp international, the distance of the truck was taken from the mill to the biggest port most likely to export the mechanical pulp bales overseas, from which again google maps was used to track its distance from the international port to the South African port of choice (as indicated by the company). For the recycled fibre, an average radius of 100 km was assumed from the recycling depots to the mill, with an average 25 km radius assumption for transport from industries and households to the depots. For the chemicals used in the process; an average 200 km transport radius was assumed. For the diesel purchased and used in the forklifts, the average distance was assumed to be 150 km. The distance from the mill to the clients is not known (to protect the customers' information), however, the province and country were known. Using this information, the distance from the mill to the capital city of the province/country was used as the average distance transported. The ash that is sent to the cement manufacturers was assumed to be within a 100 km radius of the company.

Validation: Due to the lack of concrete information for unknown transport, no validation was done. However, due to the many assumptions made, the data for known and unknown transport distances were aggregated separately, with a sensitivity analysis conducted on the unknown distances whereby the transport value of kgkm was increased significantly.

Appendix B – Data validation (WLC Outputs)

In this section, the mass and energy flow that exit the mill are validated by using mass and energy balances from the primary data collected onsite or from secondary data sources. This was done to ensure that there were no:

1. Double counting of the data,
2. Missing data
3. Calculations and readings were correct

B1. Jumbo Reels

Calculation: The jumbo reels are the large rolls of WLC that are produced by "PL 1". It represents the functional unit of the LCA.

B2. Screened waste

Calculation: The mass of screened waste was supplied by the company. The screened waste represents the waste removed from the sludge screening process. It includes particles of sand and stone, plastic, glass and small metal shards and is disposed of in landfills. The screened waste represented the entire mill, and as a result Equation (4) had to be used to determine how much waste was generated by the production of WLC.

$$W_{\mathrm{Screened,WLC}} = W_{\mathrm{Screened,Total}} \times 51.7\% \tag{81}$$

$$W_{\mathrm{Screened,WLC}} = 9770\ \mathrm{tons} \times 51.7\% \tag{82}$$

$$W_{\mathrm{Screened,WLC}} = 5051\ \mathrm{tons} \tag{83}$$

Taking this value and dividing it by the annual production volume of WLC, the flow of screened waste concerning the functional unit can be determined,

$$W_{\mathrm{Screened,WLC,FU}} = \frac{5051\ tons}{66270\ tons} \tag{84}$$

$$W_{\mathrm{Screened,WLC,FU}} = 0.0762\ \frac{\mathrm{kg}}{kg\ WLC} \tag{85}$$

Validation: There is no way to validate this information since wastes contained in the recycled fibre vary based on the source of the fibre (where it was collected and whether any prescreening took place) and the type of recycled fibre, whether paper, newspaper, carton board or corrugated boxboard.

B3. Effluent

Calculation: Effluent represents the flow of wastewater, after on-site treatment, into the municipal wastewater system. The volume of effluent was supplied by the mill (a meter was installed to measure the flow) and again represents the effluent of the entire mill. Using Equation (4), the effluent associated with WLC can be calculated,

$$V_{Effluent,WLC} = W_{Effluent} \times 51.7\% \tag{86}$$

$$V_{Effluent,WLC} = 734221\ kL \times 51.7\% \tag{87}$$

$$V_{Effluent,WLC} = 379592\ kL \tag{88}$$

Then to calculate the value per functional unit,

$$V_{Effluent,WLC,FU} = \frac{W_{Effluent,WLC}}{WLC\ total} \tag{89}$$

$$V_{Effluent,WLC,FU} = \frac{379592\ kL}{66270\ ton} \tag{90}$$

$$V_{Effluent,WLC,FU} = 5.73\ \frac{L}{kg\ WLC} \tag{91}$$

Validation: The process engineers on the mill stated that the average recycled-to-discharge ratio is around 80:20. This means that 20 % becomes effluent discharged to the municipal wastewater lines. Comparing the flowrates of effluent to recycling,

$$Ratio_{Effluent} = \frac{W_{Effluent}}{W_{Recyled}} \times 100 \tag{92}$$

$$Ratio_{Effluent} = \frac{5.73}{32.95} \times 100 \tag{93}$$

$$Ratio_{Effluent} = 17.38\ \% \tag{94}$$

Which is slightly smaller, but is better since the effluent discharge is smaller, which means that more water is recycled as opposed to fresh water being used.

B4. Sludge

Calculation: Mass was supplied by the company. Represented the sludge from water treatment of all process lines in the mill.

$$M_{Sludge,WLC,FU} = \frac{W_{Sludge} \times 51.7\%}{WLC\ total} \tag{95}$$

$$M_{Sludge,WLC,FU} = \frac{6584\ ton \times 51.7\%}{66270\ ton\ WLC} \tag{96}$$

$$M_{Sludge,WLC,FU} = \frac{3391\ ton}{66270\ ton\ WLC} \tag{97}$$

$$M_{Sludge,WLC,FU} = 0.0511\frac{kg}{kg\ WLC} \tag{98}$$

Validation: No primary validation was done due to a lack of information for effective mass balance calculation. No secondary validation was conducted since the source of the fibre significantly differs from process to process and mill to mill.

B5. Ash

Calculation: Mass was supplied by the company. Represented the ash from coal combustion for the entire mill's use. The value was calculated as follows,

$$M_{Ash,WLC,FU} = \frac{W_{Ash} \times 51.7\%}{WLC\ total} \tag{99}$$

$$M_{Ash,WLC,FU} = \frac{10191\ ton \times 51.7\%}{66270\ ton\ WLC} \tag{100}$$

$$M_{Ash,WLC,FU} = \frac{5645\ ton}{66270\ ton\ WLC} \tag{101}$$

$$M_{Ash,WLC,FU} = 0.0852\frac{kg}{kg\ WLC} \tag{102}$$

Validation: According to a report by a company that tests the coal used in the boiler, the coal should contain 14.3 wt% ash on an air-dried basis. However, by taking the annual averages, the ash to coal mass came to,

$$Ash\% = \frac{M_{Ash,WLC}}{M_{Coal,WLC}} \times 100 \tag{103}$$

$$Ash\% = \frac{0.0852}{0.354} \times 100 \tag{104}$$

$$Ash\% = 24\ \% \tag{105}$$

This value is quite a lot higher than the 14.3 % lab-scale value. There are two primary reasons for this offset, the first being the efficiency of the boilers and the second the size of the coal. The lab-scale test results consider complete combustion (100 %) of the coal, which then resulted in a 14.3 % ash composition. However, the boilers have an efficiency ranging from 75 – 80 %, which could mean that the burnout of the coal is incomplete, resulting in higher ash content. The second reason is due to the size variations of the coal. A report on the analysis of the coal showed that 16.8 % of the coal on average was larger than the desired size, which could result in unburnt coal and therefore also increase the mass of the ash.

B6. Air

B6.1 Steam:

Calculation: The calculation step was simultaneously a validation and calculation step. The value of the water lost as steam during the drying phase was unknown. By using the water balance over the process line, the volume of the steam could be calculated. The water in the process line consists of recycled water, freshwater, water that exits the treatment process (used), water lost as steam during drying and the water left in the WLC once it was produced.

$$W_{Fresh} + W_{Recyled} = W_{Used} + W_{Steam} + W_{WLC} \tag{106}$$

$$7.255 + 32.956 = 38.684 + W_{Steam} + 0.04 \tag{107}$$

$$W_{Steam} = 1.487\ l \tag{108}$$

The value is slightly higher than the results given by Ghosh (2011), who found that the average water removal is around 1.1 – 1.3 kg. However, the average was taken to produce WLC which included a grammage range of 250 – 500 gsm, and the thicker the grade the more water must be removed during drying, thus the steam removed for the average reading is higher.

B6.2 Emissions

Calculation: The emissions that were not supplied by the mill's annual testing were extrapolated from a boiler dataset in the EcoInvent database. The boiler used a similar coal grade (bituminous) with a slightly higher HHV value of 28.62 MJ kg^{-1} (the mill uses a

26.55 MJ kg^{-1}) with also an 80 % boiler efficiency. The results were extrapolated based on the mass of emissions per kg of coal.

$$Emission_{SA,FU,General} = \frac{Emission_{EU}\ \frac{kg}{MJ}}{Coal_{EU}\ \frac{kg}{MJ}} \times Coal_{SA}\ \frac{kg}{kg\ WLC} \tag{109}$$

$$Emission_{SA,FU,CO2} = \frac{0.114375\ \ \frac{kg\ CO_2}{MJ}}{0.04325\ \frac{kg}{MJ}} \times 0.358\,\frac{kg}{kg\ WLC} \tag{110}$$

$$Emission_{SA,FU,CO2} = 0.9467\ \frac{kg\ CO_2}{kg\ WLC} \tag{111}$$

With the mass value of $Coal_{SA}$ and $Coal_{EU}$ remaining constant (specific mass to energy ratio), the only changing variable was the mass of the emissions produced from coal to coal. Thus, being able to use the equations above to extrapolate the European emissions to South African emissions. This was applied to $CH_{4\ (fossil)}$, heavy metals, water and all the other emission. Table B-1 indicates the values obtained for the emissions representing South Africa extrapolated from the European dataset.

Table B-1: Emissions for South African coal-fired boiler extrapolated from the Europe dataset

Product	Unit	Value
Aluminium	kg	1.03×10^{-4}
Antimony	kg	1.52×10^{-8}
Arsenic	kg	2.42×10^{-7}
Barium	kg	1.21×10^{-6}
Benzene	kg	4.79×10^{-6}
Benzo(a)pyrene	kg	9.59×10^{-11}
Beryllium	kg	1.21×10^{-8}
Boron	kg	4.55×10^{-6}
Bromine	kg	9.13×10^{-8}
Cadmium	kg	1.52×10^{-8}
Calcium	kg	1.21×10^{-5}
Chromium	kg	2.16×10^{-7}
Chromium VI	kg	2.67×10^{-8}
Cobalt	kg	3.03×10^{-8}
Copper	kg	1.60×10^{-7}
Dinitrogen monoxide	kg	9.59×10^{-6}
Dioxins. measured as 2.3.7.8-tetrachlorodibenzo-p-dioxin	kg	1.92×10^{-13}
Ethane	kg	1.44×10^{-5}

Product	Unit	Value
Ethene	kg	2.88×10^{-5}
Ethyne	kg	4.79×10^{-6}
Formaldehyde	kg	7.67×10^{-7}
Hydrocarbons. aliphatic. alkanes. unspecified	kg	4.79×10^{-6}
Hydrocarbons. aliphatic. unsaturated	kg	4.79×10^{-6}
Hydrogen chloride	kg	3.88×10^{-4}
Hydrogen fluoride	kg	1.21×10^{-5}
Iodine	kg	1.10×10^{-7}
Iron	kg	4.24×10^{-5}
Lead	kg	7.27×10^{-7}
Lead-210	kBq	4.46×10^{-4}
Magnesium	kg	3.64×10^{-5}
Manganese	kg	2.12×10^{-7}
Mercury	kg	2.72×10^{-8}
Methane. fossil	kg	9.59×10^{-5}
Molybdenum	kg	4.55×10^{-8}
Nickel	kg	1.83×10^{-7}
NMVOC. non-methane volatile organic compounds. unspecified origin	kg	1.65×10^{-5}
Phosphorus	kg	6.06×10^{-7}
Polonium-210	kBq	8.15×10^{-4}
Potassium	kg	1.21×10^{-5}
Potassium-40	kBq	1.30×10^{-4}
Propane	kg	9.59×10^{-6}
Propene	kg	4.79×10^{-6}
Radium-226	kBq	1.15×10^{-4}
Radium-228	kBq	6.24×10^{-4}
Radon-220	kBq	9.59×10^{-6}
Radon-222	kBq	9.59×10^{-6}
Scandium	kg	1.21×10^{-8}
Selenium	kg	9.13×10^{-8}
Silicon	kg	1.52×10^{-4}
Sodium	kg	6.06×10^{-6}
Strontium	kg	1.83×10^{-6}
Thallium	kg	1.52×10^{-8}
Thorium	kg	1.83×10^{-8}
Thorium-228	kBq	5.28×10^{-5}
Thorium-232	kBq	3.36×10^{-5}
Tin	kg	6.06×10^{-9}
Titanium	kg	3.64×10^{-6}
Toluene	kg	9.59×10^{-7}
Uranium	kg	2.42×10^{-8}
Uranium-238	kBq	9.59×10^{-5}
Vanadium	kg	3.64×10^{-7}
Water	m3	1.08×10^{-5}
Xylene	kg	9.59×10^{-7}
Zinc	kg	3.03×10^{-8}

Appendix C – Data validation (Forestry and Pulping)

Similar to Appendix A and Appendix B, this section was used to validate the information used for forestry and pulping. The pulping mills and forestry companies could not supply all the data requested, therefore some of the information in this section is focused on calculating the data instead of validating it.

Since the data from the respective forestry and milling companies were given only as requested (recycled streams and additional flows were unknown), it was not possible to validate the information using primary data, therefore secondary data was used to validate the values.

C1. Forestry

C1.1 Energy:

Calculation: One of the EcoInvent requirements for the forestry dataset is to supply the potential energy per functional unit of wood. The energy of the wood was calculated using secondary sources. The energy value of 19 MJ kg^{-1} was obtained from Araújo et al. (2018) with similar results obtained by Paoloni et al.. (2016), Stanturf et al. (2013), and Telmo & Lousada (2011). Using the average density of Eucalyptus at 680 kg m^3 (Forestry Economics Services CC. 2019) the HHV value could be calculated per cubic meter of wood.

C1.2 Potential carbon content:

Calculation: Potential carbon content contained per cubic meter of wood was calculated from secondary sources. According to Bhat & Dhamodaran (1990), the basic (dry) density of the *Eucalyptus grandis* trunk is around 495 kg m^{-3}. An article by Viera & Rodríguez-Soalleiro (2019) showed that the carbon content of the trunk was 49.5 % (dry basis). Based on the dry density of the trunk, the mass of carbon (per m^3 wood) is 245 kg carbon. This converts to a total mass of CO_2 of 898.4 kg. According to Zanuncio et al. (2013), the average moisture content of eucalyptus ranges from 43 – 63 %, therefore taking the average of 53 %, the green density of eucalyptus wood is around 1053 kg m^{-3}.

C1.3 Land Occupation-Forestry:

Calculation**:** The report by Forestry Economics Services CC (2019). represents South Africa's annual commercial space and wood consumption. The total area used only for the growth of eucalyptus for pulpwood in 2019 was around 458 553 ha with a total of 8 084 142 m^3 of eucalyptus harvested and sold as pulpwood. The total land area represents the eucalyptus in all stages of its life. this means that the forest area is divided into 9 stages (a 9-year rotation period). 1st year represents new seedlings being planted and the 9th year represents mature trees being harvested. This means that the volume of wood was harvested from a ninth of the total eucalyptus forest area. With this information, the value of "Occupation. forest. intensive" in SimaPro could be calculated.

$$Area_{Harvested} = \frac{\frac{Area}{rotation\ period}}{Harvest\ volume} \tag{112}$$

$$Area_{Harvested} = \frac{\frac{458\ 553\ ha}{9\ years}}{8\ 084\ 142\ \frac{m^3\ wood}{year}} \times \frac{10\ 000\ m^2}{ha} \tag{113}$$

$$Area_{Harvested} = 63\ \frac{m^2}{m^3\ wood} \tag{114}$$

However. the same area of land is occupied for 9 years. making it unusable for any other activity. Thus. the area of land must be multiplied by the 9 years to account for land use during the 9-year rotation period. hence the rotation area per volume of wood harvested is.

$$Area_{Rotation} = 63\ \frac{m^2}{m^3\ wood} \times 9\ years \tag{115}$$

$$Area_{Rotation} = 567\ \frac{m^2 a}{m^3\ wood} \tag{116}$$

Where $m^2.a$ represents the area of land occupied for the 9-year rotation period.

C1.4 Land Occupation-Traffic area. rail/road embankment

Calculation: The details for road occupation were sourced from Immelman et al. (2004). They indicated that there are a lot of factors involved in determining the width and density of roads required based on the topography of the land. soil type. hauling weight and other variables. However. the details of the condition of the forest and surrounding areas are unknown. thus the average of the results was taken. The average road density of 37 m ha^{-1} was used with an average road width of 8 m and gravel thickness of 200 mm with a 6 m wide gravel spread.

Using this information. the “Occupation. traffic area. rail/road embankment” could be calculated.

$$Area_{Traffic} = Area_{Rotation} \times Road_{density} \times Road_{width} \tag{117}$$

$$Area_{Traffic} = \frac{567\ m^2a}{10\ 000\ \frac{m^2}{ha}} \times 37\ \frac{m}{ha} \times 8\ m \tag{118}$$

$$Area_{Traffic} = 16.78\ \frac{m^2a}{m^3\ wood} \tag{119}$$

Taking the width and thickness of the gravel layer.

$$Volume_{Gravel} = Area_{Rotation} \times Road_{density} \times Gravel_{width} \times Gravel_{Thickness} \tag{120}$$

$$Volume_{Gravel} = \frac{567\ m^2a}{10\ 000\ \frac{m^2}{ha} \times 9\ years} \times 37\ \frac{m}{ha} \times 6\ m \times 0.2\ m \tag{121}$$

$$Volume_{Gravel} = 0.279\ \frac{m^3}{m^3\ wood} \tag{122}$$

$$\rho_{Gravel} = 1680\ \frac{kg}{m^3} \tag{123}$$

$$Mass_{Gravel} = 470\ \frac{kg}{m^3\ wood} \tag{124}$$

However. this is the mass used to construct a new gravel road. The actual amount to just maintain the road was assumed to be 10 % of the value given. at 47 kg gravel used for maintenance.

C1.5 Transformation to and from the forest:

Calculation: The amount of land transformed from forest to other uses (such as agriculture or other tree species forests) and the afforestation of eucalyptus forests were sourced by Forestry Economics Services CC (2019). The report indicated that 2034 ha of eucalyptus land is transformed for other uses and 173 ha of land was afforested to eucalyptus forest. The area per volume of harvested wood was calculated as follows.

$$Area_{Forest\ Lost} = \frac{Hectares_{Lost}}{Harvest\ volume} \times \frac{10\ 000\ m^2}{ha} \tag{125}$$

$$Area_{Forest\ Lost} = \frac{2034\ ha}{8\ 084\ 142\ \frac{m^3\ wood}{year}} \times \frac{10\ 000\ m^2}{ha} \tag{126}$$

$$Area_{Forest\ Lost} = 2.516\ \frac{m^2}{m^3\ wood} \tag{127}$$

The 2.516 $m^2\ m^{-3}$ of wood is the amount of land lost to other activities per cubic meter of wood harvested in a year. The same equation was used to calculate the afforestation area of eucalyptus per volume of wood harvested.

C1.6 Transformation to and from Traffic area. rail/road embankment:

<u>Calculation</u>: This data was not available in any data source found on any search portal. The value given in the table was assumed to be proportional to the ratio of forest to road and then multiplied by the respective forest lost and afforestation values as described in the equations.

$$Ratio_{Road\ lost} = \frac{Area_{road\ lost}}{Area_{Rotation}} \tag{128}$$

$$Ratio_{Road\ lost} = \frac{16.78\ m^2 a\ Road}{567\ m^2 a\ Forest} \tag{129}$$

$$Ratio_{Road\ lost} = 0.0296\ \frac{m^2 a\ Road}{m^2 a\ Forest} \tag{130}$$

Using this ratio. the value of the traffic changing from roads and changing to roads was calculated using the product of the ratio and transformation from and to the forest.

$$From_{Traffic} = Ratio_{Road\ lost} \times\ Area_{Forest\ Lost} \tag{131}$$

$$From_{Traffic} = 0.0296\ \times\ 2.516\ \frac{m^2\ Forest\ lost}{m^3\ wood} \tag{132}$$

$$From_{Traffic} = 0.0745\ \frac{m^2\ Road\ Lost}{m^3\ wood} \tag{133}$$

The same steps were followed for the gain of roads to the newly afforested areas.

C1.7 Materials/Fuels and Electricity/Heat:

<u>Calculation</u>: No data was available for these topics. The values were adapted from the Thailand dataset for eucalyptus forestry but were kept the same since the harvesting time and oil used depends on the amount of wood harvested and both the South African dataset and the Thailand

dataset were modelled per cubic meter of wood harvested. The only change made was the use of diesel. since the commercial area per rotation period was larger for the same volume of wood harvested in South Africa as opposed to the smaller area in Thailand. the volume of diesel required was increased by 10 %.

C2. Pulping

In EcoInvent there was only one dataset available for the validation of bleached eucalyptus kraft pulp. a Latin American dataset. Apart from the minor changes in the technologies used by the South African and Latin American industries. the major differences come from the sources of electricity and energy production. To validate the flow of mass through the process. the energy sources were removed to only validate mass flows. Table C-1Table C-1 indicates the difference between the mass flows of material entering and exiting the two processes (raw materials. chemicals and wastes). Most of the mass flows with reference flow of 1 kg bleached pulp produced are all within the same decimal factor. indicating that the differences are quite small.

Table C-1: Environmental impact of pulp production for South Africa and Latin America without energy and electricity consideration

Impact category	Unit	Latin America Pulp	South Africa Pulp
Global warming	kg CO_2 eq	0.243	0.166
Ozone depletion	kg CFC11 eq	1.68E-07	3.56E-07
Ozone formation	kg NO_x eq	0.000775	0.00105
Terrestrial acidification	kg SO_2 eq	0.000936	0.00087
Freshwater eutrophication	kg P eq	0.000602	9.63E-05
Freshwater ecotoxicity	kg 1.4-DCB	0.0178	0.0068

Validating energy and electricity generation is more complex since most of the mills obtain energy from different sources such as self-generation or their local governing bodies. obtain energy from chemical recovery and/or fuel sources such as natural gas. biomass and coal. Meaning that it was not possible to validate the energy and electricity consumed without increased uncertainty in the results.

Appendix D – Impact assessment of WLC production for all ReCiPe 2016 impact categories

In the "Impact assessment" section of the results, only 6 categories were studied, namely global warming, freshwater ecotoxicity, terrestrial acidification, ozone depletion, ozone formation and freshwater eutrophication. The ReCiPe 2016 impact method conducts the LCA for 18 impact categories. This section gives the impact of WLC production for all 18 categories (Table D-1).

Table D-1: Complete impact assessment for WLC production.

Impact category	Unit	Total
Global warming	kg CO_2 eq	2.46
Stratospheric ozone depletion	kg CFC11 eq	1.33E-06
Ionizing radiation	kBq Co-60 eq	0.0654
Ozone formation, Human health	kg NO_x eq	0.00940
Fine particulate matter formation	kg PM2.5 eq	0.00595
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00946
Terrestrial acidification	kg SO_2 eq	0.0186
Freshwater eutrophication	kg P eq	0.00166
Marine eutrophication	kg N eq	0.000178
Terrestrial ecotoxicity	kg 1,4-DCB	4.08
Freshwater ecotoxicity	kg 1,4-DCB	0.0605
Marine ecotoxicity	kg 1,4-DCB	0.0835
Human carcinogenic toxicity	kg 1,4-DCB	0.138
Human non-carcinogenic toxicity	kg 1,4-DCB	2.31
Land use	m^2a crop eq	0.293
Mineral resource scarcity	kg Cu eq	0.00168
Fossil resource scarcity	kg oil eq	0.693
Water consumption	m^3	0.0213

Appendix E – Monte Carlo analysis figures for the six selected impact categories

The SimaPro 2016 Monte Carlo analysis information in the "Uncertainty analysis" section only depicted the mean values and standard deviations (error bars) for each impact category. The figures in this section represent the Monte Carlo simulations constructed by SimaPro 2016. The simulation was conducted using 1000 intervals and a 95 % confidence interval. The solid lines represent the 2.5, 50 (mean) and 97.5 percentiles (left to right) and the dashed line represents the median.

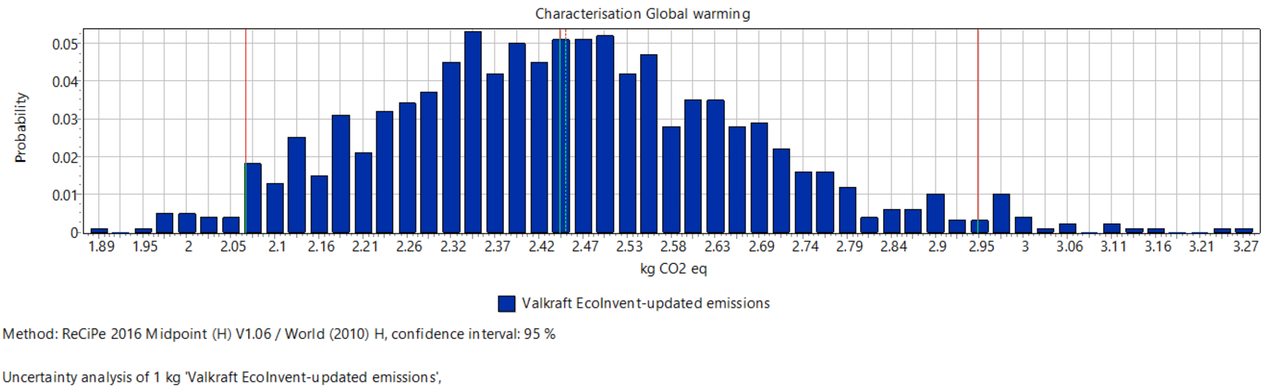

Figure E-1: Monte Carlo analysis graph for the global warming impact category.

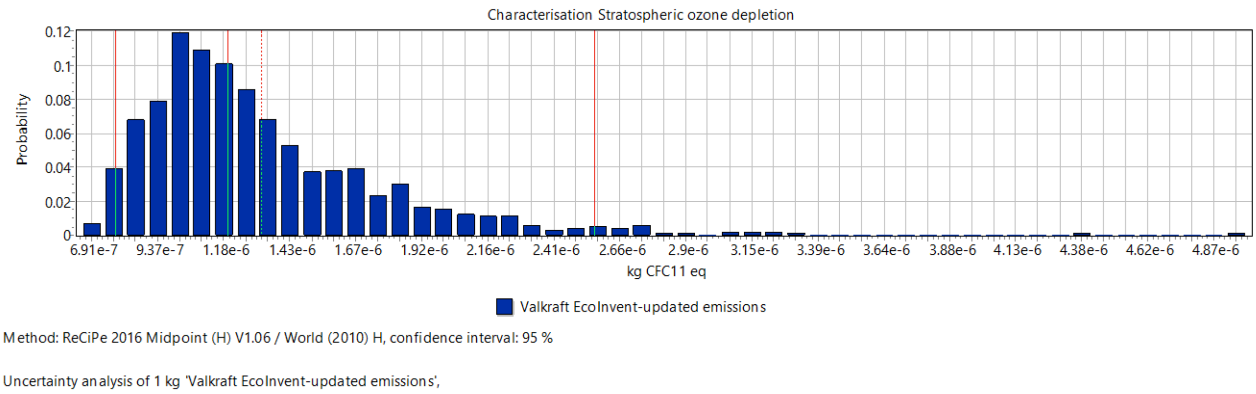

Figure E-2: Monte Carlo analysis graph for the ozone depletion impact category.

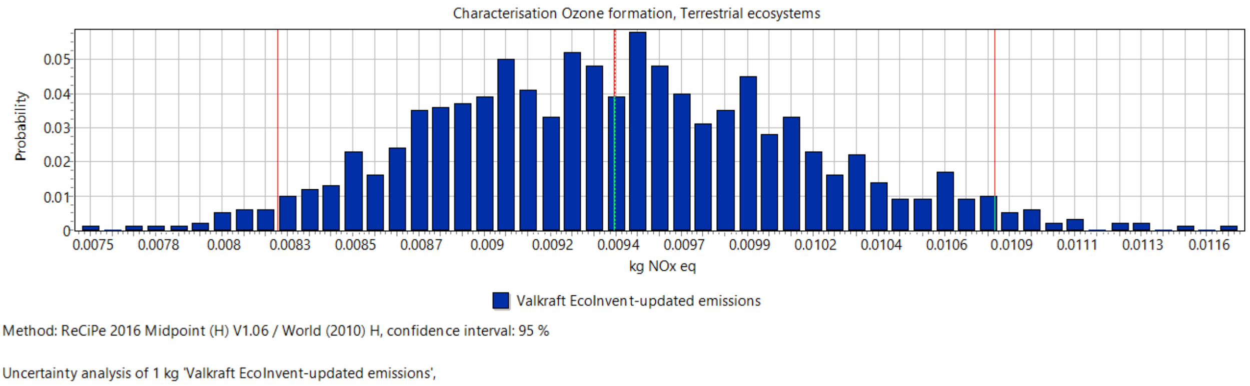

Figure E-3: Monte Carlo analysis graph for the ozone formation impact category.

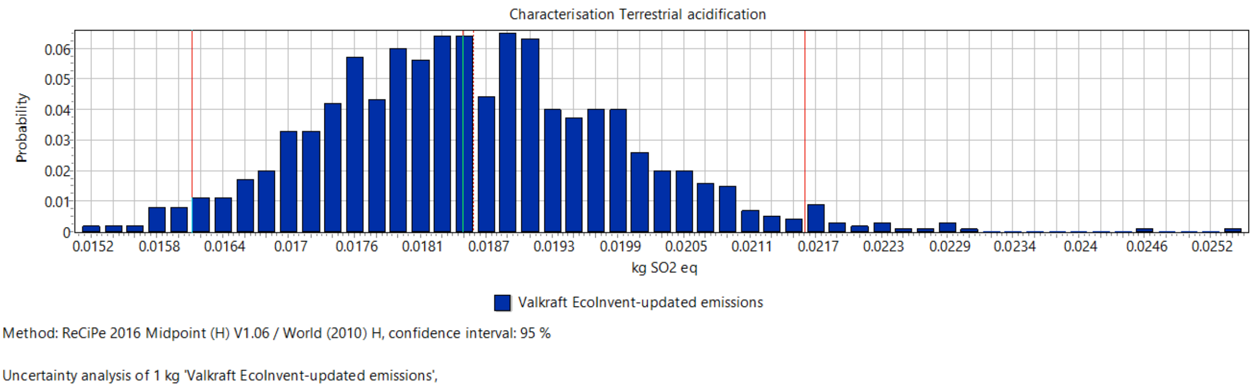

Figure E-4: Monte Carlo analysis graph for the terrestrial acidification impact category.

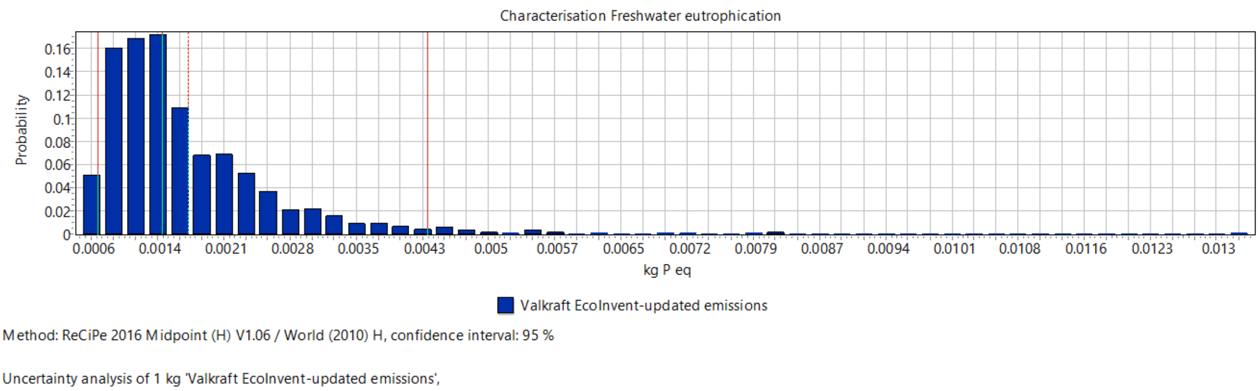

Figure E-5: Monte Carlo analysis graph for the freshwater eutrophication impact category.

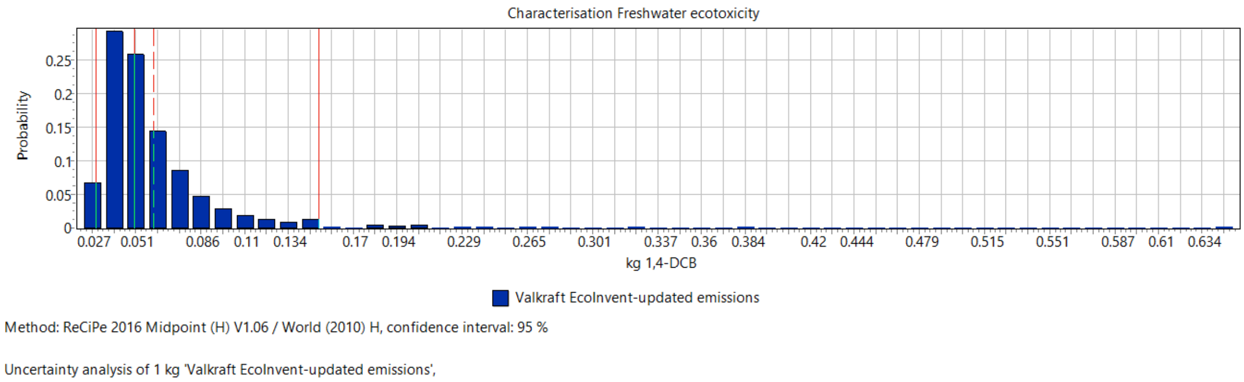

Figure E-6: Monte Carlo analysis graph for the freshwater ecotoxicity impact category.

Appendix F – PV solar power calculations

In the calculations, the 400-Watt PV panels were used, and a single 400-Watt panel covers a 2 m^2 area. Solar power cells also have an efficiency of around 80 %, accounting for dust and other electricity-generating inhibiting variables. Based on this information, the following calculations were done,

$$N_{panels} = \frac{8 - hour\ power\ supply}{\frac{Solar\ power\ supply \times 80\%}{panel}} \tag{134}$$

$$N_{panels} = \frac{144444\ kW}{\frac{0.4\ kW \times 8 \times 80\%}{panel}} \tag{135}$$

$$N_{panels} = 56424\ panels \tag{136}$$

A panel has an area of 2 m^2, the total surface area required for mounting the panels would be

$$SA_{panels} = N_{panels} \times A_{panel} \tag{137}$$

$$SA_{panel} = 54642\ panels\ \times \frac{2\ m^2}{panel} \tag{138}$$

$$SA_{panels} = 112848\ m^2 \tag{139}$$

This means that a surface area of 112 848 m^2 would be required to generate enough solar power to run the mill off the grid for 8 hours.

If the mill wanted to go completely go off the national grid and become self-sufficient, it would have to generate 433 333 kWh per day in those 8 hours of sunshine, with the remainder of energy stored in battery systems for use when the sun is not shining. Following the same calculation procedure as above,

$$N_{panels,complete} = 169271\ panels \tag{140}$$

$$SA_{panels,complete} = 338542\ m^2 \tag{141}$$

These calculations were based on 8 hours of full sunshine assuming peak energy absorption. With overcast conditions and reduced sunshine in winter, the electricity generation would be less and require more solar panels to account for those losses.

Using Google Earth, it was possible to calculate the available rooftop space. The available rooftop surface was calculated by either considering a flat rectangular shape if the pitch angle was less than 15 ° and if the roof pitch was 15 ° or more then the horizontal width of the roof was used to calculate the hypotenuse of the triangle (Figure F-1). This was then used to calculate the surface area of the rectangle by multiplying the width with the hypothenuse length of the roof indicated by the "x" on the figure.

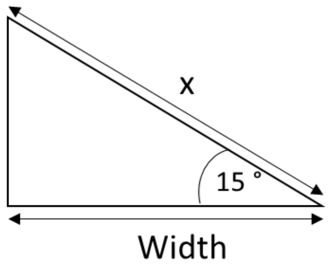

Figure F-1: Calculation of variable x (hypothenuse) using the width and pitch of the roof

Based on these calculations, the total available rooftop surface area for solar panel installation came to,

$$A_{roof} = 57551\ m^2 \tag{142}$$

This means that the total number of panels,

$$N_{panels} = \frac{SA_{panels}}{A_{panel}} \tag{143}$$

$$N_{panels} = \frac{57551}{2} \tag{144}$$

$$N_{panels} = 28775\ panels \tag{145}$$

However, the 8-hour period was a gross overestimation, with actual effective solar power generation ranging from 4.1 – 6.3 hours a day (Climatebiz, 2022) for South Africa, therefore using the 6 hours of effective sunshine a day is more accurate. The electricity generation possible is,

$$Power = N_{panels} \times \frac{Solar\ power\ supply \times 80\%}{panel} \tag{146}$$

$$Power = 28775\ panel \times \frac{0.4\ kW \times 6\ \frac{hr}{day} \times 80\%}{panel} = 55248\ kW \quad (147)$$

The total power supply of 55248 kW is in direct current (DC), assuming a 1.1 DC to AC power conversion, the actual AC power supplied is,

$$AC_{Power} = \frac{DC_{Power}}{1.1} \quad (148)$$

$$AC_{Power} = \frac{55248\ \frac{kWh}{day}}{1.1} \quad (149)$$

$$AC_{Power} = 50225\ \frac{kWh}{day} \quad (150)$$

$$Power\ supplied = \frac{50225\ kWh}{433\ 333\ kWh} \times 100\% = 11.6\ \% \quad (151)$$

This means that the mill can substitute around 11.6 % of its municipal electricity with PV solar power.