Carbon Flow Analysis of the South African Paper Converting, Paper Recycling and End User Stage of Paper.

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I Jayanth Ramlall declare that:

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Abstract

As a global citizen, South Africa is committed to contributing to greenhouse gas emissions mitigation. In an attempt to force industries to become more energy efficient and reduce their greenhouse gas emissions, the National Treasury has implemented a carbon tax. This would put the already pressurised pulp and paper industry under more economical pressure.

The aim of this study was to track the paper carbon flows and to determine the fate of the lignocellulosic carbon as it flows through the paper conversion, recycling and end user phases for the calendar year of 2011. This study forms part of a series of five projects which aim at providing a complete carbon flow analysis for the entire forestry products sector.

A mass balance of all paper flows in South Africa was developed and the paper flows were then converted into carbon flows. Data was collected from various stakeholders who include Paper Manufacturers Association of South Africa, South African Revenue Service, Paper Recycling Association of South Africa and Statistics South Africa. Methane emissions from landfill were determined using the Intergovernmental Panel on Climate Change guidelines on greenhouse gas emissions from landfill. The mass balance was also subjected to three scenarios which looked at the possibility of completely recycling all the paper available in the country and using it for paper production. The second scenario looked at possibility of recycling all the paper available and first satisfying all the paper machines that require waste paper feed stock and using the left over portion for electricity generation. The third scenario looked at achieving a maximum recovery rate of 65 % of waste paper and a production increase at the recycled paper mills.

Libraries and storage locked up 299 780 tonnes of carbon per year. Recycling had also shown the possibility of locking up carbon in the stream itself. Each year, around 416 657 tonnes of carbon is recycled. 61.7 % of the recovered paper was paperboard with the largest portion being old corrugated containers. It was estimated that 204 958 tonnes of carbon was sent to landfill and a portion of this decomposed to form 207 847 tonnes CO_2eq of methane.

The first scenario indicated that the possible board production from being able to achieve 100 % recovery of all available recovered paper would yield 1.027 million tonnes of board. The maximum tissue production possible from 100 % recovery of all recycled material is 357 524 tonnes. However, the production capacity is limited to 763 000 tonnes of board and 201 000 tonnes of tissue. Scenario two indicates that it would be possible to produce 1.1 TWh

of electricity per year by the combustion of the recovered paper that remains after satisfying the paper machine requirements at a 100 % recovery rate. The third scenario indicates that increasing production and replacement of bagasse with recycled fibre would result in a shortfall of 145 545 tonnes of recovered paper for paper production by the year 2020.

The three largest carbon sinks that were identified are the recycling stream, libraries and storage and landfill. Recycling preserves 34 % of the total carbon input into the system. Old corrugated containers were determined to be the largest portion in the recycle stream. Libraries and storage locked up 23 % of the total carbon input while landfill contributed 15 % carbon lockup. Corrugated containers are the most popular grade in the packaging industry and the most viable grade for carbon lockup. It was also found that every tonne of paper burnt for electricity generation has the potential greenhouse gas mitigation effect of 2.04 tonnes CO_2eq provided that the original virgin fibre to produce the paper was sourced from a well-managed, certified forest.

It was concluded that paper products have the potential to lock up carbon. This would aid in greenhouse gas mitigation. It is recommended that the industry be considered for concession due to the carbon offsets offered in the final products. It is also recommended that feasibility studies be conducted around the possibility of using recovered paper for electricity generation. A study should also be conducted to assess the possibility of large scale recycling of paper and other lignocellulosic material at landfills.

The industry should also look into the use of other fibre sources due to the predicted waste paper shortages forecasted in the near future.

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List of abbreviations

AD – Aerobic decomposition.

AAD – Anaerobic decomposition.

BOD – Biological oxygen demand.

COD – Chemical oxygen demand.

CO_2eq – Carbon dioxide equivalent.

CSIR – Council of Scientific and Industrial Research.

DEA – Department of Environmental Affairs.

DNT – Department of National Treasury.

DWAF – Department of Water Affairs.

GHG – Greenhouse gas.

GSM/gsm – Grams per square meter (g/m^2).

IPCC – Intergovernmental Panel on Climate Change.

LCA – Life cycle analysis.

LFG – Landfill gas.

MFA – Material flow analysis.

OCC – Old Corrugated Containers.

PAMSA – Paper Manufacturers Association of South Africa.

PRASA – Paper Recycling Association of South Africa.

SARS – South African Revenue Service.

Glossary

Aerobic decomposition – Microbiological decomposition in the presence of oxygen.

Anaerobic decomposition – Microbiological decomposition in the absence of oxygen.

Anthroposphere – It is the part of the environment that has changed through human activity or human habitation.

Bagasse – Sugar cane residue.

Broke – Paper or board that is discarded at any stage during its manufacture and is usually repulped.

Carbon offsets – The absorption of carbon dioxide or other greenhouse gases from the atmosphere in order to compensate for an emission made elsewhere.

Carbon sequestration – It is the removal and storage of carbon dioxide from the atmosphere and held in a solid or liquid form.

Carbon sinks – It is a reservoir that holds carbon dioxide from the atmosphere for an indefinite amount of time.

Carbon tax – Taxation system on greenhouse gas emissions. It is measured in carbon dioxide equivalent.

Converter – A company which processes paper to produce end products such as boxes.

Global warming – It is the gradual increase in the earth's atmospheric and oceanic temperatures.

Landfill – site for the disposal of waste material by means of burial.

Lignocellulosic – refers to plant biomass that is composed of cellulose, hemicellulose, and lignin

Methanogenic microorganisms – Microorganisms that produce methane.

Out-throws – These are all papers that are in such a condition that it is unsuitable as a raw material for the recovered paper grade specified.

Post-consumer waste – Recyclable material that has gone through to the consumer and is thereafter recycled after disposal.

Pre-consumer waste – Recyclable material after manufacture that does not makes its way to the consumer but instead goes for recycling. This is usually spoilage and offcuts.

Secondary packaging material – It is the outer layer of packaging intended to protect the product and the primary packaging. Secondary packaging includes cardboard boxes and cartons.

Woodfree paper – Paper that contains less than 10 % mechanical pulp.

Chapter 1: Introduction

This chapter aims at providing the reader with a brief outline of a Material Flow Analysis and the relevance it has to the paper recycling sector in South Africa. The reader shall also gain an understanding of the general framework of this study and the problem will be introduced.

1.1. Material flow analysis

A material flow analysis (MFA) is a systematic accounting approach to assess the stocks and flows of materials within a system in a defined geographic space and time (Brunner and Rechberger, 2005). Figure 1.1 shows a generic flow of materials though the commercial life cycle. A detailed complete MFA would look at the analysis of process chains which would include harvesting or extraction, chemical transformation, manufacturing or processing, consumption, recycling and disposal (Ayres and Ayres, 2002). The law of conservation of mass makes MFA an attractive decision-supporting method in resource management, waste management and environmental management (Brunner and Rechberger, 2005). This tool could be used to provide decision makers such as Paper Recycling Association of South Africa (PRASA), Paper Manufacturers Association of South Africa (PAMSA), Forestry South Africa and other stakeholders with evidence and empirical data on carbon flows within the forestry products sector. This could then be used to make decisions surrounding environmental and resource management in the drive for sustainable development.

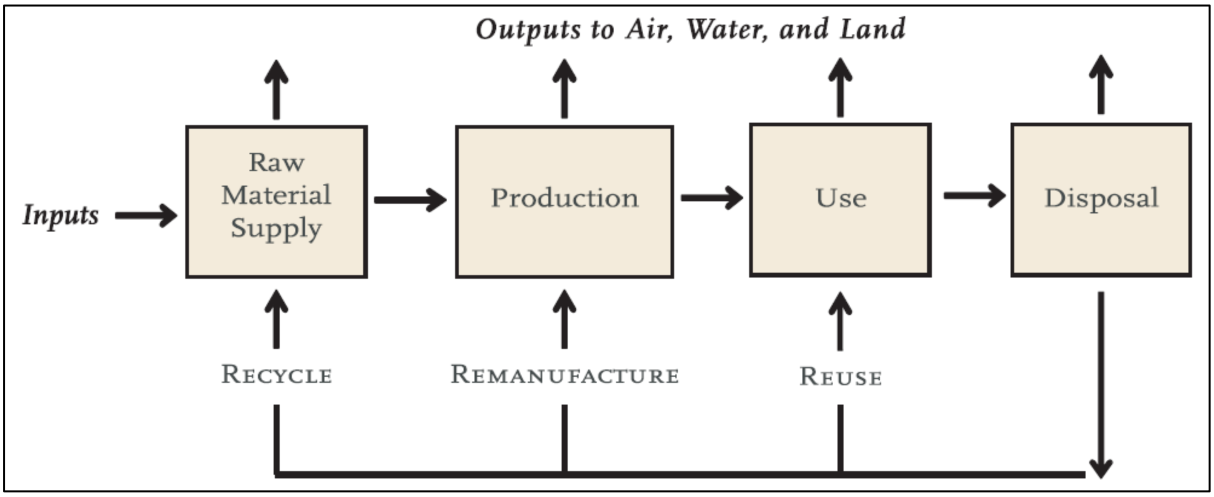


Figure 1.1: Flow of material through the commercial cycle (Wernick and Irwin, 2005).

South Africa is a developing country that is challenged by a number of economic, social and environmental issues (DEA, 2014). Globally, the world is facing environmental challenges that include ozone depletion and global warming. These challenges are the direct result of materials flow between the anthroposphere and the environment. As a global citizen, South Africa is committed to contributing towards greenhouse gas (GHG) mitigation that would keep the global temperature increase to below 2 °C. This obligation falls under the United Nations Framework Convention on Climate change i.e. the Kyoto Protocol (DEA, 2014).

In an attempt to curb GHG emissions, the South African government has decided to implement a carbon tax. This tax will effectively start on 1 January 2018 at R 120 per tonne CO_2eq. There will be an initial rebate of between 60 % and 90 %. This will eventually be phased out over the subsequent years. This tax will then increase at a rate of 10% per annum until 31 December 2019. The tax regime will then be revised and implemented in January 2020 (DNT, 2013). This among other mitigation policies will be put in place to produce a result of a 34 % and a 42 % GHG emissions deviation below the business as usual emissions growth trajectory by 2020 and 2025 respectively (DEA, 2014).

Another method of GHG emissions mitigation which is under investigation is that of carbon sequestration. Forests are considered carbon sinks as they store carbon for long periods of time. If proper forest management is applied and the standing stock of the forest remains constant, one would then expect a net reduction in atmospheric carbon dioxide (Tonn and Marland, 2007). This should then also be included in GHG accounting.

1.2. Problem statement

South Africa is considered the business hub of Africa. The country is still a developing nation and is expecting further economic growth which will lead to more intense industries and population growth (DEA, 2014). This will result in increased volumes of waste and greater GHG emissions. A large portion of municipal waste is landfilled which results in the production of methane and carbon dioxide (Baloyi et al., 2012). It is suggested that the pulp and paper industry may have the potential to lock up carbon which will add to the GHG mitigation potential of South Africa. In order to verify this, it is necessary to understand all the carbon flows of biomass origin through the industry.

1.3. Aims and Objectives

The aims of this study were to:

- Track paper carbon flows and to determine the fate of the carbon as it flows through the paper conversion, recycling and end user phases for the year 2011.
- Quantify all paper carbon inputs and outputs of lignocellulosic origin in South Africa.
- To identify carbon sinks and sources in the paper converting sector, recovered paper sector and end user stage.

1.4. Focus of this study

This study forms part of a series of five studies aimed at looking at the flow of carbon through the forestry, pulp and paper industry. In this study, the paper converting sector together with the end user fate of paper flows are traced and quantified in the form of an MFA. This MFA looked specifically at the flow of carbon of organic origin in paper products through the converting sector, recycling sector and its end user fate. The main source of fibre in South Africa originates from plantation forests (Thompson, 2012). The hardwood feed stock is mostly *Eucalyptus grandis* and the main softwood feed stock is *Pinus patula*. Some pulp mills also use bagasse as a feed stock. South Africa has shown improvement in the recovery of paper which is used as feed stock in some paper mills mainly to produce tissue and kraft boards such as linerboard and fluting.

This study will only look at carbon flows of a lignocellulosic origin that was used for paper production. Paper can be defined as a sheet-like material that is formed from individualised fibres by the removal of water (Hubbe et al., 2007). The carbon flows will be tracked through the converting, recycling and end user phases. There are other lignocellulosic products i.e. cigarette filters, textiles, microcrystalline cellulose and cellophane that are made from dissolving pulp. Dissolving pulp products were not included in this study as they did not have the same use and nature of paper.

1.5. Importance of this study

The pulp and paper industry is associated with substantial flows of carbon which is largely of biomass origin. It is one of South Africa's most sustainable industries as wood is a renewal resource and paper is recyclable (Sappi, 2015; CEPI, 2013). Most of the lignocellulosic fibre obtained for the industry is derived from sustainable plantations. However, the media and some non-governmental organisations are under the impression that the industry is not environmentally sustainable and that the fibre obtained is derived from natural forests (Thompson, 2012; McKinsey, 2013). A series of five studies will collectively produce an MFA of the forestry, pulp and paper industry in South Africa. It is hypothesised that these studies will allow stakeholders such as PAMSA to quote defensible, verifiable and reliable statistics that will revoke this misconception by showing that the industry derives its largest feedstock, fibre, from renewable and responsible sources in South Africa that also aids in carbon sequestration.

In addition to this, the plantation forests in South Africa are very well managed with a long standing stock of carbon as some tree species used for pulping, such as *Pinus patula*, can take up to 14 years to mature (Alembong, 2014; Smook, 2002). The forests are managed with the aim to maintain the standing stock over time (Alembong, 2014). The first study of the MFA Programme, conducted by Alembong in 2014 showed that nine out of the twelve forests surveyed were carbon positive. This means that the standing stock of carbon was increasing and that more trees were planted than harvested. It is also expected that during this time, the carbon stored in wood products would increase which would result in a net carbon dioxide removal from the atmosphere. This should be reflected in the accounting for GHG emissions.

This shows the potential of the industry behaving as a carbon sink. The industry would absorb more carbon than it emits from industrial activity. If the industry is shown to be carbon positive, then one may suggest the viability of using the pulp and paper industry as a possible means to GHG mitigation.

This study looked at carbon flows from South African paper machines, through the converters, the end user and into the waste and recovered paper streams. This study also looked at the carbon that is stored in finished paper products and in the waste that is stored in landfill. The carbon flows that were not considered in this study include:

- The carbon used in coal to generate electricity.
- The carbon used to generate steam from coal and/or gas.
- The carbon that exists in paper additives such as starch, calcium carbonate and other fillers.

The reason behind these exclusions were that the carbon flows above do not form part of the natural carbon flows derived from lignocellulosic material, such as wood and bagasse, which is used for pulp and paper production.

This project is based on the data collected from various stakeholders and thus no experimental work was conducted. The carbon dioxide and methane emissions were estimated using empirical correlations developed by the Intergovernmental Panel on Climate Change (IPCC). There is also inadequate data and information on the amount of waste that is sent to landfill in South Africa. The paper waste stream that is generated was determined using factors from studies done in South Africa.

1.6. Hypothesis

The paper industry can result in the storage of carbon in paper products through the action of recycling and physical storage of documents in libraries. The storage of carbon can aid in greenhouse gas mitigation through sequestration.

Chapter 2: Material flow analysis

This chapter aims at providing the reader with an overview of an MFA. The reader will be introduced to the method of conducting an MFA, importance of an MFA and other materials accounting methodologies.

2.1. An overview of material flow analysis

Material flow analysis is a systematic tool that is used to deliver a complete and consistent set of information that describes the stocks and flows of a particular material through a defined system (Ayres, 2002; Brunner et al., 2005). Raw materials, such as air, water, wood, etc. are derived from natural resources and form inputs into the industrial system which are transformed into products. These products then undergo further processing or consumption until finally being transferred back to the natural environment (Hinterberger et al., 2003). Figure 2.1 shows the basic model of an MFA where the material is extracted from natural resources and then returned back to the natural environment.

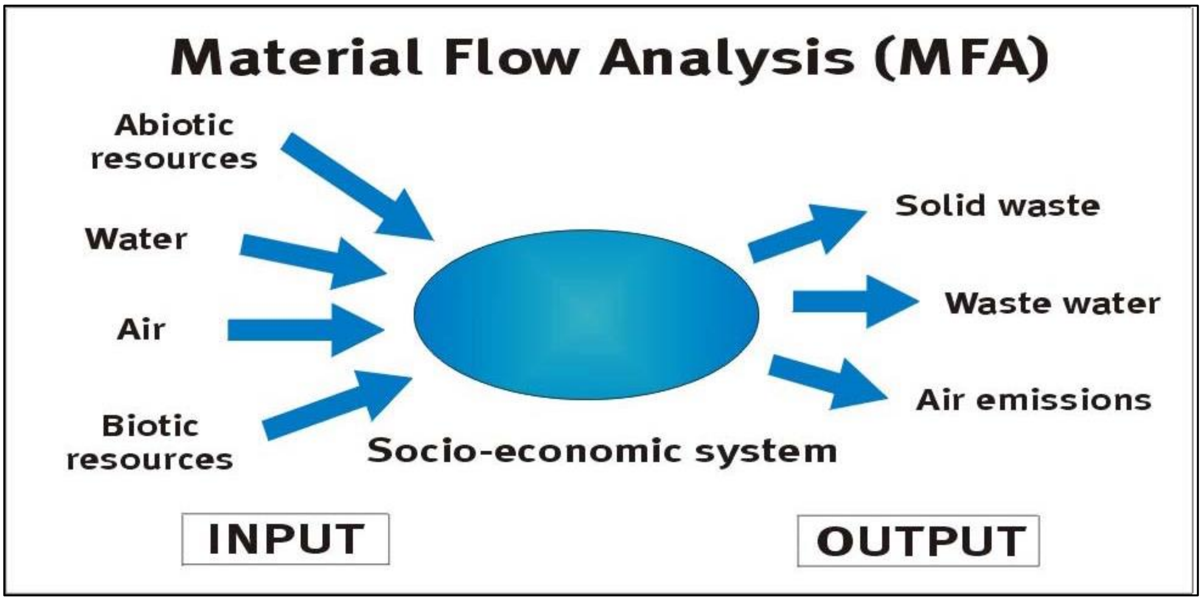


Figure 2.1: The basic model of an MFA with the system boundaries being defined from cradle to grave (Hinterberger et al., 2003).

However, an MFA does not have to look at the material flows from cradle to grave. The flow of the material under investigation is only studied within the system boundaries of interest. System boundaries are chosen so that they are as small and consistent as possible while still being reasonably broad to include all relevant stocks, flows and processes (Brunner and Rechberger, 2005).

Material flow analysis has quickly grown as a research tool with increasing importance to policy relevance. All studies usually look at the common paradigm of industrial metabolism and makes use of the simple principle of the conservation of mass (Ayres and Ayres, 2002).

Detoxification and dematerialisation form the two main types of material flow analysis. Detoxification looks at mitigating the environmental pressures that may result from industrial activities with substance flows that have a high environmental impact. Dematerialisation looks at the metabolic efficiency of industrial activities from a sustainable development point of view. The main goal of dematerialisation is to manage resources more efficiently. Both these types of MFA are used in the study of industrial ecology (Ayres and Ayres, 2002).

2.2. Importance of a material flow analysis

As industrial nations continue to grow, the constant demand for maintaining goods and services to satisfy the needs of the population grows. This forms the heart of environmental challenges as economies drive forward to satisfy the needs of the population. The environmental consequences depend largely on material extraction, nature of release, quantity of release, method of release and the manner in which it flows through its lifecycle. Materials accounting integrates two major concerns. The first major concern is the ability of ecosystems to sustain natural resource extraction and the second is the ability of the environment and society to handle pollution, waste discharges, greenhouse gas emissions and other contaminations to the natural environment (Wernick and Irwin, 2005).

Countries worldwide are striving to make drastic advances in emissions reduction. It has now become important to evaluate the stocks and flows of relevant materials through anthropogenic systems. Material flow analysis is a systematic approach that looks at stocks and flows of materials along the various pathways. It forms the basis for identifying relevant control points, resource management and efficiency improvement. This will allow relevant stakeholders in designing and creating processes or products that will aid in sustainable development, waste management and environmental protection (Adu-Poku, 2015).

2.3. Other materials accounting methodologies

2.3.1. Substance flow analysis (SFA)

SFA is a specific type of MFA. The concept of an MFA looks at the country's economy and the environment on a material level. An MFA looks at the analysis of bulk flows, such as paper or glass, through an economic system. An SFA deals only with the analysis of specific flows. It follows a basic three step methodology which includes (Ayres and Ayres, 2002):

- Definition of the system.
- Quantifying the overall stocks and flows.
- Results interpretation and presentation.

2.3.2. Physical input-output accounting (PIOT)

PIOT is a physical accounting system based on a macroeconomic activity. It comprises of the input-output table with physical units as well as the flows between the natural environment and the economy. This then allows for the generation of complete material balances for a variety of economic activities (Ayres and Ayres, 2002).

2.3.3. Life cycle analysis (LCA)

Life cycle analysis answers to a larger audience. An LCA would normally look at a number of substances from extraction through to disposal whereas an MFA would just look at a single substance through the objective defined boundaries. The definition of an LCA according to ISO 14040 is as follows: '*LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a system; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of the inventory and impact phases in relation to the objectives of the study*' (Ayres and Ayres, 2002).

The LCA framework is an iterative process with interpretation of data or results required at every step. The interconnectedness of the process may continuously increase the level of data as shown in Figure 2.2.

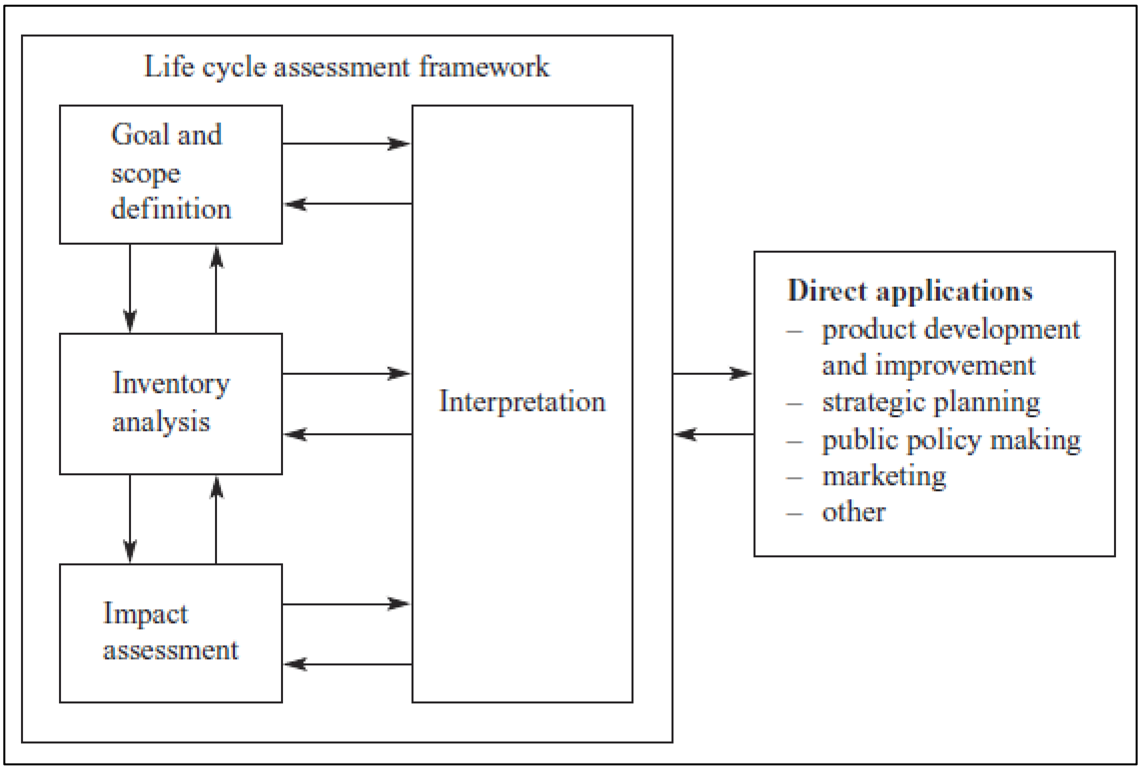


Figure 2.2: LCA technical framework (Ayres and Ayres, 2002).

2.3.4. Input-output analysis (IOA)

Input-output analysis is primarily used in economics for tracing inputs and outputs. It has been adapted as an accounting framework for tracking material and resource flows to and from industry and society. Flows in an IOA are usually recorded into an input-output table which is used to provide a holistic view of the regional economy and can be used to provide an indication of the efficiency of transforming inputs into desired outputs. Energy balances, waste streams and emission level calculations can be incorporated into an IOA to give an indication of the environmental impact for a given production quantity (Rahman and Helling, 2014).

2.4. Difference between a material flow analysis and a life cycle analysis

Material flow analysis and life cycle analysis (LCA) are very similar in methodologies. The initial step for both studies is goal and scope definition.

In an MFA, a key substance is selected according to the requirement of the study or environmental impact. Flows are quantified based on the concentration in the given streams and the conservation of mass is applied. Results are then analysed for sensitivity and error. The results are then put into a comprehensible format for policy formulation by the relevant stakeholders.

An LCA considers inventory in the given study. Inputs and outputs are quantified and resources consumption and emissions are also evaluated. The ISO 14040 standard describes a framework for an LCA study. A substance is usually followed from cradle to grave in an LCA. Table 2.1 highlights the differences between an MFA and LCA.

Table 2.1: Key methodological differences between an MFA and an LCA.

Life cycle assessment (Boguski et al., 1996)	Material flow analysis (Montangero et al., 2006)
Goal definition and scope	Identification of material flow related issues
Life cycle inventory	Key substance selection and system boundary definition
Impact assessment	Key substance mass flow and stocks quantification
Improvement assessment	Sensitivity and error analysis
	Development and evaluation of scenarios

2.5. Material flow analysis procedure

2.5.1. Problem definition for material flow related issues

This step is the basic definition of the problem which would allow for the appropriate selection of the substance for which the MFA will be conducted. This project will look at carbon flow analysis of paper in the converting, recycling and end-user stages of paper. As discussed earlier, the South African government wishes to introduce carbon taxes due to greenhouse gas emissions from industrial activity (DNT, 2013).

2.5.2. Substance selection

There are various methods for substance selection. One may use legislation standards or codes that provide listings of relevant substances that are regulated. The benefits of this approach are that there is existing work on the MFA and that all substances included in the MFA were selected by the relevant authorities. Another approach would be to determine the relevance or concentration of substances in important flows. The final approach looks at MFA studies that are carried out to determine a system's metabolism. This is usually done in line with resource and/or environmental impact aspects. The substance selection would then form part of the project definition (Brunner and Rechberger, 2005).

2.5.3. System definition in both space and time

The geographical boundary of the MFA is usually determined by the scope of the project. It is generally in line with a politically defined region, company or a hydrologically defined region. The temporal boundary is also defined by the scope of the project (Brunner and Rechberger, 2005).

2.5.4. Identifying and quantifying relevant flows, stocks and processes

The method of MFA relies on the conservation of mass. The application of this principle comes in the form of a mass balance which states that the mass of all inputs to a system is equal to the mass of all outputs plus the accumulation of materials in the system. This is shown mathematically in Equation 2.1.

$$\sum_{k1} \dot{m}_{input} = \sum_{k0} \dot{m}_{output} + m_{accumulation}$$

Equation 2.1

If the concentration of a certain substance is known, then the flow rate of this substance is found by Equation 2.2.

$$X_i = c_i(m_i)$$

Equation 2.2

Where i is the stream number; X is the substance flow rate; c is the concentration of the substance in stream i and m is the total stream flow rate.

Equation 2.1 and Equation 2.2 holds for all systems and processes. Data for a system or process is usually obtained from relevant organisations and literature. Correlations and constants from literature provide a good basis for estimations of material flows for which data are not available.

2.5.5. Presentation of material flow analysis results

The results of an MFA are usually required by stakeholders to make decisions. It is very important that the results be clear, concise and presented in an easily comprehensible manner (Brunner and Rechberger, 2005). The main goal of the results presentation is to create an understandable, clear, trustworthy and reproducible message (Brunner and Rechberger, 2005). The results are normally represented in a table format and in some cases on a diagram.

2.5.6. Significant figures in data and results reported

Material flow analysis results should be reported to a certain level of significance that would not create the impression of a great deal of accuracy. Most of the data reported in the paper industry were reported to the closest tonne. This standard was maintained and the results and data of this study were reported to the closest tonne.

2.6. Data uncertainties

The mass balancing technique applied in the MFA is prone to a certain degree of uncertainty. The inputs to an MFA are usually random variables. This would result in the final result also being a random variable. Error propagation may only be done if the probability distributions of the input data are known (Brunner and Rechberger, 2005). Two methods are proposed by Brunner and Rechberger (2005) to deal with the uncertainty.

2.6.1. Gauss's law of error propagation

Gauss's law of error propagation takes a function and expands it into a Taylor series which is expanded only to the linear term (Brunner and Rechberger, 2005). The Taylor series expansion makes it possible to determine the approximate deviation and the expected value of the functions results. The difference in the mean value of the function and the Taylor series approximation provides an indication in the uncertainty of the mean (Brunner and Rechberger, 2005). For a function $Y \approx f(X_1, X_2, X_3, \ldots.., X_n)$

$$\mathrm{Var}(Y) \approx \sum_{i=1}^{n}\left(\mathrm{Var}(X_i)\cdot\left[\frac{\partial Y}{\partial X_i}\right]^2_{X=\mu}\right) + 2\cdot\sum_{j=1}^{n}\sum_{j=i+1}^{n}\left(\mathrm{Cov}[X_i, X_j]\cdot\left[\frac{\partial Y}{\partial X_i}\right]_{X=\mu}\cdot\left[\frac{\partial Y}{\partial X_j}\right]_{X=\mu}\right)$$

Equation 2.3

Where

μ_i, = $E(X_i)$ = the mean value of X_i.

Var (X_i) = Variance in X_i.

Cov (X_i, X_j)= Co-variance in X_i and X_j.

In order to produce reliable results, Equation 2.3 relies on the input variables being normally distributed.

2.7. Material flow analysis evaluation methods

The results of an MFA are material stocks and flows which were determined based on the conservation of mass. There is usually little to discuss on the numerical results as one would have expected the study to have been done carefully, comprehensibly and in detail. However, the evaluation of MFA results is usually subjected to social, moral and political values. Another issue that arises is when MFA results for one system are compared to that of different systems. This would then require an evaluation process in which so called indicators are applied (Brunner and Rechberger, 2005).

2.7.1. Material intensity per service unit (MIPSU)

This method looks at the mass flows of materials through the process of production, consumption, recycling and disposal in a defined service unit or product. Material intensity per service unit MIPSU looks at the input flows as input usually equals output. MIPSU can be described by Equation 2.5.

$$\mathrm{MIPSU} = \frac{\mathrm{X}}{\mathrm{Y}}$$

Equation 2.5

Where X is the input mass consumed and Y is the output mass of the desired product alone.

MIPSU may be used as a method of evaluation for sustainable development (Brunner and Rechberger, 2005).

2.7.2. Statistical entropy analysis (SEA)

Substance entropy analysis looks at the degree to which a substance is diluted or concentrated as it is transformed in a system. Substance entropy analysis draws on all the information from the completed MFA without the need for any additional computation.

$$\mathrm{H}(\mathrm{P_i}) = -\lambda \sum_{i=1}^{k} \mathrm{P_i} \ln(\mathrm{P_i}) \geq 0 \qquad \text{for} \sum_{i=1}^{k} \mathrm{P_i} = 1$$

Equation 2.6

The entropy introduced in Equation 2.6 is known as Shannon's statistical entropy (Brunner and Rechberger, 2005). It is used in information systems to measure information gain or loss and the variance in finite probability.

Shannon's statistical entropy, Equation 2.6, is identical to the Boltzmann 1872 H-theorem which statistically describes a set of particles in space using their momentum, time and position Equation 2.6 is also very similar to thermodynamic entropy which was proposed by Clausius in the 1850s (Brunner and Rechberger, 2005).

Substance concentrating efficiency can also be derived from SEA which looks at a system's ability to dilute or concentrate a substance. In a carbon flow analysis, substance concentrating efficiency will provide a measure for the system's ability to lock up carbon in finished products (Brunner and Rechberger, 2005).

2.7.3. Efficiency of the life cycle stages indicator

This indicator was developed specifically for substance flow analysis by van der Voet in 1996. If one was to consider the entire system as a single independent life cycle stage in the total lifespan of the carbon, then one will be able to determine a carbon leakage. The carbon leakage can be determined by Equation 2.7 below (van der Voet, 1996).

$$\text{Carbon leakage} = \frac{\text{Total carbon losses}}{\text{Total carbon inputs}}$$

Equation 2.7

The efficiency of the system is determined by taking the inverse of Equation 2.7. The leakage of carbon in the system can be considered as all the carbon that ends up going to landfills, the atmosphere and sewer (Adu-Poku, 2015).

2.8. Summary

Chapter 2 addressed the MFA methodology. An MFA initially seeks to identify a problem and then a substance related to the problem. The system boundaries are then defined in space and time and all relevant stocks and flows are quantified. Results are then represented with an uncertainty being reported with each result.

Chapter 3: Literature review

This chapter covers literature surrounding the paper and board converting sectors, end user requirements, recycling and landfilling. Other MFA's that have been done in the forestry products sector are also discussed.

3.1. Paper and board grades

There are a variety of different paper grades according to the intended use of the paper. Paper and board grade classification has become so complex due to the constant development of new grades. Changes in markets and the increasing application of paper in a variety of packaging solutions have blurred the conventional systems of classification (Paulapuro, 2000). Copy paper, newsprint, tissue and paperboard are the main grades discussed in the following sections.

3.1.1. Copy paper and newsprint

Copy paper and newsprint are derived from chemical pulp and mechanical pulp respectively. Recycled fibre has been used as a raw material as of late but this is strongly dependant on the security of supply (Paulapuro, 2000).

Newsprint is also known as wood-containing paper with a 25-100 % mechanical pulp content. These papers may be heavily coated for uses which include telephone directories, newspapers, magazines, some books etc. There are seven methods from which mechanical pulp is derived.

- Stone groundwood and pressure groundwood – The pulp from the stone groundwood process is produced by pressing blocks of wood against an abrasive rotating surface at atmospheric pressure. The wood is usually orientated parallel to the axis of the rotating stone. Pressure groundwood is produced in a similar method with the local atmosphere in the grinder being pressurised to around 2.5 bar. The yield from these processes is around 98.5 % with the fibres being peeled from the wood blocks (Sundholm et al., 1999; Smook, 2002; Kerr, 2012b).
- Refiner mechanical pulp (RMP) and thermo-mechanical pulp (TMP) – RMP is the atmospheric refining of chips in a disc refiner to produce pulp. Thermo-mechanical pulp is similar to Refiner mechanical pulp with the difference being the preheating of the chips with steam which is usually at 3-5 bar. These processes give a yield of around 97.5 % (Kerr, 2012b; Smook, 2002; Sundholm et al., 1999) .

- Chemimechanical pulp (CMP) and chemithermomechanical pulp (CTMP) – CMP refers to chemical pre-treatment of wood chips and then the mechanical treatment either by a refiner or grinder. Chemithermomechanical pulp employs a similar process to CMP with the wood being pressurised with steam. The resultant pulp is usually stronger than SGW or RMP pulps. The yield is lower at around 90 % as some of the lignin and other wood constituents are lost due to the chemical treatment (Kerr, 2012b; Smook, 2002; Sundholm et al., 1999).

The main principle behind mechanical pulping is lignin preservation. Depending on species, lignin constitutes 21-25 % of the wood chemical make-up (Smook, 2002).

The key difference between mechanical grades and copy paper is the method of pulping. This results in differences in the lignin content of newsprint and copy paper. Most of the lignin is dissolved out in chemical pulping. Copy paper is also known as woodfree paper as it contains less than 10 % mechanical pulp. Copy paper can be coated or uncoated. Copy paper is usually derived from chemical pulp in which chemicals are used to dissolve out the lignin from the wood matrix. Chemical pulp is usually produced by sulphite pulping or kraft pulping.

The Kraft process is more attractive than sulphite pulping due to the chemical recovery circuit that allows for a high degree of soda chemical recovery (Gullichsen and Fogelholm, 1999; Kerr, 2012a; Smook, 2002).

3.1.2. Tissue

Tissue is the broad term used to describe products that are made from light weight, dry creped/non-creped paper such as napkins, facial paper, toilet paper etc. The global tissue market has grown considerably as most nations move towards good sanitation practices (Paulapuro, 2000).

Tissue paper can be produced from two types of raw materials or a blend of both depending on the end user requirements.

- Virgin fibre – Virgin pulp can be used in tissue production when the end product is required to be of the highest quality. The pulp maybe bleached or unbleached Kraft or sulphite pulp. Most of the tissue mills worldwide prefer to use bleached pulp as it gives a high degree of brightness which creates a hygienic sense and feel. Bleached pulp is also much easier to dye and has a longer life. The tissue mill maybe part of an integrated mill or the tissue mill may receive the dry pulp in bales. The chemical pulp used may either be a hardwood or a softwood derivative. Hardwood pulp usually imparts softness while softwoods impart strength to the paper (Paulapuro, 2000).

- Recycled fibre – The recycled fibre grades that can be used to produce tissue include contaminated chemical pulp fibre (office waste) and ordinary mixed waste which includes magazines and newspapers. Depending on the end user requirement different recycled grades are used. Recycled fibre that is derived from chemical pulp is used when a brightness of at least 80 % is required. Ordinary mixed waste is usually used when the brightness requirement is up to 60 % (Göttsching and Pakarinen, 2000; Paulapuro, 2000).

Fibre blends used depends strongly on the end user requirements of the paper. Facial tissue has a high softness requirement and a lot more hardwood fibres are used. When the requirement is strength for products such as industrial wipes, more softwood is added to the blend. Low quality tissue papers are made from 100 % recycled waste while high quality tissue is made from 100 % virgin fibre. Recycled and virgin may be used together when there is a higher requirement for strength in the low quality tissue papers (Göttsching and Pakarinen, 2000; Paulapuro, 2000).

The various tissue products are usually considered hygiene products. The most important products include (Paulapuro, 2000):

- Bathroom tissue or toilet paper.
- Disposable diapers.
- Kitchen towels.
- Sanitary napkins.
- Facial tissue.
- Industrial wipes.

Most of the tissue products produced are not recycled due to hygienic reasons. That paper is usually far too soiled to be used as secondary fibre.

3.1.3. Paperboards

There are several varieties of paperboards on the market. They have been broken down into three categories:

- Carton boards.
- Container boards.

- Speciality boards.

A further breakdown of the paperboards can be seen in Figure 3.1.

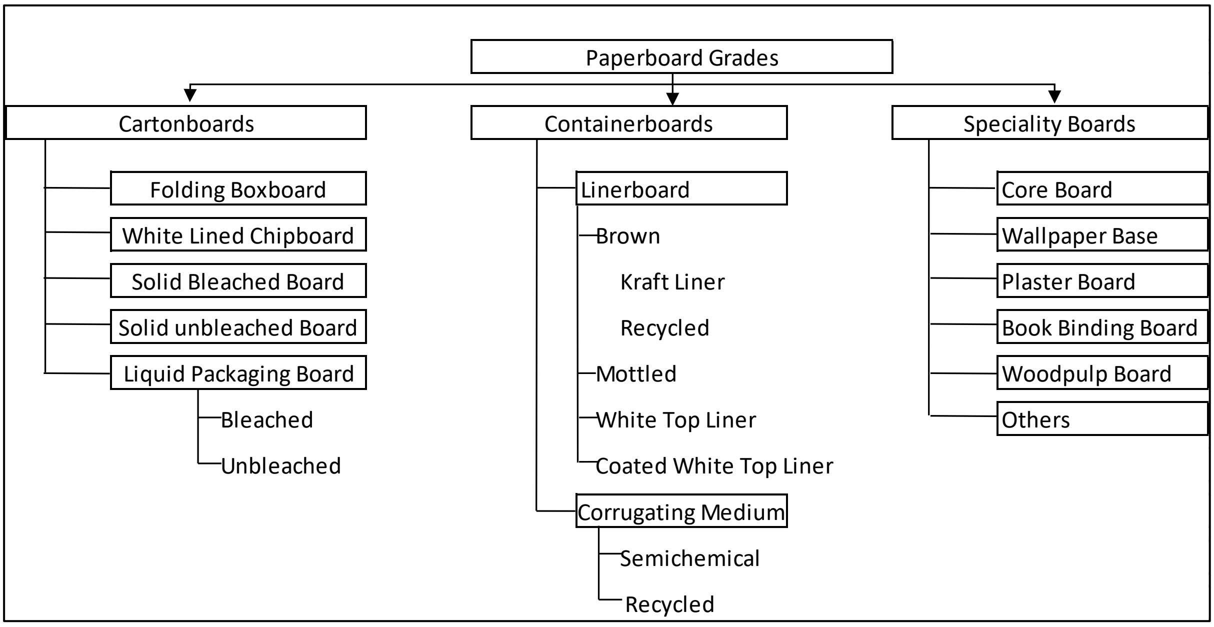


Figure 3.1: Breakdown of the different paperboard grades (Paulapuro, 2000).

There is a fine line between distinguishing paperboards from paper. Paperboards usually have a basis weight greater than 150 grams per square metre (gsm). The exception to this rule is corrugated medium as the basis weight on some grades can be as low as 100 gsm. Paperboards are usually multi-ply boards with the exception once again being corrugated medium which can be produced on a single-ply machine. Carton boards are used mainly for consumer packaging. Container boards are usually used as secondary packaging. Paperboards are considered very environmentally friendly and are recyclable which makes paperboards very competitive against other types of packaging (Paulapuro, 2000).

- Carton boards- Carton boards can be used as primary food packaging. Purity and cleanliness is achieved by the use of virgin pulp on the outer plies of the board. The board may then be coated according to the uses of the board (Paulapuro, 2000).
  - Folding boxboard – usually used for the packaging of cosmetics, food, book covers, pharmaceuticals etc. (Paulapuro, 2000).
  - White lined chipboard – Has the same uses as folding boxboard. White lined chipboard is usually in the basis weight range of 200-450 gsm. The main idea of white lined chipboard is to incorporate an under top ply which is usually

deinked secondary fibre. This reduces the cost of the expensive bleached virgin top liner (Paulapuro, 2000).

- Solid bleached board – This belongs to the same group of board as white lined chipboard and folding boxboard. The applications are also very similar. Solid bleached board is usually a 1 – 3 ply board made up of bleached hardwood and softwood, chemithermomechanical pulp (CTMP) or broke (Paulapuro, 2000).
- Solid unbleached sulphite board – Usually a multiply product of 2 – 3 plies. Solid unbleached sulphite board can be produced up to 500 gsm and is made up of unbleached virgin outer plies. Unbleached hardwood is usually used on the top ply to provide good printing properties. The middle ply can comprise of unbleached virgin, chemithermomechanical pulp, old corrugated containers (OCC) or broke. Solid unbleached sulphite board is usually used for beverage packaging (Paulapuro, 2000).
- Liquid packaging board – Liquid packaging board is usually used for the packaging of liquids such as juices, pasteurised milk, etc. Liquid packaging board is usually made out of virgin pulp for purity and cleanliness. Liquid packaging board is usually heavily coated with low density polyethylene to protect the liquid products (Paulapuro, 2000).

- Container boards – Corrugated fluting and liner fall under this category of boards. Corrugated boards can be made up of virgin fibre or OCC. Container boards are usually used as secondary packaging to protect goods. The basis weight of the board depends on the end use of the product. Liner board has a basis weight of between 100 gsm and 350 gsm while fluting has a basis weight of between 112 gsm and 180 gsm. Due to advance in chemical additives and a competitive market, lower basis weights in the corrugated market have now become one of the targets of the industry (Paulapuro, 2000).
- Speciality boards - this category of boards consists of all other types of boards that are not used for packaging. Speciality boards usually have a basis weight in excess of 500 gsm. Speciality products include wallpaper base, core board, plaster board, etc. (Paulapuro, 2000).

3.2. Paper organic composition

Paper is made up of the same organic constituents as wood. These constituents vary greatly in the different grades of paper. Table 3.1 details the organic chemical composition of three common grades of paper in South Africa.

Table 3.1: Composition of organic constituents in different grades of paper (Wang et al., 2013).

Paper Grades	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Carbon Content (%)
Newsprint	53.75	16.40	15.25	40.18
Copy paper	71.35	14.00	0.80	37.82
Corrugated	61.95	14.85	14.55	42.76

The lignin content of copy paper is extremely low due to the pulping method used. Most of the lignin is usually removed and bleached out to give copy paper a high whiteness and brightness. It is due to this low lignin content that copy paper is the preferred recycled grade used for the production of tissue. Newsprint is produced through mechanical pulping to preserve the lignin while corrugated board has a high lignin content for added stiffness in the resultant board. Other constituents in the paper and board usually include fillers such as $CaCO_3$ (Smook, 2002; Paulapuro, 2000).

3.3. Converting

Converting provides paper and boards the final requirements for application in modern society. The world has now also become more sustainably conscious and the converting sector of the paper industry has to some extent made the products more environmentally sustainable (Thompson, 2012). The paper converting sector services four principal product groups. This includes:

- Packaging.
- Paper and plastic containing bags and sacks.
- Household and similar papers.
- Industrial papers and boards.

3.3.1. Corrugated board production

Corrugated board has been in existence since 1856 (Savolainen, 1998). Since then there has been many technological advances in the industry and it has grown vastly with many innovations. Corrugated boxes are used mainly as secondary packaging material for transport and protection of products in their primary packaging (Savolainen, 1998). Water resistance has also been added to liner and fluting to allow for the storage in moist environments such as refrigerated environments (Savolainen, 1998). There are four main categories of corrugated board structures:

- Single faced corrugated board – This is produced when a sheet of linerboard is glued to corrugated material (Savolainen, 1998).
- Single wall corrugated – This is produced when the corrugated material has a single sheet glued on either side (Savolainen, 1998).
- Double wall corrugated – This is produced by gluing three flat sheets and two corrugating mediums together (Savolainen, 1998).
- Triple walled corrugated – Very strong and robust. This consists of four flat facings, and three corrugated mediums (Savolainen, 1998).

A schematic of the single and double walled corrugated is shown in Figure 3.3. Figure 3.4 shows a schematic of a typical corrugator machine.

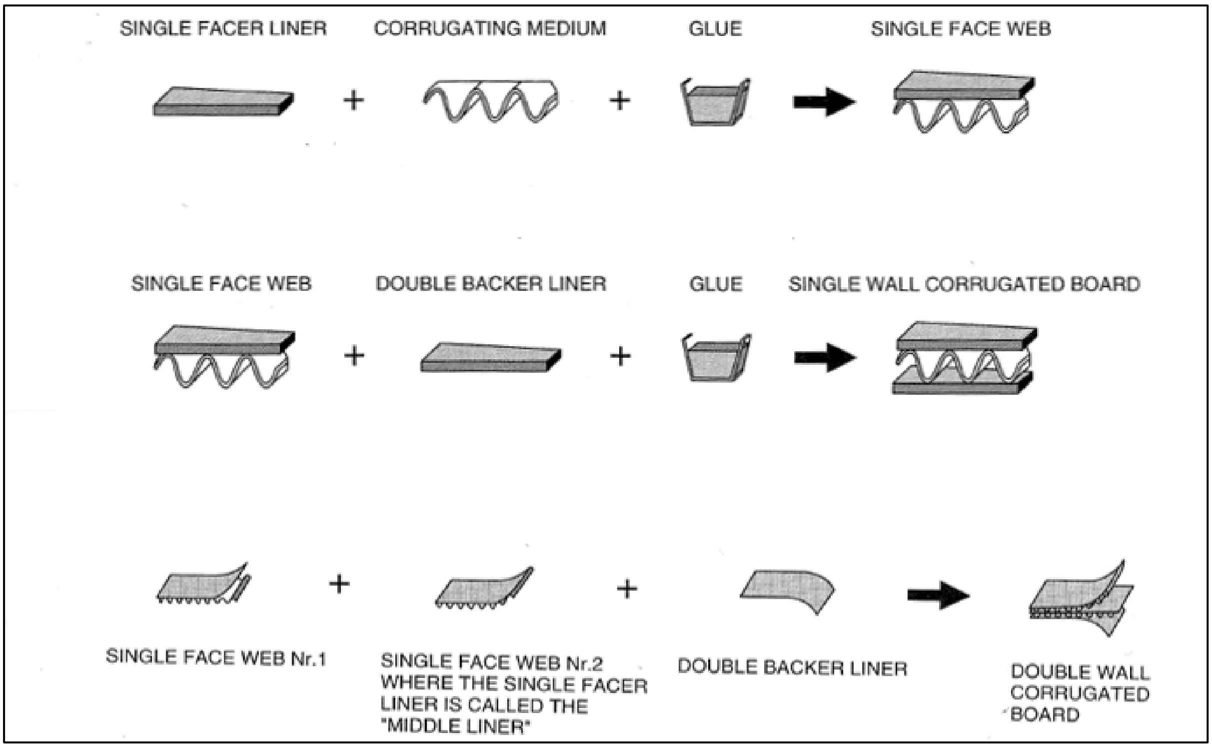


Figure 3.2: Components of a single and double walled corrugated board (Savolainen, 1998).

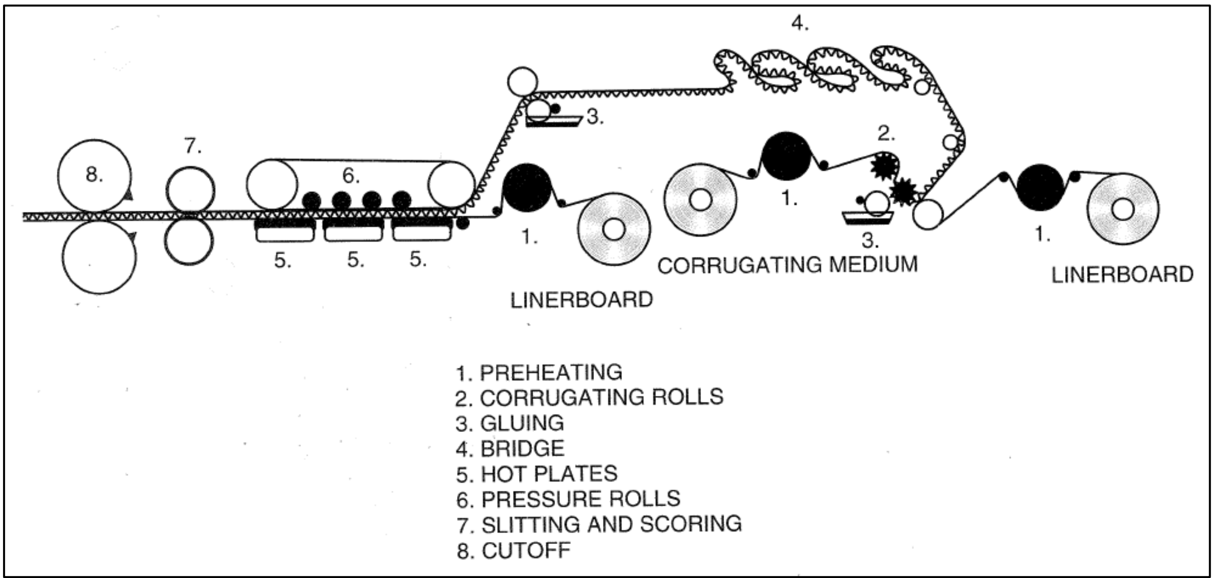


Figure 3.3: Schematic of a conventional single facer with fingers (Savolainen, 1998).

3.3.2. Carton box manufacturing

Carton box manufacture consists of several processes. Figure 3.4 is a flow diagram of the carton box manufacturing process.

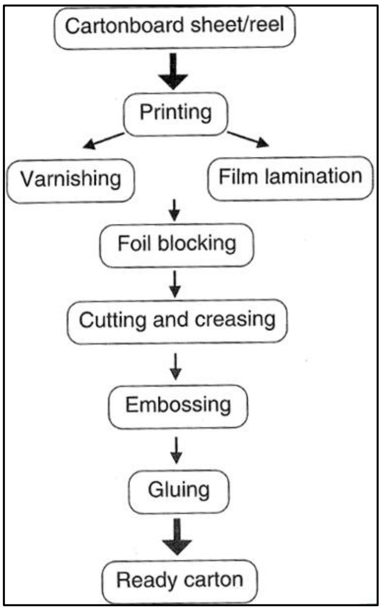


Figure 3.4: Carton manufacturing stages (Savolainen, 1998).

- Printing

  Cartons usually have high printing requirements as it is meant to be attractive and appealing. The most common printing method is sheeted offset. It is flexible for sheet sizes, has low start-up costs and produces high quality print. Rotogravure is also common but it is preferred when there are long runs of the product. Flexography is used when the print requirements of the board is less demanding (Savolainen, 1998).

- Varnishing

  The print on paperboards is required to be more durable and resistant as cartons are stacked which results in them rubbing against each other. The print is then protected by adding a layer of varnish which is dried by ultraviolet light curing. Varnishing is usually done in line with the printing press provided that the press is equipped with UV curing. Varnishing also provides a gloss to the print (Savolainen, 1998).

- Film lamination

  This is the alternative to using UV cured varnish. Lamination is the application of a plastic film on a separate machine to provide superior gloss and increases the strength to some degree of the resultant board (Savolainen, 1998).

- Foil blocking

  This creates a pigmented or metallic appearance. It is usually used when packaging cosmetics or confectionaries. It also allows for the use of holograms. Foil blocking also provides a surface with good adhesion and clean edges (Savolainen, 1998).

- Cutting and creasing

  Fold lines are creased onto blanks that are cut from the printed sheet. This allows for the formation of the packaging. This is also known as die cutting. The cutting of the waste pieces of paper form the board gives the carton its final shape that would allow for it to be folded into a carton. The waste pieces of paper from cutting and creasing is known as pre-consumer waste (Savolainen, 1998).

- Embossing

  Embossing is customer requirement and draws attentions to certain detail on the packaging. Embossing is a pair of plates with positive and negative contours. The plates are applied to the board at high pressure to alter the surface of the board. This creates the effect of an image that is engraved in the board (Savolainen, 1998).

- Gluing and heat sealing

  Glue is applied to the seams of the packaging to finally assemble the carton into a box like structure. There are three types of gluing:

  - ➢ Side stream gluing – Glue is applied to the length of one side with the top and bottom remaining unglued. This process occurs on the packaging line and is followed by erection of the carton, insertion of the product and final sealing and flap tucking.
  - ➢ Crashlock bottom – Gluing and erection occurs at the same time. The bottom of the carton is glued by applying glue to the top of two flaps that are positioned on top of the other two flaps. This type of gluing is mainly used for products that are hand packed.
  - ➢ Multipoint gluing – This type of cartons are mainly used for the packaging of sweets. The four point and six point glued types are the main types. The four point glued type is a tray while the six point glued type is a tray with a lid (Savolainen, 1998).

3.3.3. Tissue converting

Tissue converting consists of six main stages before the product can be dispatched. These stages include:

- Embossing – Most tissue products are embossed to improve the absorbency and softness of the paper. Plies can also be pressed together or at the edge. Embossing may also be used for decorative purposes and to add texture to the sheet. The three main types of embossing are:
  - Traditional embossing – All the tissue plies can be embossed simultaneously. The embossing rolls may both be hard or one may be a steel roll.
  - Nested embossing – This is carried out where by each ply is embossed separately and then combined to provide a sheet with a higher bulk.
  - Point-to-point embossing- it is an advanced type of nested embossing. The highest points of the embossing rolls are positioned opposite each other which create suction pockets between the plies. This improves the absorbency and a bulk 2.5 times greater than traditional embossing is achieved.
- Printing – Printing can take place on machine or on a separate press. Printing on tissue paper is usually done for decoration or to impart company logos on the tissue.
- Perforation – This is usually done on rolls of tissue to make it easier for one to separate the sheets. The interval distances between the perforated sheets are controlled.
- Winding and tail sealing/ folding – This usually produces rolls of tissue products with a fixed number of sheets or roll length. The paper is rolled onto a core and the tail is sealed at the end to prevent the roll coming apart. Folding is usually done for paper towels, facial tissue, serviettes, etc.
- Log sawing – Products in the form of rolls are cut to the desired width.
- Packaging – This is the final step in the converting process where the products are packed into transportable and consumer friendly packaging. The product maybe boxed or wrapped in plastic or paper. Thereafter the product may be put into plastic sacks or in corrugated boxes for handling and transportation (Paulapuro, 2000).

3.4. Recycling

Recycling of paper has seen growth in recent years. It has now formed the second largest fibre source to virgin fibre in South Africa. South Africa has a waste paper recovery rate of 62.1 % (PRASA, 2011).

3.4.1. Collection and sources of recovered waste paper

There are two broad categories of recycled waste:

- Pre-consumer waste – It is the waste that is obtained from converters. It is also any over issues such as excess pamphlets. The paper from converters usually comprise of shavings, cuttings, residues and rejects. The waste is usually obtained by dealers that have contracts with the converters. Pick-up systems are usually employed by collectors to obtain the paper waste (Göttsching and Pakarinen, 2000).
- Post-consumer waste – Post-consumer waste is more difficult to handle. It includes paper that is recovered from operations where unwrapping occurs, households and institutions. The pick-up method is employed at institutions and unwrapping operations. With households, the methods employed to obtain the waste paper is more open. The choice of collection depends on the population structure of the area. One may use the pick-up system in which the public may be issued bags or containers to put the paper waste in and it can be collected once a week. One may also use the drop-off system where the public can drop of the waste at a collection centre (Göttsching and Pakarinen, 2000).

Waste paper collection system:

- Container collection – This type of collection system is targeted at the affluent communities, some commercial buildings and offices that use containers or mono bins. With this, paper is put into a bin that is separate from normal household waste and it becomes a mixture of different grades that include magazines, packaging, writing paper, etc. The collection containers are usually picked up once a week (Göttsching and Pakarinen, 2000).
- Curb side collection – This was traditionally done by charitable organisations but has now become commercialised in Durban. The community is distributed with a different colour bin plastic bag. All recyclable waste such as plastics and paper is then place into the bags. The plastic bags are placed on the curb side with normal domestic waste and the collection company comes around to collect it. Once again, the paper waste is a mixture of used paper products.
- Drop off systems (container collection) – Large containers are usually provided in centralised publicly accessible locations for the drop-off of paper waste. The containers may be multi-compartment for different types of paper waste or different types of recoverable materials such as metals and glass. The containers are emptied weekly and it is usually taken for sorting (Göttsching and Pakarinen, 2000).

- Document destruction and waste management – Some companies, offices and institutions employ the services of waste management companies that collect recovered paper from the sites and send it off for recycling.

3.4.2. Recovered paper sorting, handling and storage

- Sorting of recovered paper – Despite technological advances in the recent years, the sorting of recovered paper still remains a labour intensive task due to the variety and composition of the recovered paper. There are various grades of paper and some of the recovered paper that is collected is far too badly contaminated that it cannot be processed further. The recovered paper is usually fed onto a conveyor from which the workers remove the contaminants in the waste paper such as metal, glass, liquid packaging, etc. This method is known as negative sorting. The contrast would be that the workers collect the recoverable paper from the conveyor. This method is known as positive sorting. Positive sorting reduces the specific sorting output per person but produce high quality recovered paper. Negative sorting has a higher specific sorting output per person but produces lower quality recovered paper as the sorters may overlook contaminants. The recovered paper is later sorted into different grades (Göttsching and Pakarinen, 2000).
- Handling – Recovered paper is handled according to the transport conditions and the requirements of the paper mills. Recovered material can be handled loosely but due to the settled density of paper, this is not very practical and it becomes costly. Recovered paper is usually sorted into different grades and baled with hydraulic pressures of around 8 MPa. Each bale normally weighs around 500-600 kg. Some recycling facilities offer the service of document destruction. The paper is usually shredded after sorting and then baled (Göttsching and Pakarinen, 2000).
- Storage - loose recovered paper is normally stored in bunkers of enclosed facilities with roofs. Bales can be stored under a roof or in the open air. The disadvantage to open storage is that the bales are exposed to environmental conditions such as wind, rain, etc. This reduces the yield that one can expect from the paper due to microbiological degradation of cellulose and other nutrients available in the recovered paper (Göttsching and Pakarinen, 2000).

3.4.3. Different grades of recovered paper:

The Paper Recycling Association of South Africa (PRASA) has defined standard grades of recovered paper and board which is shown in Table 3.2 and Table 3.3. This standard is recommended to be applied at all industrial levels to secure the quality of recovered paper to the paper mills. The standard of recovered paper and paperboard grades are approved by industry members. The industry members that have approved and developed the recovered paper grades are members of PAMSA and PRASA. PAMSA comprises of 90 % of all paper manufacturers in South Africa (Henneberry, 2017).

Table 3.2: South African standard grades of waste paper (PRASA, 2009).

Grade Abbreviations	Description	Percentage of prohibitive material allowed (%)	Total Out-throws (%)
Common mixed waste (CMW)	A mixture of different types of board and paper without any restriction on the fibre grade	1	10
Industrial mixed waste (IMW)	The waste is made up new cuttings of paperboard such as those used in the manufacture of folding paper cartons and similar box board.	1	2
Special news (SN)	This is post-consumer waste that is made up of newspaper magazines and sorted graphic paper.	1	3
Over issue (flat) news (FN)	The waste is made up of over run or unsold newspapers containing the normal percentage of inserts and no flexographic printed material.	0	1
Magazine (SBM)	The waste is made up of unsold magazines and trims from magazine printing presses which include catalogues and brochures with or without latex bindings. It may contain up to 10 % of uncoated news type paper.	0	2
Special magazine (SSBM)	The waste is made up of unsold magazines and trims from magazine printing presses which include catalogues and brochures without latex bindings. It may contain a small percentage of news type paper.	0	2
White 1 (W1)	High grade white. Very clean waste consisting of white, unprinted, wood free paper or board. It is pre-consumer waste and it is made up of shavings, trim and rejects that is free from insoluble material.	0	0

Table 3.3: South African standard grades of waste paper continued (PRASA, 2009).

Grade Abbreviations	Description	Percentage of prohibitive material allowed (%)	Total Out-throws (%)
Heavy letter 1 (HL1)	The waste is made up white printed and unprinted sheets; trim and shaving that usually originate from office waste. The waste must be free from heavily printed paper and water insoluble adhesives.	0	2
Heavy letter 2 (HL2)	The waste is made up white printed and unprinted sheets, pastel coloured paper, trim and shaving that usually originate from office waste. The waste must be free from heavily printed paper and water insoluble adhesives.	1	2
Super mixed waste (SMW)	This grade is made up of HL1 and HL2.	1	2
Sorted office paper (SOP)	Typically made up of office waste that contains white and coloured bleached woodfree papers.	1	5
Unused kraft bags (K1)	Pre-consumer waste that is made up of multi-wall kraft bags, poly liners and wet strength papers.	0	2
New corrugated kraft waste (K3)	This is pre-consumer waste made up of new corrugated cuttings, rejects, unused boxes, etc.	0	2
Kraft corrugated containers (K4)	Post-consumer waste made up of corrugated containers.	1	5
Liquid board packaging (LBP)	Special grades liquid packaging boards. Made up of used and unused liquid packaging board with or without aluminium. The waste should contain around 50 wt. % fibre with the rest being coatings and aluminium.	0	3
Telephone directories (TD)	The waste is made up of clean telephone directories.	0	2

In the defined grades of recovered paper, prohibited materials include (PRASA, 2009):

- Metals.
- Plastics.
- Glass.
- Textiles.
- Wood.
- Sand and building materials.
- Synthetic materials.
- Synthetic paper.

There has also been provision made for the amount of waste that can be deemed as out-throws. Out-throws are all papers that are in such a condition that they are unsuitable as raw material for the recovered paper grade specified. This is dependent on the grade of the recovered paper. There is also an allowable moisture content of 10 % on paper grades and 12 % on board grades (PRASA, 2009). Any excess can be claimed back by the paper manufacturer.

3.5. Waste generation in South Africa

3.5.1. Paper to landfill

Waste generation is affected by a number of factors. These factors include geographical location, settlement type and income bracket. Waste generation is linked to urbanisation, geographical location, economic productivity and population size (Bogner et al., 2008; Meyers et al., 2014; Fiehn et al., 2005). It is very expensive to conduct a quantitative analysis of all the waste that is coming into a landfill. The cheapest and quickest method would be to model municipal waste generation (Meyers and Pieterse, 2014). The reliability of the model would then be strongly dependant on the quality of the input data.

Most municipalities in South Africa do not collect data on the amount and type of waste that is sent to landfill (Meyers and Pieterse, 2014). The estimations for waste generation in South Africa are based largely on population data. From the results of the data gathering by Meyers et al., it is evident that waste generation is proportional to income level. Higher earners generate 2 to 5 times more waste than lower income earners. The definition of the income levels has created ambiguity in literature and has made it difficult to compare the available data. Some studies looked at income levels in order to establish waste generation factors while other studies looked at residential size as the definition for income brackets. Table 3.4 shows some of the results that were obtained from the data gathered by Meyers and Pieterse (2014).

Table 3.4: Waste generation factors determined in South Africa (Meyers and Pieterse, 2014).

Income level			Comments
High (kg/capita/day)	Middle (kg/capita/day)	Low (kg/capita/day)	
1.29	0.74	0.41	Although these figures are often quoted from the 2006 State of the Environment Report, they are referenced to "Waste Generation in South Africa: Baseline Studies" done by the Department of Water Affairs (DWAF) in 1998, which could not be found. The socio-economic groups are not defined. From a DEA Integrated Waste Management Plan guidelines document, it would seem that the groups are classified according to settlement type with the following earnings: High income: > R 1 000 000 per year Middle income: R 75 000 – R 999 000 per year Low income: < R 74 999 per year It is not clear whether these earnings apply to individual or household income, but it would seem that these figures are for household income.
1.5 - 3.0 (Average 2.25)	0.7 - 1.9 (Average 1.3)	0.2 - 0.7 (Average 0.45)	Figures in brackets indicate averages. These figures are quoted from unpublished "National Framework Guidelines for Integrated Waste Management Plans" by the DEAT, 2006. Again the socio-economic groups are not defined. Separate figures are given for schools, businesses centres, restaurants, industries, construction and medical facilities.
1.85	1.1	0.45	These figures are quoted from a report by Jarrod Ball and Associates for the 2004 Bojanala Platinum District Municipality Integrated Waste Management Plan. Socio-economic groups are defined as follows: High income: > R 153 000 a year Middle income: R 38 400 – R 153 000 a year Low income: < R 38 000 a year It is not clear whether these earnings apply to personal or household income, but it would seem that the figures are for personal income.
0.7	0.4	0.32	Household generation rates (kg/household/day). Results are based on on-site measurements of household waste in Ivypark, Florapark and Sterpark in Limpopo. Waste was sampled from 325 out of 2011 households. Socio-economic groups were defined according to residential stand size: High income: > 500 m^2 Middle income: 300 – 500 m^2 Low income: < 300 m^2

From the Table: 3.4, it can be seen that the waste generation factors varies for different income brackets in South Africa. The variation maybe due to the models from which these factors were derived. Meyers et al (2014). has suggested that one of the largest ambiguities in the factors quoted by most authors lies in the definition of the income level or absence of a definition. Ogola et al (2011). defined the income level according to the residential stand size of the people living in Limpopo. This may be valid for Limpopo but the income levels would not hold if the same were applied to Gauteng or the Western Cape. Many affluent people in these areas prefer to live in apartments which would constitute to a smaller stand size.

In 2012, the Department of Environmental Affairs (DEA) had provided details of the waste generation in South Africa to determine the extent of implementation of the National Environmental Management: Waste Act (Act 59 of 2008). In this report, the DEA had quoted waste generation values in kg/capita/annum from research carried out by Fiehn et al (2005). It is very difficult to determine a single national average for waste generation per capita as some provinces are more affluent than others. From research done by Meyers et al. (2014), it was found that Gauteng and the Western Cape generated the most waste per capita. Fiehn et al. (2005). reported the national waste averages as averages per province. These averages are shown in Table 3.5.

Table 3.5: Waste generation per province (Fiehn et al., 2005).

Province	Waste generation (kg/capita/annum)	Waste generation (kg/capita/day)
Western Cape	675	1,85
Eastern Cape	113	0,31
Northern Cape	547	1,50
Free State	199	0,55
KZN	158	0,43
North West	68	0,19
Gauteng	761	2,08
Mpumalanga	518	1,42
Limpopo	103	0,28

According to Ogola et al (2000), the main sources of waste to landfill is usually derived from:

- Industrial – These wastes are derived from construction sites, food processing plants and other industrial plants such as paper mills, power plants etc.
- Households – The waste generated from households consist of a large quantity of domestic waste. Domestic waste is made up of packaging (paper, board, plastic, glass cans), leftover food among others.
- Commercial – The waste producers in this category include stores, restaurants, markets, business offices etc.
- Agricultural – This waste originate from poultry, vegetation, dairy and livestock farms. A large component of these wastes is biodegradable.
- Natural – The waste is of natural origin and it includes garden clippings and trees.
- Institutional – The waste is usually obtained from institutions like offices, schools, universities etc. and it usually comprises of paper and cartons (Ogola et al., 2011).

The figures reported in Table 3.5 consist of the total waste generation per person. For this study, the paper consumption is of interest. Figure 3.5 below reports what fraction of the waste is expected to be paper.

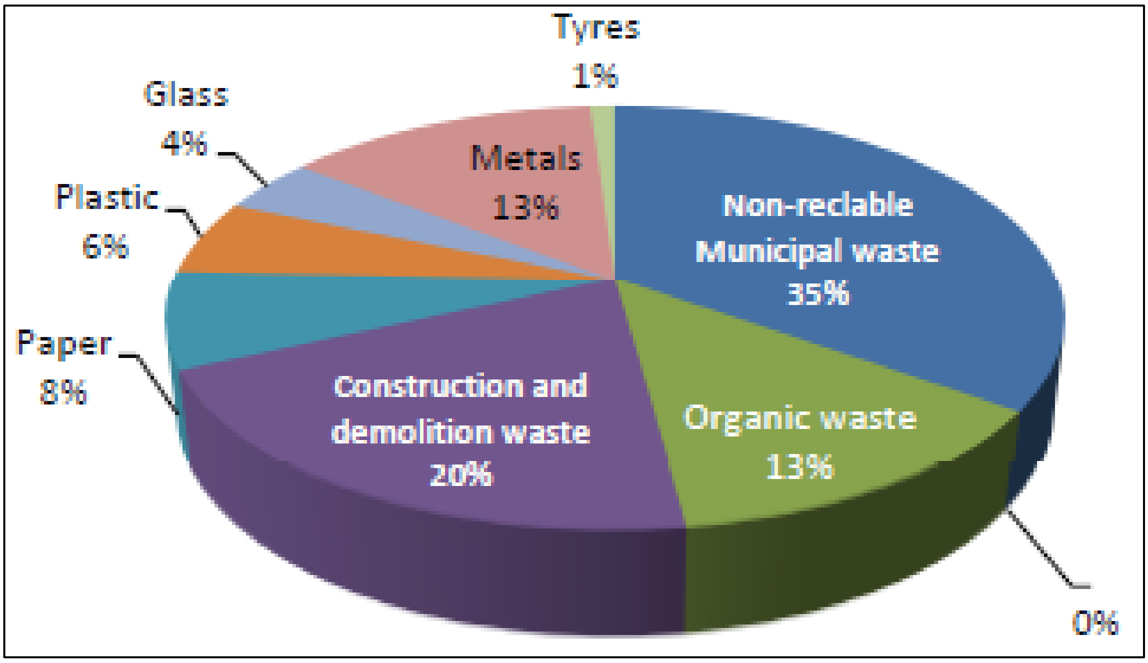


Figure 3.5: General waste composition of municipal solid waste in South Africa (Baloyi et al., 2012).

3.5.2. Landfill operation

Landfills are the final destination of all waste that is not processed again. Most of South Africa's waste is landfilled which leads to a toxic mix of all types of waste both domestic and industrial. About 90 % of the waste is considered to be general waste and most of the landfills are usually managed in a similar manner to sanitary disposal sites with some variations being employed (Bredenhann and Ball, 1998).

Two of the minimum requirements for operating a landfill are:

- Compaction – This is done to reduce the volume of the waste. Compaction is best achieved when the waste is spread out in thin layers (Bredenhann and Ball, 1998; ISWA 2010). Compaction removes void volume from the waste and it reduces the air pockets in the waste.
- Daily cover – At the end of the day, it is required that the waste be fully covered by a layer of soil. The soil is usually available from the excavations that continue at the landfill. The daily cover is usually between 0.5 m to 1 m thick depending on the type of waste (Bredenhann and Ball, 1998; ISWA, 2010). The daily cover prevents scavenging by animals and people, controls odour, reduces fire and vermin infestation risk, shed surface water and minimises the contamination of run off and windblown-litter (ISWA, 2010).

Communal landfills are usually managed using the trench technique (Bredenhann and Ball, 1998). These trenches are usually fenced and protected to prevent vehicles or people from falling in. A cell is the basic unit of landfill compacted waste. The sides are usually 1.5 m to 2 m high. There are three types of cells:

- Standard cells – There is usually sufficient cell capacity to accommodate at least a week's waste (Bredenhann and Ball, 1998; DWAF, 2005).
- Wet weather cells – These cells should have a well-drained gravel type base which would allow for vehicle access in wet weather conditions. The cell is usually close to the landfill entrance or an all-weather road and it should have enough capacity for a week's waste (Bredenhann and Ball, 1998; DWAF, 2005).
- Putrescible waste cells – These are special cells for food wastes from restaurants, food manufacturing companies, etc. The waste is immediately compacted and covered with soil or other waste to prevent odours and flies. Covering putrescible waste with other

waste prevents the need for disrupting standard operations (Bredenhann and Ball, 1998; DWAF, 2005).

Other methods of landfilling include:

- End tipping – The waste is pushed over an edge of an extended advancing face. This method is not very effective and is not permitted in a normal landfill. After many disposals, the slope may become unstable and the waste will not be sufficiently compacted (Bredenhann and Ball, 1998; DWAF, 2005).
- Area method – This method is used where the landfill does not take putrescible wastes. The waste is usually dry and spread out over a large area in a controlled manner. The wastes that are usually sent to these landfills include rubble, ash, slag, shredded fibre from mills, etc. (Bredenhann and Ball, 1998; DWAF, 2005).

3.5.3. Landfill gas emissions

Landfill gas emissions (LFG) occur by the natural decomposition of organic material in landfills. The primary components of landfill gas are methane and carbon dioxide (Jensen and Pipatti, 2000). Other smaller constituents include nitrogen, oxygen, sulphides, disulphides, ammonia, hydrogen, carbon monoxide, mercaptans, volatile organic compounds, water vapour, and several other organic gases (Senior, 1995, ISWA, 2010).

Aerobic and anaerobic decomposition are the two types of decomposition that occur in a landfill (Senior, 1995). Aerobic decomposition occurs in the presence of oxygen while anaerobic decomposition follows and it occurs in the absence of oxygen (Senior, 1995). Decomposition in the landfills occurs in distinct phases:

- Phase 1 – Aerobic.
- Phase 2 – Anaerobic non-methanogenic (acetogenic).
- Phase 3 – Anaerobic methanogenic (non-steady state).
- Phase 4 – Anaerobic methanogenic.
- Phase 5 – Aerobic (ISWA, 2010).

Aerobic decomposition (AD) occurs immediately when the waste is brought to landfill. The decomposition is fuelled by the presence of entrained oxygen. The gaseous product from AD is made up of large volumes of carbon dioxide and no methane. The duration of aerobic decomposition can last up to six months and it is influenced by the compaction of the waste and the displacement of oxygen in the waste by methane/carbon dioxide rich landfill gas from older waste below. Once the entrained oxygen has been exhausted, anaerobic decomposition (AAD) sets in with acetogenic formation. The bacteria begin to ferment and hydrolyse the organics in the waste to form acids (ISWA, 2010).

The decomposition then enters an extended methanogensis phase when the O_2 is depleted. Methanogenic microorganisms thrive in an oxygen deficient environment. Anaerobic gas production will continue until the organic material is consumed or oxygen is reintroduced into the system. The reintroduction of O_2 will not stop methane production but it will retard it. This is categorised by phase 5 (ISWA, 2010).

The volume of landfill gas that is produced is a function of all the organic waste available for decomposition (ISWA, 2010, Jensen and Pipatti, 2000). The typical concentration of LFG is indicated in Table 3.6.

Table 3.6: Landfill gas composition (ISWA, 2010).

Component	**Composition (vol. %)**
Methane (CH_4)	40 - 60
Carbon Dioxide (CO_2)	35 - 45
Oxygen (O_2)	< 1 - 5
Nitrogen (N_2)	< 1 - 10
Hydrogen (H_2)	< 1 - 3
Water Vapour (H_2O)	< 1 - 5
Other Constituents	< 1 - 3

Table 3.6 shows that a large portion of LFG is methane and with the appropriate conditions, the methane composition can go up to 60 %. The aerobic and anaerobic reactions that occur to produce LFG respectively are:

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O + \text{Biomass} + \text{Heat}$$

1 kg 0.64 kg 0.88 kg 0.34 kg 0.40 kg 9300 kJ

Equation 3.1

(Peck, 2007)

$$C_6H_{12}O_6 \rightarrow CH_4 + CO_2 + \text{Biomass} + \text{Heat}$$

1 kg 0.25 kg 0.69 kg 0.056 kg 632 kJ

Equation 3.2

(Peck, 2007)

Equation 3.1 and Equation 3.2 are the expected chemical reactions that occur in a landfill using cellulose as an example. Anaerobic digestion occurs at a lower temperature than that of the aerobic reaction. This is indicated by the lower heat evolution in Equation 3.1.

Jensen and Pipatti, (2000) also described landfill gas composition on a time line in Figure 3.6.

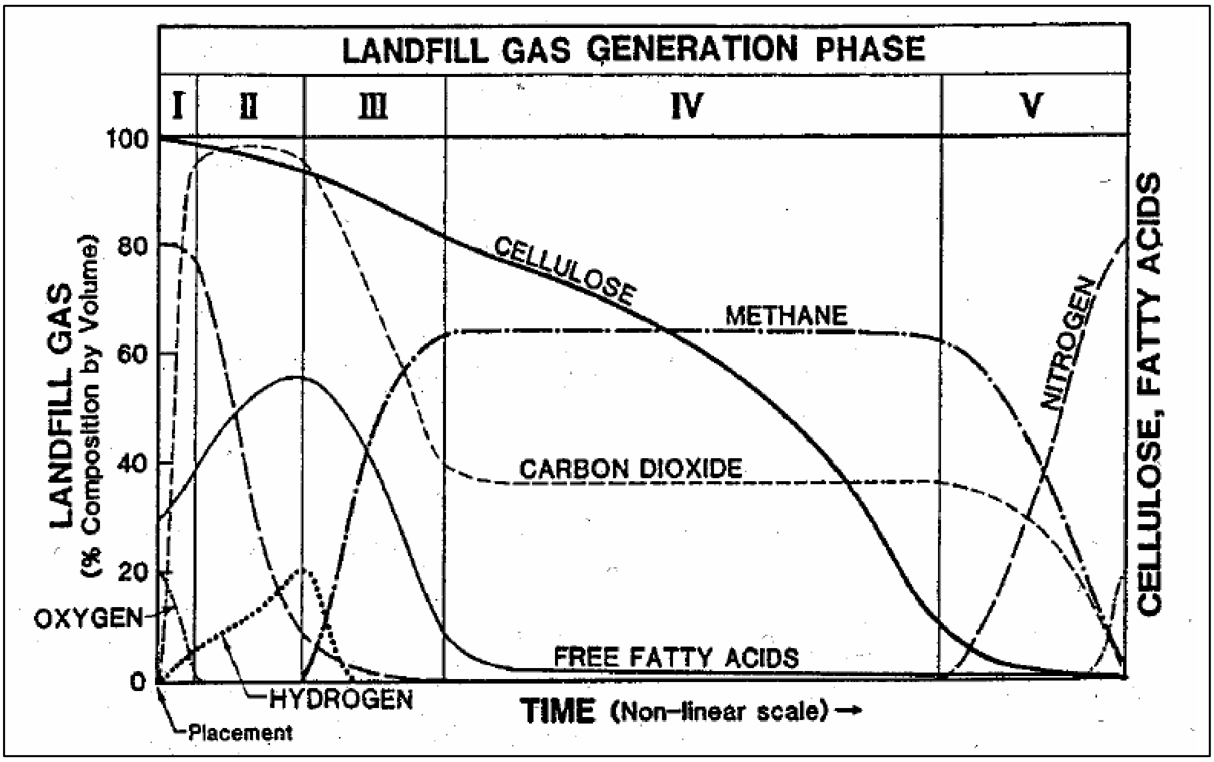


Figure 3.6: Composition of landfill gas in different phases of the degradation process (Jensen and Pipatti, 2000).

- Phase 1: Oxygen- and nitrate-reducing phase – duration range: Hours – 1 week.
- Phase 2: Acidic phase – duration range: 1 – 6 months.
- Phase 3: Unstable methane generation phase – duration range: 3 months – 3 years.
- Phase 4: Long term stable methane generating phase – duration range: 5 – 50 years.
- Phase 5: Humus-generating and/or sulphide oxidation phase – duration: 1 – minimum. 40 years (Jensen and Pipatti, 2000).

3.5.4. Landfill gas estimation

The Intergovernmental Panel on Climate Change (IPCC) has recommended two methods that can be used for the estimation of landfill gas emissions. The first method is known as the theoretical gas yield which uses a mass balance approach. The second method is a theoretical first order kinetic model.

The main drawback with the first method is that it does not take into account the time variation in the waste disposal site. The assumption is made that all the methane is released in the year of disposal. The second method suggested by the IPCC is a more accurate estimation for annual GHG emissions. The drawback to this method is that many countries are unable to get the necessary data to determine the proper basis for emissions inventories with a reasonable accuracy. The 2006 IPCC Guidelines for greenhouse gas emissions also strongly discourage the use of the mass balance approach as the results yielded from the mass balance approach are not comparable with any of the other theoretical models and laboratory studies (Pipatti and Vieira, 2006). Kumar at al. (2004) suggested that the first order kinetic model be applied for the estimation of landfill gas generation. The first order kinetic method had produced more realistic results when compared to that of the theoretical gas yield. Kumar at al. (2004) suggested that from the results produced, the first order kinetic method for landfill gas estimation could be used on a global basis (Kumar et al., 2004).

Scharff et al. (2006) suggest that a first order model would be sufficient for the estimation of landfill methane generation. The IPCC model is not intended for the use on individual landfills. Some landfills produce more methane than other landfills nationally. These outlying landfills counterbalance each other if the landfill emissions are considered nationally. The outliers may be a result of the type of waste that is deposited into the landfill and the local climate (Scharff and Jacobs, 2006).

Scharff et al. (2006) also recommends three models for the estimation of landfill gas emissions.

- First order model – A first order model takes into account the depletion of waste over time. The LFG formation is expected to behave exponentially in time. Landfill gas using this method is estimated from the degraded organic carbon in the waste (Scharff and Jacobs, 2006).
- Multi-phase model – Waste contains different organic fractions. The multi-phase model can take into account the waste compositions as different organics degrade differently. The model has eight waste categories and three distinguished fractions. The LFG is

calculated separately for each waste fraction. These are then summed for the total LFG production. It is also a first order model (Scharff and Jacobs, 2006).

Land Gem Model – This model was developed by the United States (US) Environmental Protection Agency. The mass of methane generated is determined by using the methane generation capacity coupled with the amount of waste deposited. The waste compositions used to develop this model are based solely on the composition of municipal waste in the USA (Scharff and Jacobs, 2006). The IPCC first order kinetic model was used in this study to estimate landfill gas emissions. It is well applied on a national level and takes into account the time delay in degradation. The model does not assume that everything would decay in the first year releasing methane. This makes the IPCC first order kinetic model a more attractive method for estimating landfill gas emissions for a single year as this study is confined to the boundaries of 2011.

3.6. Landfill gas recovery

Methane from landfills has the potential of being applied for the generation of electricity. Some landfills choose to flare the methane without generating electricity to reduce the potency the methane would have in the atmosphere. Methane is the second largest GHG contributor. It has a GHG potency of 25 times that of carbon dioxide and a 12 year life span in the atmosphere (Bogner and Lee, 2005; Pachauri and Reisinger, 2007). A reduction in the methane emissions from various sources will see a reduction in methane concentrations in the atmosphere within a decade (Bogner and Lee, 2005).

3.7. Carbon Sequestration

Material balances in the forestry and paper sector since the 1950s have looked mainly at wood consumption (Mantau, 2015). Due to the drive towards cleaner production and the constant need to reduce GHG emissions, recent material flow studies have looked at the forestry products industry to sequester carbon (Mantau, 2015). Carbon sequestration is the long term lock-up of the carbon from carbon dioxide in other forms of material made up of carbon (Tonn and Marland, 2007). This aids in the mitigation of global warming by storing the carbon from carbon dioxide that could have potentially remained in the atmosphere. Carbon sequestration is a proposed method to reduce the rate of carbon dioxide accumulation in the atmosphere. A carbon sequestration of over 20 years would aid in mitigation of global warming (Metz et al., 2005).

Carbon stocks in the wood products sink is said to be increasing globally (Hashimoto et al., 2002). An estimation was made that the global carbon sequestration in wood products amounted to 139 Tg of carbon in 1990 (Hashimoto et al., 2002). The Kyoto Protocol requires that industrialised countries reduce their carbon emissions to at least 5 % below the 1990 levels. This may be achieved by taking into account the carbon removals to landfill, the storage by forests and other carbon sinks (Hashimoto et al., 2002).

A study conducted by Woodbury et al. (2007) found that the United States sequesters around 149-330 Tg of carbon per year. Urban trees, forests and wood products store around 65-91 % of the carbon (Woodbury et al., 2007). Woodbury et al. also found that the largest carbon sequestration rates are not necessarily the largest stocks. Landfills were found to hold 3 % of the total stock but sequestered up to 27 % of the carbon. Conversely, forest ground was found to stock 49 % of the carbon but had a sequestration rate of only 2 % (Woodbury et al., 2007).
These studies all support the rationale that the forestry products sector has the potential to sequester large amounts of carbon. The main focus of these studies was to conduct a material balance which would enable them to track and trace carbon flows and stocks.

3.8. Carbon flow related issues in the converting and end user stages of the paper industry

With the industry now facing the looming financial difficulties that may be exacerbated by the Carbon Tax Policy (DNT, 2013), it is essential to prove the industry's sustainability, positive attributes and negative drawbacks. These issues include:

- The carbon sequestration in forestry and paper products. The industry is possibly a carbon positive activity.
- Greenhouse gas emissions that arise from decomposition of paper products.
- Alternative uses or final disposal of paper products.
- Waste management.

3.9. Material flow analysis for paper products

Material flow analysis is a broadly applied method with much development still being carried out on the concept alone. There have been a number of MFAs and LCAs conducted specifically for the forestry, pulp and paper industry. These studies have been carried out in great detail in North America, Europe and Asia. These studies were conducted to prove the carbon positive nature of, or to drive the idea of sustainable production for the forestry, pulp and paper industry. The results of some MFAs were considered in the realm of industrial ecology where substance flows, processes and pathways are considered. The studies aimed to mitigate or limit potential negative effects of substances or the process itself.

3.9.1. Material flow analysis of wood and paper in Cape Town (Nissing and Von Blottnitz, 2007)

Different paper products have very distinct properties according to their uses. It is these properties that allow for the wide variety of uses in the industry and society. Nissing et al. conducted an MFA in the City of Cape Town to determine if wood and paper products had the potential to be redirected and used as a renewable energy resource. The method employed by Nissing et al. was that of the classical approach which included data collection from available publications and organisations and telephonic interviews. A flow chart of all the relevant flows was drawn up and the main energy sources were identified within the existing material and waste streams. The study of the relevant material flows determined that 70 % of Cape Town's renewable energy target (which aims for 10 % renewable energy) can be achieved by the year 2020. The redirection of wood fibre based flows can be harnessed from various forestry product flows in the Cape Metropolitan area with the aid of innovative transformation technologies (Nissing and Von Blottnitz, 2007).

3.9.2. Carbon balance assessment of harvested wood products in Japan (Kayo et al., 2014)

Kayo et al. conducted an assessment of the carbon balance of harvested wood products (HWP) in Japan. Harvested wood products from buildings, furniture, paper and energy were taken into account as the fibre flows between the regions of Japan. A model was constructed to assess carbon projections (both flows and sinks) by the year 2050. Two scenarios were simulated with one considered to be business as usual and the other was considered to be a wood promotion period from 2004 to 2050. The model found that by promoting the use of domestic wood products, the carbon stock acted as a carbon sink year on year. The business as usual model showed a decrease in the use of harvested wood products which led to the domestic carbon stock becoming an emission source (Kayo et al., 2014).

3.9.3. Material flow analysis of paper in Korea (Hong et al., 2011)

Hong et al. conducted an MFA in Korea in an attempt to develop a system of mass balance equations that would allow for future ease when conducting an MFA in the sector. The production processes were modelled using the available statistical data, raw materials inputs, compositions and production yields. The material flows of paper were then analysed based on the derived calculation model. Accuracies were determined using mean absolute error and mean absolute percent error. The system of mass balance equations gave a relatively accurate model (Hong et al., 2011).

3.9.4. Analysis of the paper and wood flow in the Netherlands (Hekkert et al., 2000)

Hekkert et al. used the STREAMS methodology to determine the sustainability of the wood and paper industry. The STREAMS methodology consisted of supply and use data tables which describes a country's economy by looking at the supply and use of materials, products and services and the consumers (Hekkert et al., 2000). Materials in this approach were tracked through the extraction of raw materials through to final consumption and eventual disposal. STREAMS is a new method for analysing material flows through society. Hekkert et al. found that the largest contributor to the paper consumption came from packaging consumption. Households were the largest consumer of paper and wood products. Hekkert et al. also found that the recovered paper recovery rate reported was incorrect. The study found the recovery rate to be 45 % while the reported value was 51 % (Hekkert et al., 2000).

3.10. Summary

Chapter 3 discussed the literature associated with this study. The paper converting industry was discussed in detail with the potential carbon sinks and flows being identified. The processing of paper into the various products were also described. Recycling methods and waste generation in South Africa. Landfill operation, gas emissions and landfill gas estimation methodologies were highlighted. Other material flows similar to this study were also discussed.

Chapter 4: Methodology

This chapter will discuss the material flow analysis approach that was applied. The assumptions that were made in this study have also been detailed and the scenarios that were developed have been briefly described in this chapter.

The process of an MFA involves the collection of data in order to quantify flows and stocks of a substance in a well-defined geographical area over a specified time period. This requires the collection of data and the possible need for estimations of flows and stocks from correlations when the raw data is not available.

4.1. Problem definition and substance selection

In order to combat global warming, the South African government plans to implement carbon tax in 2018 to force industries to become more efficient in controlling emissions and energy consumption. The forestry and paper products industry, among other industries in South Africa has come under tremendous pressure as cost of operations escalates and the additional carbon tax will increase costs. The introduction of the carbon tax will threaten the economic and social sustainability of the industry. The forestry and paper products industry provides employment for many people. The industry caters for a wide variety of employment opportunities for people of varying educational levels such as engineers, operators, recovered paper collectors, etc. (Sappi, 2015). The forestry and paper products industry derives fibre, which is its largest feedstock, for production from plantation forests which are renewable. In order to maintain international competitiveness, the industry will need to substantially prove that it is carbon neutral or that large quantities of carbon are sequestered through the activities of the forestry and paper products. Carbon sequestration is an important aspect in greenhouse gas mitigation. Carbon was the substance selected in this study as it is the largest traceable component in the forestry and paper products sector. Carbon also plays an important role in showing the sustainability of the industry.

4.2. System definition in both time and space

This study is part of a series of five which put together forms an MFA for the whole forestry, pulp and paper industry. The boundary was defined to be the whole of South Africa as the industry's sustainability affects the whole country. To ensure that all the studies have the same time span and definition, the calendar year of 2011 was selected as the year of choice. This study specifically looked at the paper converting and recycling sectors together with the end user fate of paper flows.

4.3. Identifying and quantifying relevant stocks, flows and processes

This is easily understood with the aid of a flow diagram which is shown in Figure 4.1

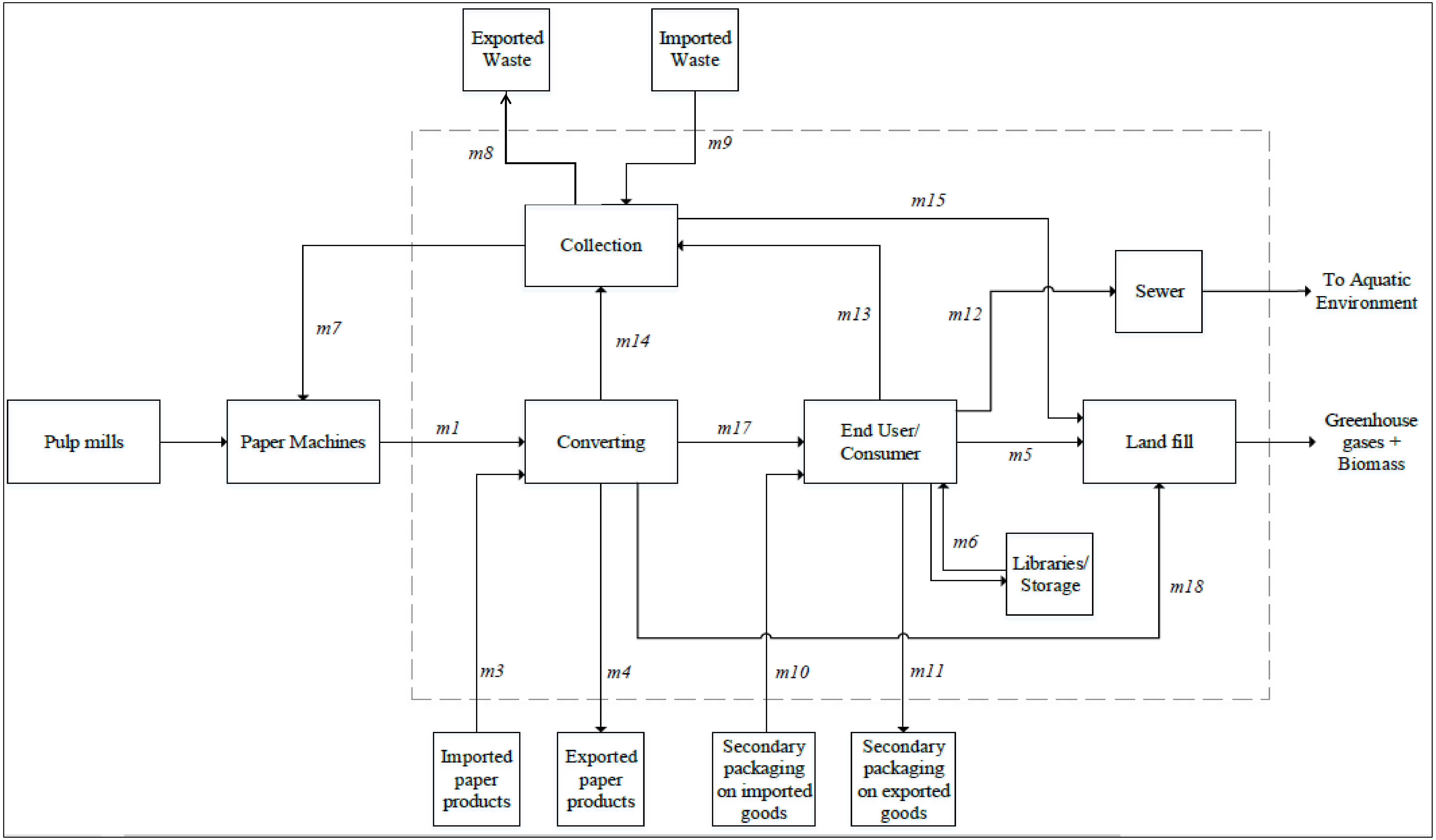


Figure 4.1: Process flow of paper-based carbon diagram for this study.

The flows of paper products were broken down according to the expected carbon pathways. Since this was done nationally, import and export data was also essential.

4.3.1. Process description

Paper is produced from wood pulp, bagasse pulp and recovered fibre on various paper machines around South Africa. It is considered to be one of the inputs to the whole process. The paper produced is usually passed to the converters to produce end products such as toilet rolls, boxes, etc. Paper is also imported by converters to make specialised or more cost effective products. Some of the paper products produced in South Africa are exported to other countries while the rest is used locally. Converters also generate waste which comes from reject production and offcuts. This type of waste is known as pre-consumer waste and it is normally sold or given to a recovered paper collection company. At times the reject production or waste may not be suitable for recovered paper collection due to contamination such as oils. This is then expected to be sent to landfill.

Products are then packaged or used as packaging and sold to the consumer. Consumers also make use of products that are imported. In most cases, the paper packaging material used to package those products is sourced in the country of origin. South Africa also exports products which contain packaging. This flow of paper packaging in and out of South Africa is expected to have an impact on the MFA. Only secondary packaging material was considered in this study.

Upon end user consumption, paper products have one of three fates. The paper is either recovered by a collector, it may be sent to landfill/sewer or it may go into storage. The carbon in the paper that goes to landfill and sewer may further be broken down to form methane and carbon dioxide.

The availability of recovered paper in South Africa has also come under pressure as the demand for recovered paper has increased. The recovered paper, particularly old corrugated containers (OCC), is a feedstock to some paper machines. The net flow of recovered paper into and out of the country was taken to be significant and was included in the MFA. Recovered paper that is collected from the end user is then sorted. After sorting, recovered paper that is unsuitable for paper production should ideally be sent to landfill. Due to the large informal communities in South Africa, a portion of paper, particularly newsprint and old magazines are at times used as a fuel source or as toilet paper. The quantification of this stream is very difficult based on the non-availability of data and is, therefore, not shown in Figure 4.1.

4.4. Data collection

This section deals with the sources of data and methods used to obtain data that was not readily available. The data obtained makes up the stocks and flows in the system. From Figure 4.1, the essential carbon sources of data were identified to be:

- The paper input into the converters from the paper machines (PAMSA).
- Paper imported and exported for converting (SARS).
- Secondary paper packaging that was imported or exported with goods (SARS).
- Libraries and storage.
- Recovered paper collected by collectors (PRASA).
- Recovered paper imported and exported by collectors (PRASA).
- Paper that is sent to landfill or sewer (Factors reported in literature by Fiehn et al. (2005) and population statistics from Statistics South Africa was used to estimate the amount of paper sent to landfill)
- Carbon to atmosphere in the form of methane or carbon dioxide which was emitted from landfill.

4.5. Assumptions

- Rural waste such as newspapers, packaging and sanitary papers, was assumed to be burned or buried. There was no available data on the quantity of rural waste that was burned or buried. It was assumed that the contribution of this flow would not have an effect on the carbon flow analysis and it was ignored.
- The paper going to landfill from the end user was estimated using factors reported by Fiehn et al. (2005). The study was published in 2005 and it was assumed that the factors would provide a reasonable estimation for 2011.
- Greenhouse gas emissions from landfill were determined using IPCC guidelines. Data for application of the guidelines were only available at Tier 1 level. The results obtained from this study were assumed to provide a reasonable estimation for GHG emissions from landfill due to the presence of paper.
- It was assumed that all toilet paper would go to sewer and that all tissue grades such as industrial wipes, household wipes and facial tissue goes to landfill. It was also assumed

that the tissue grades were included into the waste factors reported by Fiehn et al. (2005).

- The GHG emissions that would result from the decomposition of paper that goes to sewer were considered negligible in this study. Most of the sewage would be treated and then pumped out to an aquatic environment.
- The largest contribution to pre-consumer waste is newsprint and corrugated board. It was assumed that the contribution of the other paper grades to pre-consumer waste was negligible.
- Offcuts and waste paper from converting that go to landfill was assumed to be zero. The recovered paper from converting was assumed to be clean enough to be used as feedstock for the paper mills. The recovered paper was assumed to have no metal, plastics, glass and other prohibited materials. It was also assumed that there was no out-throws.
- It was assumed that all the recovered paper from recycling collection sites was baled and sold to the paper mills or other customers. In order to maximise yield, the recycling collection sites would minimise out-throws resulting in less or no waste that would go to landfill.

4.6. Error analysis

Uncertainty or errors in results usually arise from a lack of measurements. Theoretically, the error can be reduced by improving the method of measurement or by obtaining more measurements. The limitation to reducing error comes back to the required approach that can be used for error reduction. The resources and capital required to reduce an error are the usual limitations.

There are usually two areas for uncertainty in measurements:

- Data can be lost from statistics that are reported on manufacturing processes and the use of manufactured goods (Danius, 2002).
- National waste emission data, models or factors that were developed to estimate emissions and waste generation based on a small sample space (Danius, 2002).

Error in results can best be described by the use of intervals, standard deviation and other forms of statistical evidence (Danius, 2002). Statistics and data from most sources are usually not accompanied by an error. However the data are still be expected to carry some sort of uncertainty. Hedbrant and Sörme (2001) developed a model for determining the uncertainty of input data. The model (which shall be referred to as the HS model) was designed to assign an uncertainty to input data based on the source of the data. The uncertainty interval is described by asymmetric intervals. This was done to avoid a negative lower limit and to present the uncertainty as magnitude as opposed to a percentage point. The original method was developed for heavy metals and it was modified by Danius to fit data concerning nitrogen flows. A 0 level and a new level 3 were added to enable higher resolution for uncertainties as shown in Table 4.1. The level 10 described by Hedbrant and Sörme (2001) was removed as it looked at historical data as far back as the 19th century. A sample of the uncertainty calculation is shown in Appendix A.

Table 4.1: Uncertainty intervals with source of information and examples (Danius, 2002).

Level	Source of information	Example
0 (interval */1)	Values in general (from literature).	Molecular weight, e.g. N_2, NO_2.
1 (interval */1.1)	Official statistics on local, regional and national levels.	Number of households, apartments, and small houses.
	Values in general (from literature).	Nitrogen contents in products.
	Information from facilities subjected to permit requirement.	Nitrogen emissions from facilities.
2 (interval */1.33)	Official statistics on regional and national levels.	Amount of harvest (kg), different grain per hectare.
	Values in general for content (from literature or on request).	Nitrogen contents for products, e.g. wood, organic waste.
3 (interval */1.5)	Modelled data for the municipality.	Emissions of NOx from vehicles.
	Information on request from authorities.	Number of egg produced per year.
4 (interval */2)	Official statistics on national level downscaled to local level.	Harvest (kg) grain per hectare.
	Information on request from authorities.	Nitrogen emissions from facilities.
5 (interval */4)	Values in general for flows (from literature).	Emissions of NH_3 from livestock farming.

Table 4.1 above is the HS model which was modified by Danius. The asymmetric intervals are described by "*/ Z" means that for input data X, the lower limit is X/Z and the upper limit is X*Z.

4.7. Greenhouse gas emissions estimations

The largest source of GHG emissions from waste paper was determined to come from landfills. The paper deposited to landfill was determined using factors from literature and the GHG emissions were determined using the 2006 IPCC Guidelines. These guidelines can be found in Appendix B. Carbon dioxide emissions from landfill are not considered in the IPCC guidelines as it is derived from a biogenic source. The actual carbon dioxide emissions were determined based on the amount of methane that was generated. This calculation is shown in Appendix B, Equation B5.

4.8. Scenario analysis

In this study, three scenarios were considered.

- The first scenario looked at the country being able to recycle almost all of the waste paper available with only tissue paper not being suitable for recovery. The calculated rate of accumulation was maintained (libraries and storage term). This scenario was further broken down by looking at tissue and board production separately. Tissue machines normally use heavy letter one or heavy letter two as a feedstock while the board machines use a mixture of recovered paper depending on the product. Liner and fluting machines usually use K3 and K4 recovered fibre.
- The second scenario looked at the country being able to achieve 100 % recovery of all paper waste except tissue products. The paper machines would consume the same amount of recycled material that would be required for normal production in 2011. The rest of the waste would then be burnt in a multi-fuel boiler for electricity/steam generation.
- The third scenario looked at an increase in the export of waste paper by 100 %, a 10 % increase in capacity to process recycled material, the substitution of bagasse for recovered paper and a maximum recovery rate of 65 % being achieved in the country.

The scenarios were developed based on local and global trends. The contributing factors to these scenarios were the greenhouse gas mitigation, supply and demand for waste paper and the possible move to use biofuels such as paper and bagasse for electricity generation.

4.9. Presentation of results

The result of this study will be presented in tables and in the form of Sankey diagrams. This will make for ease of reading and the Sankey diagrams will allow the reader to easily see the flow quantities.

Chapter 5: Results and discussion

This chapter presents and discusses the results of the material flow analysis. The results are presented in flow diagrams and in tables. Three possible scenarios are also discussed in this chapter.

5.1. Overall mass balance

Figure 5.1 looked specifically at the flows and stocks in the country-wide mass balance. The collection process is not the end fate of the paper as this process aims to feed paper back into the system. Most of the paper derived from collection is usually sent back to the paper machines for paper production.

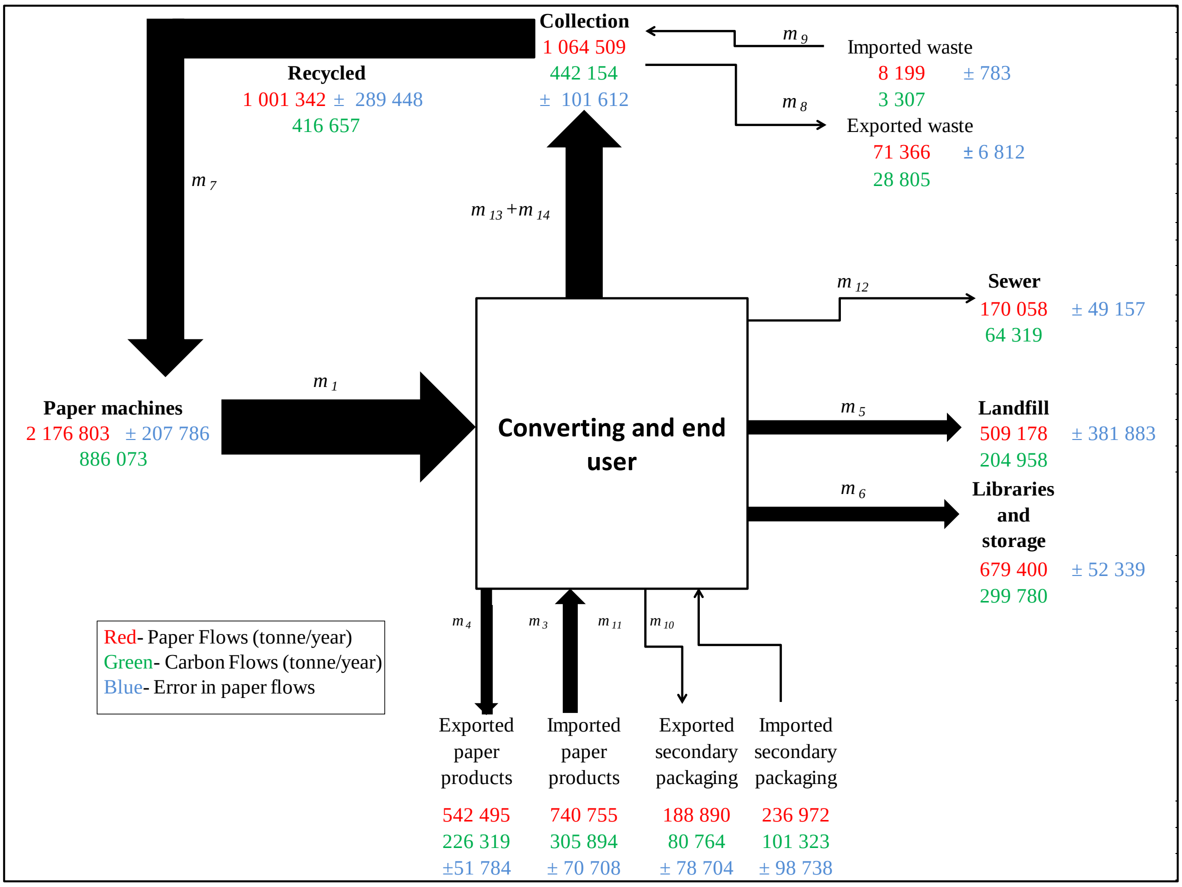


Figure 5.1: Simplified block diagram of inputs and outputs through the process for the 2011 calendar year.

Figure 5.1 shows that 1 001 342 tonnes of paper is recycled back into the system. This contributes to 416 657 tonnes of carbon per year being put back into the paper industry by recycling. Libraries and storage stores 679 400 tonnes of paper which locks up 299 780 tonnes of carbon per year.

5.2. Converting sector mass balance

Figure 5.2 is a flow diagram of the converting sector. The stream coming of the paper machines has a rich mixture of various grades of paper. These grades were broken down into six major categories. The paper and carbon flow rates of the streams can be found in Table 5.1 and Table 5.2 respectively.

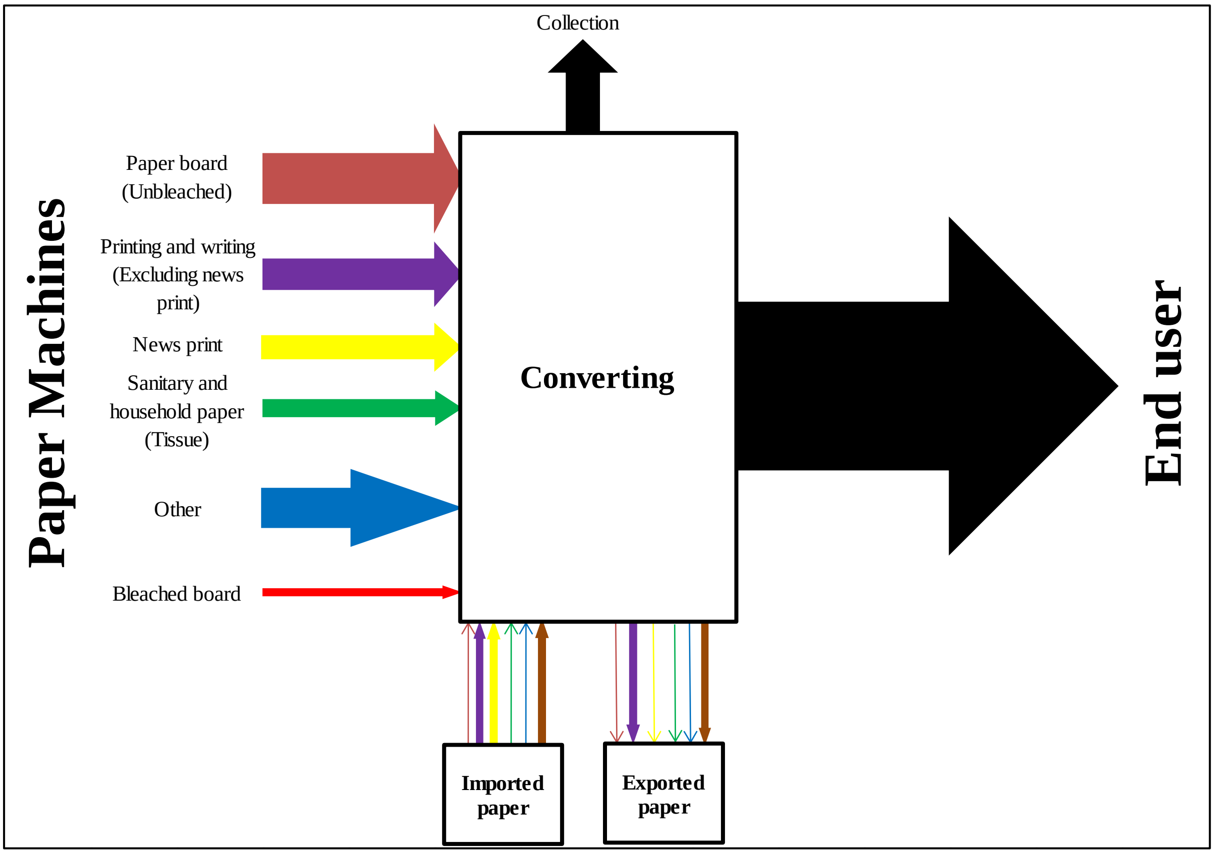


Figure 5.2: Flow diagram of the converting sector.

Table 5.1: Paper flows around the converting sector (PAMSA, 2011; PRASA, 2011, SARS, 2011).

Different grades of paper (Paper Flows)	Produced in South Africa (tonnes)	Imported to South Africa (tonnes)	Exported from South Africa (tonnes)	To Collection (Pre-consumer) (tonnes)	Arrow colour key
Newsprint	316 725	38 883	69 615	21 535	
Paperboard (unbleached)	1 047 555	105 040	313 850	58 712	
Paperboard (bleached)	27 876	281 262	24 114	19 952	
Sanitary and household paper (tissue)	219 000	69 127	11 384	-	
Printing and writing (excluding newsprint)	474 236	10 167	7 725	-	
Other	91 411	236 276	115 808	-	

Table 5.2: Carbon flows around the converting sector.

Different grades of paper (Carbon Flows)	Produced in South Africa (tonnes)	Imported to South Africa (tonnes)	Exported from South Africa (tonnes)	To Collection (Pre-consumer) (tonnes)	Arrow colour key
Newsprint	127 259	15 623	27 971	8 653	
Paperboard (unbleached)	447 907	44 912	134 194	25 104	
Paperboard (bleached)	11 919	120 260	10 311	8 038	
Sanitary and household paper (tissue)	82 829	26 145	4 305	-	
Printing and writing (excluding newsprint)	179 364	3 845	2 922	-	
Other	36 796	95 108	46 616	-	

South Africa produces a large variety of different paper grades. These paper grades may be woodfree or wood-containing paper. Some speciality paper grades are imported as the volumes used in the country are so small that full scale production may not be feasible. Paper going to converting from the paper machines is turned into final products such as toilet rolls, newspapers, boxes, etc. Production of these products results in a certain amount of spoilage or waste (pre-consumer waste). Pre-consumer waste is sent from converting straight to recycling. This waste is of a higher quality and is usually sold at a higher price. In this study, only the generation of corrugated waste and spoilt newsprint from printing houses were accounted for. These two grades were selected as newsprint; fluting and linerboard contribute the highest fraction to pre-consumer waste. The waste generation from a corrugator and box converting plant was found to be 7 % on average of the total throughput of the plant (Kowlassur, 2016). From an Australian study by the Australian Environment Business Network and the Printing Industries Association, the spoilage on printing presses was found to be 7.53 % on average (Australian Environment Business Network and the Printing Industries Association, 2003).

5.3. End user mass balance

Figure 5.3 is a flow diagram of the end user or consumer stage. The stream coming out of converting was depicted in black as it has a rich mixture of various end user products. These products include packaging products such as corrugated boxes, liquid packaging, wrapping paper; sanitary products such as toilet paper, kitchen wipes, hand towels; writing and printing paper products such as books, magazines, newspapers, etc. The paper and carbon flow rates of the collection stream was broken down into four classifications that is used to classify paper collected for recycling in South Africa. The paper, carbon flow rates and the arrow colour key for Figure 5.3 can be found in Table 5.3.

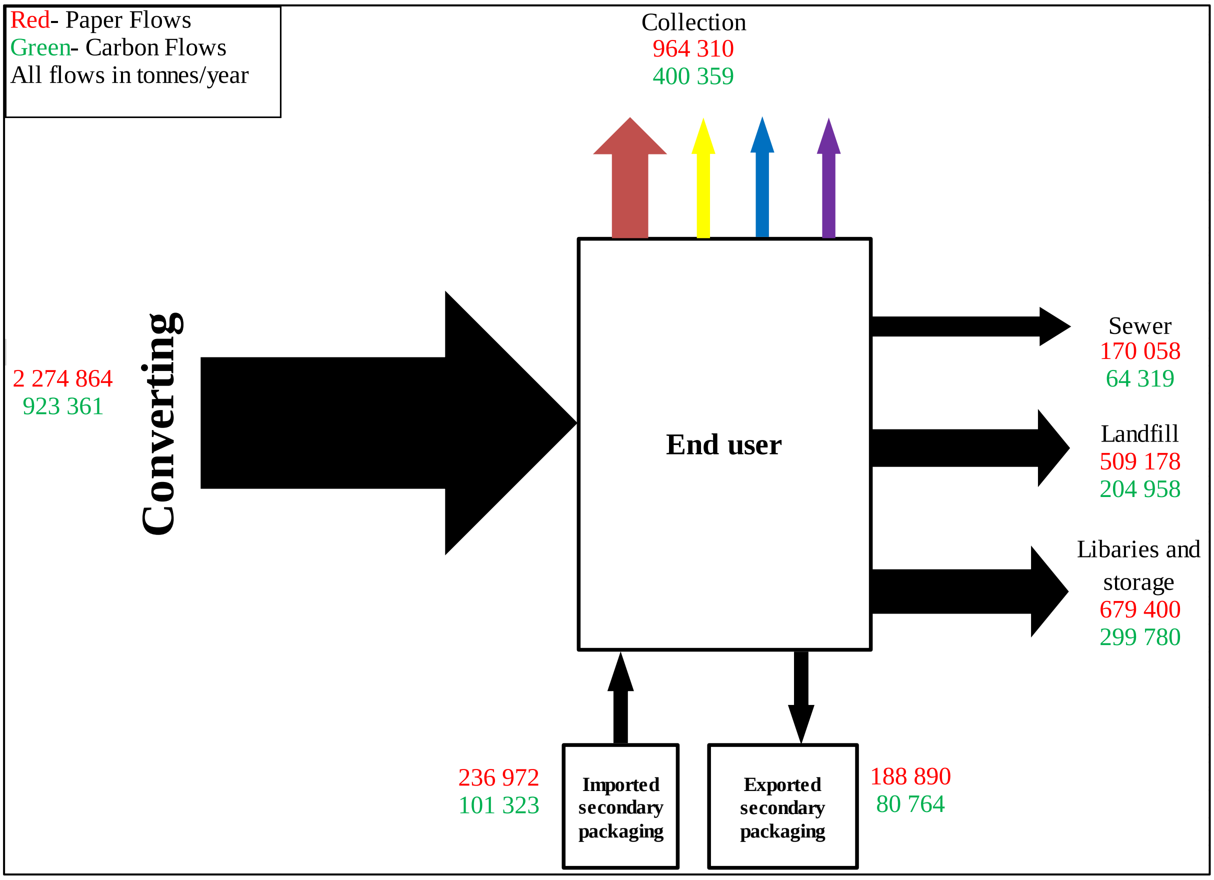


Figure 5.3: End user mass balance block flow diagram for the 2011 calendar year.

Table 5.3: Recycled paper and the respective carbon masses that was collected in South Africa for 2011(PAMSA, 2011; PRASA, 2011).

Different grades of recovered paper	**Paper flows (tonnes/year)**	**Carbon flows (tonnes/year)**	**Arrow colour key**
Newsprint and magazines	149 622	60 117	
Old corrugated containers (K3 and K4)	578 067	247 659	
Office and graphic papers (Usually HL1 and HL2)	109 545	41 432	
Mixed and other papers (Usually IMW and CMW)	127 076	51 152	

The end user is the most complicated stage of the whole process. Paper products fed in from the converter have one of three fates. The paper may be stored, disposed of or recycled. Paper that is sent to sewer comes largely from toilet paper. It was assumed that all facial tissue would go to landfill and that all the toilet paper would go to the sewer. Through communication with the process development manager at the Twinsaver group, it was found that 25 % of Twinsaver's total production was facial tissue, serviettes, household and industrial wipes (Steyn, 2016). The rest of the production was toilet paper.

In the statistics provided by PRASA, it is assumed that the net contribution of secondary corrugated packaging being exported and imported into the country can be considered zero. This is misleading as a study conducted by Bothma in 2013 found that PRASA's assumption was incorrect as the net contribution for the year 2011 was 48 082 tonnes imported (Bothma, 2015). Bothma's conclusion was considered as correct and his findings were applied to this study. This is a significant contribution as it affects the overall recycling rate in the country.

The amount of paper that is kept in libraries and storage is largely controlled by the end user. Paper products that are usually kept in storage include packaging, books and documents. Packaging is kept for shorter periods of time as opposed to books and documents that contain valuable information. There is constant movement of paper between storage and end user. From this study, it was noted that 299 780 tonnes of carbon was kept in storage for 2011. This movement is assumed to be unsteady.

5.4. Collection mass balance

Figure 5.4 is a flow diagram of the collection stage. The stream that is recycled back to the paper machines is a rich mixture of old corrugated containers, newsprint, printing and writing papers, etc. The paper and carbon flow rates of the collection stream was broken down into four classifications that are used to classify paper collected for recycling in South Africa. The paper flow rates and carbon flow rates can be found in Table 5.4 and Table 5.5 respectively.

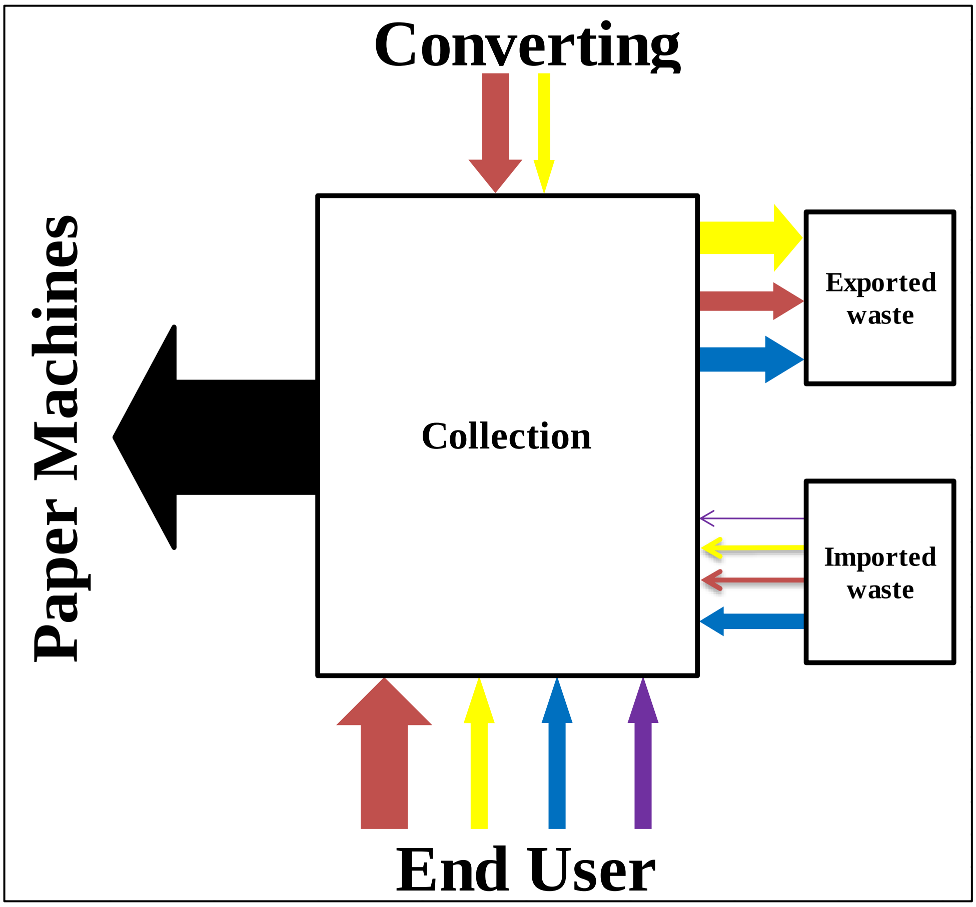


Figure 5.4: Collection mass balance block flow diagram.

Table 5.4: Paper flows through the collection sector (PAMSA, 2011; PRASA, 2011).

Different grades of waste paper	Exported waste (tonnes/year)	Imported Waste (tonnes/year)	End user (Post consumer) (tonnes/year)	Converting (Pre-consumer) (tonnes/year)	Arrow colour key
Office and graphic papers (Usually HL1 and HL2)	0	21	103 545	-	
Newsprint and magazines	63 633	246	149 622	21 735	
Paperboard (Bleached and unbleached)	4 957	303	578 067	78 664	
Mixed and other papers (Usually IMW and CMW)	2 776	7 630	127 076	-	

Different grades of waste paper	Exported waste (tonnes/year)	Imported Waste (tonnes/year)	End user (Post consumer) (tonnes/year)	Converting (Pre-consumer) (tonnes/year)	Arrow colour key
Office and graphic papers (Usually HL1 and HL2)	0	8	41 432	-	
Newsprint and magazines	25 568	99	60 117	8 653	
Paper board (Bleached and unbleached)	2 120	129	247 659	33 142	
Mixed and other papers (Usually IMW and CMW)	1 117	3 071	51 152	-	

Table 5.5: Carbon flows through the collection sector.

Recycling contributes to a carbon lock up of 416 657 tonnes of carbon in total. Paperboard constituted 61.7 % of the paper recovered. Most of the paperboard recovered was OCC which is used for the production of corrugated boxes. The smallest contribution to recycling was made by printing and writing papers. This is consistent with the global trend as the world is now moving into a digital era which has led to a decrease of the demand for fine paper and newsprint across the world. Recovered printing and writing papers are usually used in the production of tissue. Tissue paper normally ends up in landfill or in the sewer. It is not recycled due to hygienic reasons. Tissue is usually too soiled and unsuitable for reprocessing.

5.5. Landfill and sewer

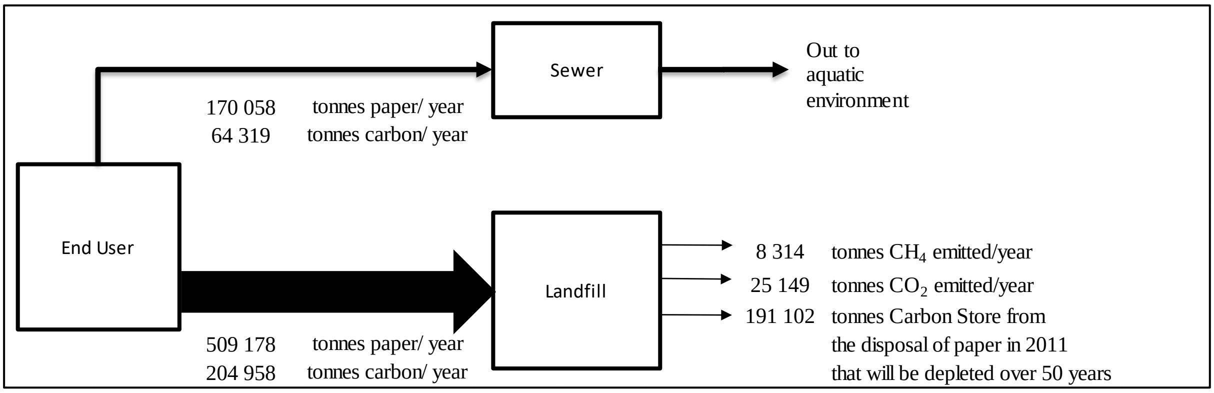


Figure 5.5: Results of landfill and sewer gas emissions for the 2011 calendar year.

There is a large quantity of paper that finds its way to landfill. This paper then degrades to form methane and carbon dioxide. Methane is considered to have a greenhouse gas effect 25 times that of CO_2 (Pachauri and Reisinger, 2007). Paper deposited in the year of 2011 in a landfill would only begin to degrade in the next year (2012). Degradation was considered to start in the year 2011. This method was chosen to show the carbon flow of paper through the system and the contribution to greenhouse gas emissions that is made by landfill and sewers. Paper going to landfill was estimated using factors that were reported by Fiehn et al., who estimated the waste generation per capita for each province. These factors were chosen over values reported by (Ogola et al., 2011). Ogola et al. (2011) considered the waste generation in Limpopo only and the income brackets were determined by the size of the land owned by individuals. The work done by Fiehn et al. was chosen as it was used in the National Waste Baseline report which was compiled by the CSIR. The greatest uncertainty in the factors used is the age of the data. There has not been any reasonable research done in the recent past regarding the waste generation per capita in South Africa.

Landfill is an emission source for greenhouse gases as well as a carbon store. The paper contribution to landfill gas emissions was determined using the IPCC 2006 first order model. The method used is outlined in Appendix B. The contribution of organic carbon from sources other than paper was ignored. This was due to the presence of other sources of carbon accelerating the paper decomposition by adding to the carbon concentration in the landfill. The IPCC first order kinetic model looks at carbon concentration. If one were to consider the total carbon concentration in the landfill, this may skew the greenhouse gas emission contribution by paper. It was assumed that no aerobic degradation took place in the landfill as major South

African landfills are managed well with daily compaction and coverage. Figure 5.5 shows that 8 314 tonnes/year of CH_4 is contributed by paper in landfills. This is equivalent to 207 850 tonnes of CO_2. The South African sewer system is fairly well managed when compared to the rest of Africa. The residence of the sewage in the sewer before being pumped out to an aquatic environment was considered to be negligible. Once the sewage is pumped out to an aquatic environment, there is an abundance of oxygen in water which promotes aerobic degradation. Carbon dioxide from biogenic sources are not considered to add to the greenhouse gas effect (Doorn et al., 2006). The greenhouse gas emissions that would occur in the ocean are outside the boundaries of South Africa and are therefore outside the scope of this study. It was decided that the greenhouse gas emission from sewer would be ignored.

The 2006 IPCC Guidelines reports a default reaction rate constant of 0.07/year for paper and textiles. The half-life and reaction rate relationship is shown in the following equation:

$$Reaction\ rate = \frac{\ln(2)}{t_{1/2}}$$

Equation 5.1

Applying Equation 5.1 with a reaction rate of 0.07/year results in a half-life of 9.9 years. It can be argued that one should consider that all the paper going to landfill would eventually decompose to form methane or carbon dioxide. This argument would hold true for a Life Cycle Analysis. The same argument does not hold true for a Material Flow Analysis. An MFA considers a fixed time frame and it is only methodologically correct to consider the fate of carbon within the boundaries of 2011. Figure 5.5 does however show the decomposition of carbon with time according to Equation B1, Appendix B.

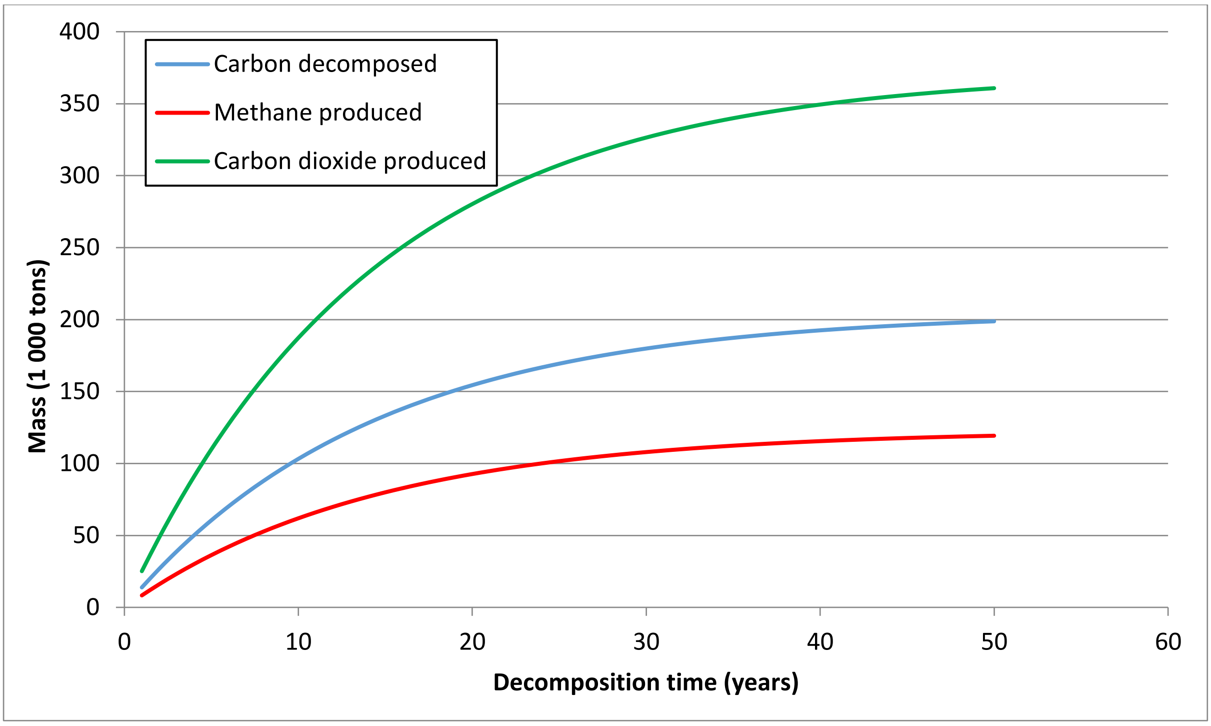


Figure 5.6: Decomposition of carbon and the formation of methane and carbon dioxide over time.

Figure 5.6 shows the decomposition of carbon into methane and carbon dioxide over time. Fifty years is considered to be the end of the reaction and as shown in Figure 3.6, methane production is relatively stable between years 5 – 50 and decreases sharply after year 50. Figure 5.6 also shows that the carbon available for decomposition is almost completely consumed by year 50 with only 4 % of the carbon remaining for decomposition, thereafter. Figure 5.6 also indicates that by 2061, the carbon deposited to landfill in the form of paper for the year 2011 would be almost completely decomposed and the carbon would have been returned to the atmosphere in the form of methane or carbon dioxide.

5.6. Scenario analysis

5.6.1. Scenario 1

The first scenario considered that all the paper in the country is recyclable except for sanitary grades such as tissue. It was also assumed that a recovery of 100 % of all recoverable paper could be achieved. This scenario looked at the possible production of paperboard and tissue that could be achieved with 100 % recovery of recoverable paper. It was also assumed that at some point, the amount of paper that is kept in libraries would reach an equilibrium or steady state. Figure 5.7 and Figure 5.8 shows the scenario of being able to recover 100 % of all recoverable paper for the production of paperboard and tissue respectively.

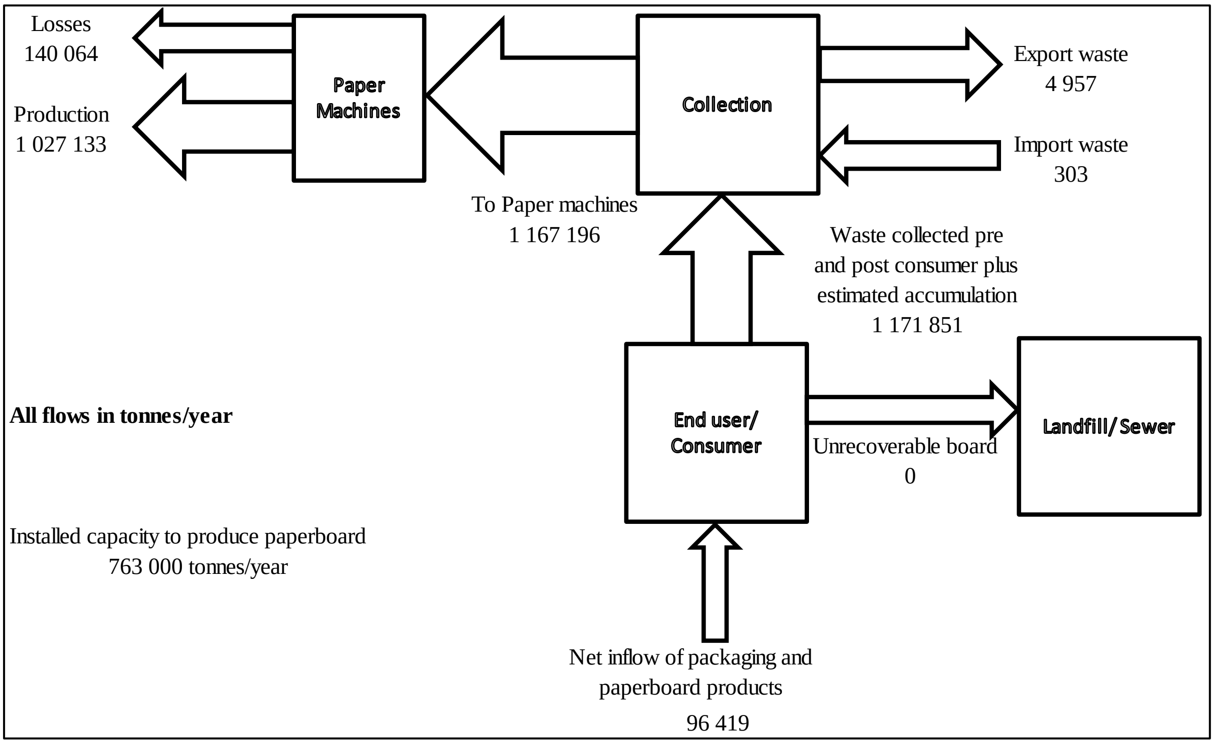


Figure 5.7: Scenario with 100 % recovery of paperboard for paperboard production.

Figure 5.7 indicates that it would be possible to achieve production of 1 027 133 tonnes of paperboard. The installed capacity in 2011 was 763 000 tonnes (Kerr, 2016) of capacity to process recycled paperboard. This oversupply would imply the need to build more paper machines to process the recycled material if it was possible to achieve a recovery rate of 100 %. A yield of 88 % can be achieved on a paperboard machine (Metafore Hired Pyramid Communications, 2006). The yield loss was taken into account in the calculation for the possible production. It is estimated that 140 064 tonnes would make its way to the drain or landfill.

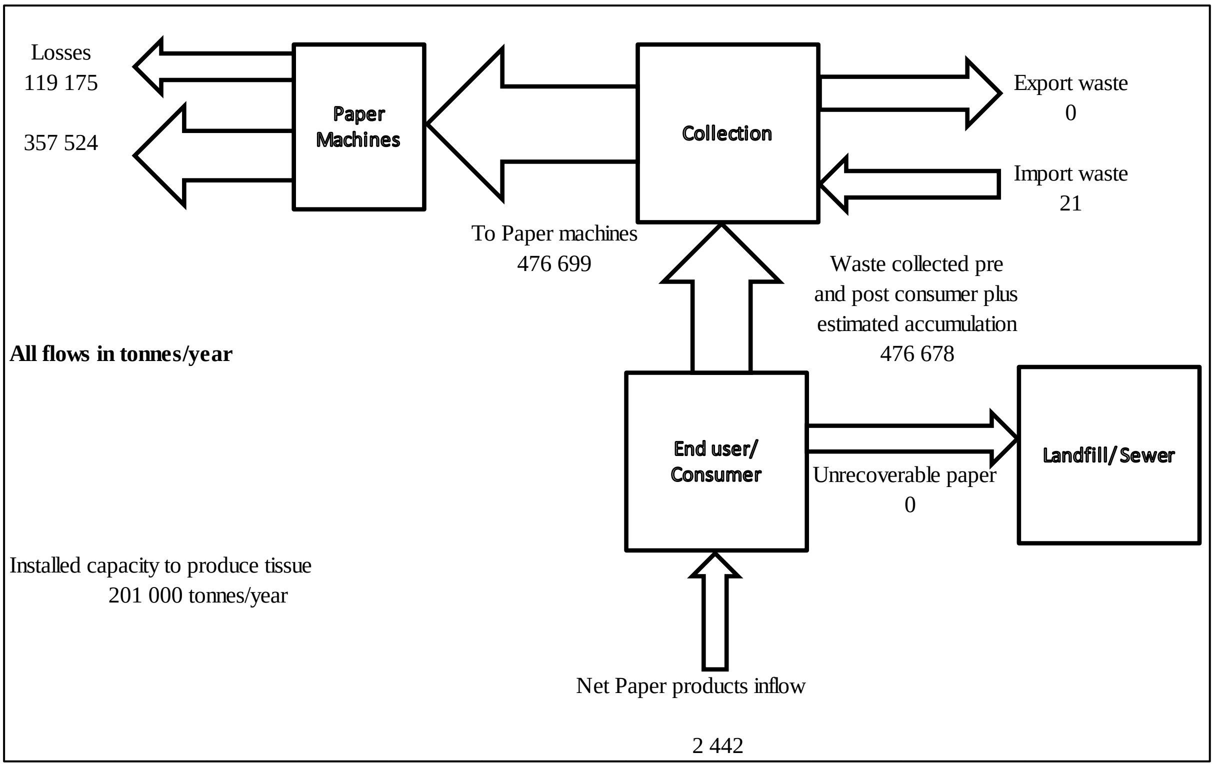
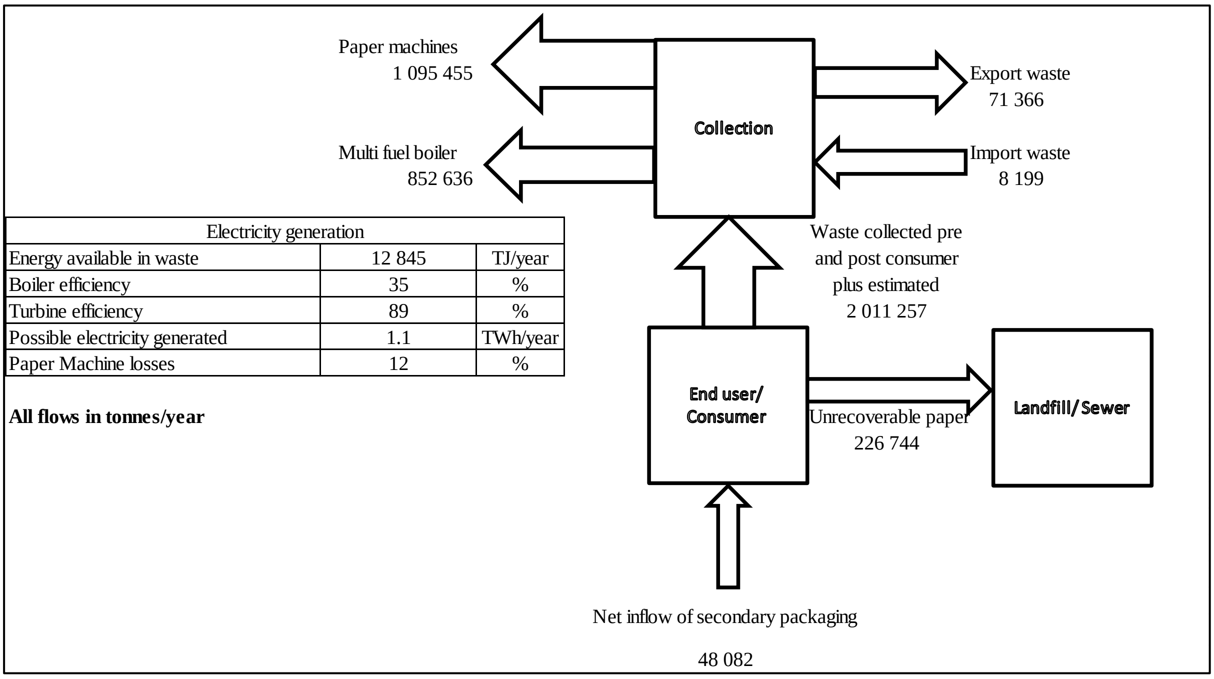


Figure 5.8: Scenario with 100 % recovery of paper for tissue production.

Figure 5.8 indicates that it would be possible to achieve a tissue production of 357 524 tonnes. The installed capacity in 2011 was 201 000 tonnes (Kerr, 2016) of capacity to process recycled paper. This oversupply would imply the need to build more tissue machines to process the recycled material if it was possible to achieve a recovery rate of 100 %. A yield of 75 % can be achieved on a tissue machine (Metafore Hired Pyramid Communications, 2006). The yield loss was taken into account in the calculation for the possible production. It is estimated that 119 175 tonnes would make its way to the drain or landfill

5.6.2. Scenario 2

The second scenario considered 100 % recycle of all paper products except the sanitary grades such as tissue. It was assumed that of all the paper recovered, a portion would go towards production at full capacity in all paper mills that use recycled fibre as a feedstock. The rest of the recovered paper would then be sent to a multi-fuel boiler for electricity generation. Figure 5.9 shows the paper flows in the described scenario.



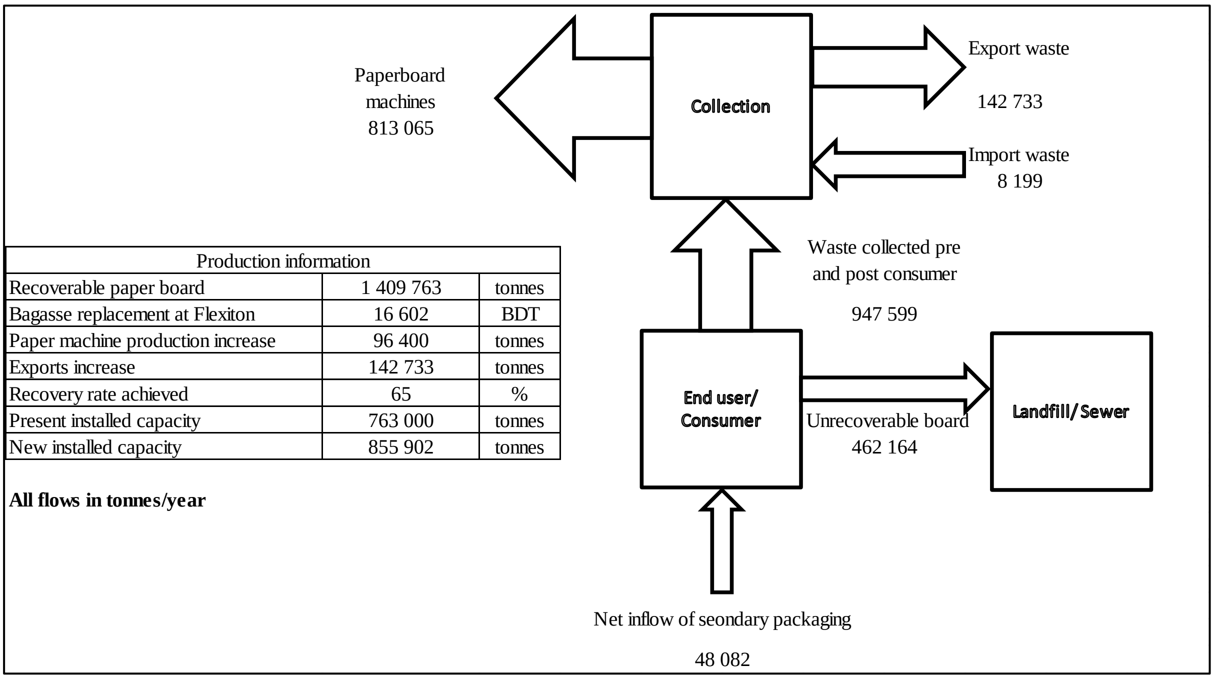
Electricity generation		
Energy available in waste	12 845	TJ/year
Boiler efficiency	35	%
Turbine efficiency	89	%
Possible electricity generated	1.1	TWh/year
Paper Machine losses	12	%

Figure 5.9: Scenario with 100 % recovery of paper products with a portion going towards paper production and the rest to a multi-fuel boiler for electricity generation.

Figure 5.9 indicates that with a 100 % recovery and satisfying all the feedstock requirements for the paper machines, there exists the possibility of using the surplus recovered paper for electricity generation. An average paper machine loss on both tissue and board machines was taken to be 12 % (Metafore Hired Pyramid Communications , 2006). The boiler efficiency and turbine efficiency were taken to be 35 % and 89 % respectively (Ramlall, 2016). The average calorific value of paper was taken to be 15.07 MJ/kg (UCUNCU, 1992). It would be possible to generate 1.1 TWh of electricity per year. The generation of electricity from bioorganic material such as paper is desired as it is considered to be a carbon neutral source. Lignocellulosic material absorbs carbon dioxide from the atmosphere and the carbon is returned into the atmosphere upon combustion. Taking coal (Lignite – Anthrasite) to have an average calorific value of 21 000 kJ/kg (Engineering Toolbox, 2015), every tonne of paper burnt would have a greenhouse gas mitigation effect of 2.04 tonnes CO_2eq. This would only be true if the original fibre source that the paper was produced from was a well-managed certified forest. Scenario two would result in a mitigation effect of 1 740 kilotonnes of CO_2eq per year. Burning recovered paper for electricity generation is controversial. By the year 2017, local municipality supported renewable energy development projects are expected to add 270 MWh per year of electricity to the grid (Sustainable Energy Africa, 2015). This contribution comprises of photovoltaic, wind and landfill gas to electricity projects. In comparison with the possible 1.1 TWh per year that can be produce from scenario 2, it is far larger than the municipal projects. Eskom has recently been tasked to procure 9.6 GWh of nuclear electricity per year (DOE, 2016). The 1.1 TWh suggested by scenario 2 indicates that it is 115 times larger than the proposed nuclear power procurement. Scenario two indicates that there is a considerable the energy potential that is been sent to landfill daily. This occupies space in the landfill and the carbon in the landfill adds to the greenhouse gas effect. For carbon sequestration and for the industry to be carbon positive, it would always be best to convert the recovered fibre into paper products. Landfilling paper should be the last resort as it has the potential to become methane and contribute to global warming. It also takes up valuable landfilling space.

5.6.3. Scenario 3

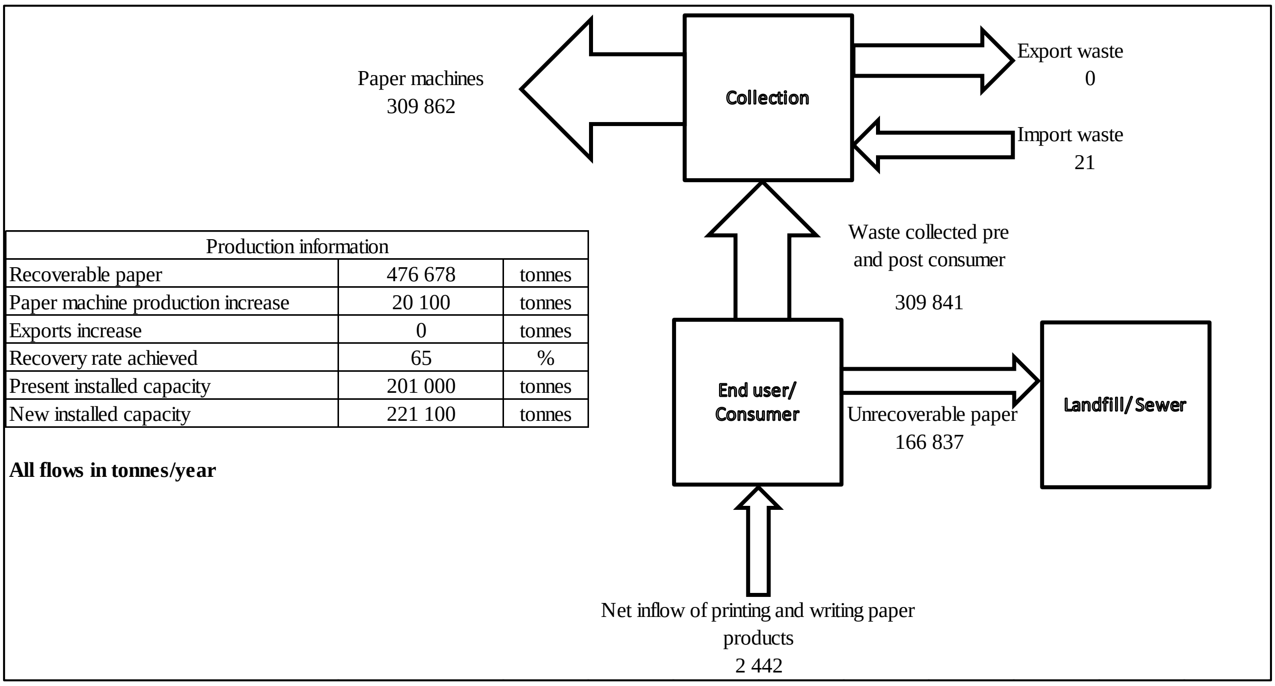
The third scenario looked at increasing the installed capacity to process recovered paper by 10 % and the replacement of bagasse at Mpact Felixton with recycled fibre. This scenario also included a 100 % increase in recovered paper exports and an equilibrium being achieved with all the paper that is kept in libraries and storage. It was also assumed that all recovered newsprint would go for board or newsprint production and a maximum overall recovery rate of 65 % would be achieved. Figure 5.10 looked at paper board production while Figure 5.11 looked at tissue production.



Production information		
Recoverable paper board	1 409 763	tonnes
Bagasse replacement at Flexiton	16 602	BDT
Paper machine production increase	96 400	tonnes
Exports increase	142 733	tonnes
Recovery rate achieved	65	%
Present installed capacity	763 000	tonnes
New installed capacity	855 902	tonnes

Figure 5.10: Scenario with a board production increase, an increase in the export of waste paper board and the substitution of bagasse for recovered paper.

The third scenario was considered in line with the industry and global trends. Tissue and board were looked at separately as the feed stock interchange for the production of either of these grades is very minimal. Paper board production was assumed to increase by 10 % as the global demand for packaging papers is increasing. Mpact has also recently approved an upgrade of the Felixton plant. This upgrade includes a slight production increase and the complete replacement of bagasse with recycled fibre. Exports of recycled fibre would also be expected to increase due to the weakening of the South African Rand. Figure 5.10 shows that there would likely be a shortage of recycled fibre for board production in the country. With current trends, it is assumed that the installed capacity to process recycled fibre would increase from 763 000 tonnes to 855 902 tonnes by the year 2020. There would be 813 065 tonnes of recovered paper available for board production. This would result in a 145 545 tonnes shortage when taking into account the losses on the paper machines. The recycled paper mills may need to consider the addition of virgin fibre to make up the shortfall.



Production information		
Recoverable paper	476 678	tonnes
Paper machine production increase	20 100	tonnes
Exports increase	0	tonnes
Recovery rate achieved	65	%
Present installed capacity	201 000	tonnes
New installed capacity	221 100	tonnes

Figure 5.11: Scenario with a tissue production increase and an increase in the export of waste paper.

Figure 5.11 shows that there would still be surplus of 255 578 tonnes of recovered paper available for the production of tissue. This is a highly desirable situation as it is expected that tissue consumption will increase tremendously due to urbanisation.

5.7. Carbon stores

Figure 5.11 indicates that the largest carbon output in the system was all the paper collected and sent off to recycling. The carbon collected for recycling amounted to 442 154 tonnes. Recycling has the potential to lockup carbon for a long time. It is estimated that a single fibre can be recycled up to 7 times (PRASA, 2011) before it becomes so small that it pass through the wire of a paper machine and contributes to the mills COD in the effluents.

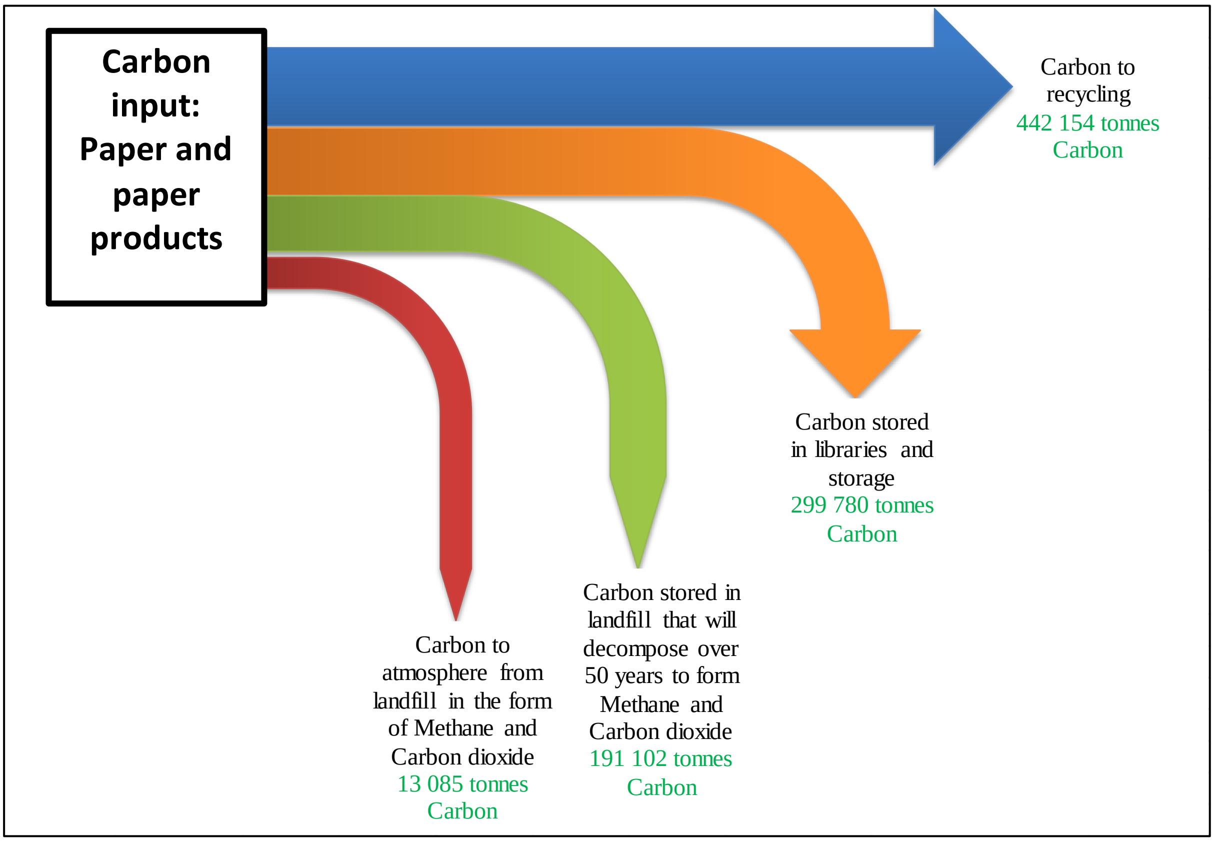


Figure 5.12: Sankey diagram that depicts the four largest carbon outputs for the 2011 calendar year.

Libraries and storage were calculated to sequester 299 780 tonnes of carbon. The duration that the paper products spend in storage depends on the end users requirements. It was inconclusive as to whether the trend is increasing or decreasing as this study was limited to the time span of the 2011 calendar year.

The landfill carbon store was calculated to be 191 102 tonnes. This equates to 20.8 % of the carbon input to converting and the end user. It was also noted from research that lignin containing paper degraded slower than woodfree papers (Wang et al., 2013). This factor is not taken into account in the 2006 IPCC Guidelines and it would affect the calculated greenhouse gas emissions result.

The carbon that enters a landfill will eventually degrade into methane and carbon dioxide. This adds to the greenhouse gas effect.

5.8. Summary

Chapter 5 presented and the discussed the results of this study. The recycling stream had the potential to sequester carbon. However, an LCA would need to be conducted to determine the time frame. Landfill acted as a temporary paper carbon store holding 191 102 tonnes of carbon. The carbon in the landfill due to the presence of paper would take 50 year to completely decompose and move into the atmosphere. Libraries and storage also provided a carbon sink by sequestering 299 780 tonnes of carbon. However the duration that the carbon spends as a sink in libraries and storage would need to be evaluated by an LCA.

Chapter 6: Conclusions and recommendations

6.1. Conclusions

In this study, a material flow analysis of the paper recycling and end user sector was conducted. The aim was to track and quantify the paper and carbon flows through the system for the 2011 calendar year. The three largest paper carbon sinks were also determined.

The largest carbon sink was determined to be recycling which preserved 34 % (416 657 tonnes) of the total paper carbon input into the system. South African paper machines took back 32 % (416 657 tonnes) of the total carbon input to the system in the form of recovered paper. Of all the paper recycled, 61.7 % was OCC. This indicates that container boards, especially liner and fluting, lock up the most carbon in the system of all the paper grades.

The MFA also showed us that 23 % (299 780 tonnes) of the total carbon input to the system for 2011 was locked up in libraries and storage. Landfill also acts as a temporary carbon store with 15 % (191 102 tonnes) of the total input into the system being locked up in landfill. Over a 50 year period, this carbon would eventually find its way into the atmosphere in the form of carbon dioxide or methane. Landfill emitted 25 149 tonnes of carbon dioxide together with 207 847 tonnes of methane as CO_2eq due to the presence of paper in 2011. This amounts to 13 085 tonnes of carbon as carbon. With the introduction of carbon tax in January 2018, one would argue that paper mills that recycle should be considered for a concession due to the carbon offsets offered. This is due to the large quantities of carbon that are sequestered in the products produced.

From scenario two, with the introduction of a multi-fuel boiler and the possible combustion of all the waste paper, one would be able to generate 1.1 TWh of electricity per year. The suggested 1.1 TWh of electricity per year is far larger than the proposed local municipality supported renewable energy development projects and it is also 115 times greater than the proposed nuclear power procurement by Eskom. Every tonne of paper that would be used to generate electricity would have a greenhouse gas mitigation effect of 2.04 tonnes of CO_2eq.

From scenario 3, it is evident that in the near future there would be a paper shortage. It is estimated there may be a shortage of 145 545 tonnes of waste paperboard for production in 2020.

In 2011, it was reported that South Africa's greenhouse gas emissions were 433 million tonnes of CO_2eq. Taking into account the population of 51 million (Statistics South Africa, 2011) this would equate to 2.32 tonnes carbon/capita. The total carbon lockup in libraries/storage and recycling amounts to 0.015 tonnes carbon/capita which equates to 0.63 % of the total greenhouse gas emissions. This proves that the hypothesis of the paper industry being able to store or sequester carbon in products true. This sequestration can aid in greenhouse gas mitigation.

6.2. Recommendations

- The feasibility of generating electricity from waste paper should be looked into together with combustion of other sources of lignocellulosic material. A complete life cycle analysis should also be considered to determine the carbon foot print of such a venture. Lignocellulosic material is biogenic and does not add to the greenhouse gas effect if the material originates from a responsible supplier who is certified with the Forest Stewardship Council or a similar organisation. Fibre originally derived from a well-managed forest where every tree that is cut down is replaced by a sapling which would aid in negating the greenhouse gas effect.
- With paper having the potential to be recycled up to 7 times, it is recommended that a study be conducted to determine what is the average duration of recycle carbon lock-up.
- Further research would need to be conducted to determine if the stock of paper products in storage has an increasing or decreasing trend. This would indicate if the end user is sequestering carbon in the form of paper products.
- Further studies regarding the economic and social implications of carbon flows should be conducted. This would be done to assess the sustainability of the industry and possible recommendations that can be made for sustainable production. The study should also employ the method of statistical entropy analysis which has been shown to be a powerful tool in assessing the sustainability of an industry.
- A study should be conducted to assess the resources that would be required to implement possible large scale recycling at landfills. Most of the paper and other lignocellulosic material that makes its way to landfill can be burnt in a multi-fuel boiler for electricity generation. Some of the paper that would be recovered from the landfill could be sent for recycling.

- The industry should invest in research to find ways to combat the shortage of recovered paper that is predicted in the near future. It is also suggested that appropriate contingency measures be put in place to avoid the paper industry shrinking due to a shortage of recovered paper.

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Appendix A: Sample calculations

Mass balance:

This section will endeavour to provide the reader with a detailed and chronological algorithm on how the overall mass balance was conducted. The sample calculations presented in this section have been done for the overall mass balance only and a short explanation will be provided for the origin of the data in this mass balance. The calculation principle used for the overall mass balance is similar to that used to determine the unknown flows around the other blocks. This could be achieved only when the degree of freedom was zero and no other data was required to solve the system.

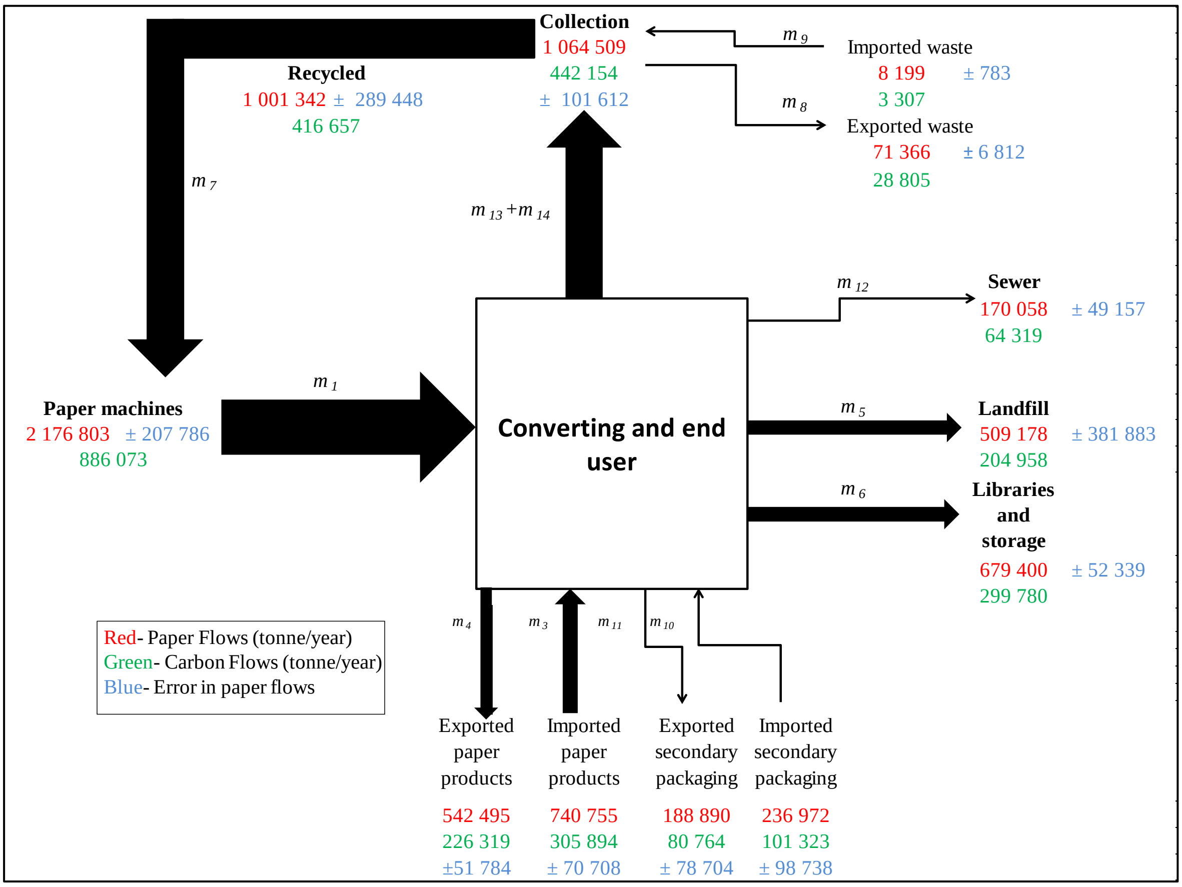

Figure A1: Overall mass balance.

Mass balance rationale

Data for the mass balance was collected from various sources. These included SARS, PAMSA, PRASA, Neopak and literature. There is no data available for the amount of paper that would be stored by the end user. This unknown was made the subject of the mass balance. The overall mass balance becomes:

$$m_6 = m_1 + m_3 + m_{10} - m_4 - m_5 - m_{12} - m_{11} - m_{13} - m_{14}$$

Equation A1

m_9, which is waste paper that was imported, was excluded from the overall mass balance. Inclusion of m_9 would have skewed the overall results once all five studies were combined. m_7 was the recovered paper feedstock to the paper machines and m_9 would be included there.

Substitution into Equation A1:

$$m_6 = 2\,176\,803 + 740\,755 + 236\,972 - 542\,459 - 509\,178 - 170\,058 - 188\,890 - 100\,199 - 964\,310$$

$m_6 =$ 679 436 tonnes

Conversion of mass flows to carbon flows

Chapter 3, section 3.2 discusses the organic composition of paper. The three most common paper grades in South Africa are newsprint, copy paper and corrugated. The organic carbon composition of these paper grades are outlined in Table A1.

Table A1: Composition of organic constituents in different grades of paper (Wang et al., 2013).

Paper Grades	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Carbon Content (%)
Newsprint	53.75	16.40	15.25	40.18
Copy paper	71.35	14.00	0.80	37.82
Corrugated	61.95	14.85	14.55	42.76

The mass flows in the MFA were converted to carbon flows by using the carbon content for the different grades in Table A1. Since heavy letter 1 and heavy letter 2 are the preferred recycled grades used for tissue production, tissue was assumed to have the same carbon composition as copy paper.

Carbon flow calculation method

Table A2 details the mass and carbon flows for all the recycled paper collected in 2011.

Table A2: Recycled paper and the respective carbon masses that was collected in South Africa for 2011(PAMSA, 2011; PRASA, 2011).

Different grades of recovered paper	**Paper flows (tonnes/year)**	**Carbon flows (tonnes/year)**
Newsprint and magazines	149 622	60 118
Old corrugated containers (K3 and K4)	578 067	247 659
Office and graphic papers (Usually HL1 and HL2)	109 545	41 432
Mixed and other papers (Usually IMW and CMW)	127 076	51 150

From Table A1, newsprint and magazines had a carbon content of 40.18 %,

Therefore, from Table A2 the recycled newsprint and magazine paper flows were determined to be 149 622 tonnes/year.

Carbon flows = Paper flows X carbon content

= 149 622 X 40.18 %

= 60 118 tonnes/year

For mixed paper flows, an average carbon content was used from Table A1. The average carbon content for mixed paper flows was determined to be 40.25 %.

Error analysis

The method applied in the error is that of which was described by Hedbrant et al. (2001). According to the source of the input data, the most likely uncertainty interval was selected from Table 4.1 Chapter 4. Two formulas are applied to estimate the uncertainty of the result by combining input data.

When addition applies the formula is:

$$f_{a+b} = 1 + \frac{\sqrt{[m_a \times (f_a - 1)]^2 + [m_b \times (f_b - 1)]^2}}{m_a + m_b}$$

Equation A2

$$f_{a \times b} = 1 + \sqrt{(f_a - 1)^2 + (f_b - 1)^2}$$

Equation A3

Where:

m is the most likely value.

f is the uncertainty factor.

Note: Subtraction is considered to be negative addition. It is for this reason that negative signs are ignored when applying the error equation.

Application of the error is shown below by performing error analysis around the end user.

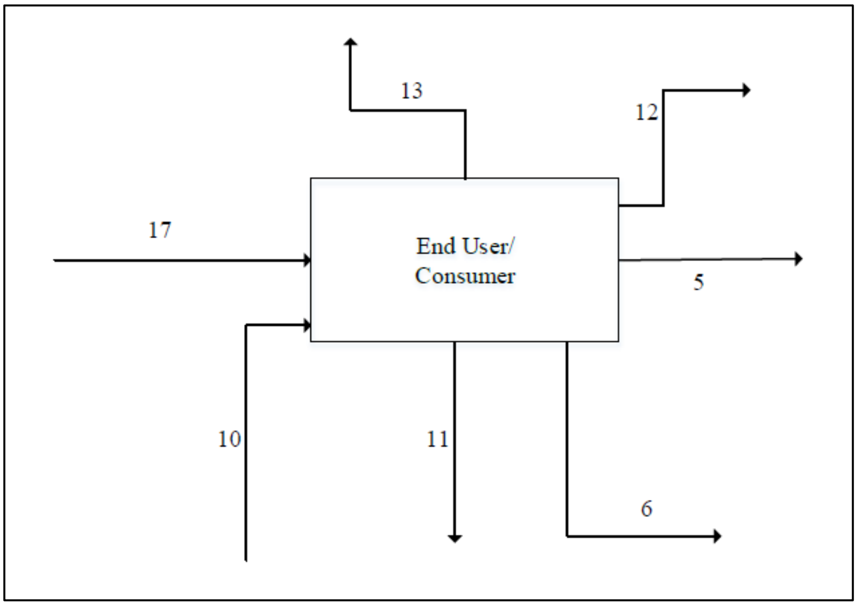

Figure A2: End user/consumer flow diagram schematic.

From Figure A2, the mass balance around the end user is

$m_{17} + (m_{10} - m_{11}) = m_{12} + m_5 + m_6 + m_{13}$

Solving for m_6 the equation becomes

$m_6 = \{(m_{17} + m_{10}) – [(m_{13} - m_{12}) - (m_5 - m_{11})]\}$

The uncertainty formula can only be applied to two terms at a time. To calculate the uncertainty for the addition of six terms, the terms were grouped in pairs and the uncertainty was determined. Initially, the uncertainty was determined for the addition of the terms in the parentheses, then a combination of the terms in the square brackets and finally the uncertainty factor for m_6 was determined by all the terms in the braces. The uncertainty was determined by repetitively applying Equation A2.

Table A3: Data used in error analysis sample calculations.

Term	Likely value	f_{ab}	Comments
m17	2 274 863,78	1,09	Calculated using Equation A1
m10	236 971,56	1,5	From Table 4.1, level 3
m11	188 890,00	1,5	From Table 4.1, level 3
m12	170 057,83	1,33	From Table 4.1, level 2
m5	509 177,52	1,5	From Table 4.1, level 3
m13	964 309,84	1,1	From Table 4.1, level 1

$$f_{m5-m11} = 1 + \frac{\sqrt{[509\,177.52 \times (1.5-1)]^2 + [188\,890 \times (1.5-1)]^2}}{509\,177.52 + 188\,890}$$

$$f_{m5-m11} = 1.39$$

Similarly,

$$f_{m13-m12} = 1.1$$

Table A4: Data used in error analysis sample calculations.

Term	Likely value	f_{ab}
(m13-m12)	794 252,01	1,10
(m5-m11)	320 287,52	1,39

Substituting into Equation A2

$$f_{(m5-m11)+(m13-m12)} = 1 + \frac{\sqrt{[320\ 287.52 \times (1.39-1)]^2 + [794\ 252.01 \times (1.1-1)]^2}}{320\ 287.52 + 794\ 252.01}$$

$$f_{(m5-m11)+(m13-m12)} = 1.13$$

Table A5: Data used in error analysis sample calculations

Term	Likely value	f_{ab}
m17-m10	2 037 892,22	1,09
(m13-m12)-(m5-m11)	4739 64,49	1,13

Substituting into Equation A2

$$f_{m6} = 1 + \frac{\sqrt{[2\ 037\ 892.22 \times (1.09-1)]^2 + [473\ 964.49 \times (1.13-1)]^2}}{2\ 037\ 892.22 + 473\ 964.49}$$

$$f_{m6} = 1.08$$

m_6 = 679 400 tons

$$\text{Upper error} = m_6 \times f_{m6}$$

$$\text{Upper error} = 679\ 400 * 1.08 = 733\ 752 \text{ tonnes}$$

$$\text{Lower error} = \frac{m_6}{f_{m6}}$$

$$\text{Lower error} = \frac{679\ 400}{1.08} = 629\ 074 \text{ tonnes}$$

$$\text{Error} = \frac{\text{Lower error} - \text{Upper error}}{2}$$

$$\text{Error} = \frac{679\ 400 - 629\ 074}{2} = \pm 52\ 339 \text{ tonnes}$$

Table A6: Error values for overall mass balance.

Stream names	Paper flows (tonnes/year)	f_{xx}	* f_{xx}	/f_{xx}	Error in paper flows (± tonnes/year)
m1	2 176 803	1,10	2 394 484	1 978 912	207 786
m3	740 755	1,10	814 830	673 414	70 708
m4	542 495	1,10	596 745	493 178	51 784
m5	509 178	2,00	1 018 355	254 589	381 883
m7	1 001 342	1,33	1 331 785	752 889	289 448
m8	71 366	1,10	78 503	64 879	6 812
m9	8 199	1,10	9 019	7 454	783
m10	236 972	1,50	355 457	157 981	98 738
m11	188 890	1,50	283 335	125 927	78 704
m12	170 058	1,33	226 177	127 863	49 157
m6	679 400	1,08	733 752	629 074	52 339
m14	100 199	1,10	110 219	91 090	9 564
m13	964 310	1,10	1 060 741	876 645	92 048

Appendix B: Greenhouse gas calculation method

Calculation method below was adapted from the 2006 IPCC Guidelines (Pipatti and Vieira, 2006).

The calculation was done using the first order decay model

$$\mathrm{DDOCm} = \mathrm{DDOCM}(0) \times \mathrm{e}^{-\mathrm{kt}}$$

Equation B1

Where:

DDOC is Decomposable Degradable Organic Carbon (tonnes).

t is time (years).

k is the rate of reaction.

The mass of DDOC that decomposes to form CH_4 and CO_2 at the end of year 1 is given by

$$\mathrm{DDOCmdecomp} = \mathrm{DDOCm}(0)(1 - \mathrm{e}^{-\mathrm{k}})$$

Equation B2

Where:

DDOCmdecomp is the amount of organic carbon the decomposed under anaerobic conditions (tonnes).

The amount of CH_4 that is generated is given by

$$\mathrm{CH}_{4\_\mathrm{generated}} = \mathrm{DDOCmdecomp} \times \mathrm{F} \times \frac{16}{12}$$

Equation B3

Where:

$CH_{4\_generated}$ is in tonnes.

F is the volume fraction of CH_4 in landfill gas.

The amount of CH_4 that is emitted is given by

$$\mathrm{CH}_{4\_\mathrm{emitted}} = \mathrm{CH}_{4_{\mathrm{generated}}}(1 - \mathrm{OX})$$

Equation B4

Where:

$CH_{4\_emitted}$ is in tonnes.

OX is the oxidation factor of the soil.

The amount of CO_2 generated from landfill was estimated using a method outlined in (RTI International, 2010).

CO_2 emissions where estimated by

$$CO_{2\_emitted} = CH_{4_{generated}}(\frac{1-F}{F} + OX) \times \frac{44}{16}$$

Equation B5

Where:

$CO_{2\_emitted}$ is in tonnes.

Table B1: Constants used in greenhouse gas emissions calculations (Pipatti and Vieira, 2006).

Constant	**Value**
k	0.07
F	0.5
OX	0.1

Appendix C: Paper mill capacities for 2011 and the calorific value of paper

Table C1: Production capacity of recovered paper mills (Kerr, 2016).

Company	Mill	Products	2012 Capacity (1 000 tonne/year)
Kimberley-Clark	Enstra Mill	Crepe Tissue	54
Mondi			
Mpact	Felixton Mill	Fluting Medium	150
	Piet Retief Mill	Unbleached linerboard	133
	Springs Mill	Cartonboard	140
Nampak Tissue	Bellville Mill	Crepe tissue	24
	Kliprivier Mill	Crepe tissue	24
	Riverview Mill	Crepe tissue	8
Nampak Rosslyn	Rosslyn Mill	Fluting and testliner	150
	Cape Kraft Mill	Testliner, fluting and ceiling board	60
Gayatri	Germiston Mill	Testliner	70
Lothlorien		Packaging Papers	40
SA Paper Mills	Merebank Mill	Packaging and wrapping papers	15
	Richards Bay Mill	Corrugating papers	5
Other paper producers	Other mills		91
TOTAL			964

Table C2: Calorific values of different paper grades (UCUNCU, 1992).

Type of paper waste	Mean gross calorific value (Btu/lb)	Mean gross calorific value (MJ/kg)
Newspaper	7 540	17.54
Cardboard	6 907	16.07
Kraft	6 897	16.04
Beverage and milk boxes	6 855	15.94
Bowboard	6 703	15.59
Tissue	6 518	15.16
Coloured office paper	6 348	14.77
White office paper	6 234	14.50
Glossy paper	6 370	14.82
Mixed	6 477	15.07