LIGNOCELLULOSIC CARBON FLOW ANALYSIS OF THE SOUTH AFRICAN PAPER INDUSTRY

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Chemical Engineering, of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard College, South Africa. This research was financially supported by the Paper Manufacturers Association of South Africa (PAMSA).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are a result of investigations by the candidate.

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Signed:

Date:

PLAGIARISM DECLARATION

I, **NIGEL TAFADZWA CHIKORE** declare that

(i) The research reported in this dissertation, except where otherwise indicated, is my original work.

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As the candidate's supervisor, I agree to the submission of this dissertation.

Name: Iain Kerr **Signed:** **Date:**

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ABSTRACT

This research study is one of five studies undertaken by the Paper Manufacturers Association of South Africa (PAMSA) to optimize the use of fibrous raw materials across the life-cycle phases of harvested wood products. This research study involved conducting a Material Flow Analysis (MFA) of the papermaking production process. The aim was to track the flow of lignocellulosic carbon (LCC) through the South African paper mills based on data from 2011. The results of this MFA study were envisaged to compliment similar studies of LCC flows conducted in South Africa on the other stages of the value chain (such as forestry, pulp mills and disposal) which were not considered in this study. In addition, the material flows presented in this study, provide quantitative data through which a framework can be developed to optimize the usage of fibrous raw materials across all paper mills in South Africa.

The relevant papermaking raw materials were identified and classified into fibrous and non-fibrous materials. All paper grades produced in South Africa were classified into three categories; namely graphic paper, tissue paper and paperboard. The paper machines were defined according to the paper grade produced on each machine. The materials flow data required for this MFA was collected through interviews (conducted with paper mills personnel during paper mill visits), questionnaire surveys and statistical data from published annual production reports. Assumptions (based on available literature and knowledge provided by paper mills personnel) were used to supplement the production data where necessary. Two software packages namely Microsoft Excel and STAN were used in the modelling and visual presentation of material flows across all paper mills in South Africa.

The results show that the total mass of LCC flows through the South African paper industry in 2011 were estimated at 1 010 ± 6.01 kt. Virgin fibre pulp contributed the largest share (63.3 %) of the total input LCC flows into the industry compared to recovered paper (36.7 %). The largest LCC sink across all paper mills in South Africa in 2011 was determined to be paper (94.8 ± 0.9 %); the balance (5.2 ± 0.3 %) went to waste. The production of tissue paper (dry mass basis) in 2011 resulted in highest mass of LCC diverted to waste. For every tonne of dry mass tissue paper produced in 2011, 6.9 kg of LCC was diverted to waste; while, on average, for every tonne of dry mass paper produced in 2011, 2.7 kg of LCC was diverted to waste. Three scenarios were developed based on market-related changes that have happened, or are likely to happen, in the South African paper industry. The production of tissue paper from only

virgin fibre (whilst keeping the production of all paper categories constant) would result in a decrease of the LCC diverted to waste by 14.3 % (i.e. from 62.3 kt to 53.4 kt) across all paper mills in South Africa. The production of paperboard from only recovered paper (whilst keeping the production of all paper categories constant) would result in an increase of the LCC that goes to waste by 41.7 % (i.e. from 62.3 kt to 88.2 kt) across all paper mills in South Africa. The shutting down of a newsprint machine coupled with the diversion of the old newspapers and magazines to replace virgin fibre in the production of tissue paper (whilst keeping the production of other paper categories constant) would result in a decrease of the LCC diverted to waste by 18.2 % (i.e. from 62.3 kt to 51.0 kt) across all paper mills in South Africa. However, it is important to note that the results and conclusions made from this MFA study need to be taken in fuller context i.e. in combination with similar studies of LCC material flows at other stages of the value chain (e.g. fibre production, usage and disposal of paper) in order for holistic conclusions to be drawn.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Actual model	Defines a material flow analysis model created in this dissertation work using the production data from South African paper producers for the calendar year of 2011.
Approach flow	The section on a paper machine system that starts at the machine chest to the headbox lip.
Boxboard:	Any paper grade that goes into the manufacturing of folding cartons and used to package commodities such as cereal boxes and fast food boxes.
Broke	any off-specification paper grade produced and reused within the paper mill at the same site.
Consistency	A measure of the solids content in a pulp slurry or pulp furnish.
Containerboard	Paper grade that goes into the manufacture of corrugated containers or boxes. This consists of facings called linerboard and the intervening called corrugating medium.
Dry-end broke	Any paper grade that fails to meet the quality standards and therefore, rejected for final shipment to customers. It is then usually recycled and combined with recovered paper and virgin pulp.
Fines	Smaller particles such as broken/fragmented fibres, fillers and most dissolved or colloidal additives. Materials that pass through a 76 µm screen.
Furnish	A mixture of different types pulp fibres and/or additives used in the production of a particular paper grade.
Lignocellulosic carbon.	Carbon derived from fibrous (lignocellulosic) materials.
Papermaking waste	Defines the summation of papermaking sludge and effluent from paper mills.
Pre-consumer waste	Any paper (printed or unprinted) generated in the fabrication or conversion of finished paper i.e. before use by a consumer as a final end product.
Post-consumer waste	Any paper grade that has passed through the end-usage as a consumer product.
Recovery Rate	A measure of the amount of paper that is diverted from landfill. It gives an indication of the amount of recovered paper as a function of the total possible recoverable paper.
Utilization rate	The fraction of secondary/recycled fibres in paper products. It is a measure of the amount of recovered paper used in the production of a specific paper grade.

Recycled fibre	Fibre that has previously been used in a manufacturing process and reclaimed as raw material for another process. Secondary fibre is usually classified as pre-consumer and post-consumer waste.

1 INTRODUCTION

In this chapter, the general framework of this research study is presented. The paper industry (international and local context), the background of this research study, the purpose, the aims, hypothesis and limitations of this study are reviewed.

1.1 An overview of the paper industry: an international and a South African context

Paper[1] is one of the most important commodities in modern-day societies. It is a commodity with a high practical value in communication, hygiene, art, economy, education, sanitation and technical applications (Holik, 2006; Biermann, 1996; Roberts, 2007). Paper still remains a reliable, tangible and portable means of long-term documentation and data preservation in this modern day digital and electronic age (Holik, 2006). It is for these reasons that a world without paper is difficult to envisage.

The production of paper has significantly increased over the years from 238.8 Mt in 1990 to 406.1 Mt in 2015 (FAO, 2015)[2]. Blanco et al. (2004) predicted an average annual growth of 2.5 % in paper. A graphical presentation of the total global paper production over the years is shown in Figure 1-1. South Africa's paper production has steadily increased in line with the global trend[2]. The total production tonnage in South Africa increased from 2.29 Mt in 2001 to 2.50 Mt in 2010 with a peak production of 2.73 Mt in 2007 (PAMSA, 2011).

China and the USA are the two largest global paper and paperboard producers contributing approximately 40 % of the global production (FAO, 2015; Sarma, 2000). Africa contributed 4 Mt of the global production in 2011 which equates to 1 % of the world's paper production (FAO, 2015; Bajpai, 2015). South Africa's paper production in 2015 stood at 2.29 Mt (PAMSA, 2016) thus contributing approximately 60 % of Africa's production in 2015. Based on data recorded by PAMSA from 2013-2017, approximately 15-20 % of the paper produced in South Africa is exported; the bulk of the South African exports being packaging grades i.e. 48-60 % of the total exported paper. Despite South Africa's small contribution towards global paper production, the South African paper industry does achieve its primary purpose of generally meeting the local demand for paper.

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[1]The term paper hereafter describes all grades of paper such as newsprint, tissue, board, printing and writing

[2] The increase in demand for packaging paper has outweighed the decrease in demand for certain printing and writing grades such newsprint thus resulting in an overall increase of the total paper produced.

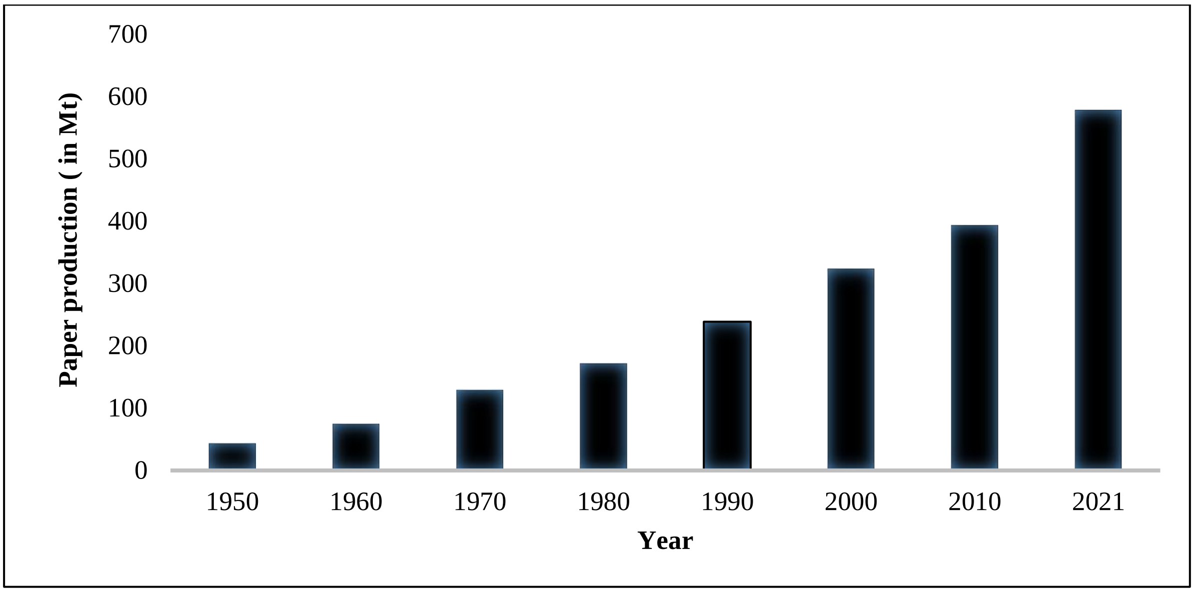

Figure 1-1. The total global paper production over the years including the predicted production in the year 2021 based on information extracted from FAO (2015) and Blanco et al. (2004).

The United States of America and Japan - two of the most industrialised nations in the world - had the highest paper consumption per capita values of 300 kg and 218 kg per year respectively in 2015 (Bajpai, 2015). The consumption of paper per capita is seen as an important index of the general level of economic development of a country and standard of living (FAO, 2014; Sarma, 2000; Bolton, 1998). The minimum needed to meet the basic needs for literacy and communication is generally considered to be 30-40 kg of paper per capita (ILO, 1992) although this is constantly changing in the modern digital age. South Africa's paper consumption per capita value of 48 kg of paper per year (PAMSA, 2016) in 2015 compares well with the world's average of 57 kg of paper per year (Bajpai, 2015; FAO, 2015). Figure 1-2 shows the distribution of the paper consumption by category in South Africa for the year 2015. It indicates that the consumption of corrugating materials (packaging grade) was the highest amongst all the grades contributing 55 % of the total paper consumption.

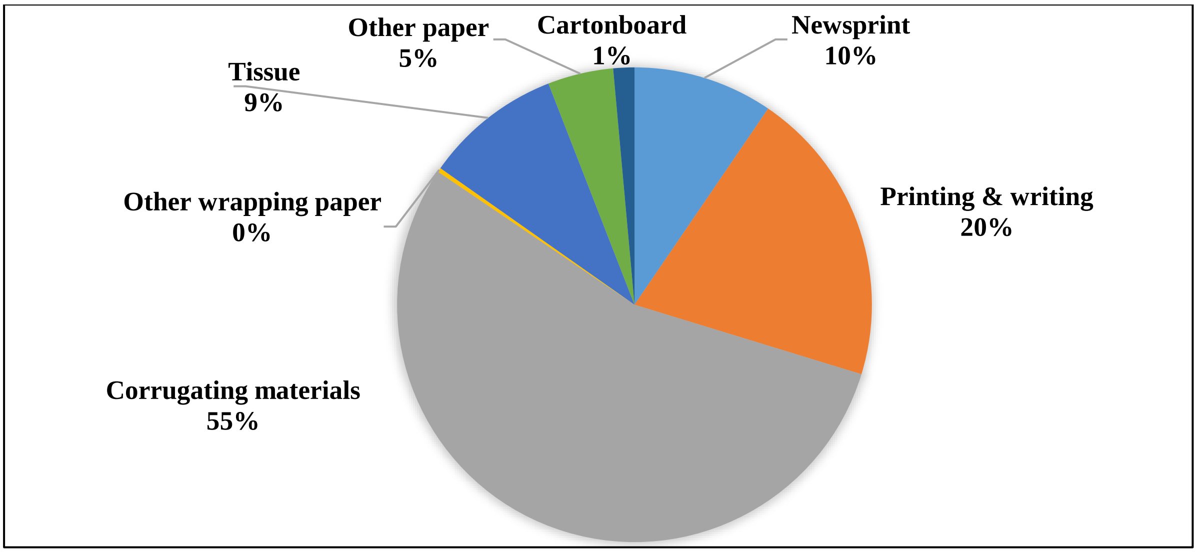

Figure 1-2. Paper consumption by grade in South Africa in 2015 based on data provided by PAMSA (2016).

1.2 Raw materials management and environmental concerns in papermaking.

Papermaking is a technology based mainly on cellulose fibres derived from wood and non-wood plants (Montgomery and Chaffin, 1982; World Wildlife Fund, 2015; Davies, 1984; Smook, 2002). Fibre - the principal raw material for papermaking - is the costliest of all the raw materials used in paper production (Kerr, 2015). According to Bethlehem (1994), fibre constitutes approximately 50 % of the final cost of producing pulp. Ideally, it follows that the fibre losses into anything other than the desired paper product should be minimised.

The availability and cost of raw materials thus becomes the top priority for management of papermaking companies (World Wildlife Fund, 2015). A wisely and thoroughly planned fibre management strategy would have to be implemented for sustained success in the paper industry. This strategy would have to:

- keep the costs of fibre to a minimum
- seek efficient fibre usage with losses kept to a minimum and
- provide long-term security in the availability of fibre for production.

This challenge spans the whole supply chain i.e. from where the wood is grown, harvested, processed and reused (Word Wildlife Fund, 2015; Paper Industry World, 2013).

Further to this, the environmental impacts associated with papermaking have continued to attract considerable scrutiny over the years both internationally (Duley et al., 1996; Mark

Hewitt et al., 2006) and locally (Davies, 1984; Hunt and Pretorius, 2002). The local environmental concerns are chiefly air pollution, water pollution and land pollution (Hunt and Pretorius, 2002; Davies, 1984;). Stringent laws have been progressively developed and passed in South Africa to continually improve the impact of any industrial activity on the environment. These include the National Water Act (1998), Air Quality Act (2004), National Environmental Management Amendment Act (2004) and the Carbon tax policy (2013).

The success of the fibre management strategy proposed by the World Wildlife Fund (2015) and the South African legislative measures put in place hinges on the extensive knowledge of material flows across the paper industry. Such information forms the basis for argument on whether or not the target materials are utilised effectively and pollution-reduction targets met.

The use of the material flow analysis (MFA) approach has become a widely accepted tool in resource and environmental management (Sundin et al., 2001; Bringezu and Moriguchi, 2002; Brunner and Rechberger, 2004; Hoekman, 2015). A Materials Flow Analysis is 'a systematic assessment of the flows and stocks of materials within a system defined in space and time' (Brunner and Rechberger, 2004). A Materials Flow Analysis study provides detailed information on the industrial metabolism of materials across a defined system (Bringezu and Moriguchi, 2002; Brunner and Rechberger, 2004; Hesselbach and Herrmann, 2011). This is essential in understanding the synergy between the environment and an economic activity. Table 1-1 provides a few examples of the MFA studies conducted globally and locally since 1995.

Table 1-1. Material flow analysis studies performed across the world across various industries.

Country or continent	Industry / sector	Reference
Africa (Nigeria)	Waste management	Ibrahim et al. (2013)
Africa (Zimbabwe)	Manufacturing (mining)	Gumbo (1999)
Asia (South Korea)	Manufacturing (papermaking)	Hong et al. (2011)
Asia (Japan	Manufacturing (mining)	Matsubae-Yokoyama et al. (2009)
Europe (France)	Manufacturing (forestry)	Lenglet et al. (2017)
Europe (Netherlands)	Manufacturing (plastics)	Joosten et al. (1998)
South America	Manufacturing (all industries)	Russi et al. (2008)
North America	Manufacturing (mining)	Spatari et al. (2005)
Australia/Oceania	Manufacturing (mining)	Kwonpongsagoon et al. (2007)
South Africa	Urban development	Hoekman (2015)
South Africa	Manufacturing (pulp making)	Adu-Poku (2015)

1.3 Background of study: The Paper Manufacturers Association of South Africa's (PAMSA) fibre optimisation project

The Paper Manufacturers Association of South Africa (PAMSA) embarked on a comprehensive fibre optimisation investigation in 2012. This was to be achieved by tracking and quantifying the flow of lignocellulosic carbon (LCC) across the harvested wood products (HWP) life cycle. The reference year was 2011. The lifecycle phases of HWP include forestry, manufacturing (pulp production, papermaking, furniture-making), consumer use, recycling and disposal. No previous research had been undertaken in South Africa to provide a basis for comparison for which the effective usage of timber in terms of fibre utilisation could be determined.

Lignocellulose is a generic term that describes plant or woody materials that consist mainly of three polymers namely: cellulose, hemicellulose and lignin (Bajpai, 2016). Lignocellulosic carbon is thus defined in this dissertation as the carbon derived from fibrous or lignocellulosic materials. Globally, references to research focusing on tracking the flow of only LCC across the papermaking process were not found in literature to guide the development of a methodology for this investigation. However, similarities were drawn from the studies conducted by Cote et al. (2002) and Hong et al. (2011) in the USA and South Korea respectively. Cote et al. (2002) performed an MFA to track the flow of carbon across a manufacturing process defined as an integrated pulp and paper mill. The carbon referred to herein was inclusive of the carbon in the wood fibres, papermaking additives, carbon emissions attributed to pre-and post-manufacturing phases and transport of materials. Hong et al. (2011) conducted an MFA of paper in which they separately quantified primary and secondary raw materials, and paper grades in the South Korean paper industry. However, Hong et al. (2011) neither quantified nor tracked LCC flows. A detailed review of the studies conducted by Cote et al. (2002) and Hong et al. (2011) is provided in **Chapter 2**.

Figure 1-3 shows a flowchart indicating system boundaries of PAMSA's fibre optimisation project, which was divided into five MFA studies that complimented each other. Three studies that focused on tracking the flow of LCC in the: (i) forestry industry (Alembong, 2014), (ii) pulp-making industry (Adu-Poku, 2015) and (iii) consumer use, recycling and disposal (Ramlall, 2017), have already been completed. The other MFA study focusing on furniture and construction products was conducted concurrently with this study. This research investigation focused on conducting an MFA study to track and quantify the flow of LCC through all paper mills in South Africa for the calendar year of 2011. The dashed red boundary lines shown in Figure 1-3 represent the system boundary of this research. The data gathering process of material flows commenced at the point where virgin fibre pulp and recovered paper was received at a paper mill and terminated at the point the paper left the mill for delivery to the different consumers.

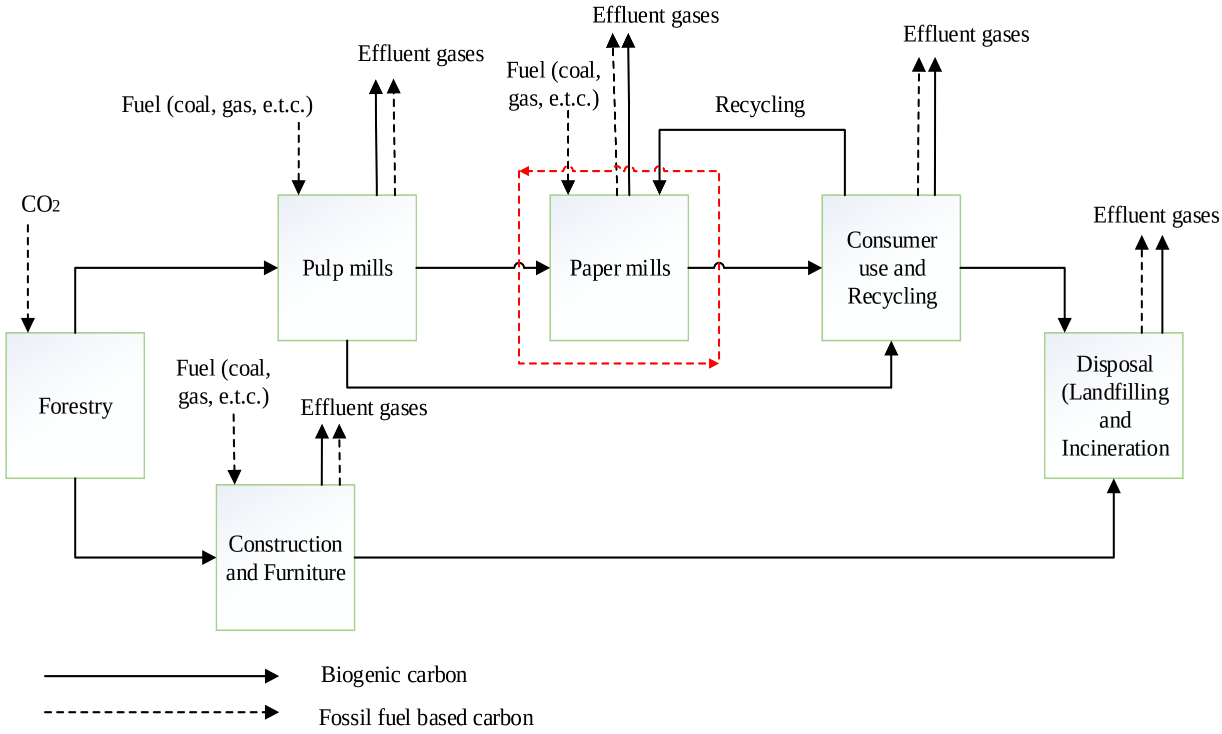

Figure 1-3. The system boundaries of PAMSA's fibre optimisation research project showing the sources and sinks of carbon. The boundaries for this MFA study i.e. paper mills, assumes that recovered paper fibres and virgin pulp fibre inputs, are distinguishable. However, the effluent gases are indistinguishable.

1.4 Purpose of the investigation

This research provides the material flows in the form of LCC across the papermaking processes all paper mills in the South African paper industry. This would allow the determination of the quantity of LCC emissions across paper mills in South Africa. The lignocellulosic carbon in raw materials entering the paper production cycle can end up in various products which include: paper, paper sludge i.e. fibre in the sludge, and effluent i.e. fibre in process wastewater. The results of this MFA and the other four PAMSA-funded MFA studies would provide quantitative data through which a framework can be developed to optimize the usage of fibrous raw materials across paper mills in South Africa. In addition, the results would assist in discerning whether lignocellulosic raw materials are effectively used across the papermaking industry. Presently, no published work on LCC flows of paper mills in South Africa exist. exist.

1.5 Research aims:

The aims of the research were to quantify and track the flow of LCC only across paper mills in South Africa for the calendar year of 2011. The system boundary of the paper mills in South Africa commenced at the point where virgin fibre pulp and recovered paper was received at a paper mill and terminated at the point the paper leaves the mill for delivery to the different consumers.

1.6 Objectives of the research

a. Identify and quantify the raw materials used, paper and waste[3] produced across each paper machine and the paper industry.

b. Quantify the fibre and LCC in the raw materials used, paper produced and waste produced across each paper machine and the South African paper industry.

c. Determine the composition of LCC in the paper and waste streams.

d. Quantify the yield of LCC across each paper machine and the South African paper industry.

e. Determine the paper grade production that results in the highest LCC yield or LCC locked up in the product relative to the waste streams.

1.7 Research questions

a. What raw materials were used in the production of paper across all paper machines in South Africa in 2011?

b. What were paper grades the produced on all paper machines in South Africa in 2011?

c. What was the quantity of all paper grades produced across all paper machines in South Africa in 2011?

d. How much waste was produced by each paper machine in South Africa in 2011?

[3] Waste is defined as the combination of paper sludge and effluent.

e. What is the amount fibre and LCC in the raw materials used, paper and waste produced by each paper machine and the South African paper industry in 2011?

f. How much of the LCC in the raw materials used across each paper machine ends up in the paper produced?

g. Which paper grade results in the highest amount of LCC being locked up in the product relative to the waste streams?

1.8 Hypothesis

It was hypothesised that most of the LCC that enters all paper mills in South Africa will end up in the desired product i.e. paper relative to the waste streams.

1.9 Research design

The material flows data required for this investigation was mainly collected through interviews (conducted during paper mill visits) with paper mill personnel (engineers, operators and technicians) and questionnaire surveys. In cases where historical paper mill production data could not be provided, statistical data from published annual production reports and assumptions were used to supplement production data. The assumptions made were based on available literature and knowledge provided by paper mills personnel. The material flows were then modelled using mass balance principles to determine the various flows of paper and waste streams. An elemental mass balance was then conducted to determine the flows of LCC. An analysis of the LCC flows was then carried out and the relevance of MFA results on the production of various paper grades assessed.

1.10 Limitations

Paper comprises of LCC and mineral carbon amongst other components. This investigation focused only on tracking the flow of LCC across paper mills in South Africa in 2011. The source of raw materials used in the production of paper was taken into consideration in this study. For instance, the pulp type- depending on type of wood used and pulping method- affects the amount of LCC in paper. The fate of the paper after it leaves the paper mill gate were not considered in this study. No emphasis was made in reporting the flows of mineral carbon except where it assisted in explaining the LCC flows. In addition, carbon flows introduced through energy generation (e.g. burning of coal) and the associated carbon emissions attributed to paper manufacturing and transport of materials were omitted from this study. For this reason, the results of this investigation cannot be interpreted as the flow of generic carbon across paper mills in South Africa.

1.11 Structure of the dissertation

The rest of the dissertation was structured as follows:

Chapter 2 presents a critical discussion of the MFA as a scientific tool to provide an insight and awareness of different arguments and theories applied in conducting an MFA study. Material Flow Analysis case studies are critically reviewed with arguments for and against, which helped in deciding on a methodology for this research.

Chapter 3 presents an overview of the South African paper industry necessary to understand the flow of materials across the industry. Paper grades, raw materials composition and the papermaking process are concisely but comprehensively discussed.

Chapter 4 presents the MFA study methodology used to identify and track the flow of lignocellulosic carbon (LCC) across paper mills in South Africa for the calendar year 2011. The relevant materials, procedure and assumptions adopted are discussed.

Chapter 5 presents the findings and a discussion of the MFA study across paper mills in South Africa for the calendar year of 2011. In addition, three scenarios - developed based on the South African paper industry's market-related changes - were investigated using the paper machine models.

Chapter 6 presents the conclusions and recommendations drawn from the findings of this MFA study across paper mills in South Africa for the calendar year of 2011.

1.12 Summary

In this chapter, the role of the South African paper industry in both the international and local context was discussed. The purpose of this research investigation was clearly outlined as part of a fibre management strategy that seeks to verify the effectiveness in the utilisation of fibre across paper mills in South Africa. This was to be achieved by conducting an MFA study to track the flow of LCC. The spatial and temporal boundaries were defined as the geographical boundaries of South Africa and calendar year of 2011 respectively. A brief review of MFA was discussed to see how it would provide relevant material flows required. The objectives of this research investigation and the subsequent research questions were outlined. It was hypothesised that most of the LCC will report to the desired final paper product compared to that lost as waste. The research design was briefly reviewed identifying the data collection and data analysis. The results of this investigation will provide materials flows data to inform an assessment of the papermaking life cycle in South Africa. The limitations associated with this study concluded this chapter. A critical review of the literature on the MFA approach is presented in the next chapter.

2 MATERIAL FLOW ANALYSIS

In this chapter, a critical discussion of the MFA as a scientific tool is conducted to provide an insight and awareness of different arguments and theories applied in conducting an MFA study. Published work on MFA case studies is critically reviewed with arguments for and against, which helped in deciding on a methodology for this research. A life cycle assessment is reviewed as an alternative approach to determining and analysing material flows.

2.1 What is a Material Flow Analysis?

Different authors have offered similar definitions for a Material Flow Analysis (MFA). Brunner and Rechberger (2004) and Cencic and Rechberger (2008) define an MFA as a 'systematic assessment of flows and stocks of materials within an arbitrary system defined in space and time'. According to Bringezu and Moriguchi (2002), an MFA is a study of the throughput of various process chains based on quantifying the associated inputs and outputs. Hashimoto et al. (2004) define an MFA as a procedure that captures the flow of inputs and outputs through each production node using material balance equations, and process and equipment parameters. In analysing these definitions, it is clear that an MFA study seeks to deliver a complete and consistent set of information about flows and stocks of a specified material within a defined system (Brunner and Rechberger, 2004). It is impossible to optimize the metabolism of anthropogenic systems without knowing the material flows and stocks. Material flow analysis studies are thus carried out to determine a systems' metabolism of one or several substances usually for resource and/or environmental management. The aim of an MFA study is to describe and analyse a real system as simple as possible whilst providing sufficient details about flows of materials (Brunner and Rechberger, 2004; Boersema et al., 2009). The basic principle underpinning any material flow analysis is the law of conservation of matter. It specifies that the sum of inflows into any system must equal outflows and any accumulated stock within the system over a defined period of time (Brunner and Rechberger, 2004).

2.1.1 Historical background: Applications of a Material Flow Analysis

Historically, the MFA approach has been widely used to identify and trace the flow of materials among different sectors of the economy (Nakamura and Nakajima, 2005; Bringezu and Moriguchi, 2002). It has proved to be indispensable in its application as a basic tool in fields such as economics, environmental management, resource management and waste management (Bringezu and Moriguchi, 2002; Patrício et al., 2015; Wang and Ma, 2018). Various MFA studies have been conducted to quantify industrial metabolism of materials across processes, industries, cities or entire biogeochemical cycles. Examples include environmental engineering and management applications such as remediation of hazardous waste, the design of air pollution strategies and sewage- sludge management amongst others (Baccini and Brunner, 1991; Brunner and Rechberger, 2004; Hashimoto et al., 2004). In resource management, an MFA is helpful in identifying the accumulation and depletion of materials in natural and anthropogenic environments (Brunner and Rechberger, 2004). Thus, it forms the basis for modelling resource consumption and changes in stocks hence providing a forecast on the scarcity of resources. In all this, the ability of an MFA to provide a thorough understanding of the flows of stocks and materials makes it an indispensable tool.

2.1.2 Material Flow Analysis studies on paper flows

Material flow analysis, as a subject and approach, has been used to gain an insight into material flows in the paper industry in various countries. As cited by Hong et al. (2011), these countries include the United States (Ince, 1996), the Netherlands (Hekkert et al., 2000), Japan (Hashimoto et al., 2004) and South Korea (Hong et al., 2011). However, the aims and objectives of analysing the flow of target materials in these studies varied as discussed below.

2.1.2.1 Analysis of paper and wood flows in the Netherlands: STREAMS method

In analysing the flows of wood and paper products in the Netherlands, Hekkert et al. (2000) conducted a material flow analysis incorporating an approach he called the STREAMS method. STREAMS is an acronym for STatistical REsearch for Analysing Material Streams. This method seeks to provide detailed information about the final consumption of paper grades particularly the material flows normally difficult to track such as packaging materials. The method is useful in that it provides valuable information on both the final direct and indirect consumption of products and materials usually hard to establish. In the absence of this information, apparent consumption data would be used as an estimate of the final consumption (Hekkert et al., 2000). Apart from the study on wood and paper flows conducted by, Hekkert et al. (2000), Joosten et al. (1998) have also used the STREAMS method to analyse the flow of plastics in the Netherlands.

The STREAMS method is based on 'make and use' tables that provide a view of the monetary value of material flows in an economy. Every product, producer and consumer is taken into account. In the flows analysis done by Hekkert et al. (2000) the 'monetary supply and use' data for paper and wood products were converted to physical (mass) flows. This critical step of performing the conversion calculations is subject to different published approaches. Hekkert et al. (2000) adopted the conversion of monetary values to physical flows by using Statistics Netherlands data and then disaggregated the data by assuming uniform prices within industrial categories. In the STREAMS approach on plastic flows conducted by Joosten et al. (1998), the total monetary value of plastics in the supply and use tables was divided by the mean export prices of plastics to get the physical data. Furthermore, Hekkert et al. (2000) indicate that the calculation of the indirect final consumption is a complicated process involving a lot of matrix multiplication carried out on the physical use and supply tables.

The conversion of the monetary value of a commodity to physical data introduces inaccuracies and uncertainties to the material flows in physical terms. This is a concern, especially for paper and paperboard products because of the large range in quality of paper grades and the associated prices (Hekkert et al., 2000). In this case, most prices were derived from foreign trade statistics. These prices would give the market value of paper products and not the production costs of paper products which would be required if such an approach is to be used in this MFA study. The aim of this research study was to determine the flows of lignocellulosic carbon across the production processes. As such, the production cost (not market value) of paper would be required in order to convert monetary values into mass flows of paper only if the latter is not available. Further, prices fluctuate throughout the year due to inflation and monetary exchange rate variations. The conversion of monetary value to physical data thus does not give a true reflection of the total paper production as it introduces considerable inaccuracies. The STREAMS method has another drawback in that it addresses only products that have an economic value. Data on waste streams would only be available when the monetary value associated with treatment and transport costs is provided. In simple terms, the STREAMS methodology does not provide insight into the production processes, waste flows and waste treatment processes as corroborated by Hekkert et al. (2000). Information on these streams was necessary to conduct a concise MFA study so as to trace the fate of LCC across all paper mills in South Africa. The STREAMS method does provide information on final consumption patterns of paper products such as packaging that are usually difficult to gather. However, this information was not relevant in this study since the system boundaries of this research study exclude the consumption of the paper products. Based on the uncertainties in price estimates used and unavailability of information on the papermaking production processes and waste flows, the STREAMS method was considered undesirable for use in this research study.

2.1.2.2 Material flow analysis of paper in Korea: Flow relationships model

Hong et al. (2011) performed an MFA of paper across the papermaking industry in Korea using a data model based on flow relationships. In his approach, he argues that most MFA studies conducted in various countries to track the flows of paper were not analysed in detail. For instance, he argues that the MFA studies conducted in the United States (Ince, 1996) and Netherlands (Hekkert et al., 2000) simplified the material flows by considering different paper grades as a single paper product. He cites that the Japanese MFA study provided more detailed information on different paper products, but it did not distinctively separate the input flows into primary raw materials and secondary raw materials. Hong et al. (2011) thus quantified and separated primary and secondary raw materials fed into the South Korean paper industry.

However, Hong et al. (2011) mentions that information on the types and quantity of pulp and recovered paper used in the production of each paper grade was not readily accessible. This information was regarded as sensitive to corporate operations in the South Korean paper sector. In light of this, Hong et al. (2011) collected the amount of each paper grade, its composition and the production yield. They used that to calculate the respective quantity of pulp (primary or secondary) required for production. This information was readily obtainable from Korea's Paper Manufacturers Association. Paper, paperboard and tissue grades were divided into 8 grades as governed by the South Korean standards[4].

A set of 27 equations based on gathered data was used to define the material balance calculation model. Of particular interest, was the fact that the life-time distribution of products was incorporated into the mass balance model. If a product's lifetime was shorter than the temporal boundary i.e. less than one year, its net stock was assumed to be zero. A population balance model (PBM) was used to describe a product's lifetime characteristics if product lifetime was greater than one year. The results of the model were then compared with the published national statistical data to determine the degree of accuracy associated with the model[5]. An accuracy

[4] The eight classes of paper products in Korean study is as follows: newsprint; printing papers, sanitary & household papers, speciality paper, corrugating board, boxboard, wrapping & packaging papers and other paperboard.
[5] The assumption was that published statistical data is accurate and can thus be used as reference.

analysis using the mean absolute error (MAPE) method was then conducted to describe the deviation between this proposed model results and provided statistical data.

Based on the above-mentioned detailed analysis of this method, the Hong et al. (2011) mass balance model covered most of the aspects that are of interest in this PAMSA-funded MFA study. Most importantly, its ability to quantify material flows, for example, pulp and additives throughout the production process. However, an elemental mass balance model would be required to quantify the LCC flows within the production processes of paper mills. The lifetime distribution aspects of Hong et al. (2011) mass balance model were not relevant to this research study because the spatial system boundaries of this research i.e. the residence time of stock (fibrous pulp and additives) across the production process is a year. The paper produced at every paper mill was assumed to be consumed or sold within a year hence the net stock will be zero.

2.1.2.3 A carbon balance method for paper and wood: the USA

Cote et al. (2002) performed an MFA study to track the flow of carbon across a manufacturing process defined as an integrated pulp and paper mill. The carbon referred to herein was inclusive of the carbon in the wood fibres, papermaking additives, carbon emissions attributed to pre-and post-manufacturing phases manufacture, and transport of materials. This approach by Cote et al. (2002) was basically a carbon balance model focused on quantifying the carbon stored in forestry products compared to the carbon released into the atmosphere. This carbon balance model allowed consideration of different carbon accounting scenarios regarding the handling of emissions and sequestered carbon. The carbon accounting scenarios were based on a set of assumptions employed in the analysis. An example is a set of assumptions that addresses carbon emissions according to fuel usage. The “Fuel Accounting” assumption counts all emissions from combustion of fuel irrespective of fuel type. In contrast, the “Kyoto accounting” assumption accounts for emissions from fossil fuels only thus excluding biofuel emissions since they are renewable (Cote et al., 2002). The consequences of these assumptions on the carbon balance model won’t be discussed in this dissertation as it does not consider pre and post emissions associated with the paper production process. An in-depth analysis of the assumptions can be found in the work of Cote et al. (2002). On completion of the carbon balance, the input wood fibres and the various forestry products were converted to respective carbon equivalents. A sequestration ratio (mass of sequestered carbon/mass of carbon emitted) was then computed using these carbon equivalents (Cote et al., 2002)[6].

The carbon balance approach by Cote et al. (2002) - unlike the other methods discussed in this research - provides an insight on how to perform an elemental carbon balance . Bone dry tonnes of fibre are converted to their carbon equivalents. This was the fundamental basis of this research study i.e. to quantify the LCC flows across the paper production processes. However, the aspects of manufacturing energy emissions were not included in this research study as specified in the research aims defined in section 1.5.

2.1.2.4 Summary

In all the case studies discussed above, each was unique in terms of its objectives and the approach to arrive at the desired results. Each study employed a different approach, however, the underlying principles in each case were defined by MFA principles. Hong et al. (2011) argue that the flows of paper are quite difficult to trace due to the existence of the many types of paper grades available on the market. None of these studies employed the same procedure to quantify the flows of paper. For instance, the flows of wood and paper were simplified by considering different paper products as a single product, in both the US (Ince, 1996) and Netherlands (Hekkert et al., 2000) studies. The Japanese study (Hashimoto et al., 2004) provided detailed information on different paper products but did not separate the input flows into primary and secondary raw materials. The Korean study (Hong et al., 2011) separated input flows into primary and secondary raw materials. Nevertheless, all of these studies were systematic. The end result was to provide information and data on material flows of the target materials. In this research investigation, an MFA study was conducted to gain an understanding of the flow of LCC over a system defined in space and time as the paper mills within the geographical borders of South Africa for the production year of 2011.

2.1.3 Objectives of a Material Flow Analysis

According to Brunner and Rechberger (2004), the objectives of any MFA study can be summarised as follows:'

a. Describe a system of material flows and stocks by use of well-defined and consistent terms.

[6] A sequestration ratio of greater than 1.0 indicates that more atmospheric carbon is being stored in wood and wood products than is emitted into the atmosphere during the manufacturing wood products by the facility in question.

b. Simplify the system as far as possible while still guaranteeing a basis for sound decision making.
c. Assess the relevant flows and stocks in quantitative terms.
d. Present results of flows and stocks of a system in a reproducible, understandable and transparent way.
e. Use the results as a basis for managing resources and the environment.'

2.1.4 Material flow analysis terminology

According to Brunner and Rechberger (2004), the exact definition of terms and procedures should be used. This allows the generation of reproducible and transparent results which facilitates a good communication among users of the MFA results. The terminology developed by Baccini and Brunner (1991 cited by Brunner and Rechberger, 2004) for use in MFA studies is as follows:'

i. Material –an umbrella term that refers to both goods and substances.
ii. Substance –any (chemical) element or a compound composed of uniform or identical units only e.g. carbon or calcium carbonate.
iii. Goods –substances or mixtures of substances that have a positive or negative economic value associated with them. As an example, wood is composed of different substances such as cellulose, hydrogen, oxygen, etc. whose compositions are non-uniform across species.
iv. Process **-** defined as the transportation, transformation or storage of materials.
v. Stocks – defined as material (mass) reservoirs within a specified system. It is a part of the process comprising of the mass that is stored within the process. Stock can either accumulate, deplete or stay constant within a system.
vi. System – is the actual object of any MFA investigation. It comprises of material flows, stocks, processes and the interaction of all these within a boundary defined in space and time.
vii) Transfer coefficients – describe the partitioning of a substance within a process.'

2.1.5 Material Flow Analysis procedure

Even though all MFA studies are based on providing information on industrial metabolism, there are various methodological approaches, which are based on different goals, concepts and target materials. This diversity in MFA approaches comes from the differences in conceptual backgrounds. This is corroborated in the studies conducted by Cote et al. (2002), Hekkert et al. (2000) and Hong et al. (2011) reviewed earlier in section 2.1.2. This brings forth the argument provided by Bringezu and Moriguchi (2002) that there is no general consensus on a methodological framework for conducting MFA studies. Based on the approach by Bringezu and Moriguchi (2002) and Brunner and Rechberger (2004), an MFA procedure comprises of the following steps:

- goal and systems definition,
- identification and selection of relevant substances, goods, processes and stocks,
- process chain analysis,
- accounting and balancing,
- modelling and presentation of results

2.1.5.1 Goals and system definition

This involves defining the problem and adequate goals, formulation of target questions and definition of the scope. Target questions should be defined according to the primary objectives. The system boundary should be defined both in time and space (temporal and spatial boundaries) through which the system is investigated and balanced. An MFA system should be chosen to be as small and consistent as possible while still being broad enough to include all necessary processes and material flows. The spatial system boundary is usually determined by the scope of the project. It can often coincide with the politically defined region or administrative regions, such as nations, states since information is systematically collected on these levels. In addition, decisions based on the results of an MFA can be implemented more easily in such administratively defined regions. A temporal boundary describes the time span through which the system is balanced; it can range from 1 sec for a combustion process to 1 000 years for landfills. Commonly applied temporal boundaries are 1 hour, 1 day, or 1 year (Brunner and Rechberger, 2004; Bringezu and Moriguchi, 2002).

2.1.5.2 Identification and selection of relevant goods, substances, flows, stocks

The selection of goods and substances depends on the scope of the system, purpose of MFA, and the resources (financial and human) that are available for the MFA study. The relevance of substances in the important flows of goods has to be evaluated. A practical rule is to determine these flows at the beginning of the MFA study by grouping all input and output flows into solids, liquids and gases. For each group, as many flows are selected to cover at least

90 % of the total mass flow of the group. This criterion yields a set of important flows of goods for the system. In some cases where an MFA study is carried out to determine a system's metabolism of one or several substances, the selection of substance becomes part of the project definition (Brunner and Rechberger, 2004).

The search for, collection, evaluation and handling of data are fundamental tasks in an MFA study. Published reports by regional, national or international administrative bodies such as industry associations and bureaus of statistics usually provide statistical data on production, consumption and sales of goods. Material flows are usually measured directly or indirectly on site. In cases where direct material flows measurement is unavailable, flows are assessed based on comparisons between similar systems' or proxy data. Scientific journals, proceedings and books also provide production and process information that contributes to accounting for material flows. Depending on the financial resources available for an MFA study, mass flows of goods and substance concentrations can be measured through sampling. Nevertheless, the source of all data used should be clearly stated (Brunner and Rechberger, 2004).

2.1.5.3 Process chain analysis

This defines the processes for which the inputs, stocks and outputs are to be quantitatively determined (Bringezu and Moriguchi, 2002). The number of processes necessary to describe a system depends on the objectives of the study, the complexity of the system, the objectives of the MFA study and the system boundaries. Processes can be further divided into sub-processes. The number of processes should be kept minimum so as to develop a simple and reliable model to picture reality. As a general rule, a system with more than 15 processes tends to be unnecessarily complex (Brunner and Rechberger, 2004).

2.1.5.4 Accounting and balancing: assessment of total flows and stocks

The mass of inputs into a system or process equals the mass of all outputs plus a change in the storage term which represent either accumulation or depletion of materials within the process considered. The substance flows are often calculated based on the mass flows of goods and substance mass fraction in these goods. The mass balancing is used to check the accuracy of empirical data, to improve consistency and to fill in missing data (Brunner and Rechberger, 2004). This is usually performed on the basis of stoichiometric or technical coefficients and may be assisted by computer simulation based on mathematical modelling (Bringezu and Moriguchi, 2002).

2.1.5.5 Modelling and presentation of results

Modelling of material flows may be applied in the form of either basic book-keeping or with increasing complexity such as static or dynamic modelling (Bringezu and Moriguchi, 2002). Brunner and Rechberger (2004) indicate that the software used in conducting an MFA study has to meet special requirements namely terminology; methodology, data handling and calculations. An in-depth discussion of these requirements is found in Brunner and Rechberger (2004). Various software packages such as Umberto, Simbox, Gabi and STAN can be used to simulate the processes considered in a typical MFA study. Simbox and STAN are the two software packages that have been designed to strictly adhere to MFA methodology (Brunner and Rechberger, 2004; Cencic and Rechberger, 2008).

The results of an MFA study should be presented in an appropriate way that is easily comprehensible to the relevant audience. There are particularly two crucial audiences of MFA study results namely: (i) technical experts and (ii) stakeholders with little or no technical scientific background. The latter group, though not familiar with MFA terminology and procedures, is the most important. In most cases, they control the policy and decision-making processes. Hence, MFA results need to be presented in a comprehensive way and the terminology used must be understandable to this group. The findings of every MFA study need to be presented in an appropriate way to visualize the conclusions whilst also facilitating the implementation of goal-oriented decisions. Flowcharts, Sankey diagrams, partitioning diagrams etc. are used for the purpose of illustrating the results visually. A Sankey diagram is usually the preferred choice. At a glance, a reader can check whether materials are accumulated or depleted in the system and identify which sources, pathways, and sinks are most important (Brunner and Rechberger, 2004; Cencic and Rechberger, 2008).

2.1.6 A brief remark on the Material Flow Analysis procedure

In order to achieve the best results with an MFA study, Brunner and Rechberger (2004) suggest that the MFA procedure described in section 2.2.5 need not be implemented in chronological order. The procedure has to be optimized iteratively. For instance, they suggest starting with rough flow estimates and provisional data, constantly refine and improve the system and data until the required quality of data certainty is achieved.

2.2 Material Flow Analysis: weaknesses

A Material Flow Analysis study alone is not an adequate tool to assess and support engineering or management's measures since anthropogenic systems consist of more than material flows and stocks. Any changes in material and energy flows are not in isolation from socio-economic parameters. If the anthroposphere is to be managed in a responsibly sound manner; energy, information, space and socio-economic issues have to be considered in conjunction with the material flow analysis. Economic decision-making coupled with physical and economic constraints of a defined system can influence changes in material flows. Hence a traditional MFA study, with its lack of reference to socio-economic parameters, may misrepresent in some contexts, the physical realities of production. Inevitably, an MFA study cannot provide realistic descriptions of industrial behaviour, industrial future and associated environmental impacts (Ruth and Davidsdottir, 2009; Hesselbach and Herrmann, 2011).

Ruth and Davidsdottir (2009) argue that current MFA studies should not only assess the quantity and physical dynamics of flows and stocks. They argue that MFA studies be further developed to provide an assessment of what influences changes in stock and flow dynamics. To address this, questions are not only asked about the materials flows, but also how to influence these flows. This identifies behavioural leverage points for changes in the system (Ruth and Davidsdottir, 2009). Nevertheless, an MFA study, for the sake of obtaining information on material flows, can be performed independently without considering socioeconomic aspects. However, these aspects are needed to interpret and make use of the MFA results (Brunner and Rechberger, 2004; Ruth and Davidsdottir, 2009).

2.3 Comparison of a Material Flow Analysis and a Life Cycle Assessment (LCA)

The International Organisation for Standardisation (ISO) defines an LCA as a compilation and evaluation of the inputs and outputs and the potential impacts of a product's system throughout its life cycle. It is a comprehensive environmental accounting tool with well-established procedures and methods that are governed by specific standards and rules. An LCA procedure follows four fundamental steps namely:

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

For each life cycle stage, all the processes are identified and all the inputs (materials and energy) and outputs for each process are identified. Each input and output is grouped into potential environmental impact categories. The corresponding impact indicators such a climate change or toxicity are calculated. The sum of impacts is interpreted and considered together against the original goals of the LCA. For an LCA to be most useful, the targets and goals of the assessment should be clearly set out in advance (Hesselbach and Herrmann, 2011; Brunner and Rechberger, 2004). Examining a product over its entire lifecycle allows informed decisions to be made such as restricting the transfer of pollutants from one life stage to another. A life cycle analysis has the ability to communicate multiple benefits or shortfalls of different initiatives underway to an audience due to the comprehensive picture it provides. However, it is time-consuming to perform and technically challenging but if well planned, its benefits overshadow the costs (Brunner and Rechberger, 2004).

2.3.1 The relevance of Material Flow Analysis over Life Cycle Analysis in this study

The focus of this study was to track the flow of LCC across all paper mills in South Africa. The scope of this research study thus specified that only lignocellulosic materials and non-fibrous materials used in the production of paper were tracked across paper mills in South Africa for the calendar year of 2011. The fate of the paper after it leaves the paper mill gate and other material inputs for instance coal (used in energy production for pulping and papermaking operations) were not considered in this study. A Material Flow Anaysis was thus sufficient to provide an analytical view of the system of interlinked processes across paper mills in South Africa and the relevant flows required to track the flow of LCC. In essence, an MFA study is regarded as an inventory analysis within the LCA approach (Hesselbach and Herrmann, 2011; Brunner and Rechberger, 2004).

2.4 Data uncertainties

Every physical quantity measurement has a degree of uncertainty associated with it or deviation from the true value i.e. it cannot be entirely accurate (Cencic and Rechberger, 2008). It is, therefore, important to know or estimate just how much the measured value deviates from the unknown true value of the quantity. In every MFA study, data on physical flows and stock is collected from various sources with varying quality (Laner et al., 2014; Rechberger et al., 2014; Wang and Ma, 2018; Lenglet et al., 2017), harmonised and analysed. Inherently, data limitations, inconsistencies and uncertainties are unavoidable in conducting materials flow studies (Laner et al., 2014; Hedbrant and Sörme, 2001; Lenglet et al., 2017). The uncertainty in all measured physical flows or input data is mainly source-dependent (Hedbrant and Sörme, 2001; Danius, 2002; Lenglet et al., 2017). The reliability of MFA results is closely linked to the evaluation of uncertainty in all physical flows (Rechberger et al., 2014; Wang and Ma, 2018) and this particularly important to policymakers that handle resource management issues (Wang and Ma, 2018). It is for this reason that various authors (Danius, 2002; Laner et al., 2014; Patrício et al., 2015; Wang and Ma, 2018; Rechberger et al., 2014) have investigated and reviewed approaches to address uncertainty in MFA studies. The sources of data uncertainties include data resources, calculation procedure, data quality, model assumptions and investigative methods (Wang and Ma, 2018; Lenglet et al., 2017).

2.4.1 Propagation of uncertainty

Different methods have been proposed in the literature to assess data uncertainty propagation. The most commonly used methods include the:

- Gauss Law of error propagation (Brunner and Rechberger, 2004; Laner et al., 2014; Wang and Ma, 2018)
- Monte Carlo Simulation (Brunner and Rechberger, 2004; Laner et al., 2014; Wang and Ma, 2018),
- Hedbrant and Sörme (HS) model (Hedbrant and Sörme, 2001; Danius, 2002; Laner et al., 2014; Wang and Ma, 2018) and
- use of the software STAN (Cencic and Rechberger, 2008; Laner et al., 2014).

Wang and Ma (2018) proposed the collaborative usage of two methodologies such as the HS model and the Monte Carlo Simulation in the propagation of data uncertainties. Lin (cited in Wang and Ma 2018) applied the HS model and MC simulation methods to analyse the uncertainty in copper flows. The aim was to exploit the advantages of the chosen methods in determining the data uncertainties. However, Wang and Ma (2018) further argue that this approach is more difficult in quantifying the data uncertainty range due to the individual limitations of the different methods.

2.4.2 Gauss Law

Gauss Law involves developing a function based on random variables which is expanded into a Taylor series and cut off after the first term. A first order linear approximation is thus produced. This makes it is possible to approximately determine the expected or mean value and the deviation of the function's result. It is important to note that reasonable results can be expected when the random variables are normally distributed and the uncertainties are small (Brunner and Rechberger, 2004).

2.4.3 Monte Carlo (MC) simulation

The Monte Carlo simulation is based on a computer algorithm that produces probability distributions and an uncertainty range for both measured and calculated variables (Brunner and Rechberger, 2004; Wang and Ma, 2018). A random number is generated for each input variable based on its known statistical distribution i.e. the mean and standard deviation. The output is used to calculate the resultant function's statistical distribution. The MC simulation method is more useful when data is not normally distributed and the deviations are too large (Brunner and Rechberger, 2004). It also very useful for performing data sensitivity and scenario analysis (Wang and Ma, 2018). The MC simulation is mainly used in MFA studies where sufficient data is available as it provides an uncertainty range that is close to that of observed/measured data (Brunner and Rechberger, 2004; Wang and Ma, 2018). However, Wang and Ma (2018) argues that the MC simulation method is generally difficult and time-consuming to perform.

2.4.4 Hedbrant and Sörme (HS) model

This is a useful method for determining the uncertainty of input and output flows where the former is unavailable or unknown (Danius, 2002). Asymmetric intervals and uncertainty factors are assigned to input or measured data based on the source of data (Danius, 2002; Laner et al., 2014; Hedbrant and Sörme, 2001). The intervals are specified and assumed to contain the uncertain value to within a probability of 95 %. This allows the use of the normal distribution to describe the measured or input value as its uncertainty value will thus fall within a range of two standard deviations (Danius, 2002). The propagation of data uncertainty is then calculated using two formulae that allow for either addition (or subtraction) and multiplication (or division) of input variables and their associated uncertainties (Hedbrant and Sörme, 2001). The method was designed initially for the metabolism of heavy metals; three asymmetric intervals were proposed. However as cited by Laner et al. (2014) and Wang and Ma (2018), the number of asymmetric intervals can be changed to suit the needs of the study and constraints of the data sources; the choice rests on the analyst. This can be observed in the work by Danius (2002). The HS model has a shortcoming in cases where larger uncertainties are used since the normal distribution assumption holds well for uncertainty factors close to one (Laner et al., 2014). Nevertheless, Danius (2002) performed a literature survey on 50 articles on MFA studies which dealt with data uncertainties. He concluded that the HS model dealt with data uncertainties in a complete way where the data uncertainty in measured values is unknown.

2.5 Summary

In this chapter, a critical discussion of the MFA approach as a scientific tool was conducted. This provided to provide an insight into arguments and theories applied in conducting an MFA study. Material Flow Analysis case studies were critically reviewed with arguments for and against, which helped in deciding on a methodology for conducting this MFA study. In the next chapter, an overview of the South African paper industry is reviewed.

3 OVERVIEW OF THE SOUTH AFRICAN PAPER INDUSTRY.

Papermaking is a large, multidisciplinary and sophisticated technology. The papermaking process contains many different process units that work through different mechanisms to produce the desired effects on the paper sheet formed. The need for a detailed understanding of the fundamentals of raw materials, unit processes and product properties has considerably intensified in modern papermaking (Gullichsen and Paulapuro, 2000). Different blends of fibre furnish, a number of paper grades formed (each with its own recipe and processing requirements) make the process too broad to discuss in detail. It is important to recall that the aim of this research study was to track lignocellulosic carbon (LCC) from the paper mill plant gate until the final paper grade is ready for delivery to the different consumers. Accordingly, the paper grades, raw materials composition and the papermaking process are concisely but comprehensively discussed so as to understand the flow of materials across all paper mills in South Africa.

3.1 Paper

Various authors have defined paper in terms of the raw materials composition, method of production or the end-use of the paper grade. Holik (2006) and Roberts (2007) define paper as a random web of mostly lignocellulosic fibres woven together after dewatering an aqueous suspension of fibres and additives on a screen. Biermann (1996) defines paper as a pliable material used for a variety of specialized purposes such as writing, printing and packaging. Combining these two definitions; paper is a generic term for versatile materials produced mainly using naturally occurring lignocellulose fibres and made for specialized purposes such as printing, writing and packaging.

3.1.1 Classification of paper products into grades

There are various ways in which paper can be classified into different grades. A general description of paper grades can prove to be complicated. New products are always being developed as the industry seeks to keep up with the customers' needs. The major grade classifications are shown in Table 3-1. Paper mills in South Africa classify their paper grades interchangeably; no single classification system is in place as a standard for all paper mills. However, for commercial and statistical purposes PAMSA and SARS classify paper products based on either basis weight or end - usage.

Table 3-1. Classification of paper products into different grades (extracted from Paperonweb.com, 2017)

Grade classification	**Description**
Based on basis weight	Tissue[7] : low weight < 40 g / m^2 Paper : medium weight 40 - 120 g / m^2 Paperboard : medium high weight , 120 - 200 g / m^2 Board : 200 g / m^2
Based on colour	Brown : unbleached grades White : bleached Coloured : bleached and dyed or pigmented
Based on finish	Fine / coarse Calendered / supercalendered Machine Finished (MF) / Machine Glazed (MG) Glazed / Glossed
Based on raw material	Wood : contain fibres from wood Agricultural residue: fibres from non-wood plants e.g. straw, sugarcane bagasse. Recovered or secondary fibre
Based on the surface treatment	Coated : coated with clay or other minerals Uncoated : no coating Laminated : aluminium, poly etc.
Based on usage	Industrial : packaging, wrapping, etc. Printing : copy or print paper, newspaper, currency etc. Food : food wrapping, coffee filter, tea bag etc. Hygienic : tissues, towels, sanitary paper

3.2 Papermaking raw materials

Paper is made from a complex mixture of raw materials that can be classified into two categories namely fibrous (lignocellulosic) and non-fibrous raw materials. Figure 3-1 is a flowsheet showing the raw materials used in the manufacture of paper.

[7] Some newsprint grades fall within this basis weight range.

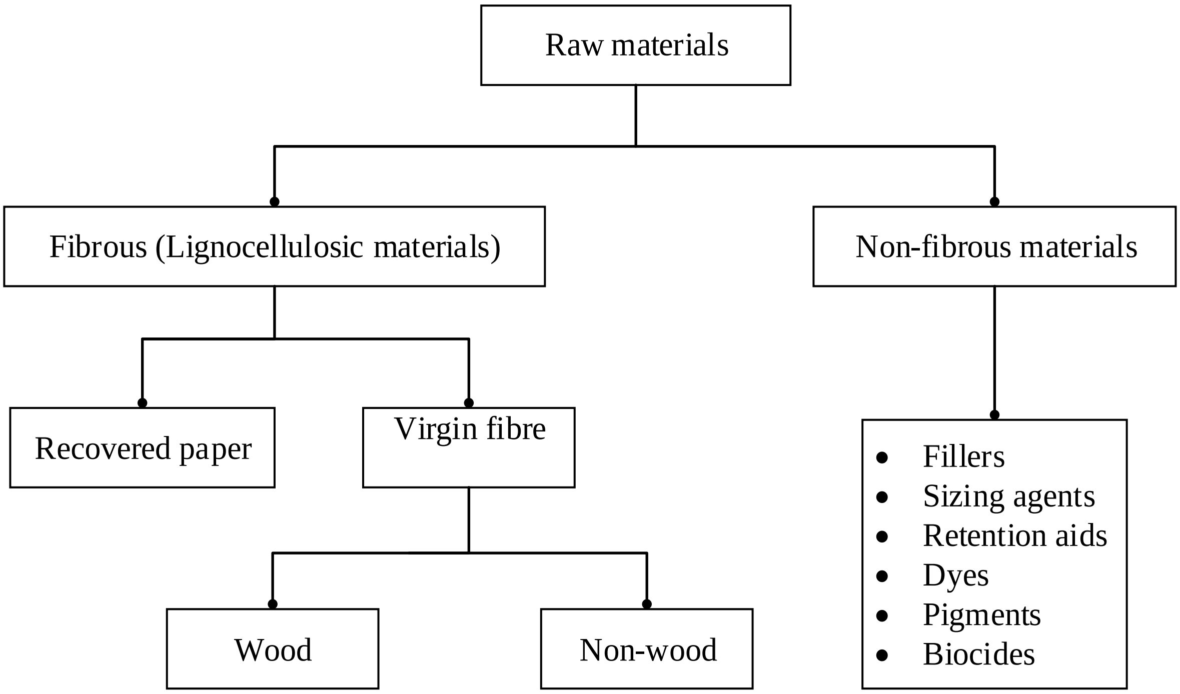

Figure 3-1. A hierarchical representation of the raw materials used in the papermaking industry.

3.2.1 Fibrous (lignocellulosic) raw materials:

The production of paper is mainly based on lignocellulosic materials (Davies, 1984; Smook, 2002; Biermann, 1996); their properties and morphology determine the different characteristics of paper grades (Biermann, 1996). Fibrous materials can be further classified as either virgin (primary) fibre or recovered (secondary fibre).

3.2.1.1 Virgin fibre

Virgin fibre describes fibrous material being used for the first time in the papermaking process. Examples include wood and non-wood fibres.

a. Wood

Wood is the primary raw material for papermaking accounting for 90 % of global paper production (Holik, 2006; Sixta, 2006; Davies, 1984). It is further classified botanically into two major groups namely softwoods (SW) and hardwoods (HW) each providing different morphological properties and applications in papermaking (Roberts, 2007, Smook, 2002).

Softwoods

Gymnosperms, commonly called softwoods or conifers, comprise of two types of cells namely the long tapering vertically aligned *Tracheids* - and shorter horizontally aligned *Parenchyma* cells. *Tracheids*, which constitute over 90 vol% of most softwoods, form the basis of papermaking cells hence are commonly referred as wood fibres (Gullichsen and Fogelholm, 1999, Smook, 2002, Roberts, 2007). An example of a commonly grown softwood species grown in South Africa is *Pinus patula* (Adu-Poku, 2015), which is one species of pine.

Hardwoods

Angiosperms are commonly referred to as hardwoods or deciduous trees. The vertical structure primarily comprises of relatively short narrow fibres called *tracheids* that constitute about 50 vol% of the wood. In addition, hardwoods comprise mainly of the vertically aligned large-diameter cells called *vessel elements* - large empty cells or grooves - and horizontal *Parenchyma cells* (Gullichsen and Fogelholm, 1999, Smook, 2002*)*. The former is more abundant hardwoods than softwoods (Roberts, 2007). Commonly grown hardwood species grown in South Africa include *Eucalyptus grandis* and *Acacia mearnsii* (Adu-Poku, 2015).

Comparison between softwoods and hardwoods

The structural characteristics of lignocellulosic fibres determine the properties of any paper product. Two of the most important characteristics are fibre length and cell wall thickness. Softwoods and hardwoods fundamentally exhibit different papermaking properties due to the different fibre morphologies as shown in Table 3-2. Fibre length is proportional to tear strength; thinner cell walls collapse readily resulting in better inter-fibre bonding (Roberts, 2007, Smook, 2002). Softwood fibres are typical longer, stronger and have thinner cell walls than hardwood fibres thus making the bulk of fibres in papermaking globally. However, SW pulp tends to produce non-uniform paper sheets, whereas HW fibres exhibit good uniform formation properties together with good bulking, opacity and stiffness (Roberts, 2007). It is thus common practice that a blend of SW and HW fibres is used in papermaking to achieve an appropriate compromise between formation and strength.

Table 3-2. Comparison of morphological properties of softwoods and hardwoods (Smook, 2002; Roberts, 2007).

Property	Softwoods	Hardwoods
Fibre length (mm)	Long (~3 mm)	Short (~1 mm)
Cell wall thickness	Thinner	Thicker
Lignin	More	Less
Holocellulose	More	Less
Wood (fibre) density	Higher	Lower

b. Non-wood sources

Examples of non-wood fibrous sources include agricultural residues such as cotton, cereal straw, bagasse, bamboo, reeds, hemp, jute, and others. In South Africa, only bagasse was used commercially as a non-wood fibrous raw material at two paper mills namely Sappi Stanger and Mpact Felixton as of 2011. The latter has since progressively replaced bagasse with recovered paper as a raw material since mid-2015 (TAPPSA, 2016). Bagasse is the fibrous residue portion of sugar cane processing from which sucrose juice has been extracted (Anukam et al., 2016; Lois-Correa et al., 2010). Fresh bagasse, as obtained in the sugar mills contains around 50 % moisture. The dry mass portion consists of approximately 60-65 % fibre, 30-35 % pith and about 5 % water solubles (Rainey and Covey, 2016). The pith is composed mainly of *parenchyma* cells. Bagasse is depithed prior to its use in papermaking due to the non-fibrous physical nature and significantly shorter length of pith (Lois-Correa et al., 2010; Rainey and Covey, 2016).

3.2.1.2 Recovered fibre

Recovered fibre (RCF) is defined as fibrous material that has been previously used in a manufacturing process and reclaimed as raw material for another manufacturing process (Smook, 2002). The source of RCF is recycled paper products arising outside of the mill; it is usually classified as pre-consumer and post-consumer waste. On the other hand, RCF is distinguished from broke, which is off-specification paper produced at, and reused, within the mill (Biermann, 1996).

c. Use of recovered fibre in papermaking across all paper mills in South Africa

The recovered paper grade definitions as provided by the Packaging Council of South Africa (PACSA) provide the guidelines for the collection and trading of recovered paper. A summary of the recovered paper grades definitions as outlined by PACSA (2015) are shown in Table 3-3. Recovered paper - especially post-consumer paper - contains contaminants such as metals, plastics, inks, wood, building materials, glass, stickies etc. which are referred to as *prohibitives* (PACSA, 2015). The maximum allowable amount of *prohibitives* in the different recovered paper grades for trading purposes as standardized by PACSA (2015) is shown in Table 3-3. This information would be essential when accounting for the mass of dry fibre in RCF.

Table 3-3. Recovered paper grade definitions used across paper mills in South Africa as outlined by PACSA (2015).

Grade	Abbreviation	Prohibitives
Mixed Paper	CMW	1 %
Cartonboard cuttings	IMW	1 %
Mechanical Grades		
Special News	SN	1 %
Over Issue News	FN	none permitted
Magazine	SBM	none permitted
Special Magazine	SSBM	none permitted
High (quality) grades		
White One	W1	none permitted
Heavy Letter 1	HL1	none permitted
Heavy Letter 2	HL2	1 %
Super Mix	SMW	1 %
Sorted Office Paper	SOP	1 %
Kraft papers		
New Corrugated Kraft containers	K3	none permitted
Corrugated containers	K4	1 %
Unused Kraft Bags	K1	none permitted
Special Grades		
Liquid Board Packages	LBP	none permitted
Telephone directories	TD	none permitted

The use of recovered paper in papermaking is not uniformly distributed across the production of all paper grades. Recovered paper is mainly used to make similar or lower quality paper grades relative to the recovered paper grade as shown in.Table 3-4. The production of low-quality paper grades relative to the recovered paper grades is referred to as downcycling (Roberts, 2007).

Table 3-4. Recycling of recovered paper into paper grades (Roberts, 2007).

Recovered paper grade	Recycled into
A mix of office paper, newspaper, magazines and printer off-cuts (CMW, IMW, SBM, FN, HL1, HL2, SMW etc.)	Bath tissue products, kitchen & industrial towelling.
A mix office paper, corrugated boxes, newspaper, cartoon board trims and printer off-cuts (CMW, IMW, FN, SN, K3, K4 etc.)	Cartonboard (folding boxboard) e.g., cereal boxes, soap carton etc. .
A mix of newspaper & cartonboard trims (SN, FN, IMW)	Moulded paper e.g. egg boxes
Corrugated boxes (K1, K3, K4)	New corrugated boxes
Newspapers and Magazines (SN, FN, SBM)	Newspaper

3.2.1.3 Chemical composition of fibrous materials:

All fibrous raw materials consist of three major cell wall chemical components or compounds namely cellulose, lignin and hemicellulose. The minor cell wall chemical components of all fibrous materials include low molecular weight substances such as extractives and ash (Smook, 2002; Gullichsen and Fogelholm, 1999; Sixta, 2006, Biermann, 1996). The average composition of the three major chemical components of wood is shown in Table 3-5. A cross-sectional view of wood indicating the main cell wall chemical components is shown in Figure 3-2.

Table 3-5. The chemical composition of wood on an oven dry (OD) basis (Smook, 2002; Gullichsen and Fogelholm, 1999; Biermann, 1996; Sixta, 2006).

Chemical component	Softwood	Hardwood
Cellulose	42 ± 2 %	45 ± 2 %
Hemicellulose	27 ± 2 %	30 ± 5 %
Lignin	28 ± 3 %	20 ± 4 %
Extractives	3 ± 2 %	5 ± 3 %

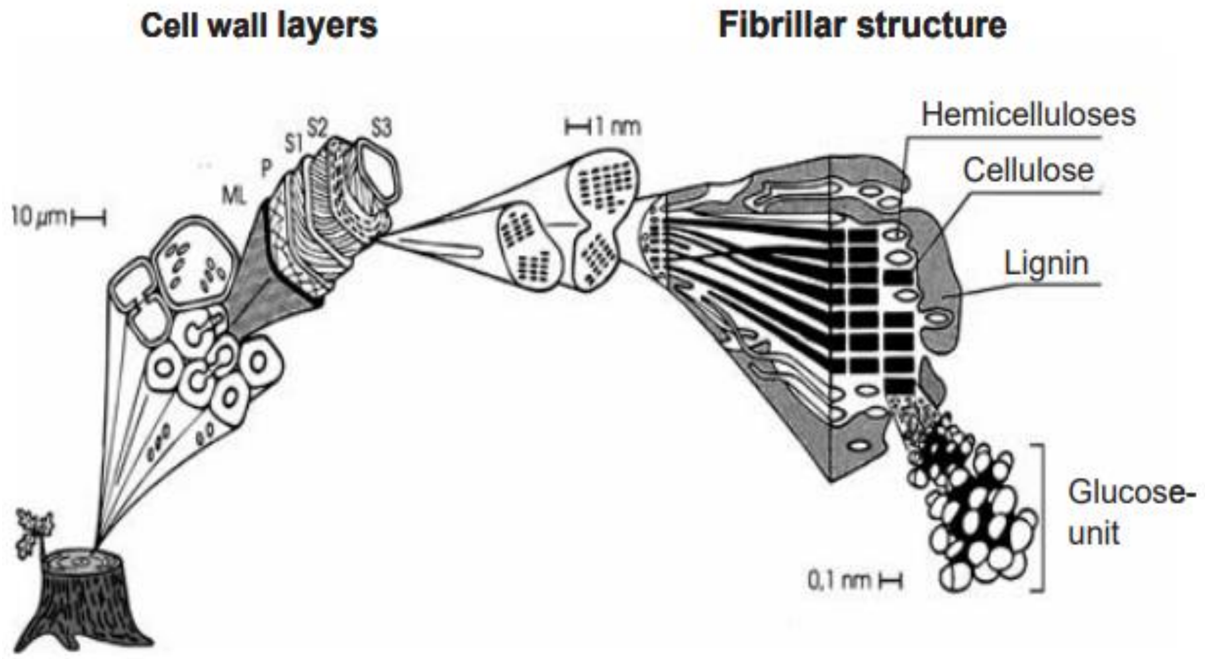

Figure 3-2. A cross-sectional view of wood showing the main cell wall chemical component (illustration by Hoffmann cited in Sixta, 2006).

Bagasse, like wood, also has cellulose, lignin and hemicellulose as the three major cell wall chemical components. However, the existence of many species of sugarcane globally results in the varied chemical composition of bagasse. This has been analysed and reported by numerous authors using bagasse sourced from around the world with fairly consistent findings (Rainey and Covey, 2016) as summarised in Table 3-6. Raw bagasse is depithed prior to use in papermaking as discussed in section 3.2.1.1; hence, only the chemical composition of depithed bagasse is shown in Table 3-6. Based on this data, the average composition of bagasse is as follows: 38-56 wt% α-cellulose, 23-34 wt% hemicellulose, 17-28 wt% lignin, and 8-12wt% extractives and ash.

a. Cellulose

Cellulose, a carbohydrate, is the main component of fibrous or lignocellulosic materials that permits its use in papermaking. Cellulose, with a chemical formula $(C_6H_{10}O_5)_n$, is a linear polymer made up of cellobiose units (Sixta, 2006; Smook, 2002). The degree of polymerization (DP) represented by n, indicates the number of repeat sugar units that can go up to 10 000; most papermaking fibres have a weighted average DP ranging from 600-1 500 (Gullichsen and Fogelholm, 1999, Smook, 2002). The cellulose content in wood and bagasse, as shown in Table 3-5 and Table 3-6. respectively accounts for 35 to 55 % of the dry mass of fibre. Cellulose molecules exist in either amorphous or crystalline form; the latter is most abundant in wood i.e. approximately 50 to 70 % (Biermann, 1996). The crystalline form of cellulose is particularly resistant to chemical, acid or alkaline attack, during the delignification of pulp fibres. The amorphous regions are more susceptible to hydrolysis reactions hence giving rise to cellulose degradation during chemical pulping (Biermann, 1996, Smook, 2002).

Table 3-6. The chemical composition of depithed sugarcane bagasse as cited in various publications.

Cellulose %	Hemicellulose %	Lignin %	Extractives %	Ash %	Reported by
42.34	28.60	21.7	7.42	2.10	Agnihotri et al., (2010)
55.8			1.85	3.25	Hemmasi et al., (2011)
44.09	23.89	21.42	7.14	3.25	Zeinaly et al., (2017)
40.50	33.20	27.70	3.80	4.80	Hamzeh et al., (2013) cited in Zeinaly et al., (2017)
47.40		20.35	3.15	1.74	Samariha and Khakifirooz 2011 cited in Zeinaly et al., (2017)
43.60	33.50	18.10		2.30	Sun et al., (2004) cited in Zeinaly et al., (2017)
45.00	28.80	17.10	2.50	1.10	Sunjan et al.,(2001) cited in Zeinaly et al., (2017)
38.0	24.2	21.7	2.9	5	Rao 1997 cited in Rainey and Covey (2016)

b. Hemicellulose

Hemicellulose like cellulose is a carbohydrate. However, unlike cellulose which is made up of only glucose units, hemicelluloses are a class of polymers made up of five carbon sugars (Pentoses) and six-carbon sugars (Hexoses). Examples include

- Pentoses: arabinose and xylose
- Hexoses: galactose, glucose, mannose and 4-0-methyl- D-glucuronic acid

The monomers include glucomannan, xylan, galactan, galactoglucomannan and arabinogalactan. Softwoods and hardwoods contain different hemicelluloses monomers in different concentrations (Sixta,2006; Chen, 2014; Gullichsen and Fogelholm, 1999; Smook, 2002). Their respective compositions are shown in Table 3-7. Xylan and glucomannan are the most abundant hemicelluloses in hardwoods and softwoods respectively (Biermann, 1996; Sixta, 2006). Hemicelluloses are much more soluble and susceptible to chemical degradation than cellulose during chemical pulping due to their mostly non-crystalline structure and lower DP (Biermann, 1996; Gullichsen and Fogelholm; 1999, Smook, 2002; Chen, 2014).

Table 3-7. The composition of hemicellulose monomers in Softwoods and hardwoods (Gullichsen and Fogelholm, 1999).

Hemicellulose component	Wood components		Kraft Pulp components	
	Pine (SW) [%]	Birch (HW) [%]	Pine (SW) [%]	Birch (HW) [%]
Glucomannan	15-20	15-21	5	1
Xylan	7-10	25-30	5	16

c. Lignin

A three dimensional, highly polymerized aromatic and amorphous substance found in fibrous materials whose primary role is to hold or glue the fibres together (Smook, 2002). The approximate chemical formula of lignin is $C_{10}H_{11}O_4$ (Roberts, 2007). Lignin primarily consists of phenyl propane units nonlinearly and randomly linked together. Lignin is removed during chemical pulping and softened in mechanical pulping to liberate the cellulose fibres for use in papermaking (Smook, 2002; Biermann, 1996).

3.2.1.4 Lignocellulosic carbon content of fibrous raw materials

The carbon found in wood and bagasse is bound mainly in cellulose, hemicellulose and lignin and in smaller quantities, in the ash and extractives. The lignocellulosic carbon content of these organic compounds in wood is considerably different as shown in Table 3-8. Lignin has the highest percentage carbon by mass. Matthews (1993) cites that the proportions of these organic compounds vary with species, geographic location, age, position in the tree amongst other factors. Hence there will be appreciable variations in the carbon content of trees. However, as a general rule of thumb, it is tacitly accepted that trees contain approximately 50 % LCC (Biermann, 1996; Matthews, 1993; Smook, 2002; Roberts, 2007; Sixta, 2006). This number compares very well to the carbon contents of different wood species compiled by Matthews (1993) from different literature sources as shown in Table 3-9. A comparison of the elemental composition of bagasse from different publications is shown in Table 3-10.

Table 3-8. Elemental composition of the main components of fibrous raw materials (Cagnon et al., 2009, Chen, 2014).

Component	C (%)	H (%)	O (%)	N (%)	S (%)	H_2O (%)	Ash (%)
Cellulose	44.4	6.17	49.4	-	-	-	-
Hemicellulose	38.1	6.0	48.5	< 0.2	< 0.4	6.4	6.7
Lignin	58.6	5.7	30.8	0.7	< 0.5	5.9	3.9

Table 3-9. The carbon content of several of wood species obtained from direct analysis (extracted from Matthews (1993)).

Species name	Carbon Content [%]	
	Average	**Range**
Ash	49.29	49.18 - 49.4
Aspen	49.85	49.39 - 50.3
Beech	49.14	49.50 - 50.9
Birch	48.76	46 - 50.6
Chestnut	50.28	
Hickory	51.6	
Lime	49.4	
Maple	50.0	49.8 - 50.2
Oak	48.95	46 - 50.6
Poplar	49.8	49.7 - 49.9
Willow	50.56	49.92 - 51.12
Fir	50.59	50 - 51.4
Larch	49.78	49.57 - 50.1
Pine	49.91	45.8 - 50.9
Spruce	49.34	47 - 50.31
Wood	50	

Table 3-10. Elemental composition of depithed bagasse (oven dry basis)

C	H	O	N	S	Reported by
44.10	5.70	47.70	0.20	2.30	Anukam et al., 2013 cited in Anukam et al. (2016)
43.77	6.83	47.46	-	-	Islam et al., 2003 cited in Anukam et al. (2016)
56.32	7.82	27.54	0.89		Ganesh et al., 2013 cited in Anukam et al. (2016)
41.75	-	-	-	-	Ado-Poku (2015)

3.2.2 Non-fibrous raw materials

Non-fibrous raw materials are referred to as papermaking additives. These are chemicals and minerals added to the fibre slurry in order to impart or enhance certain desirable sheet properties; in some cases to aid the process of papermaking (Biermann, 1996, Smook, 2002). Additives and fillers do not contain LCC. Additives are further divided into two categories as follows:

1. Functional additives – these impart certain qualities such as opacity, wet and dry strength to the paper product. Examples include sizing agents, fillers and adhesives. A high retention of functional additives on the paper sheet must be achieved for effective results. (Biermann, 1996, Smook, 2002).
2. Process additives are introduced to improve the papermaking process without directly affecting the product properties. They are not necessarily retained on the paper sheet. Examples include slimicides, biocides, drainage aids, retention aids, pitch dispersants, and defoamers (Biermann, 1996, Smook, 2002).

Some additives are multifunctional i.e. they exhibit both process and functional additive properties. For example, alum is used as a sizing agent under acid conditions but also serves as a retention and drainage aid (Biermann, 1996, Smook, 2002). A list of additives and their respective purposes in papermaking are shown in Table 3-11.

Table 3-11. A list of papermaking additives and their respective purposes (Biermann, 1996, Smook, 2002)

Additives	Purpose	Examples
Functional additives		
filler	improves optical and surface properties	clay, $CACO_3$, TiO_2, talc
sizing agent	increases resistance to penetration by fluids	rosin, starches
dry strength resins	improve strength and stiffness properties	starches, gums
wet strength resins	add wet strength to grades like towelling	
dyes and pigments	impart desired colour	
Process additives		
defoamers	increase drainage and sheet formation	
drainage aids	increase water removal on wire	
fibre flocculants	increase sheet formation	
slimicides	control slime growth	
retention aids	improve retention of fillers and fines	

3.3 The papermaking process

A paper mill can be described as either integrated or non-integrated. For integrated paper mills, pulp manufacturing and papermaking take place on the same site. The pulp made on site for own use is packed into thick sheets of 50 % solids. This is referred to as wet lap. Non-integrated or stand-alone paper mills have no pulping capacity on-site. The pulp is bought packed in the form of bales of sheets comprising of 80-85 % solids which are referred to as dry lap (Bajpai, 2011, Biermann, 1996). An integrated or non-integrated paper mill can house a single or several paper machines. Each paper machine is capable of manufacturing a single or variety of paper grades. The manufacturing of each paper grade necessitates its own set of paper mill operations, mill concepts and pieces of equipment. However, the basic process of paper-making remains fairly the same regardless of the paper machine size or the type or grade of being paper manufactured (Bajpai, 2012). These are discussed below. An overview of the papermaking process is shown in Figure 3-3. In this dissertation, the papermaking process was divided into five sections which are discussed below namely pulping, stock preparation, approach flow, paper machines and finishing

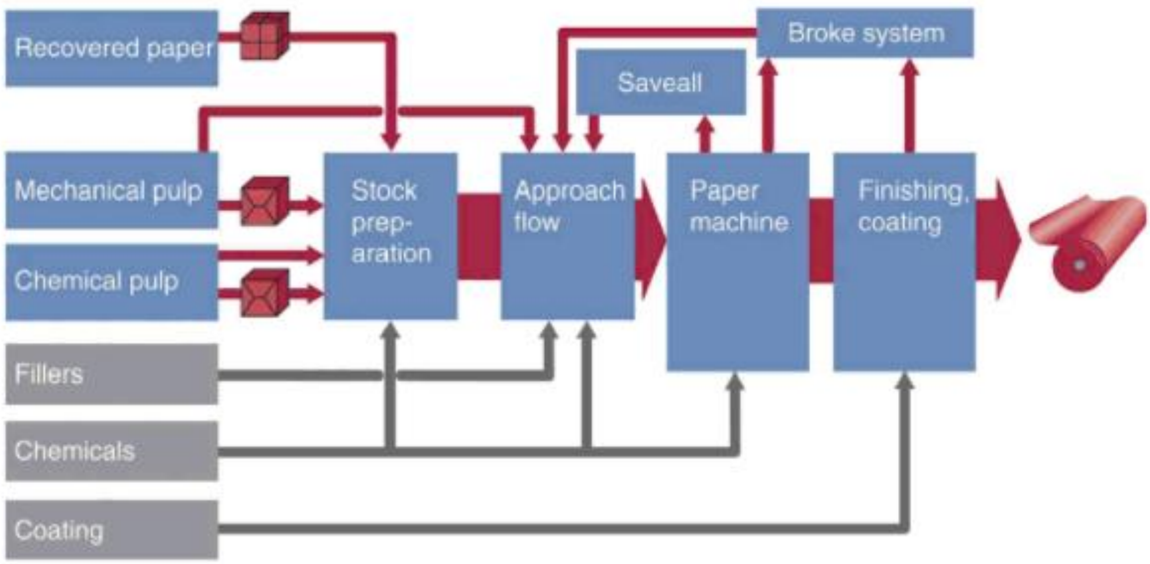

Figure 3-3. An overview of the papermaking process (extracted from Holik, 2006).

3.3.1 Pulping: raw material preparation:

Pulping and papermaking processes are fundamentally different processes. In this research, the focus is on the papermaking process. However, the close synergy between these two processes necessitates the need to briefly discuss the pulping process as a precursor to papermaking. The choice of pulpwood and the pulping process has a downstream effect on the paper grade produced, the series and sequence of the papermaking process adopted. Pulping is defined as the process(es) through which cellulose fibres are liberated from the fibrous matrix by systematically breaking the bonds within the fibrous structure (Smook, 2002, Ek et al., 2009). Pulping methods are categorized into mechanical, chemical and/or a combination of the two methods (Biermann, 1996; Gullichsen and Fogelholm, 1999; Smook, 2002). Chemical pulping involves the cooking of fibrous raw materials with appropriate chemicals to dissolve and remove lignin. The alkaline kraft (sulphate) and the acidic sulphite processes are the two principal chemical pulping methods; the former being the most commonly used. Mechanical pulping involves the application of mechanical energy to break or soften the bonds between fibres thus releasing single fibres; most of the lignin remains intact within the individual fibres (Bajpai, 2011; Biermann, 1996; Smook, 2002; Ek et al., 2009). The characteristics and examples of the mechanical and chemical wood pulp are shown in Table 3-12.

Table 3-12. Comparisons between mechanical and chemical pulping methods (Biermann, 1996, Ek et al., 2009, Smook, 2002).

	Mechanical pulping	**Chemical pulping**
Examples	Groundwood pulping (GWP),	Alkaline kraft (sulphate)
	Chemi-thermo-mechanical (CTMP)	Acidic sulphite
	Thermo-mechanical pulping (TMP)	Soda
		Neutral sulphite semi-chemical (NSSC)
Pulp properties		
Yield (%)	Very high (90-98)	Low (40-50)
Stiffness	High (rigid and uncollapsed fibres)	Low (flexible and collapsed fibres)
Strength	Low	High
Opacity	High	Low
Lignin content	High	Low
Fines (%)	Relatively high	Low
Drainability	Good	Poor

The choice of pulping method has an impact on the chemical composition of the raw material and hence the properties of the final paper product. The factors that determine the choice of pulping methods are not discussed in this dissertation. Each pulping method offers a set of advantages and disadvantages. Hence, the different types of pulp are suitable for the production of specific paper products each having a commercial significance. As an example, mechanical pulps are predominantly used in newsprint and magazine production. Chemical pulps are used are mostly used in the production of graphic paper, tissue and paperboard produced (Bajpai, 2011; Ek et al., 2009).The choice of pulping method and pulping process sequence also depends on whether virgin fibre or recovered fibre is used (Bajpai, 2011).

3.3.1.1 Virgin fibre pulping

During chemical and mechanical pulping of fibrous materials, there is always residual lignin within the pulp fibres i.e. no chemical pulping method can remove all the lignin. (Gullichsen and Fogelholm, 1999, Smook, 2002). The higher the pulp lignin content, the lower the interfibre bonding which results in lower paper strength. In addition, residual lignin results in a great deal of ageing or yellowing of particularly highly noticeable in newsprint. Hemicellulose and to a lesser extent cellulose degradation accompanies lignin degradation or removal during chemical pulping (Gullichsen and Fogelholm, 1999, Smook, 2002) as discussed in section 3.2.1.3.

The residual lignin content and the level of cellulose and hemicellulose degradation has an effect on the LCC content of the pulp furnish. The higher the removal of lignin, and holocellulose (cellulose and hemicellulose) degradation, the lower the LCC content of the pulp. It is for this reason that mechanical pulps have a higher composition of LCC compared to chemical pulps. Various methods are employed to quantify the residual lignin content of pulp. These include: the Kappa number test, the K (potassium permanganate) number test, the Roe number and the Chlorine or hypo number (Biermann, 1996, Gullichsen and Fogelholm, 1999). The Kappa number test is predominantly used in the South African pulp and paper industry. According to Gullichsen and Fogelholm (1999), the Kappa number test though not absolute correlates well with the residual lignin found in pulp. The correlation is sufficient to serve the needs for process control in technical and operational contexts. The Klason lignin equation represented by Equation 3-1 provides a correlation between the Kappa number and the lignin content:

$$\text{Klason lignin \%} = 0.15 \times \text{Kappa number} \qquad \textbf{Equation 3-1}$$

This relationship holds for kraft and sulphite hardwood chemical pulps and is approximately correct for softwoods as well (Biermann, 1996). Historically, chemical pulps made from conventional cooking methods, leave the digester typically at Kappa numbers ranging from 28 to 34 for softwoods and 16 to 18 for hardwoods (Shackford, 2003). Using the Klason lignin equation, the Kappa numbers translate to a residual lignin content ranging from 4.2 to 5.1 % for softwoods and 2.4 to 2.7 % for hardwoods. Vena et al. (2013) in her work, cites that the amount hemicellulose dissolved during kraft pulping of *E. grandis* may reach 62 % of the original amount. In addition, approximately 10 % of the cellulose is lost whilst achieving an industrially acceptable pulp yield of 50 % with a Kappa number of 22 or less.

3.3.1.2 Recovered fibre pulping

The objective of recycling is to take recovered paper and convert it into pulp fibres with consistent properties thus allowing usage in paper production (Letcher and Vallero, 2011). During recovered paper pulping, most non-fibrous materials and contaminants are removed; useful cellulose fibres are lost too. In addition, the fibre strength is degraded each time fibre is repulped with more fines produced. It is generally accepted that fibre can be repulped between 4 to 7 times before the loss in quality becomes too high for effective reuse (Smook, 2002, Biermann, 1996).

The recovered paper fibre yield depends on various factors. These include: the recovered paper furnish, recycling process operations applied (e.g deinking, screening, washing etc) and the operating conditions under which these recycling processes take place. Improved contaminants removal is accompanied by lower fibre yields. In addition, contaminant removal efficiencies are typically higher when the fraction of the feed rejected is larger. Efficiency is defined as the percentage of rejects removed from the dry recovered paper. Rejects rate is defined as the ratio of rejects flow to feed flow (Biermann, 1996). It gives an indication of the fraction of useful fibre that is discharged with the rejects. During recovered paper pulping, there is always a trade-off between improved efficiency (i.e. producing cleaner pulp) and maintaining a higher fibre yield i.e. lower rejects rate (Biermann, 1996).

After pulping, the unbleached virgin or recovered paper pulp is sent through a series of different processes to remove impurities and any residual cooking liquor (from chemical pulping). These steps include screening, cleaning and washing, bleaching where necessary is undertaken (Bajpai, 2011).

3.3.2 Bleaching

Pulp fibres can be used in papermaking either as bleached or unbleached pulps. For instance, unbleached mechanical pulps are used to make newsprint and packaging grades where low brightness is acceptable. Bleached pulps are used in the manufacture of tissue paper, white-top linerboard and printing and writing paper. Bleaching involves the of treatment pulp fibres with certain chemicals to increase pulp brightness or whiten the pulp. Brightness describes the whiteness of pulp or paper, on a scale from 0 % (absolute black) to 100 % relative to a magnesium oxide standard. Two approaches are used in the bleaching of pulp namely lignin preserving and lignin removal. Lignin preserving bleaching or 'brightening' involves utilizing chemicals that selectively discolour the lignin - destroying the chromophoric groups on lignin - without removing the lignin. The process of lignin removal or "delignification' involves the use of chemicals to remove all the residual lignin from the unbleached pulp. High-quality chemical pulps are principally subjected to lignin removal bleaching. High-yield mechanical pulps are generally subjected to lignin preserving bleaching. (Smook, 2002; Biermann, 1996).

3.3.3 Stock preparation

Stock preparation involves the conversion of raw material stock into papermaking furnish. Stock preparation begins with repulping of baled dry lap pulps or the dilution of pulp from the high-density storage towers and terminates at the machine chest (Biermann, 1996; Bajpai, 2012; Smook, 2002). The stock preparation process units can be observed from Figure 3-4 which shows both the stock and approach flow system. This stage is the interface between the pulp mill or pulp storage facility and the paper machine (Weise et al., 2000, Bajpai, 2012, Smook, 2002). Different fibrous pulps are blended, diluted, refined and mixed with papermaking additives such as fillers. The result is a uniform and continuously flowing papermaking stock which ensures stable papermaking operations. Stock preparation is crucial since the quality of the finished paper furnish leaving the machine chest determines the properties of the paper (Smook, 2002, Bajpai, 2012). The following operations are performed in stock preparation:

3.3.3.1 Bale handling and repulping (dispersion)

Bale handling and repulping are the first stages of a stock preparation system. These involve the de-wiring of individual bales, de-stacking, mechanical dispersion and separation of pulp fibres into a slurry that can be pumped. Water and papermaking additives are added. Repulping is performed either batchwise or continuously in a processing unit called a pulper. (Gullichsen and Paulapuro, 2000; Smook, 2002).

3.3.3.2 Refining or beating

This refers to the mechanical treatment of fibres to enhance and modify papermaking properties to suit the specific needs for different paper grades. The primary aim of refining is to improve the inter-bonding abilities of fibres without considerably damaging them. The degree of refining is tailor-made to suit the different morphological properties of the fibre being used (Bajpai, 2012; Smook, 2002).

3.3.3.3 Addition of wet-end additives

Papermaking additives are introduced and blended with pulp furnish. The choice of additives is paper grade specific and the purpose of each additive was explained in Table 3-11.

3.3.3.4 Metering and stock blending

Various fibrous and non-fibrous materials are continuously blended to form a completely uniform papermaking stock in a blend chest. The specific recipe for each paper grade determines the type, quantity and quality of the different components of the stock. The functional paper properties are determined to a great degree by the properties of the stock components used. The blended pulp is then pumped at a constant rate to the machine chest typically at a consistency of about 0.2 % - 0.3 % (Smook, 2002, Weise et al., 2000).

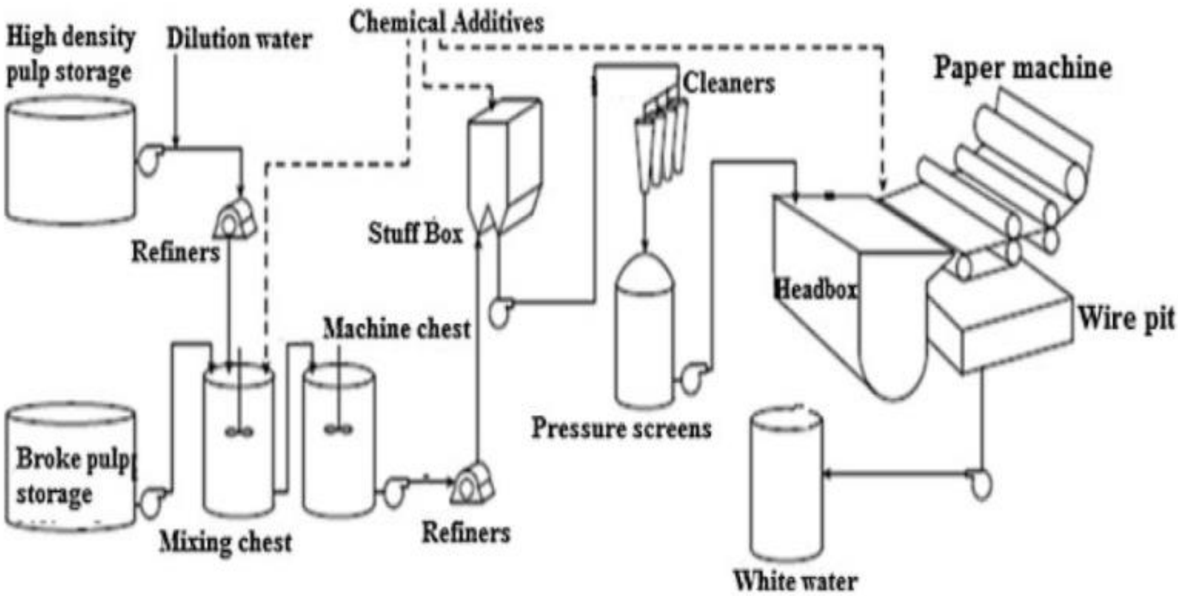

Figure 3-4. A section of the papermaking process showing the stock preparation system and the approach flow system (extracted from Pant et al., 2016).

3.3.4 Approach flow system

The system extends from the machine chest to the headbox lip. The approach flow process units can be observed from Figure 3-4. The main purpose is to meter and dilute the stock, and mix with necessary papermaking additives which had not been added during stock preparation. The low-consistency stock undergoes several stages of screening and cleaning stages to remove fibre bundles flakes and contaminants such as sand and grit which is discharged as papermaking sludge. This ensures that a clean pulp stock enters the forming wire. Stock de-aeration may be included. The resulting stock is fed from a constant head tank through the basis weight control valve to ensure a uniform dispersion to the headbox (Smook, 2002, Weise et al., 2000).

3.3.5 Paper machines

The paper machine system is the section between the approach flow system and finishing as shown in Figure 3-3. It is the section of the papermaking process where sheet-forming takes place through dewatering of the papermaking stock through filtration, pressing, drying processes and reeling of the paper sheet (Smook, 2002, Biermann 1996; Holik, 2006). The paper machine system consists of the following sections: headbox, forming section (wire), press section, broke system, drying section, calendar and the reeler or winder (Smook, 2002) as shown in Figure 3-5.

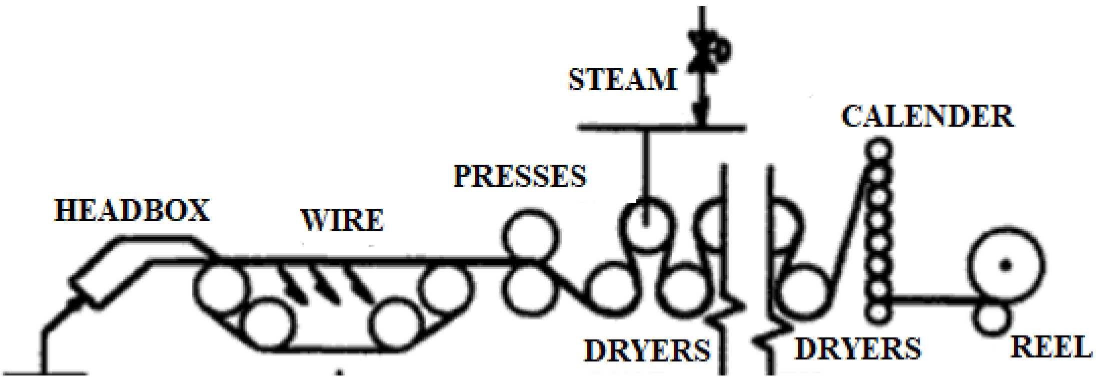

Figure 3-5. A generalised diagram of the paper machine section (extracted from Levine, 1996)

3.3.5.1 Headbox

A headbox is "a pressurized device that delivers a pulp slurry on to the forming fabric or wire" (Biermann 1996) through a full-width and adjustable orifice called a slice (Biermann 1996; Smook, 2002). The papermaking stock discharged through the slice onto the forming section impinge the forming table or wire to begin the filtration process of forming (Biermann 1996; Smook, 2002).

3.3.5.2 Forming section

The function of the forming section is to initiate the sheet-forming process through dewatering by the filtration mechanism. The consistency of the papermaking stock increases 0.5 - 1.5 % from the headbox to approximately 20 % as it enters the press section (Walker, 2006). Paper machines are generally divided into three types based on the forming section configuration namely: fourdrinier machines, twin-wire formers and vat (cylinder) formers. The Fourdrinier machine configuration is the most common type of paper machine in use today (Biermann, 1996; Smook, 2002). The details of each paper machine configurations are not considered in this dissertation. The forming fabric on each paper machine is made up of either a wire cloth or plastic fabric (Biermann, 1996) woven into a mesh to achieve drainage of water whilst retaining fibres (Smook, 2002).

3.3.5.3 Press section

The paper sheet that leaves the forming section enters the press section. This is a system which consists of rollers or squeezes that mechanically dewater by compressing the wet paper sheet in a nip formed by a shoe and a roll (shoe press) or two rolls (Gullichsen and Paulapuro, 2000; Biermann, 1996; Holik, 2006). The main objective of pressing is to further remove water thus increasing the consistency of the paper sheet to about 40-45 % (Smook, 2002). The other objectives of the press section, depending on the paper being produced, include providing surface smoothness and increasing wet web strength (Smook, 2002; Holik, 2006).

3.3.5.4 Drying section and calendering

After the press section, the paper sheet enters the drying section. The paper sheet is further de-watered through the evaporation mechanism by using high pressurised steam. The paper sheet's consistency increases from 40-45 % (maximum achievable through mechanical means) to the desired paper consistency which is grade specific for instance 5-7 % for tissue paper (Smook, 2002, Holik, 2006 and Biermann, 1996). Once the paper sheet is dried, calendering is performed on most paper grades. Calendering is achieved by passing a paper sheet through one or more two roll-nips under pressure. The aim of calendering is to improve surface smoothness on a paper sheet (usually for printing purposes) and improving the uniformity of the cross-direction (CD) thickness. (Smook, 2002).

3.3.5.5 Broke system

Once the paper sheet has been dried to the desired consistency, the paper sheet is sent for winding or reeling. However, broke system prior to winding serves as a recycle stream loop as shown in Figure 3-3. Completed or partially completely manufactured paper (both deemed unusable) discarded from any point across the papermaking process is referred to as broke. It can be further divided into wet and dry end broke. Wet-end broke is defined as broke collected from the forming and press sections whereas dry broke is defined as from collected from the dryers, calendars, winder and finishing operations (Biermann, 1996; Smook 2002). A broke system also serves the purpose of providing sufficient broke storage capacity in situations of long periods of an upset in the papermaking operations (Smook, 2002)

3.3.5.6 White-water system: fibre recovery and water clarification

White-water (WW) is defined as the water removed from the wet end operations such as sheet-forming and wet-pressing. It usually contains fibre, fines and a variety of other papermaking stock-derived materials which are referred to as suspended solids. The aim of the WW system is to recover fibre (thus minimizing fibre losses) and clarify the WW for reuse in the paper mill. Generally, the separation of suspended solids and water is achieved by filtration, flotation, fractionation and sedimentation (Weise et al., 2000, Smook, 2002). Low fibre effluent is discharged from the WW system. Flotation savealls and disc filters are the two most common types of equipment used for fibre recovery and water clarification (Smook, 2002).

3.3.5.7 Reeling and winding

The reel collects the paper sheet (after drying and calendering) which is then wound on a spool that rotates around a reel drum or pope reel. The aim of reeling and winding is to cut large diameter, full-width paper reel into desired size rolls. A complete or filled reel is either sent to finishing operations or further processed through subsequent operations on-site such as coating.

3.3.5.8 Coating

Coating involves the application of polymers, pigments or other materials onto one or both surfaces of a paper sheet to improve properties such as gloss, brightness, and printing detail. Coating can be applied on-machine or off-machine (Biermann, 1996; Smook, 2002).

3.3.6 Finishing

Coated or uncoated paper is sent for finishing operations such as scaling, wrapping, crimping and labelling of paper reels prior to being sent for deliveries to customers. Subsequent operations such as converting performed off-site are not considered within the boundaries of the dissertation as specified in section 1.5.

3.4 Summary

In this chapter, the raw materials used, paper grades produced and the papermaking process across paper mills in South Africa were discussed. This provided a basis for identifying and understanding the flow of materials across all paper mills in South Africa. In the next chapter, the MFA methodology used to identify and track the flow of material across paper mills in South Africa is presented.

4 METHOD

In this chapter, the MFA study methodology used to identify and track the flow of lignocellulosic carbon (LCC) across paper mills in South Africa for the calendar year 2011 is explained. The relevant materials, procedure and assumptions adopted are discussed.

4.1 Methodology

This research was carried out by making use of the MFA methodology and terminology outlined by Brunner and Rechberger (2004) as described in section 2.1.5.

4.1.1 Definition of problem and system boundaries

The system's spatial boundaries are defined as all 'graphic' paper, paperboard and tissue mills within the geographical borders of the Republic of South Africa i.e. the paper production process stating with receiving of pulp to the production of the desired paper grade. The production of virgin fibre pulp and the consumption or usage of paper are not part of this dissertation, but were carried out separately as complimentary studies commissioned by PAMSA. For an integrated paper mill, materials flow data was collected starting at the pulp storage chests to the final manufactured paper grade. In a non-integrated paper mill, materials flow data was collected starting at the re-pulping section of the mill. For mills that use recovered paper fibre (RCF) pulp, data was collected from the bale handling through pulping to the final paper grade. The system's temporal boundary was defined as the calendar year of 2011 as explained in section 1.3.

4.1.2 Identification and selection of relevant flows of goods & substances

The MFA study was carried out to track the metabolism of LCC across paper mills in South Africa. In this research work, paper grades were divided into three categories namely graphic paper, paperboard and tissue as outlined in Table 4-1. The term paper was used hereafter to refer to all grades of paper i.e. graphic paper, paperboard and tissue whilst graphic paper refers to printing and writing grades. The distinction between graphic paper, paperboard and tissue is largely based on weight, thickness and rigidity of the paper sheet as presented in Table 4-1.

Table 4-1. Classification of paper products adopted for this research study.

Paper grade	Description
Graphic paper	Printing and writing paper used in newspaper magazines, books etc. can be coated or uncoated.
Paperboard	Corrugated board or containerboard i.e. linerboard and fluting; folding boxboard e.g. cereal boxes, fast food boxes.
Tissue	Sanitary tissue, wrapping tissue, towel.

A list of the relevant goods and substances is shown in Table 4-2. Relevant goods and substances were defined as the papermaking raw materials and products that contain either lignocellulosic or mineral carbon. Not all the required material flows data had been recorded by some paper mills. For instance, some paper mills did not have a record of effluent and paper sludge flows. For this reason, paper sludge and effluent were thus combined to be represented by the term waste. In such cases where historical paper mill production data could not be provided, assumptions based on available literature were used to supplement this information.

Table 4-2. Relevant goods and substances defined for this MFA study.

Goods	Substances
Hardwood and softwood pulp	Cellulose
Bagasse pulp	Hemicellulose
Recovered paper fibre (RCF)[8] pulp	Lignin
Recovered paper	Mineral carbon
Graphic paper, paperboard & tissue	Lignocellulosic carbon (LCC)
Process water & white water (WW)	
Papermaking additives (filler and starch)	
Effluent	
Ash	
Paper sludge	

4.1.3 Identification and selection of processes

The data requested from each paper mill depended upon the paper grades produced on each paper machine as classified in section 4.2.2. This dictated the raw materials and papermaking process used. All the paper machines were thus defined according to the paper grade produced on each machine as follows:

a. graphic paper machines,
b. paperboard machines, and

[8]Recovered paper fibre (RCF) is defined as the pulp derived from the repulping of recovered paper in which contaminants and non-fibrous materials have been removed

c. tissue machines.

To satisfy the non-disclosure agreements (NDA) requirements, the names of each paper machine's holding company were omitted in this dissertation. Instead, all the paper machines were labelled as shown in Table 4-3.

Table 4-3. Classification and labelling system of paper machines used in this dissertation.

Paper machine class	**Label**	**Paper grades**	**Pulp furnish**
Graphic paper machines	GP 1	Uncoated wood-free paper	UBSW & UBHW
	GP 2	Uncoated wood-free paper	FBSW & FBHW
	GP 3	Coated wood-free paper	FBSW, FBHW & Bagasse
	GP 4	Uncoated wood-free paper	FBSW, FBHW
	GP 5	Newsprint	FBSW & FBHW
	GP 6	Newsprint	GWP, RCF& FBHW
Paperboard machines	PB 1	Containerboard	TMP, RCF & FBSW
	PB 2	Containerboard	RCF
	PB 3	Containerboard	RCF
	PB 4	Containerboard	RCF
	PB 5	Containerboard	RCF
	PB 6	Containerboard	RCF
	PB 7	Containerboard	RCF
	PB 8	Cartonboard	GWP, RCF & UBHW
	PB 9	Containerboard	Bagasse, FBHW & RCF
	PB 10	Containerboard	FBHW, UBHW & UBSW
	PB 11	Containerboard	NSSC (unbleached)
	PB 12	Containerboard	RCF, FBSW & NSSC
	PB 13	Containerboard	RCF, FBSW & NSSC
	PB 14	Containerboard	FBHW & UBSW
	PB 15	Containerboard	UBHW & UBSW
	PB 16	Containerboard	RCF
Tissue machines			
PAMSA member tissue machines	TM 1	Tissue wadding	FBSW, FBHW & RCF
	TM 2	Tissue wadding	FBSW & RCF
	TM 3	Tissue wadding	FBHW & FBSW
	TM 4	Tissue wadding	FBSW & RCF
	TM 5	Tissue wadding	FBSW, FBHW & RCF
	TM 6	Tissue wadding	FBSW, FBHW & Bagasse
	TM7	Tissue wadding	FBHW & FBSW
non-PAMSA member machines	NPM	Tissue wadding	RCF, FBSW & FBHW

Each paper mill was defined as one big black box system with materials flowing in and out. It was further broken down into sub-systems that comprise of different processes and flows. This constituted a simplified PFD for modelling material flows in this study. However, no emphasis was placed on the detailed information of what takes place inside these subsystems. The number of processes necessary to describe each paper machine system was kept to a maximum of fifteen as recommended by Brunner and Rechberger (2004). This was done to provide simple but reliable models that describe reality. An example of a simplified PFD of a paperboard machine is shown in Figure 4-1.

4.1.3.1 Graphic paper machines

These were described as paper machines that produce all printing and writing paper grades such as newsprint, coated paper and uncoated paper. There were six operational graphic paper machines in 2011 as shown in Table 4-3. Materials flow data was provided for all of the six graphic paper machines.

4.1.3.2 Tissue machines.

These are described as paper machines that produce all tissue wadding which is further converted to sanitary tissue, wrapping tissue and towelling tissue. In this MFA study, tissue machines were categorised into two classes namely PAMSA member (PM) tissue machines and non-PAMSA member (NPM) tissue machines chiefly due to access of production data. There were approximately 40 tissue machines/producers in South Africa operational in 2011; seven were PM tissue machines as shown in Table 4-3. The exact number could not be ascertained from records due to the closure and opening of new machines. All PAMSA member tissue producers were cooperative in providing all the production data required for this MFA whereas only two non-PAMSA member tissue producers were cooperative. All non-PAMSA member tissue machines were thus lumped together into one generic paper machine.

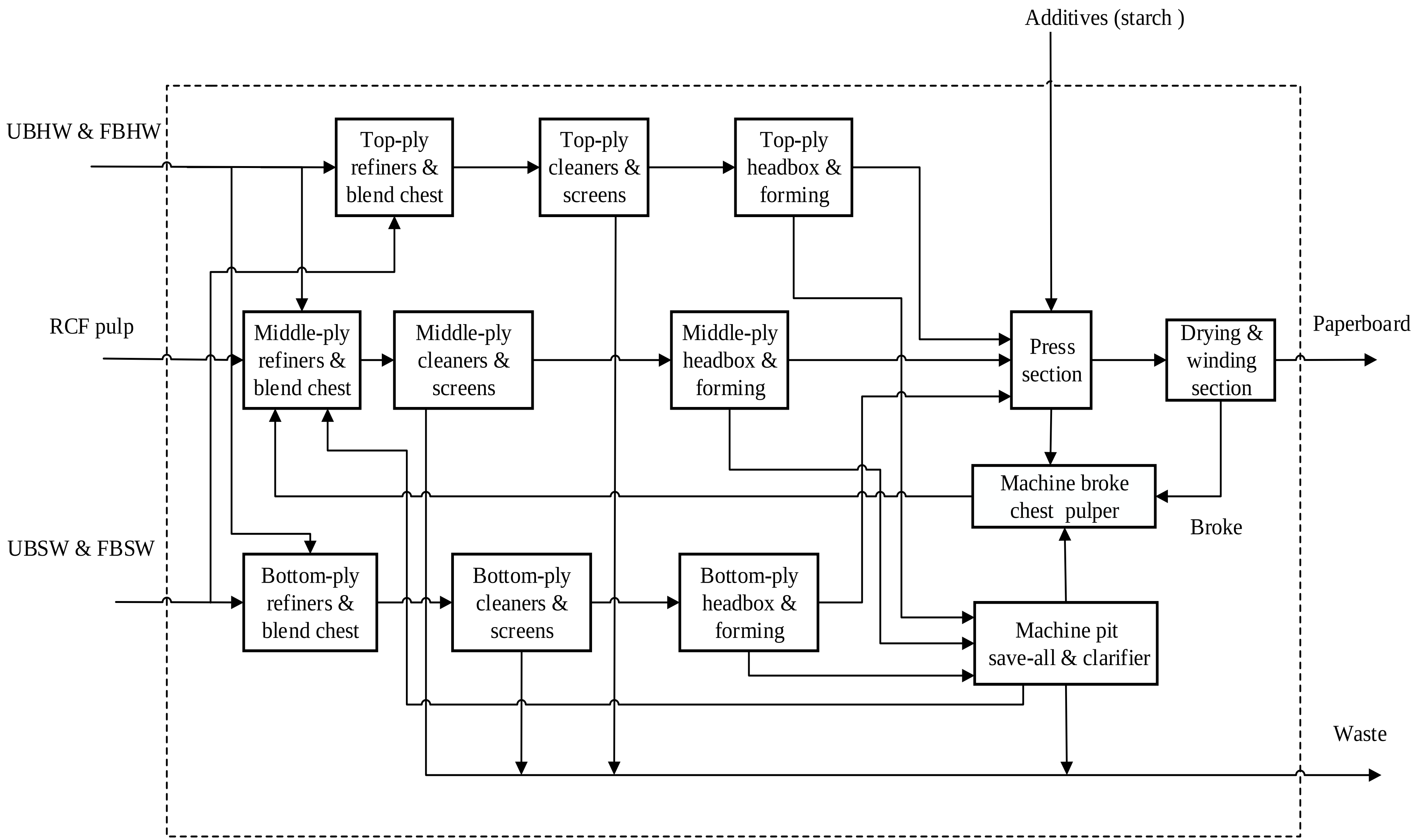

Figure 4-1. An example of a simplified PFD of a paperboard machine used in the modelling of this MFA study.

4.1.3.3 Paperboard machines

These were described as paper machines that produce containerboard, cartonboard and other speciality board grades such as chipboard or ceiling board. Containerboard was defined as paperboard grades that are used in the manufacture of corrugated containers or boxes. Cartonboard was defined as paperboard grades used in the manufacture of folding boxboard. There were sixteen paperboard machines operational in South Africa in 2011 as shown in Table 4-3. In this investigation, it was deemed necessary to further categorize the paperboard machines into three categories for convenience and simplifying the materials flow analysis model. The three paperboard machine categories are:

- •Recovered paper fibre (RCF) based containerboard machines - these are paperboard machines producing containerboard from a pulp furnish comprising of at least 50 % recovered paper.
- Virgin fibre-based containerboard machines - these are paperboard machines producing containerboard from a pulp furnish that comprises of at least 50% virgin fibre.
- •Cartonboard machines - these are paperboard machines producing cartonboard.

4.1.4 Data collection

The relevant goods and substances necessary for this MFA study are shown in Table 4-2. The relevant materials flow for goods that constitute the input data for this MFA were collected through questionnaires and face-to-face interviews conducted during paper mill visits. A list of the data requested from paper mills to undertake this MFA is shown in Table 4-4**.** The interviews were held with knowledgeable paper mills personnel such as Process Engineers and Technicians to discuss the materials flow data requested on the questionnaires. This was crucial in providing clarity and understanding of the limitations of what could and could not be provided by paper mills. In addition, the questionnaires were constantly reviewed and improved over time to ensure better clarity and relevancy of questions. All subsequent changes to the questionnaires resulted in requests to previously surveyed companies for additional data. This also improved the reliability of the data provided by paper mills. Statistical records from organisations such as PAMSA, Stats SA and SARS were used either to supplement the collected data or for comparison purposes.

Table 4-4. A list of the data requested from paper mills through questionnaires and interviews to compile the MFA study.

a. Raw material	b. Final product
• mass of bleached HW and SW pulp	• mass of paper grades produced
• mass of unbleached HW or SW pulp	• the moisture content of the paper
• mass of bagasse pulp (bleached or unbleached)	
• Kappa number of each type of pulp used	
• moisture content or consistency of all pulp	**c. Waste data**
• classification of recovered paper grades used.	• mass of paper sludge
• mass of recovered paper grades	• the volume of effluent
• moisture content of the recovered paper	• total suspended solids
• mass of recovered paper fibre (RCF) pulp	
• mass of all non-fibrous additives used or their respective addition rates	**d. Process and Production Data**
	• overall paper grade yield
	• retention rates of additives
	• Process Flow Diagram (PFD of each paper machine

4.1.5 Data modelling

The materials flow data collected was modelled using mass balance principles to quantify LCC flows across the papermaking process. An overall goods balance was conducted to determine the various flows of paper across each machine on a dry and wet basis using input data flows. The fibre flows across each paper machine were then calculated from the dry mass material flows. An elemental mass balance on dry mass fibre flows was then conducted to determine the flows of LCC. A summary showing the steps followed in modelling the mass flows for this MFA study are shown in Figure 4-2. All the pulp received at the paper mill gate for a non-integrated mill or at pulp storage chests for an integrated paper mill was assumed to have been used within a year. The mill products were assumed to have been sold within a year hence the net stock was assumed to be zero as suggested by Hong et al. (2011). This was justifiable since the lifetime of raw materials and paper on site are shorter than the temporal boundary of one year.

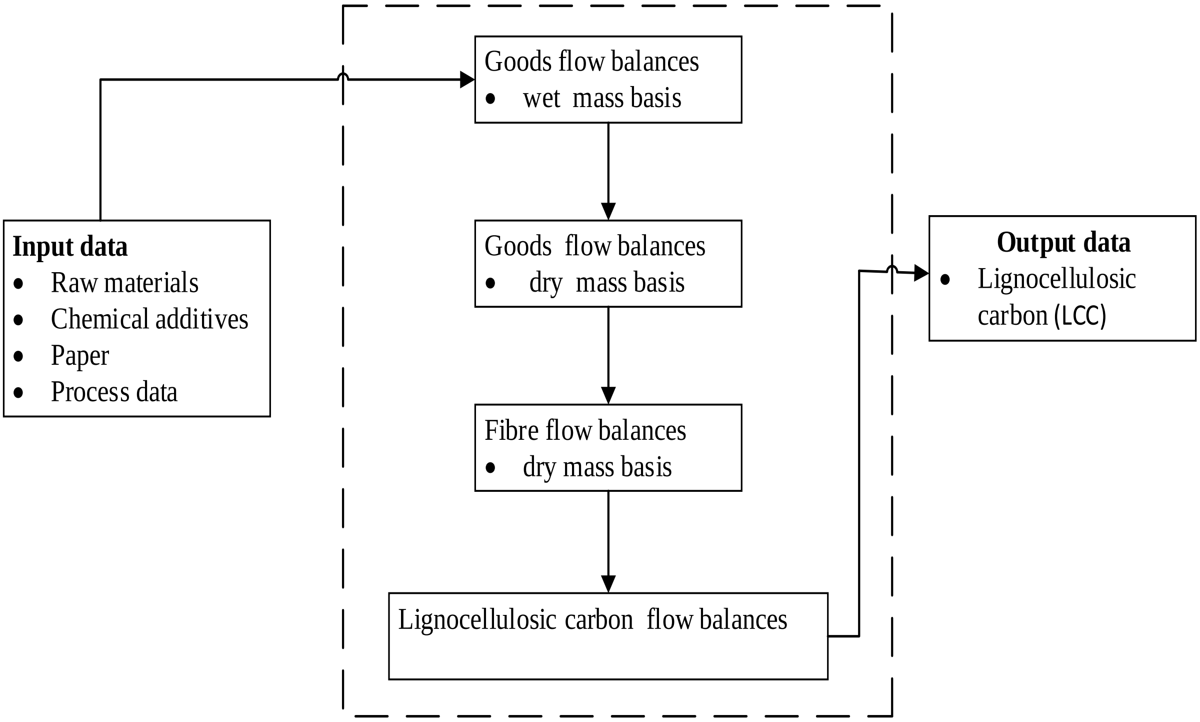

Figure 4-2. A flowsheet of the data modelling sequences used to quantify LCC flows in this MFA study.

4.1.5.1 Data modelling of tissue machines

As mentioned earlier in section 4.1.3.2, only two NPM tissue producers from approximately 33 NPM tissue producers provided materials flow data required for conducting this MFA study. Interviews were thus conducted with personnel from PRASA, and Martin Botha (an independent consultant) to gain a better understanding of process characteristics of NPM tissue producers. The following information was established:

a. Non-PAMSA member tissue producers primarily focus on the production of low-grade tissue paper from mostly recovered paper fibre without deinking. PAMSA member tissue machines produce mainly the premium grade tissue using both virgin pulp and recovered paper fibre where the latter undergoes deinking.

b. The exact tonnage of tissue paper produced from all NPM tissue producers was not known. PAMSA estimated that South Africa's total tissue production tonnage for 2011 was 219 000 tonnes. However, estimates based on an interview conducted (M Bothma 2017, personal communication, 02 November) indicate that PM tissue machines account for 60-80 % of the total tissue paper production. As such, the non-PAMSA member tissue machines account for approximately 20-40 % of the total production.

c. The average shrinkage across NPM tissue machines was estimated to be between 25-30 % in comparison to 20-25 % across the PM tissue machines (M Bothma 2017, personal communication, 02 November). Shrinkage represents the loss of material from the original recovered paper feedstock during re-pulping to produce recovered fibre pulp (Biermann, 1996).

Based on this information, the following assumptions were adopted in creating a materials flow analysis model for NPM tissue machines:

- The tissue paper production tonnage across all NPM member machines was estimated to be 30 % of the total tissue paper production tonnage in South Africa for 2011.
- The average shrinkage across NPM tissue machines was assumed to be 28 %.
- The ratio of recovered paper to virgin pulp used on both the PM and NPM tissue machines was assumed to be the same.
- No starch or filler was used on NPM tissue machines. The same quantity of papermaking additives per tonne of tissue produced was used on PM and NPM tissue machines.
- The moisture content of tissue paper produced on PM and NPM tissue machines was the same.
- The recovered paper fibre pulp contains no contaminants i.e. all pulp was fibrous material. All papermaking additives and prohibitives (discussed in section 3.2.1.2) in the recovered paper were removed during pulping.

4.1.5.2 Software considerations

Microsoft Excel and STAN (Cencic and Rechberger, 2008; Yiougo et al., 2011) were used in this MFA study as the software packages of choice for modelling the material flows balances and performing data analysis. Microsoft Excel, as a spreadsheet software, was used for data handling and mass balance calculations. It was chosen because of its ease of availability and user-friendliness (Cencic and Rechberger, 2008). The materials flow results for each paper machine obtained using MS Excel were used as input data into the software STAN. STAN provides further data reconciliation and produces a graphical representation (Cencic and Rechberger, 2008) of material flows in the form of Sankey diagrams. In addition, STAN strictly adheres to MFA methodology and terminology (Cencic and Rechberger, 2008).

A similar approach of using MS Excel and STAN in collaboration was also used in an MFA study conducted by Yiougo et al. (2011) and corroborated by Cencic and Rechberger (2008). However, Cencic and Rechberger (2008) warn that such an approach can be tedious. The application of STAN and its suitability to this investigation were discussed in section 2.2.5.5.

4.1.5.3 Input data flows

The quantity of pulp, paper, non-fibrous additives and effluent (in some cases) as described in, was provided by each paper mill from their accounting records. All papermaking additives as discussed in section 3.2.2, are non-fibrous additives, therefore, do not contain any LCC. However, papermaking additives are components of most paper grades hence it was necessary to quantify and subtract them from the mass of the paper grade considered.

4.1.5.4 Material flow balances: wet -mass basis and dry-mass basis

Pulp and all paper grades contain moisture. Paper mills report the pulp as either air-dry tonnes (ADt) or bone-dry tonnes (BDt) to account for moisture in the pulp. All paper grades produced are reported in tonnes with the moisture content specified. A goods flow balance was conducted to determine the various flows of paper and waste streams on a wet-mass basis from which the dry-mass flows were calculated, thus eliminating the mass of water from the balance.

4.1.5.5 Material flow balances: fibre & LCC basis

The amount of LCC in papermaking flows i.e. pulp, paper and waste streams is seldom measured or reported in paper mills production statistics. The varying composition of pulp and additives in each paper grade makes it challenging to quantify the exact amount of LCC in a paper sheet. Hence, this information was determined from mass balances using goods flows, correlations and assumptions supported by the literature reviewed. A goods flow balance (dry- mass basis) was followed by a fibre flows balance (dry- mass basis) which provided the mass of dry mass fibre in each good in every process stream. The amount of LCC in the virgin pulp or RCF pulp was calculated using the LCC composition in the chemical components of wood fibre provided in Table 3-8. The detailed calculations of the LCC composition in virgin pulp and RCF pulp are shown in **Appendix 1**. The weighted-average LCC composition in the total dry mass fibre furnish used on each paper machine was then calculated. This also represents the average LCC composition in the paper grade produced and waste streams.

The dry mass fibre flows and the respective LCC compositions were then used to determine the amount of LCC in the paper produced and waste for each paper machine system. Sample calculations are shown in **Appendices 2** to **4**.

4.1.5.6 Data uncertainties and propagation of uncertainty

Input data has a degree of uncertainty or deviation from the true value associated with it (Hedbrant and Sörme, 2001; Danius, 2002; Lenglet et al., 2017; Cencic and Rechberger, 2008). The fractional uncertainty in all mass flows obtained from paper mills was estimated to be ± 1.5 % as reported by paper mill operators and engineers. The uncertainty in all the mass flows of input data was determined based on the fractional uncertainty using Equation 4-1.

$$\text{uncertainity} = \text{fractional uncertainity} \times \text{measured or expected (mean) value} \qquad \textbf{Equation 4-1}$$

The uncertainty was attributed to the default variability in mass recorded from the mass scales used to quantify the tonnage of materials. The uncertainty in all the moisture content or dryness values of the pulp and recovered paper was estimated to be ± 1. 5 % of the reported or target value as recommended by paper mill operators and engineers. This uncertainty accounts for the variation of moisture in pulp and the paper produced.

a. Propagation of measurement uncertainties

The Monte Carlo simulation (Brunner and Rechberger, 2004; Wang and Ma, 2018) was chosen as the method of propagating measurement uncertainties into calculated values that are based on input data. The input mass flows and their respective moisture content were converted into Gaussian random variables to account for measurement uncertainty. The use of the Gauss distribution to describe quantities such as mass flows and concentrations is known to result in negative values for such quantities. This is theoretically inappropriate (Brunner and Rechberger, 2004). The suitability of using the Gauss distribution was verified (as recommended by Brunner and Rechberger, 2004) prior to its application in this MFA study. This was achieved by calculating the coefficient of variation (v) in each of the input data flows using Equation 4-2.

$$v = \frac{\sigma}{\mu}$$ **Equation 4-2**

where v = coefficient of variation

μ = the mean or expected value

σ = standard deviation

As a rule of thumb, Rechberger and Brunner (2004) cite that a coefficient of variation (v) value of less than 0.2 indicates that the probability of obtaining observations more than five standard deviations away from the mean is quite small or very unlikely. Only then can the problem of the existence of negative values be safely ignored. All measured values were converted into Gaussian (normal) random variables using Equation 4-3 after verifying the suitability of using the Gaussian distribution. Rechberger and Brunner (2002) indicate that the MS Excel syntax *norm.inv (rand (); mean; standard deviation)* creates a random number that follows a normal distribution function defined by its mean and standard deviation. The mean (expected) value and the standard deviation were replaced by the measured value and the uncertainty in the measured value respectively. The MC simulation was conducted using a thousand iterations for each Gaussian variable. Sample calculations are shown in **Appendices 2** to **4**.

Gaussian random variable = f (mean, standard deviation)
= norm.inv (rand ();mean;standard deviation) **Equation 4-3**

4.1.6 Results analysis

An analysis of the results of the MFA study was conducted through studying and interpreting the material flows shown on the Sankey diagrams produced using the STAN software. This provided information on the fate of LCC across the papermaking process. The hypothesis presented in section 1.8 was accepted or rejected based on the analysis of the results. Additionally, three scenarios were developed based on the South African paper industry's market-related changes that have taken place or future possibilities likely to happen in the paper industry. The scenarios were investigated using MS Excel to ascertain the effect of the market-related changes on the flow of materials within the paper industry. In the next section, the MFA study results are presented and a critical analysis of the results provided.

4.2 Summary

In this chapter, the MFA study methodology used to track the flow of LCC across all paper mills in South Africa was presented. The relevant material flows and processes were identified, the data collection process and data modelling steps clearly outlined, and a preview of the results analysis indicated. In the next chapter, the findings of the MFA study is presented.

5 RESULTS AND DISCUSSIONS

In this chapter, the results and discussion of the MFA study of paper mills in South Africa are presented. The aims of the research study were to quantify and track the flow of LCC across all paper mills in South Africa for the calendar year of 2011. In addition, three scenarios developed based on the South African paper industry's market-related changes that have happened or are likely to happen were investigated.

5.1 Material Flow Analysis results

Material flows enter the papermaking system in the form of fibrous and non-fibrous raw materials and leave the system as either paper or waste[9]. The results of this MFA study primarily focus on the transfer of LCC from raw materials into the two output streams. Based on the system's spatial definition as set out in section 4.2.3.1, the MFA results were split into three composite paper machine category models. These include graphic paper machines, paperboard machines, and tissue machines. A grand composite model, defined as a system encompassing all three paper machine categories, was created to provide an overall representation of the metabolism of LCC across all paper mills in South Africa. Figure 5-1 illustrates the hierarchical structure of the paper machine categories used in this MFA study.

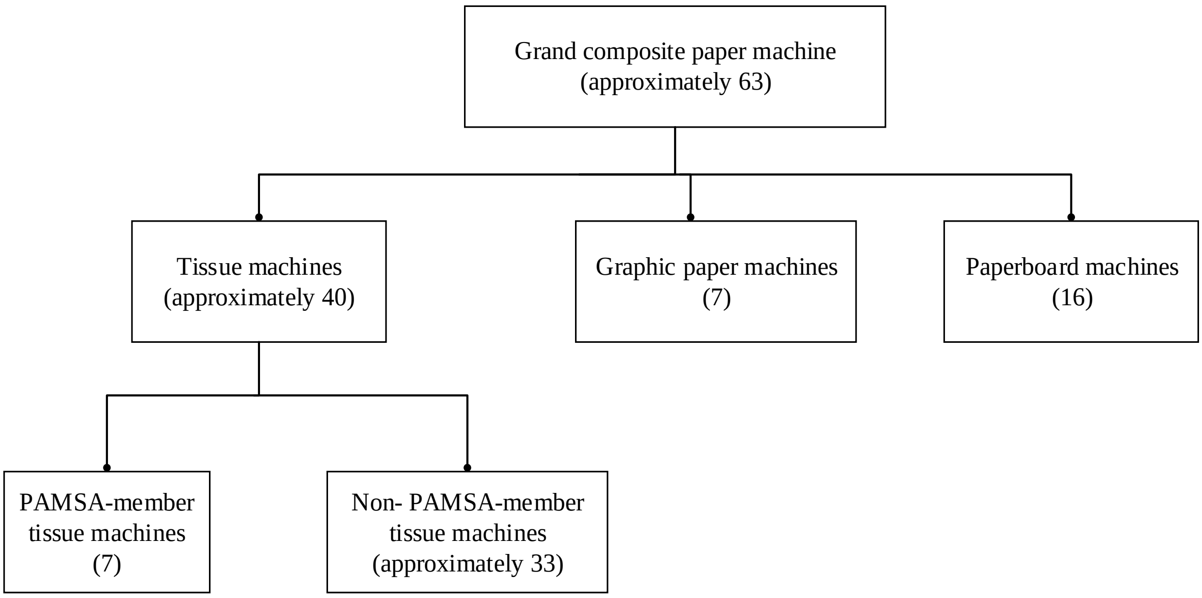

Figure 5-1. A hierarchical structure of the paper machine categories used in this MFA study of paper mills in South Africa for the calendar year of 2011.

[9]Waste was defined as the summation of effluent and sludge.

It is important to note that all mass balance models were carried out on a dry mass basis. Each paper machine category e.g. tissue machines, comprised of two models namely the individual machines model and composite machines model as shown in Figure 5-2. The latter was a collection of all the individual paper machines within a paper machine category combined into one model. Each of these two models comprised of three layers of mass balances as discussed in **Chapter 4** and itemised in Figure 5-2. Goods are defined as substances or mixture of substances that have a positive or negative economic value associated with them (Brunner and Rechberger, 2004). Based on this definition, all fibrous and non-fibrous raw materials, waste and paper were defined as goods in this dissertation. Lignocellulosic carbon, derived from the cellulose fibres found in goods, was the substance of interest in this dissertation.

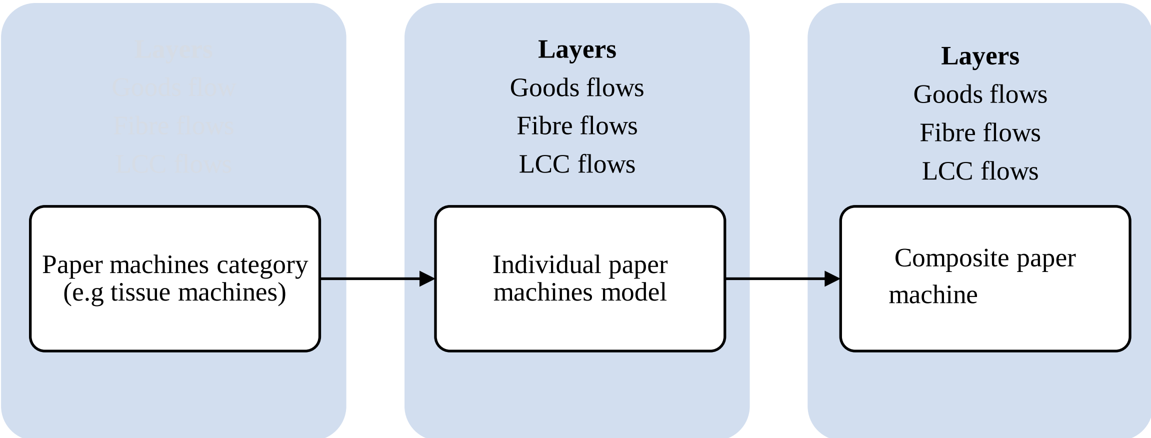

Figure 5-2. A breakdown of the mass balance calculations for each paper machines category.

The set of results chosen for presentation in this section are summarised in Table 5-1. The rest of the results were presented in **Appendices 2** to **5**.

Table 5-1. The set of the mass balance models chosen for presentation in the results section of this dissertation.

Paper machine category	Graphic paper machines	Tissue paper machines	Paperboard machines	Composite paper machines
Individual paper machines model : Goods flow	-	-	-	✓
: Fibre flow	-	-	-	✓
: LCC flow	✓	✓	✓	✓
Composite paper machines model : Goods flow	-	-	-	✓
: Fibre flow	-	-	-	✓
: LCC flow	✓	✓	✓	✓

The definitions of the pulp acronyms used in the South African paper industry is provided in Table 5-2. These were used in the presentation of paper machine model results. The terms 'imports' and 'exports' as denoted in the paper machines model results obtained using the software STAN represent the sum of input and output flows respectively.

Table 5-2. Definitions of pulp acronyms used in the South African paper industry.

Pulp acronym	Definition
UBHW	Unbleached hardwood
UBSW	Unbleached softwood
FBHW	Fully-bleached hardwood
FBSW	Fully-bleached softwood
GWP	Groundwood pulp
TMP	Thermo-mechanical pulp
RCF	Recovered paper fibre
NSSC	Neutral sulphite semi-chemical

5.1.1 Graphic paper machines

Six graphic paper machines comprising of two newsprint machines and four fine paper (coated and uncoated machines) were operational during the calendar year of 2011. Figure 5-3 and Figure 5-4 present the LCC flows in goods across the individual graphic paper machines and the composite graphic paper machines model respectively. The full set of the material flows results and the associated mass balances calculations for graphic paper machines is shown in **Appendix 2.**

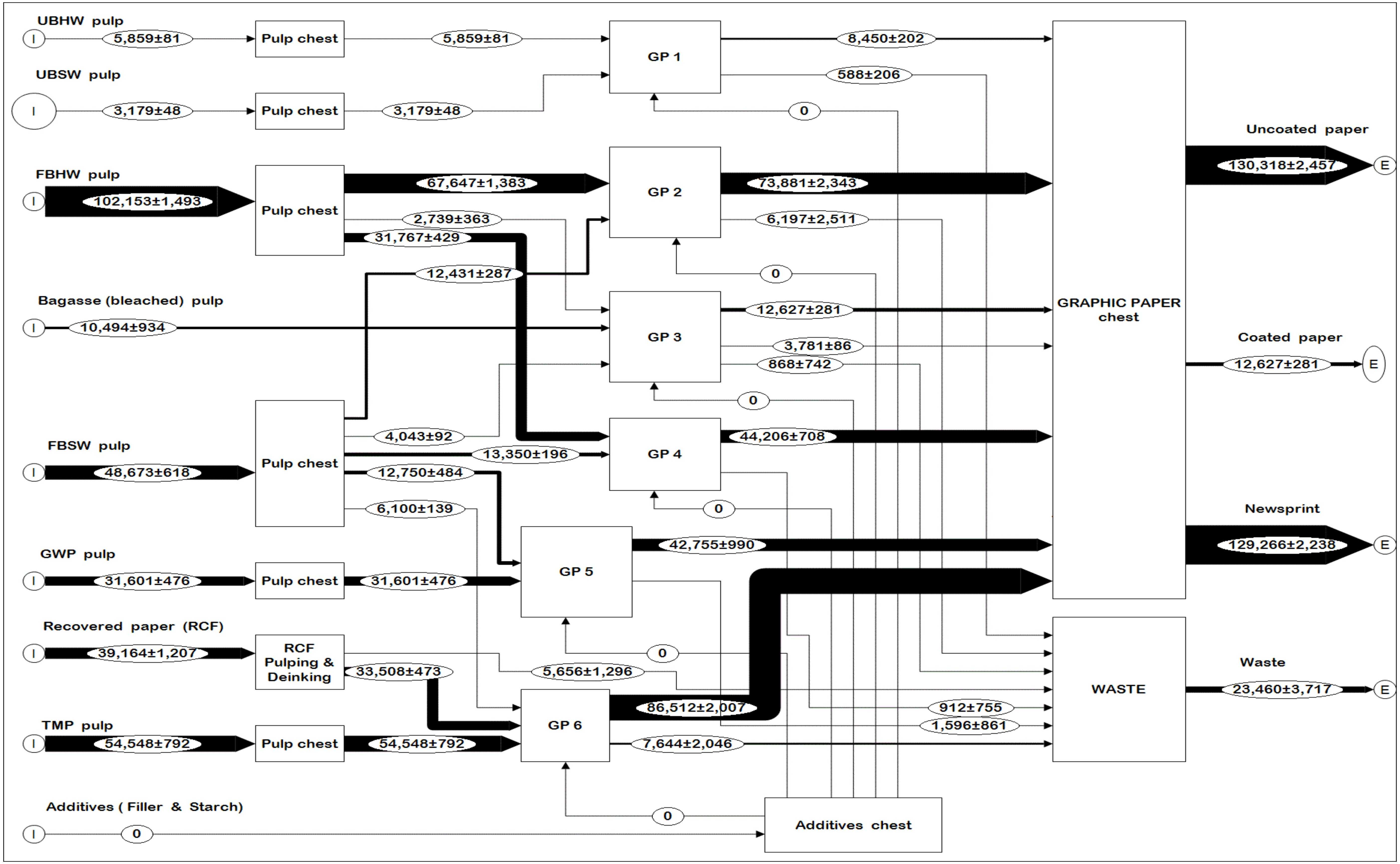

Figure 5-3. Lignocellulosic carbon flows across the individual graphic paper machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

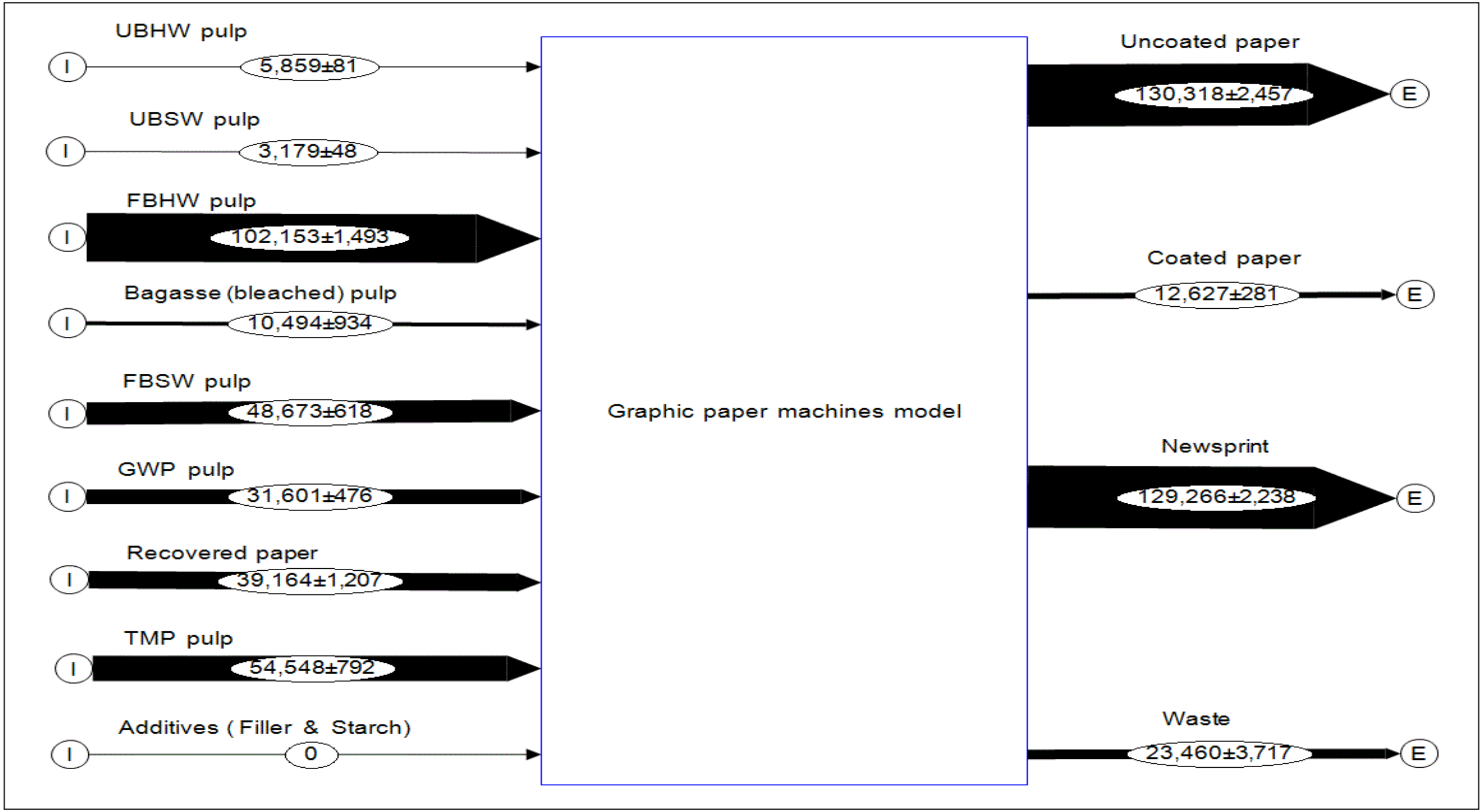

Figure 5-4. Lignocellulosic carbon flows across the composite graphic paper machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

The overall LCC yield across graphic paper machines was calculated to be 92.1 ± 1.4 % Figure 5-3. The yield is defined as the ratio of the mass of a material in the desired product stream to the mass of material in the input stream (Biermann, 1996). It was evident from Figure 5-3 that the bulk of the LCC that is locked-up in the graphic paper category was in newsprint (47.5 %) and uncoated paper (47.8 %).

5.1.2 Tissue machines

Tissue machines were divided into PAMSA member (PM) and non-PAMSA member (NPM) machines as explained in section 4.3. Only the LCC flow balance results across the composite tissue machines are presented as indicated in Table 5-1.

5.1.2.1 PAMSA member tissue machines model

There were seven PM tissue machines operational in 2011. The LCC flow results across the individual PM tissue machines and the composite model are shown in Figure 5-5 and Figure 5-6 respectively. The full set of the goods flows results and the associated mass balance calculations for PM tissue machines is shown in **Appendix 3**. The overall LCC yield across PM tissue machines was calculated to be 89.8 ± 1.1 % (Figure 5-6).

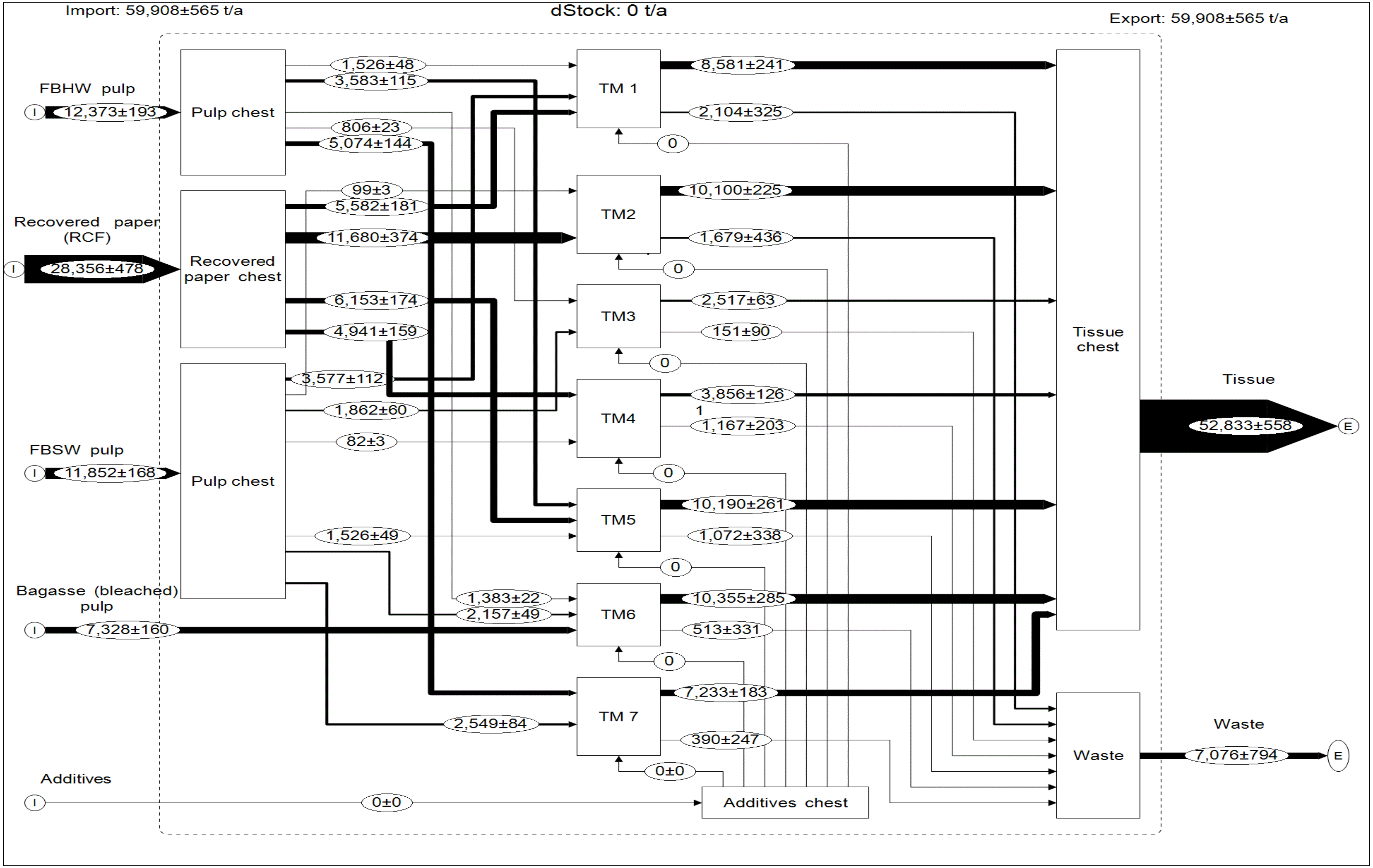

Figure 5-5. Lignocellulosic carbon flows across the individual PAMSA member tissue machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

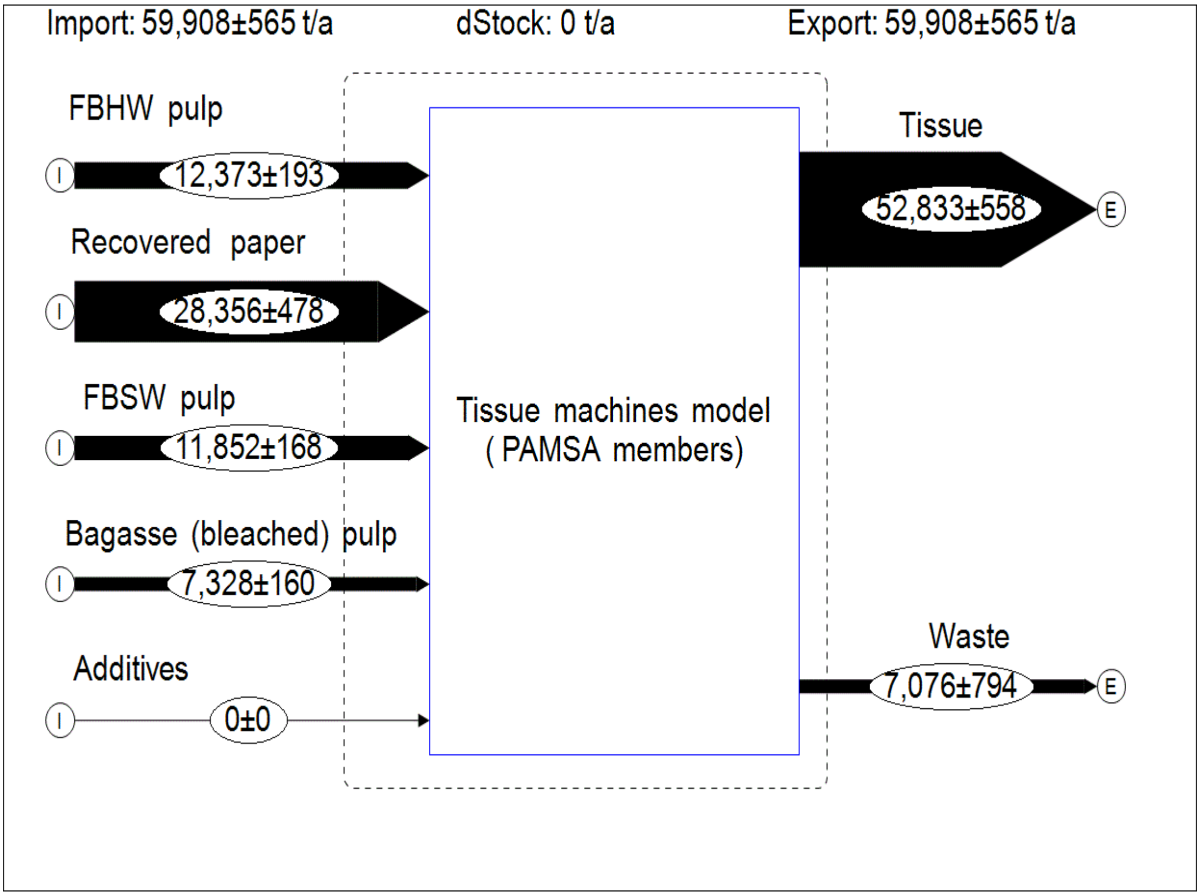

Figure 5-6. Lignocellulosic carbon flows across the composite PAMSA member tissue machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

5.1.2.2 Non-PAMSA member tissue machines model

There were approximately 33 NPM tissue machines operational in 2011. This was based on the data collected from PRASA and during an interview conducted with an independent consultant (M Bothma 2017, personal communication, 02 November). The exact number of NPM tissue machines was difficult to ascertain as discussed in section 4.1.5.1, hence all NPM tissue machines were lumped into a composite NPM tissue machine model. The goods flow balances on the individual NPM tissue machines could not be evaluated since neither the exact number nor the production data for every individual tissue machine could be established. The LCC flows across the composite NPM tissue machines model were established based on the procedure and assumptions discussed in section 4.1.5.1. The results are shown in Figure 5-7. The full set of the materials flow results and the associated mass balance calculations for NPM tissue machines is shown in **Appendix 3**.

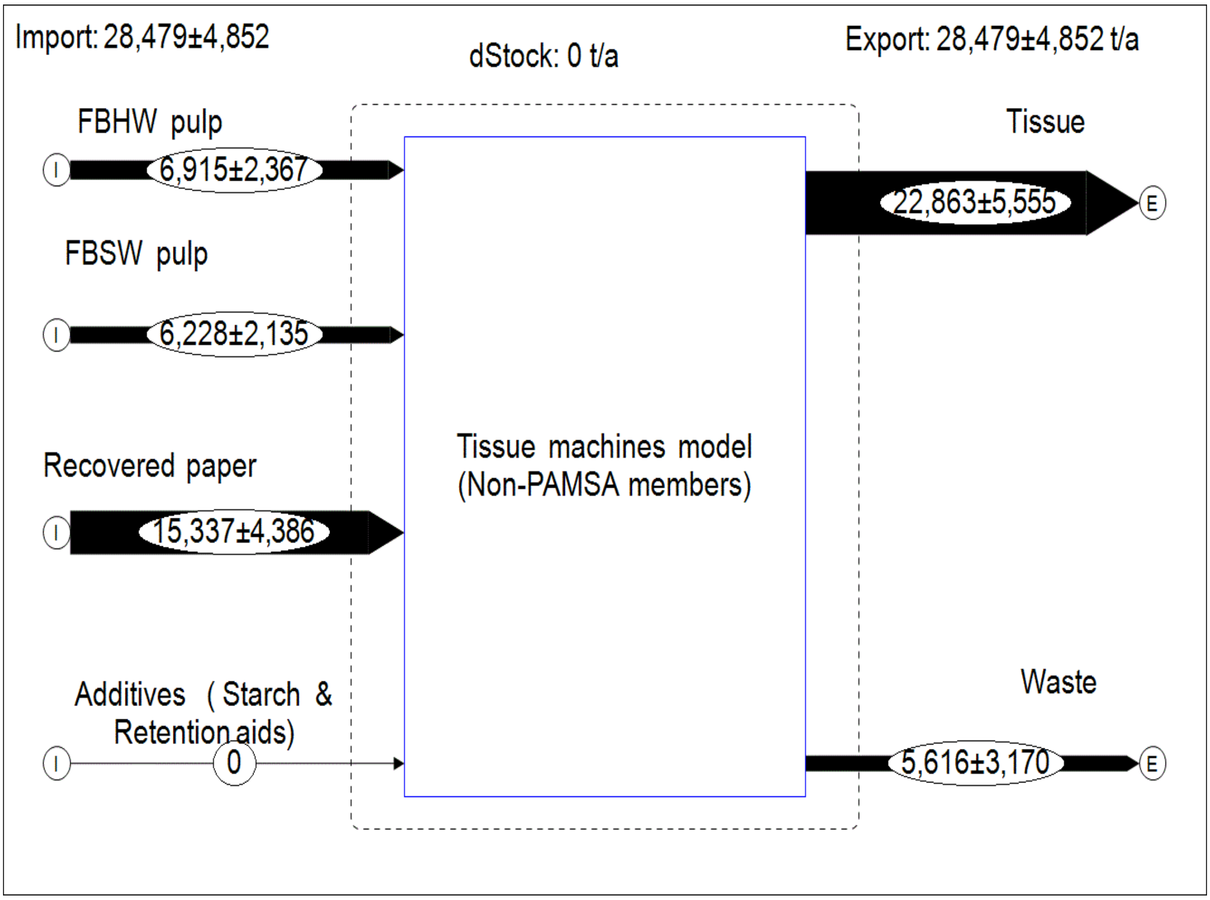

Figure 5-7. Lignocellulosic carbon flows across the composite non-PAMSA member tissue machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

The overall LCC yield across NPM tissue machines was calculated to be 80.3 ± 1.1 % (Figure 5-7). The overall weighted LCC yield across all (i.e. both PM and NPM) tissue machines was calculated to be 85.6 ± 6.6 %.

5.1.3 Paperboard machines

There were sixteen paperboard machines operational in South Africa in 2011. In this investigation, it was deemed necessary to categorize the paperboard machines into three categories as explained in section 4.1.3.1. Figure 5-8 and Figure 5-9 show the LCC flows in goods across the composite paperboard machines and the grand composite paperboard machines model respectively for the calendar year of 2011. The full set of the material flows results and the associated mass balances calculations for paperboard machines is shown in **Appendix 4**.

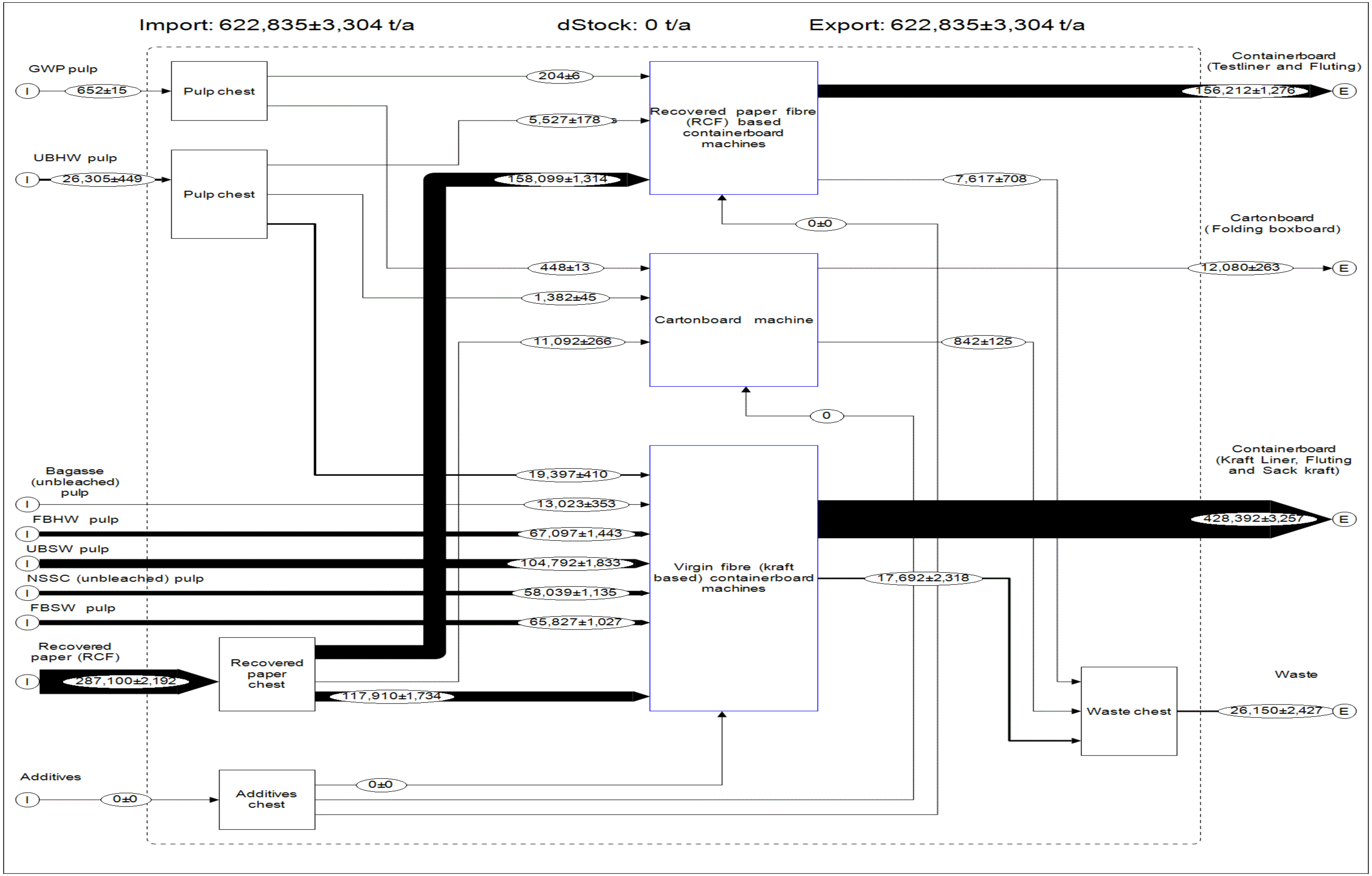

Figure 5-8. Lignocellulosic carbon flows across the composite paperboard machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

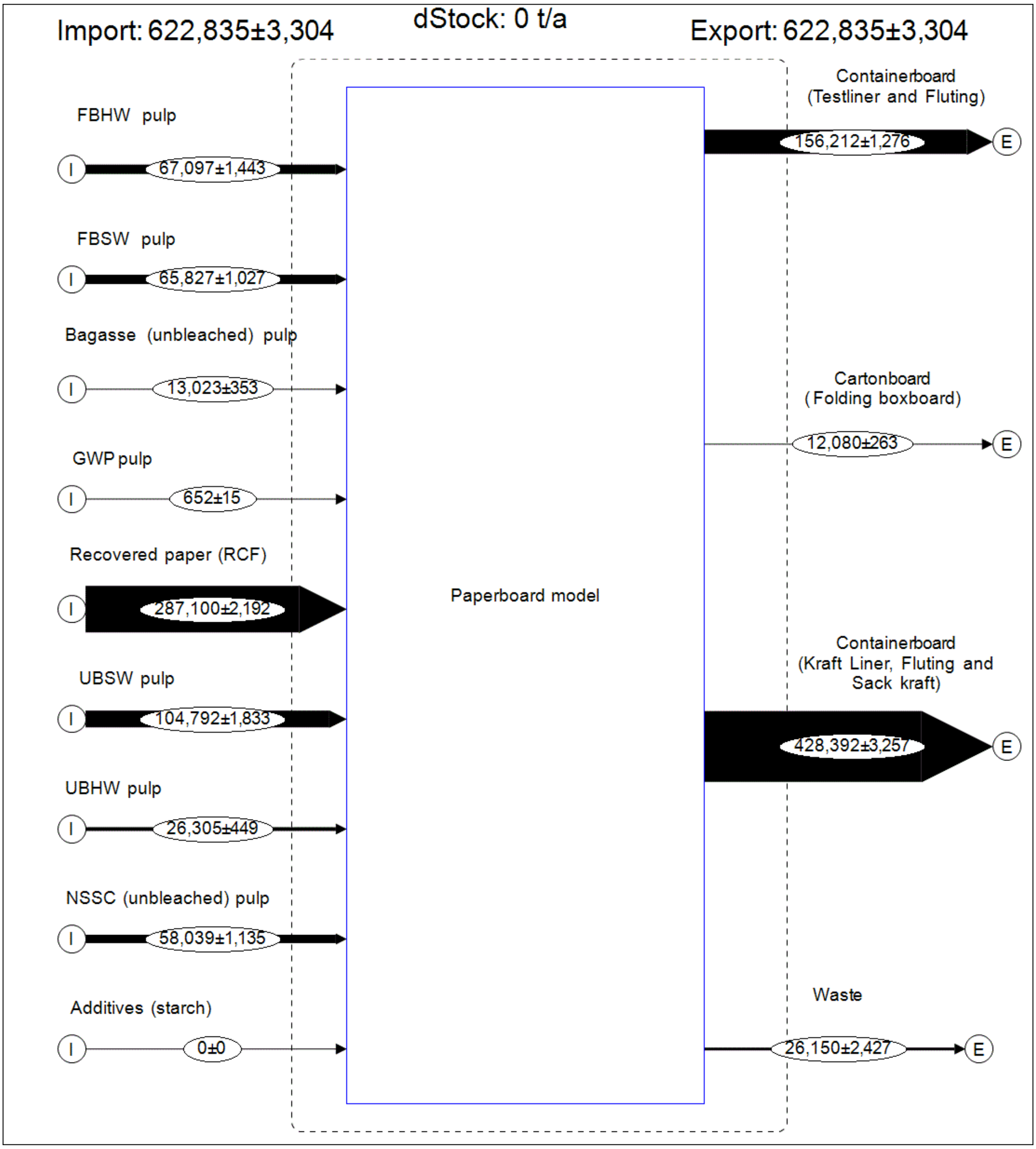

Figure 5-9. Lignocellulosic carbon flows across the grand composite paperboard machines model (as extracted from STAN). Refer to Table 5-2 for definitions of pulp acronyms.

The overall LCC yield across paperboard machines was calculated to be 95.8 ± 0.8 %. Figure 5-8 shows that the bulk of the LCC locked up in the paperboard category was from virgin fibre based containerboard.

5.1.4 Grand composite paper machines model

A grand composite paper machines model was created by combining all paper machines into one model. This was necessary to provide a summarised illustration of the metabolism of fibrous resources across all paper mills in South Africa. In creating the grand composite paper model, it was deemed convenient to classify the fibrous raw materials into two categories namely virgin fibre pulp and recovered paper. The LCC flows results were also presented across a sub-system of the grand composite paper machines model to get a better understanding of the contribution of each paper machine category towards the grand composite model.

5.1.4.1 Goods flow balance models (dry mass basis)

The goods flow balance results (dry-mass basis) of the grand composite paper machines model and its corresponding subsystem are shown in Figure 5-10 and Figure 5-11. The yield of goods (dry-mass basis) across all paper machines was calculated to be 90.0 ± 0.7 %. An analysis of the average virgin fibre to recovered paper ratio in the fibrous pulp furnish used on each of the three paper machine categories and the composite paper machine model was performed. The results are shown in Figure 5-12. The Food and Agriculture Organisation of the United Nations (2010) defines the recovered paper utilization rate (UR) as the amount of recovered paper used for paper production as a fraction of the total fibre used for production. Figure 5-12 indicates that the recovered paper utilization rate on tissue machines was the highest amongst the three paper categories at 55.2 ± 2.5 %. The weighted average recovered paper utilization rates across paperboard machines and graphic paper machines were calculated to be 48.2 ± 0.2 % and 13.9 ± 0.3 % respectively in 2011. The weighted average recovered paper utilization rate across all paper machines in South Africa was 39.1 ± 0.5 % in 2011. Conversely, the use of virgin fibre across all paper mills in South Africa was highest on graphic paper production (86.1 ± 0.3 %) and the lowest on tissue machines (44.8 ± 2.5 %). In comparison the average recovered paper utilization rate in 2009 for China, Japan and USA were 71 %, 64 % and 36 % respectively (Holik, 2013). The low utilization rate of recovered paper in South Africa and USA relative to China and Japan can be attributed to the virgin fibres being the primary raw material source for papermaking in South Africa. This is a result of the vast forest resources and a strong wood pulp industry in South Africa and USA (Bajpai, 2015).

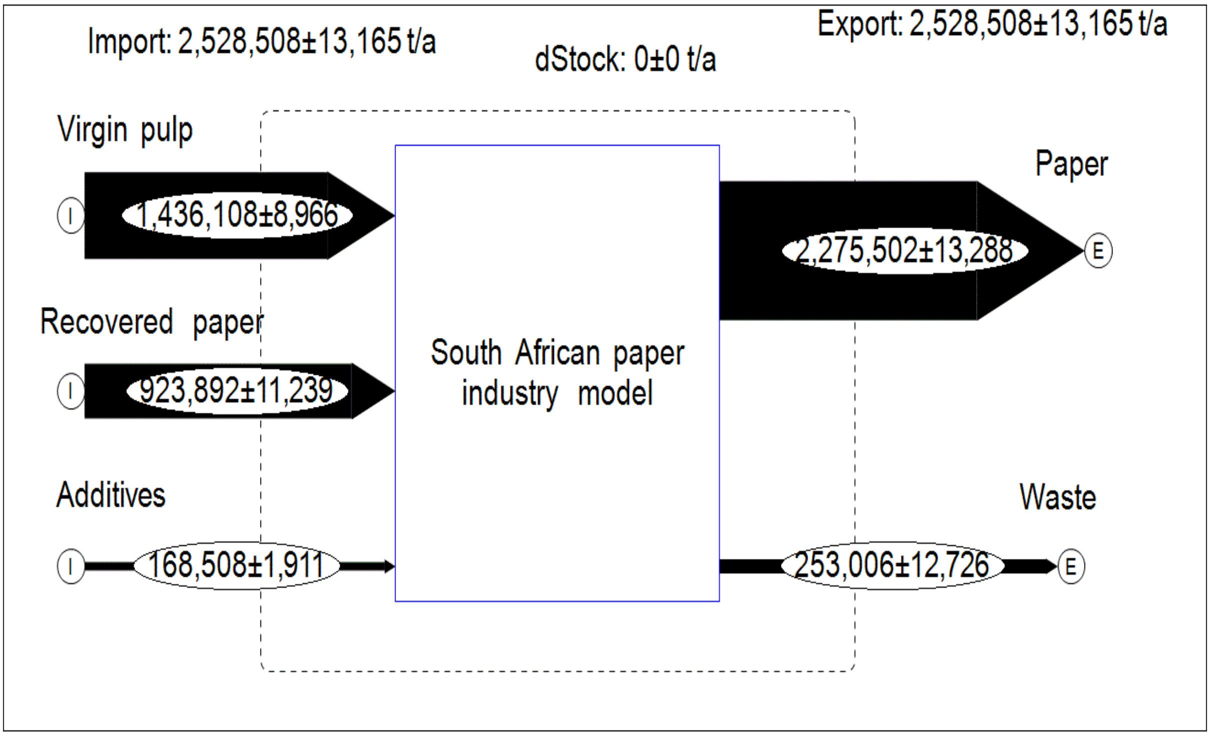

Figure 5-10. The goods flow balance results (dry-mass basis) of the grand composite paper machines model (as extracted from STAN).

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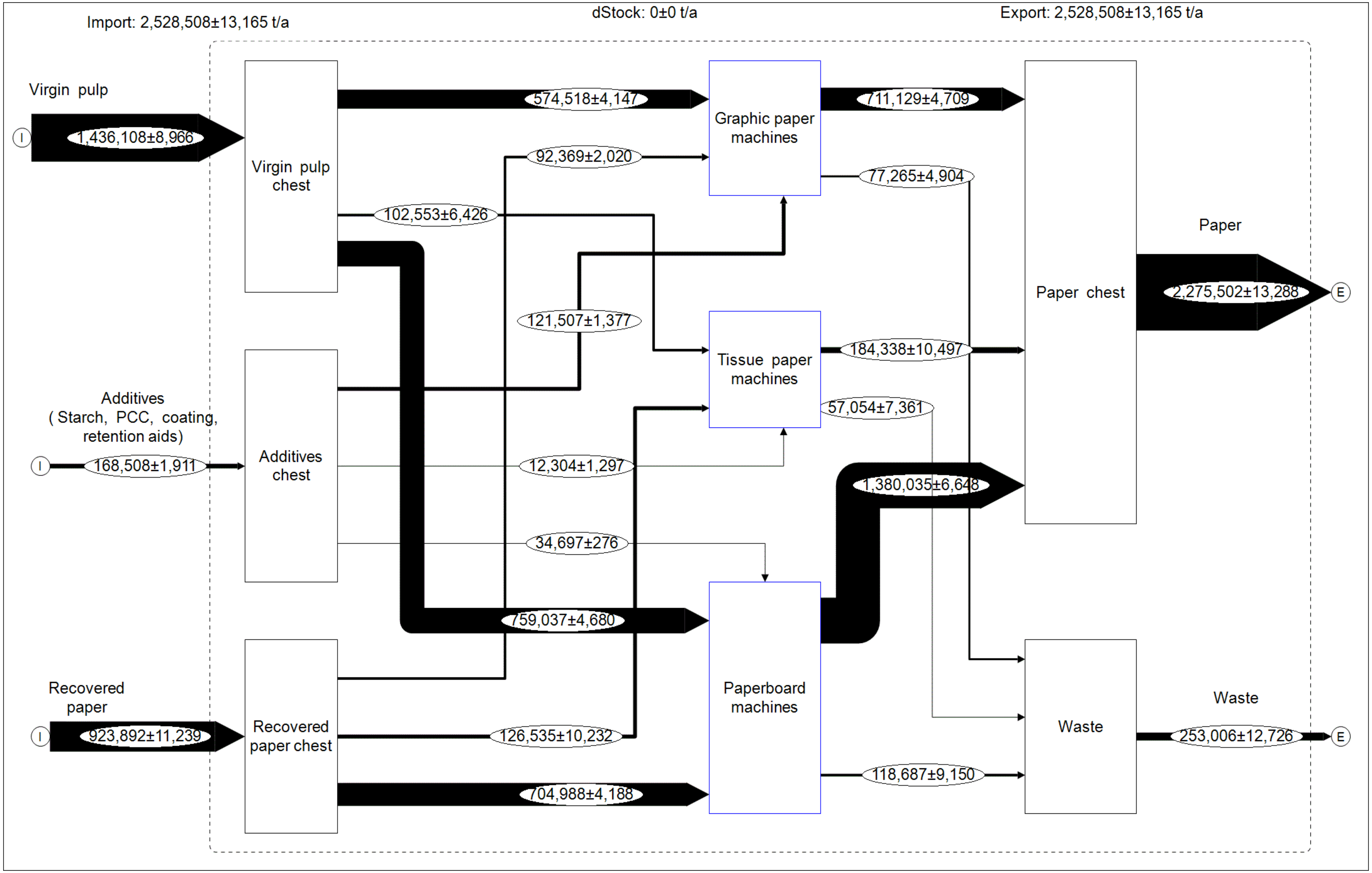

Figure 5-11. The goods flow balance results (dry-mass basis) of the subsystem of the grand composite paper machines model (as extracted from STAN).

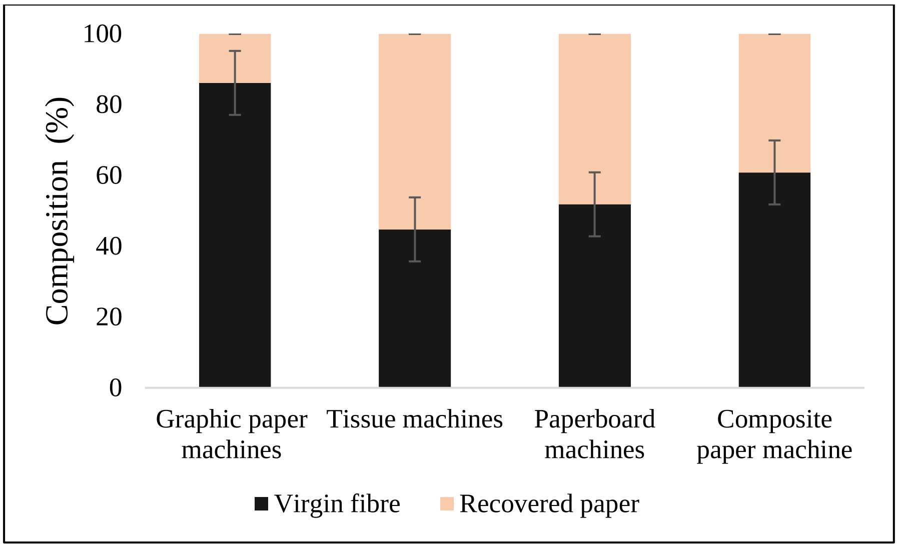

Figure 5-12. Comparison of the average virgin fibre to recovered paper ratio in the fibrous pulp furnish used on each of the three paper machines category and the composite paper machine model.

5.1.4.2 The fibre flow balance models (dry mass basis).

The dry mass fibre flows results of the grand composite paper machines model and the corresponding subsystem are shown in Figure 5-13 and Figure 5-14 respectively. The fibre yield (dry mass basis) across all paper machines was calculated to be 93.8 ±0.9 %.

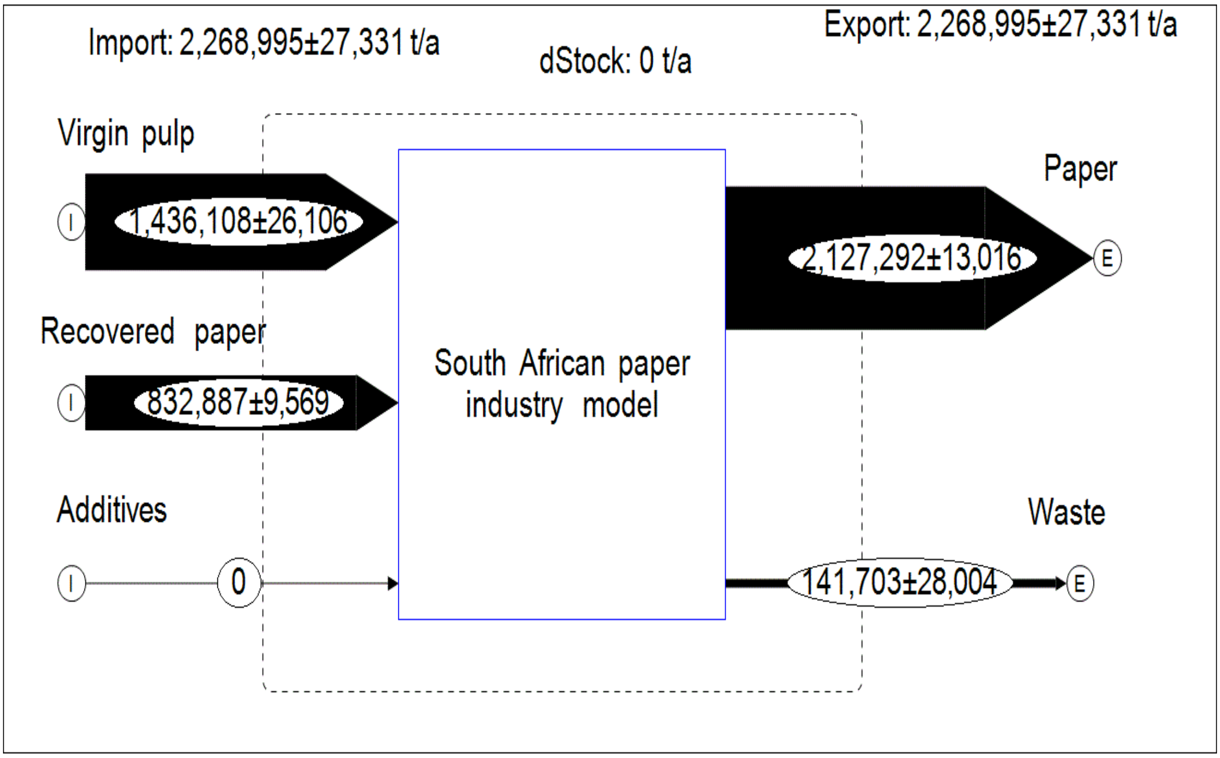

Figure 5-13. Fibre flows balance results (dry-mass basis) of the grand composite paper machines model (as extracted from STAN).

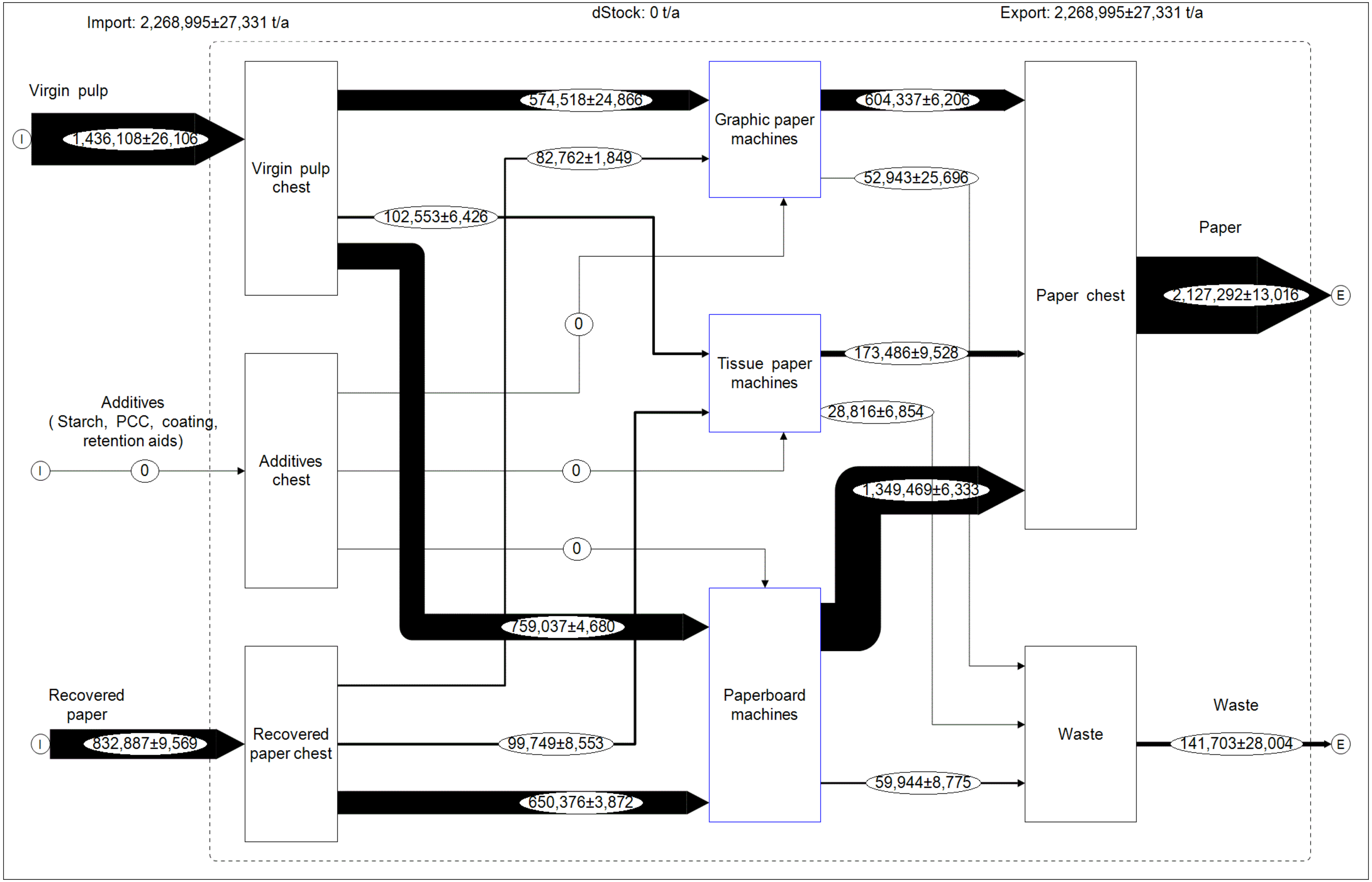

Figure 5-14. Fibre flows balance results (dry-mass basis) of the subsystem of the grand composite paper machines model (as extracted from STAN).

5.1.4.3 LCC flow balance models

The dry mass LCC flows results of the grand composite paper machines model and the corresponding subsystem are shown in Figure 5-15 and Figure 5-17. The overall LCC yield across all paper machines was calculated to be 93.8 ± 0.9 % (Figure 5-15). The fractional contribution of each paper grade towards the total output LCC flow across all paper grades was evaluated and is shown in Figure 5-16. It can be observed that 63.0 ±1.5 % of the total 945.0 ± 0.010 kt/y of the LCC in all the paper produced came from paperboard.

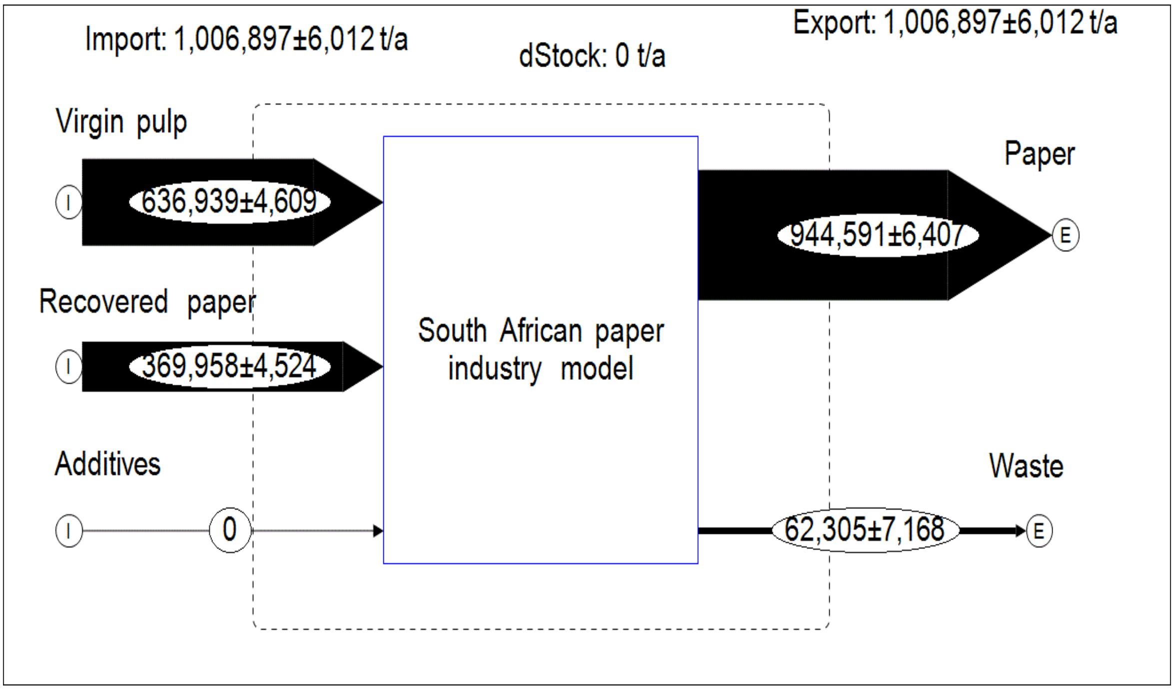

Figure 5-15. Lignocellulosic carbon flows balance results of the grand composite paper machines model (as extracted from STAN).

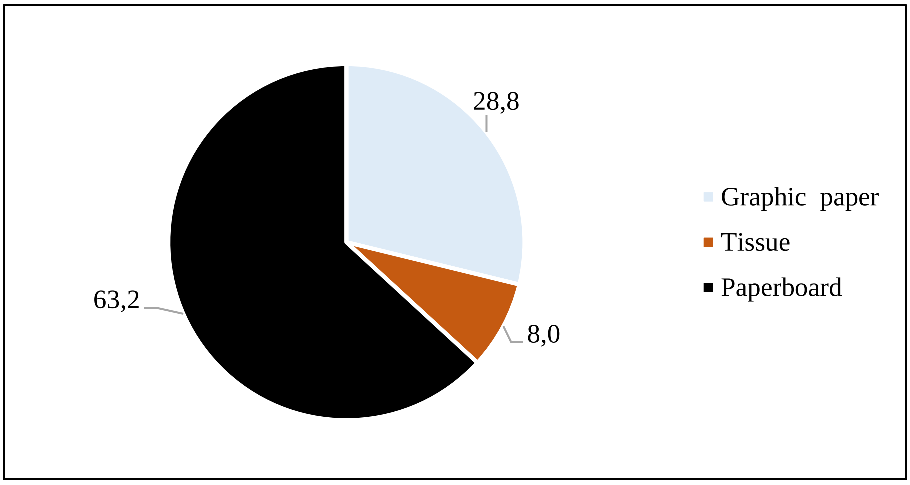

Figure 5-16. The contribution of each paper grade towards the total LCC flow across all paper grades.

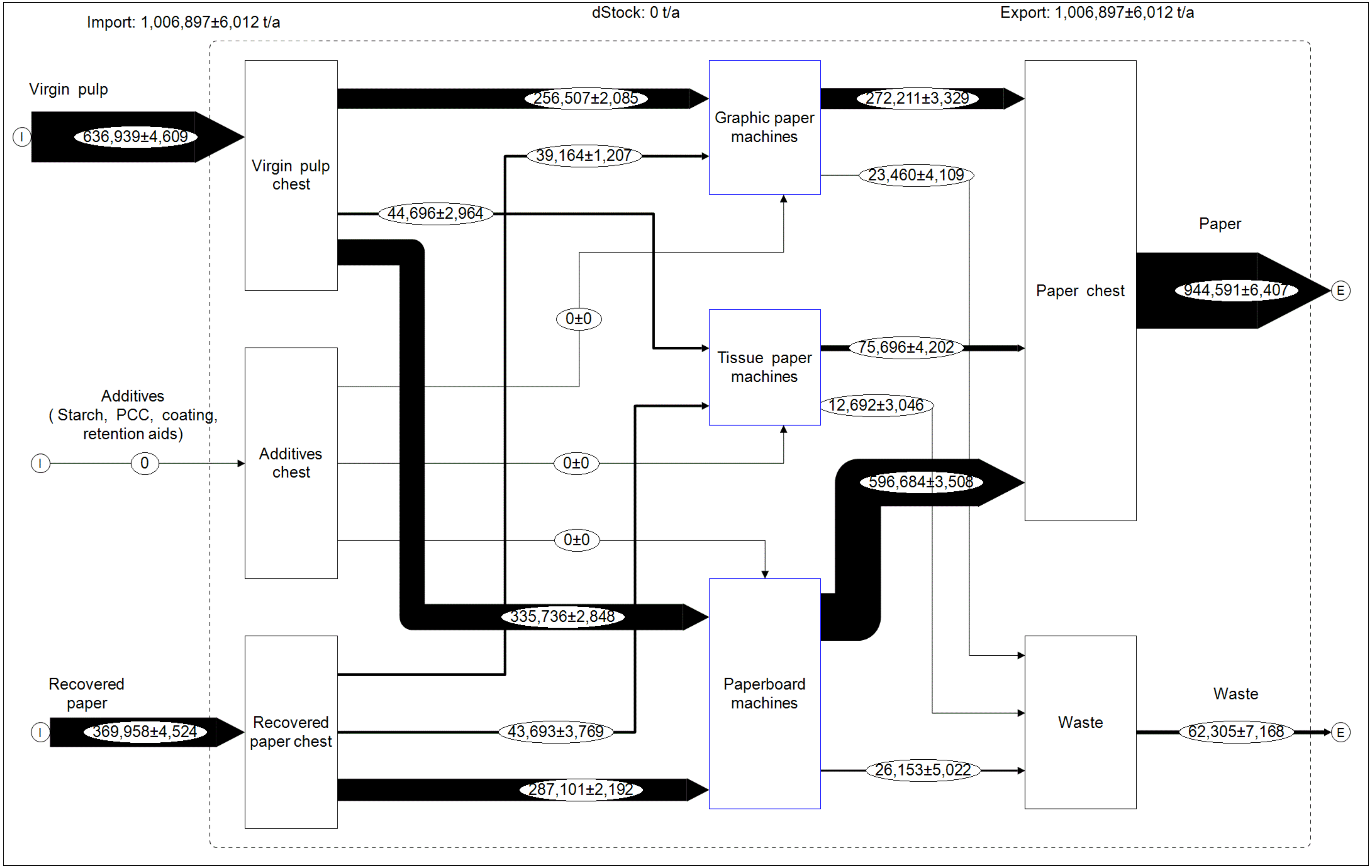

Figure 5-17. Lignocellulosic carbon flows balance results of the subsystem of the grand composite paper machines model..

5.2 An analysis of the lignocellulosic carbon flows results

In this section, an analysis of LCC flows across all paper mills in South Africa for the calendar year of 2011 is presented. This was conducted by comparing the LCC content of raw materials, the LCC content of the three paper grade categories and the yield across all the three categories of paper machines.

5.2.1 Comparison of lignocellulosic carbon content of raw materials

Lignocellulosic carbon is defined in this dissertation as the carbon found in fibrous raw materials as discussed in section 3.2.1. By definition, all papermaking additives do not contain LCC. The pulp furnishes - used on the paper mills in South Africa in 2011 - and the associated average LCC content are presented in Table 5-3. The calculations for the average LCC content of the various pulp furnish are shown in **Appendix 1**. The data presented in Table 5-3 indicates that unbleached mechanical pulp contains the highest LCC content by mass of all the pulp furnishes. This is because mechanical pulp contains the highest content of residual lignin as well as hemicellulose and cellulose after pulping relative to all chemical pulp as discussed in section 3.3. Lignin has the highest LCC fraction of the three major components of wood and bagasse as shown in Table 3-8. The pulp furnish on each paper machine category was further classified into bleached and unbleached pulp as shown in Table 5-4. The weighted average LCC content of all fibrous raw materials used on all paper machines was calculated to be 44.4 % (fibre basis) and 42.7 % (goods basis). The calculations are shown in **Appendix 6**.

Table 5-3. The average LCC composition in each of the pulp fibres used on the paper machines in South Africa. The definitions of the pulp acronyms are provided in Table 5-1.

Pulp furnish	Pulping method	Average LCC (%)
GWP – HW (unbleached)	mechanical	47.4
TMP – SW (unbleached)	mechanical	46.0
UBHW (unbleached)	chemical	44.9
NSSC (unbleached)	semi-chemical	44.7
UBSW (unbleached)	chemical	44.6
Bagasse (unbleached)	chemical	43.8
FBHW (bleached)	chemical	43.7
NSSC (unbleached)	semi-chemical	43.7
FBSW (bleached)	chemical	43.5
Bagasse (bleached)	chemical	42.8

Table 5-4. Classification of the pulp furnish and the corresponding fraction used on each paper machine category and the composite paper machine model for paper mills in South Africa in 2011.

Pulp class	Graphic paper %	Tissue %	Paperboard %	Paper %
Bleached pulp	55.4	100	20.8	38.3
Mechanical pulp	-	-	-	-
Chemical pulp (FBHW, FBSW & Bagasse)	55.4	44.8	20.8	32.9
Recovered paper	-	55.2[10]	-	5.4
Unbleached pulp	44.6	-	79.2	61.7
Mechanical pulp (GWP & TMP)	27.7	-	0.1	7.9
Chemical pulp (UBHW, UBSW, NSSC & Bagasse)	3.0	-	31.0	20.1
Recovered paper	13.9	-	48.1	33.7

5.2.2 Comparison of the lignocellulosic carbon content of the three paper grade categories.

It can be observed that 0.945 Mt/y (Figure 5-15) of the 2.27 Mt/y (Figure 5-10) total bone-dry mass paper[11] produced in South Africa in 2011, was LCC. This translates to a weighted average LCC composition in the dry mass paper of 41.5 %. The corresponding weighted average LCC composition in dry mass paper and fibre in each of the three paper grades is shown in Figure 5-18.

The proportion of LCC in paper fibre is greater than that in the dry mass paper across all paper grades. This is because dry mass paper contains fibre and papermaking additives such as filler and starch. The average composition of fibre and additives in each of the three paper grade categories is shown in Figure 5-19. It is important to recall that paper refers to the summation of the three paper categories defined in this dissertation as was specified in section 4.1.2. As shown in Figure 5-18, paperboard (43.2 %) contains the highest amount of LCC on a dry mass basis; graphic paper (38.3 %) contains the least amount of LCC. This is because the weighted average content of additives (filler) in paperboard grades is the least amongst the three paper grades categories at 2.2 %. Graphic paper grades were found to have the highest average additives (filler) content paper at 15.0 % as seen from Figure 5-19. This was further supported by Holik (2006) who cites that the mass fraction (dry-mass basis) of additives (filler) in coated and uncoated woodfree paper ranges from 20-35 % and 8-15 % in newsprint. In this MFA

[10] Some of the recovered paper fibre used on tissue production is not bleached during repulping. However, the recovered paper grades such HL1, HL2, IMW are mostly produced from bleached pulps.

[11] Bone-dry mass paper refers to the paper produced on a paper machine minus its moisture content.

study, the graphic paper category comprises of both paper grades therefore, a weighted average filler content (dry mass basis) of 15 % was acceptable.

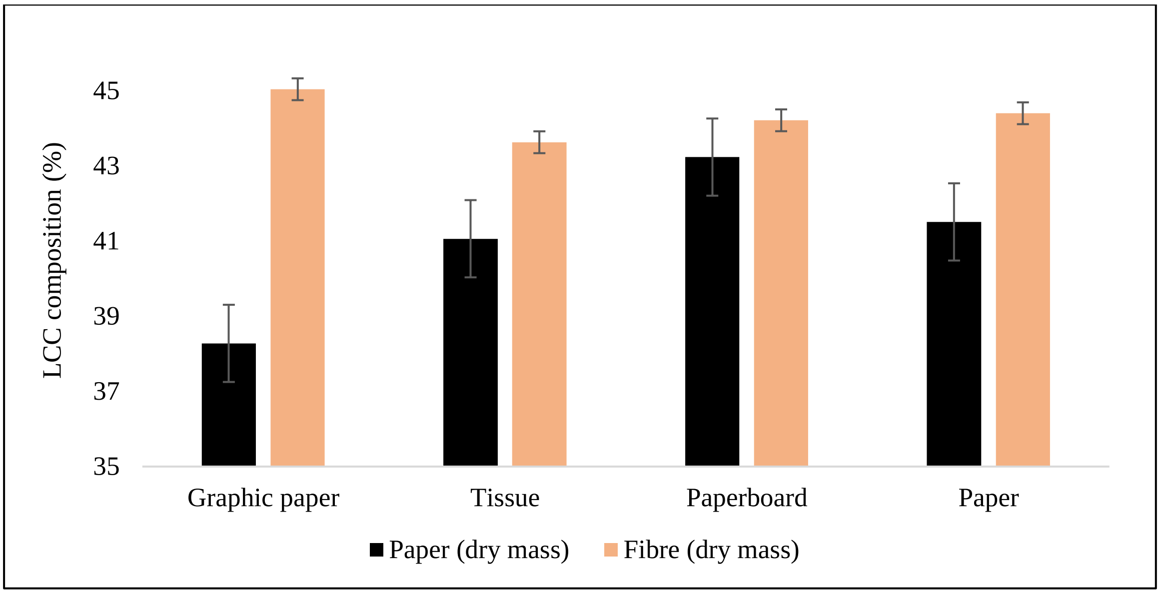

Figure 5-18. The weighted average LCC composition in dry mass paper and fibre flows in each of the paper grades.

Figure 5-18 illustrates that on a dry mass fibre basis, the graphic paper category contains the highest amount of LCC (45.0 %) .This is because approximately 45 % (Table 5-4) of the fibrous pulp furnish used on graphic paper machines category was unbleached mechanical pulp fibre i.e. TMP, GWP and recovered paper (mainly FN and SN grades). Unbleached mechanical pulp contains the highest LCC content by mass of all the pulp furnish (discussed in section 3.3.1) as shown in Table 5-3. As such, the greater the quantity of unbleached mechanical pulp in a pulp furnish, the higher the LCC content in the fibre. No mechanical pulp was used on tissue production whilst approximately 0.1 % of the pulp furnish used on paperboard machines was mechanical pulp.

It can also be observed from Figure 5-18 that tissue paper contains the least amount of LCC (43.6 %) on a dry mass fibre basis. This is because almost all of the fibrous pulp furnish used on tissue machines category comprises of bleached chemical pulp (Table 5-4). This includes the recovered paper grades such as HL1 and HL2 which are predominantly bleached chemical pulp grades. Bleached chemical pulps contain the least LCC content amongst all the pulp types

(Table 5-3). This is a result of the removal of almost all of the residual lignin in the chemical pulp and carbohydrate degradation during pulping and bleaching as discussed in section 3.3.1.

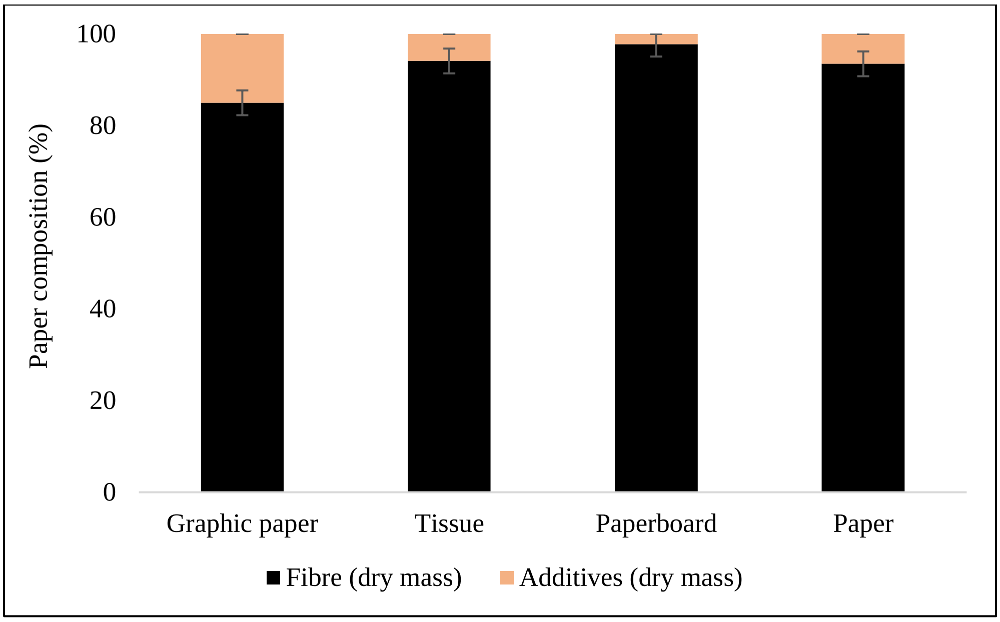

Figure 5-19. The average composition of fibre and additives in each paper grade category on a dry mass basis.

5.2.3 Comparison of the yield across the three paper machines categories.

The yield of goods, fibre and LCC across each of the three paper machines categories and the composite paper machines model is illustrated in Figure 5-20. It is evident that the yield of goods, fibre and LCC was the lowest across the tissue machines at 76.4 ± 5.9 %, 85.8 ± 6.4 % and 85.5 ± 6.6 % respectively. This was because of the differences in recovered paper utilization rates - defined in section 5.1.4.1 - and the composition of recovered paper used on paper machines. Figure 5-12 shows that the recovered paper utilization rate on tissue machines was the highest amongst the three paper categories at 55.2 %. Paperboard machines and graphic paper machines had recovered paper utilization rates of 48.2 % and 13.9 % respectively. This indicates that most of the recovered paper relative to virgin pulp was used in the manufacture of tissue paper as compared to paperboard or graphic paper.

The differences in the recovered paper utilization rates between tissue machines and paperboard machines was 7 % (Figure 5-12), whereas the difference in overall yield of goods was approximately 16 % (Figure 5-11). The recovered paper furnish on tissue machines consists of a mix of office paper, newspaper, magazines and printer off-cuts grades (CMW, IMW, SBM, FN, HL1, HL2, SMW etc.). The recovered paper furnish on paperboard machines consists mainly of corrugated boxes (K3 and K4) and a mix office paper, corrugated boxes, newspaper, cartonboard trims and printer off-cuts (CMW, IMW, FN, SN, K3, K4 etc.). Recovered paper used on tissue machines contains more additives (Figure 5-19) and contaminants as compared to recovered paper used on paperboard machines coupled with the de-inking process on some of tissue machine systems in South Africa. This results in more waste being generated across tissue machines relative to paperboard machines.

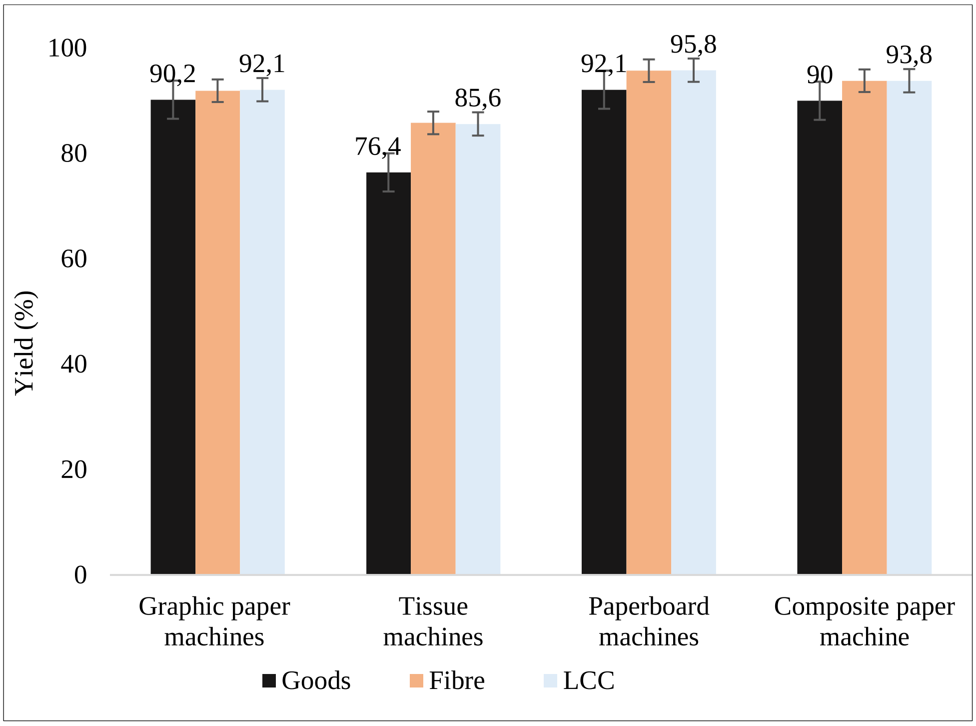

Figure 5-20. A comparison of the yield of goods, fibre and LCC across the graphic paper machines, tissue machines, paperboard machines and the composite paper machine model in South Africa.

The difference in the recovered paper grades used on tissue machines and paperboard machines was crucial due to the difference in the amount of fibre and additives (filler) in the recovered paper grades. On average corrugated boxes contain approximately 5-10 % filler whereas a mix of office paper, newspaper, magazines contains 8-30 % filler (Holik, 2006). This indicated that the amount filler per tonne of recovered paper used was higher on tissue machines relative to paperboard machines. During repulping of recovered paper, most of the filler is removed. As such, the mass lost per tonne of recovered paper used was higher on tissue machines relative to paperboard machines. The exact amount could not be ascertained because the data on waste collected from paper mills was reported as a collective of waste generated on the repulping section and papermaking sections for almost all of the tissue machines and paperboard machines using recovered paper. In addition, further materials processing - such as deinking - across tissue machines resulted in the further mass loss of recovered paper. This resulted in a significantly lower yield of goods across tissue machines relative to both paperboard and graphic paper machines.

It is important to note that the overall yield of fibre (dry mass basis) was equal to the overall yield of LCC across all the paper machines categories. Lignocellulosic carbon is a chemical component of the fibre; the amount of LCC in paper is directly proportional to the amount of fibre present. As such the ratio of fibre flows to LCC flows in paper grades is the same.

5.3 Scenario development and analysis

Three scenarios were developed based on the South African paper industry's market-related changes that have taken place or future possibilities likely to happen in the paper industry. These were investigated; the aim of the scenario analysis was to check the effect of these changes on the flow of LCC across paper mills in South Africa. In the development of all scenarios, it was assumed that the total production of paper remains constant over the years[12].

5.3.1 Scenario A: Manufacture of tissue using virgin fibre pulp only

In developing scenario A, it was noted that the demand for high premium grade tissue paper has generally increased in the past decade in South Africa (M Bothma 2017, personal communication, 02 November). The production of all tissue paper i.e. on both PM and NPM machines in South Africa using 100 % virgin fibre pulp was considered. This means that only the premium grade tissue paper will be produced. The following assumptions were used in creating this scenario model.

- The virgin fibre pulp is locally produced.
- The average goods yield is 94.5 %. This was taken to be the average yield across tissue machines producing tissue paper from virgin fibre only.
- The total mass of tissue paper produced is taken to be the same for both the actual model and the scenario model.

[12]The total paper produced in South Africa has increased from 2.26 Mt to 2.29 Mt between 2011 and 2015. This represents a 1.1 % increase in paper production over 5 years hence it is justifiable to assume that the total paper production remains constant in developing the different scenarios.

The results of this scenario model detailing the goods and LCC flows are shown in **Appendix 6**. A comparison of the actual model and the scenario model characteristics for tissue machines and the grand composite paper machines model when tissue paper is made from virgin fibre only are shown in Figure 5-21 and Figure 5-22 respectively. An actual model was defined in this dissertation as a model developed based on production data collected for the calendar year of 2011 across all paper mills in South Africa. It is evident from Figure 5-21 and Figure 5-22 that an increase of the virgin fibre content of the total pulp furnish from 44.8 % (actual model) to 100 % (scenario model) in the production of tissue paper will have the following results:

a) An increase of the yield of goods from 76.4 % to 94.6 % across all tissue machines. This results in a corresponding increase, i.e. from 90.0 % to 91.7 %, across all paper mills in South Africa as illustrated in the grand composite paper machines model.
b) An increase of the LCC yield from 85.6 % to 95.4 % across the tissue machines. This results in a corresponding increase from 93.8 % to 94.6 % across paper mills in South Africa as illustrated in the grand composite paper machines model.
c) A decrease in the ratio of LCC in waste to the LCC in the tissue paper across all tissue machines from 16.8 % to 4.8 %. A ratio of LCC in waste to the LCC in the tissue paper of 16.8 % means that for every tonne of LCC in the tissue paper produced, 168 kg of LCC ends up in the waste. This results in a corresponding decrease in the ratio of LCC in waste to the LCC in the tissue paper across all paper mills in South Africa as illustrated in the grand composite paper machines model from 6.6 % to 5.7 %.

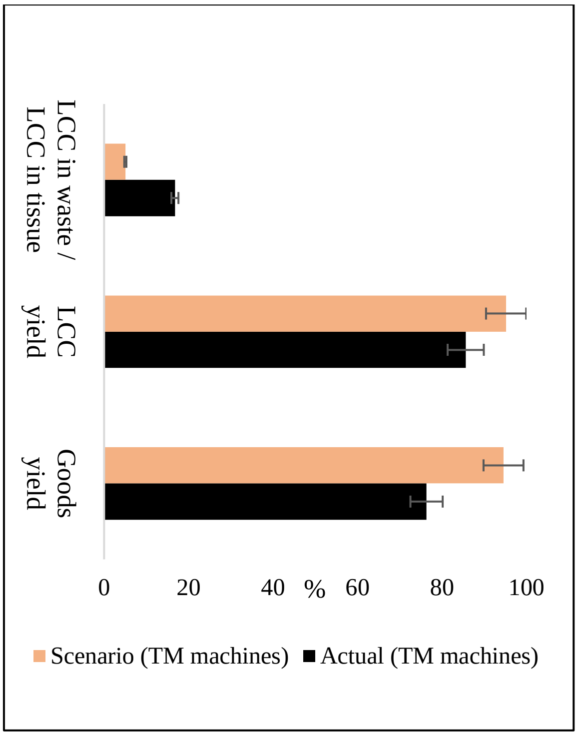

Figure 5-21. A comparison of the actual model and the scenario model characteristics for tissue machines when all tissue paper is made from 100 % virgin fibre.

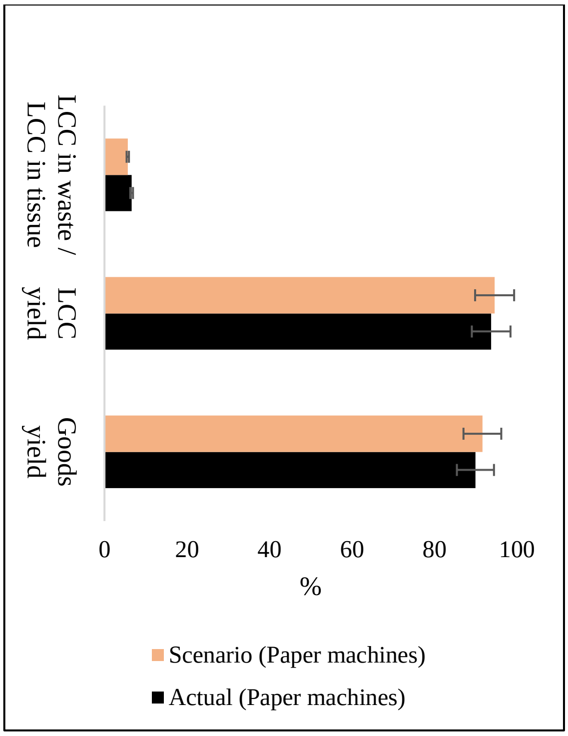

Figure 5-22. A comparison of the actual model and the scenario model characteristics for the grand composite paper machine model when all tissue paper is made from 100 % virgin fibre.

5.3.2 Scenario B: Manufacture of paperboard using only recovered paper pulp

The following assumptions were used in creating the model for Scenario B model i.e. the production of all paperboard in the country using only recovered paper:

- The balance of recovered paper required to meet the total paper production tonnage of 2.27 Mt (bone-dry mass basis) would be imported. The quality of the imported recovered paper is the same as the locally available recovered paper.
- The average dry mass goods yield is 88 %. This is taken to be the average yield across all paperboard machines producing paperboard from recovered fibre only.
- The total tonnage of paperboard produced is taken to be the same for both the actual model and the scenario model.

The results of this scenario model detailing the goods and LCC flows are shown in **Appendix 6.** A comparison of the actual model and the scenario model characteristics for paperboard machines and the grand composite paper machines model is shown in Figure 5-23 and Figure 5-24 respectively.

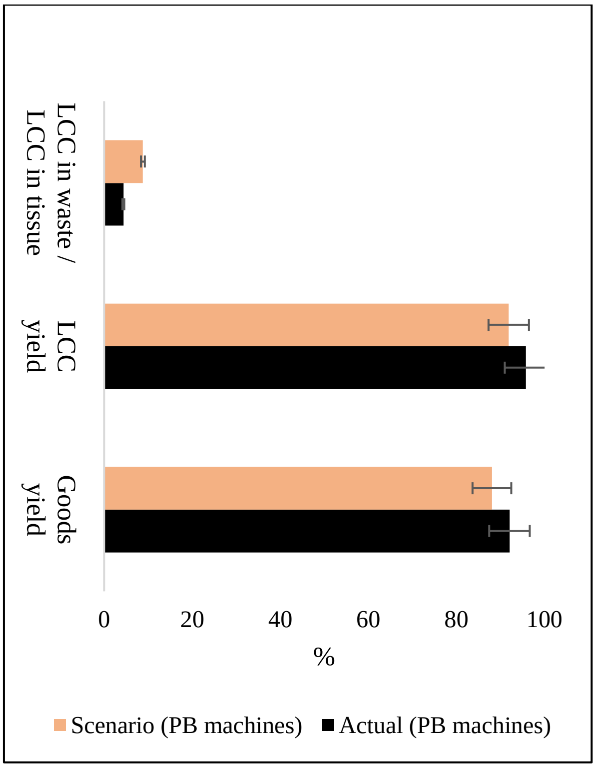

Figure 5-23. A comparison of the actual model and the scenario model characteristics for paperboard machines when all paperboard is made from 100 % recovered paper.

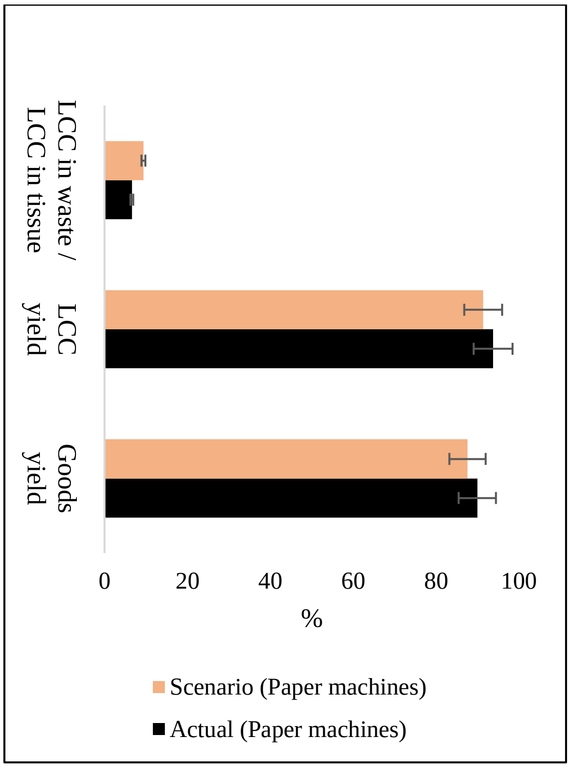

Figure 5-24. A comparison of the actual model and the scenario model characteristics for the grand composite paper machine when all paperboard is made from 100 % recovered paper fibre.

It is evident that an increase of the recovered paper fibre content in the pulp furnish from 48.2 % (actual model) to 100 % (scenario model) in the production of paperboard will have the following results:

a) A decrease of the yield of goods from 92.1 % to 88.1 % across all paperboard machines. This result in a corresponding decrease, i.e. from 90.0 % to 87.6 %, across all paper mills in South Africa as illustrated in the grand composite paper machines model.

b) A decrease of the LCC yield from 95.8 % to 91.9 % across all paperboard machines. This translates to a decrease in the quantity of LCC that goes to paperboard from 597 kt/y to 592 kt/y. The corresponding quantity of LCC in waste across all paperboard machines increases from 26 kt/y to 52 kt/y. This results in a corresponding decrease, i.e. from 93.8 % to 91.4 %, across all paper mills in South Africa as illustrated in the grand composite paper machines model. The corresponding quantity of LCC in waste across all paper mills in South Africa increases from 62 kt/y to 88 kt/y.

c) An increase in the ratio of LCC in waste to the LCC in the paperboard across all paperboard machines from 4.4 % to 8.8 %. A ratio of LCC in waste to the LCC in the paperboard of 4.4 % means that for every tonne of LCC in the paperboard produced, 44 kg of LCC ends up in the waste. This results in a corresponding increase, i.e. from 6.6 % to 9.4 %, across all paper mills in South Africa as illustrated in the grand composite paper machines model.

5.3.3 Scenario C: Shutdown of one newsprint machine (GP6)

The decrease in the demand for newsprint in South Africa over the past 5-10 years (Kotze, 2013) has necessitated the complete shutdown of the graphic paper machine, GP6 in 2017[13] (K Govender 2016, personal communication, 26 July 2016). This was the only newsprint machine- of the two newsprint machines in South Africa - using recovered paper fibre in addition to mechanical pulp. The shutting down of the newsprint machine has had the following effects on the paper industry:

- Discontinuation in the production and usage of TMP since there is no longer use or demand for it in South Africa.
- Availability of excess FBSW pulp and recovered paper (old newspapers and used magazines).

It is proposed that the recovered paper portion i.e. old newspapers and magazines be used in the manufacture of newspapers paper as discussed below.

5.3.3.1 Old newspapers and magazines to tissue paper

This option involves the use of old newspapers and magazines to replace/displace virgin fibre i.e. FBSW and FBHW in the production of tissue paper. The old newspapers and magazines are diverted from the shutdown newsprint machine's (GP6) raw material feed. It is important to note the total amount of old newspapers and magazines is not sufficient to replace all the virgin fibre pulp required to maintain the tissue production for the calendar year of 2011. As such, a certain amount of virgin fibre will be retained in the production of tissue paper in this scenario. Tissue paper products such as bathroom tissue, facial tissue and paper towels can be

[13]The demand for newsprint and consequentially production has progressively decreased between 2010 and 2017 until the production was ceased completely.

produced from old newsprint paper and magazines i.e recycled mechanical fibres (Back et al., 1996, McKinney, 1994, Bajpai, 2013). This is commercially viable when the mechanical fibres are enzymatically modified and a small amount residual printing ink oil is left within the deinked pulp (DIP) as set out in the patent of Back et al. (1996).

The following assumptions were used in creating this scenario model:

a) Old newspapers and magazines (mechanical fibres) are sufficiently modified as set out in the patent of Back et al. (1996) to produce good quality tissue paper.
b) The mass of tissue produced remains constant i.e relative to 2011 production.
c) The average dry mass shrinkage of recovered paper across all tissue machine is 75 %. This was taken to be the average shrinkage across all PM and NPM tissue machines using recovered paper only. The recovered paper fibre is sufficiently whitened to produce white tissue paper. No further fibre losses are encountered during this process.
d) The average dry mass shrinkage of virgin fibre pulp across all tissue machine is 93 %. This was taken to be the average shrinkage across all PM tissue machines using virgin fibre only.

A comparison of the actual model and the scenario model characteristics for the grand composite paper machine are shown in Figure 5-25. The detailed calculations and results on goods and LCC flows of this scenario model are shown in **Appendix 6**. It is evident from Figure 5-25 that the production of graphic paper (virgin fibre only) and tissue paper (from recovered paper only) using the shutdown newsprint machine's raw material feed will have the following results:

a) A slight increase in the yield of goods from 90.1 % to 90.3 % across the grand composite paper machines model.
b) A slight increase in the yield of LCC 93.8 % to 94.4 % across the grand composite paper machines model.
c) A decrease in the ratio of LCC in waste to the LCC in the paper across the grand composite paper machines model from 6.6 % to 5.9 %
d) A decrease in the quantity of virgin fibre used across tissue machines by i.e. 85 % 102.6 kt/y to 15.8 kt/y.

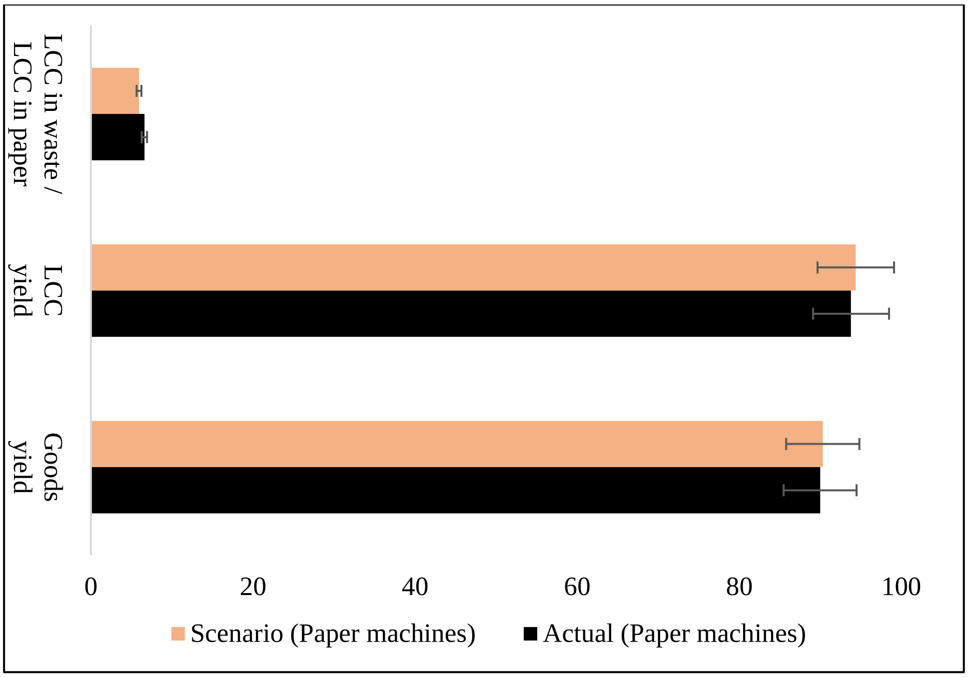

Figure 5-25. A comparison of the actual model and the scenario model characteristics for the grand composite paper machines model when the pulp furnish (old newsprint and magazines) of the shut newsprint machine was used in the production of tissue paper and graphic paper.

5.3.4 Summary of the scenario development and analysis

The three scenarios developed were analysed separately (in sections 5.3.1 to 5.3.3) relative to the actual models developed for paper mills in South Africa. Table 5-5 shows a summarised comparison of the three scenarios developed relative to the actual models of paper mills in South Africa. However, it is important to note that the conclusions made from this scenario analysis need to be taken in a broader context so that holistic and practical recommendations can be implemented. This means that the conclusions from this scenario analysis will need to assessed further in conjunction with similar studies of LCC material flows for the other stages of the value chain (e.g. fibre production, usage and disposal of paper). For instance, Scenario B suggests the production of paperboard products using recovered paper fibre only i.e. ceasing the use of virgin fibre for paperboard production. However, recovered paper fibre can only be recycled and re-used for up 5-7 cycles for papermaking purposes before unused recovered paper is required to replace it, which will not be available as there would not be any virgin fibre based recovered paper in the system.

Table 5-5. A summarised comparison of the characteristics of the three scenarios relative to the model developed for paper mills in South Africa for the 2011 calendar year.

	Actual models SA paper industry	Scenario A only premium brand (100% VF)	Scenario B 100 % RCF based paperboard	Scenario C Old newspapers to tissue paper
Goods flows (kt/y)				
Virgin fibre	1 436	↑ (5.60%)	↓ (52.8%)	↓ (15.3%)
Recovered paper	924	↓ (13.7%)	↑ (90.7%)	↔
Graphic paper	711	↔	↔	↓ (26.9%)
Tissue paper	184	↑ (0.60%)	↔t	↔
Paperboard	1 380	↔	↑ (0.80%)	↔
Paper	2 276	↔t	↑ (0.60%)	↓ (8.4%)
Waste	253	↓ (18.4%)	↑ (27.0%)	↓ (11.7%)
LCC flows (kt/y)				
Virgin fibre	637	↑ (5.60%)	↓ (52.7%)	↓ (15.5%)
Recovered paper	367	↓ (11.8%)	↑ (96.6%)	↔
Graphic paper	272	↔	↔	↓ (31.8%)
Tissue paper	76	↑ (0.70%)	↔	↑ (1.60%)
Paperboard	597	↔	↓ (0.80%)	↔
Paper	945	↑ (0.10%)	↓ (0.50%)	↓ (9.00%)
Waste	62	↓ (14.3%)	↑ (41.7%)	↓ (18.2%)
Yield (%)				
Goods	90.0	91.7	87.6	90.3
Fibre	93.8	94.6	91.4	94.4
LCC	93.8	94.6	91.5	94.5
LCC in waste / LCC paper	6.6	5.7	9.4	5.9

5.4 Summary

In this chapter, the findings and an analysis of findings of this MFA study were presented. The total mass of LCC flows across all paper mills in South Africa in 2011 was estimated to be 1 010 ± 6.01 kt. Virgin fibre pulp contributed 63.3 % of the total input LCC flows into the industry whilst the balance came from recovered paper. It was estimated that approximately 94 % of the LCC was locked up in paper grades produced with the balance ending up in papermaking waste streams. Additionally, three scenarios were developed - based on market-related changes that have happened or likely to happen in the South African paper industry - and reviewed. A comparison of the three scenarios relative to the actual model of paper mills in South Africa for the calendar year of 2011 was presented. One of the findings was that the production of tissue paper from only virgin fibre (whilst keeping the production of all paper categories constant) would result in a decrease of the LCC diverted to waste by 14.3 % across all paper mills in South Africa. However, - as mentioned earlier- it is important to note that the conclusions made from this MFA study need to be taken in a broader context so that holistic and practical recommendations can be implemented. This means that the conclusions from MFA need to assessed further in conjunction with similar studies of LCC material flows for the other stages of the value chain (e.g. fibre production, usage and disposal of paper). In the next chapter, the conclusions and recommendations based on the findings of this MFA study are presented.

6 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusions and recommendations drawn from the findings of this MFA study across all paper mills in South Africa for the calendar year of 2011, are presented.

6.1 Conclusions

A material flow analysis of across all paper mills in South Africa was conducted in this research investigation. The aim was to track and quantify LCC flows across the papermaking process within the geographical boundaries of South Africa for the calendar year of 2011. The sources of LCC flows within the papermaking industry were identified as fibrous raw materials. The carbon sinks were identified as the paper produced (divided into three categories namely graphic paper, tissue paper and paperboard) and papermaking waste. The following conclusions are made:

1. **Virgin fibre pulp contributed the largest share of the input LCC flows across all paper mills in South Africa.**

   Virgin fibre pulp contributed a total of 639.9 ± 4.6 kt of LCC (i.e. 63.3 %) towards the input LCC flows across all paper mills in South Africa in 2011. In comparison, the recovered paper contributed 370.0 ± 4.6 kt of LCC (i.e.36.7 %).

2. **The largest LCC sink across all paper mills in South Africa in 2011 was determined to be paper.**

   A total of 944.6 ± 6.4 kt of LCC was stored in all the paper produced in 2011. This constitutes 93.8 % of the total input LCC flows. The balance of the LCC flows which amount to 62.3 ± 7.2 kt (6.7 %) were diverted into the waste streams. Based on this, the hypothesis that most of the LCC that enters paper mills in South Africa will end up in the desired product i.e. paper relative to the waste streams is accepted.

3. **The production of tissue paper (dry mass basis) in 2011 resulted in the highest mass of LCC diverted to waste relative to other paper grade categories.**

   For every tonne of dry mass tissue paper produced in 2011, 6.9 kg of LCC was diverted to waste. For every tonne of dry mass graphic paper produced in 2011, 3.3 kg of LCC was diverted to waste. For every tonne of dry mass paperboard produced in 2011, 1.9 kg of LCC was diverted to waste. On average, for every tonne of dry mass paper produced in 2011, 2.7 kg of LCC was diverted to waste.

4. **The production of tissue paper (LCC basis) in 2011 resulted in the highest mass of LCC diverted to waste relative to other paper grade categories.**
   For every tonne of LCC in all the tissue paper produced in 2011, 167.7 kg of LCC was diverted to waste. For every tonne of LCC in all the graphic paper produced in 2011, 86.1 kg of LCC was diverted to waste. For every tonne of LCC in all the paperboard produced in 2011, 43.8 kg of LCC was diverted to waste. On average, for every tonne of LCC in the paper produced in 2011, 66.0 kg of LCC was diverted to waste.

5. **The production of paperboard in South Africa in 2011 resulted in the highest LCC yield; tissue paper production had the least LCC yield of the three paper categories.**
   The yield of LCC across all paperboard machines, graphic paper machines and tissue machines was 95.8 ± 0.8 %, 92.1 ± 1.4 % and 85.5 ± 6.6 % respectively. The weighted average LCC yield across all paper mills in South Africa in 2011 was 93.8 ± 0.9 %.

6. **The production of tissue paper from only virgin fibre (whilst keeping the production of all paper categories constant) would result in a decrease of the LCC diverted to waste across all paper mills in South Africa.**

For every tonne of LCC in all the tissue paper produced, the mass of LCC diverted to waste would decrease from 167.7 kg (2011 production) to 48 kg. This results in an overall decrease in the mass of LCC diverted to waste across all paper mills in South Africa from 66.0 kg to 57 kg for every tonne of LCC in the paper produced. However, it is unlikely that the paper industry can completely do away with recovered paper in tissue paper. Recovered paper is significantly cheaper than virgin fibre.

7. **The production of paperboard from only recovered paper (whilst keeping the production of all paper categories constant) would result in an increase in of the LCC that goes to waste across all paper mills in South Africa**.

For every tonne of LCC in all the paperboard produced, the mass of LCC diverted to waste would increase from 44.0 kg (2011 production) to 88 kg. This results in an overall increase in the mass of LCC diverted to waste across all paper mills in South Africa from 66.0 kg to 94.0 kg for every tonne of LCC in the paper produced. The conversion to production of paperboard using only recovered paper though cheaper in terms of cost of raw materials, would mean high quality/premium-grade paperboard is no longer produced locally. However, the grammage or basis weight of the paperboard produced from 100 % recovered paper may be increased for instance from 125 gsm to 150 gsm to improve strength and stiffness properties.

8. **The shutting down of the newsprint machine coupled with the diversion of the old newspapers and magazines to replace virgin fibre in the production of tissue paper (whilst keeping the production of other paper categories constant) would result in a slight increase of the LCC diverted to waste.**
   For every tonne of LCC in all the tissue paper produced, the mass of LCC diverted to waste would increase from 167.7 kg (2011 production) to 191 kg. However, this result in an overall decrease in the mass of LCC diverted to waste across all paper mills in South Africa from 66.0 kg to 59.0 kg for every tonne of LCC in the paper produced. Most importantly, the mass of virgin fibre used across all tissue machines decreases by 85 % i.e. from 102.6 kt/y to 15.8 kt/y.

A summary of the conclusions drawn from the findings of this MFA study are presented in Table 6-1.

Table 6-1. A summary of the conclusions drawn from the findings of this MFA study of across all paper mills in South Africa for the calendar year of 2011.

Property	Value / Description
Total LCC flows	1 010 ± 6.01 kt
Largest raw material source of LCC	Virgin fibre
LCC yield	94 ± 1%
Largest sink of LCC flows	Paper
Best paper grade category i.to reducing LCC emissions	Paperboard
Worst paper grade category i.t.o. reducing LCC emissions	Tissue paper

6.2 Recommendations

Based on the findings and conclusions made from this MFA study, the following recommendations are put forward:

1. Tissue producers should consider improvements in technology and practice to reduce the amount of fibre diverted to waste hence indirectly reducing the LCC that goes to waste.
2. Tissue producers should consider replacing at least 75 % of virgin fibre (FBHW and FBSW) pulp with recovered paper pulp comprising of old newspapers and magazines. The latter has become available in the South African paper industry after the shutdown of the newsprint machine that used old newspapers and magazines.

6.2.1 Future work

The following recommendations are proposed to improve the reliability of the MFA study across all paper mills in South Africa:

- provision of the production data from non-PAMSA member tissue machines. Perhaps the industry, particularly PAMSA can lobby for the provision of data to PAMSA by all tissue producers.
- provision of data on effluent and paper sludge from all paper producers. This would allow for the separate quantification of LCC flows into effluent and sludge.
- use of this MFA model to review the current production characteristics as well as provide a preview of projected future production and the associated effects of the changes.
- PAMSA creates a database where all the relevant material flow data required (as laid out in this research study) to conduct an MFA study is kept. This can be updated annually. In turn, PAMSA lobbies all South African paper producers to participate in this exercise. This would allow for easier access to production data to researchers and stakeholders hence saving a lot of time in conducting such research.

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APPENDICES

Refer to attached CD.