UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

University of Pretoria

University of Pretoria

School of Engineering

Department of Chemical Engineering

CVD 800

Dissertation

Life Cycle Assessment (LCA) technique as a holistic tool for environmental impact and economic analysis of a co-pulping process

By: David K Mokebe
Student No: 23126052
Date: September 07

School of Engineering
Department of Chemical Engineering
University of Pretoria
Pretoria 0001

Distribution:

1. Professor Thokozani Majozi

This dissertation is submitted in partial fulfillment of the requirements for the course CVD 800 in the curriculum for the degree MEng in Chemical Engineering at the University of Pretoria

As the pressure on the chemical and process industries to improve environmental and economic performance increases, the need to move away from narrow system definitions and concepts in environmental system management is becoming more apparent. Life Cycle Assessment (LCA) has been a gaining wider acceptance as a holistic tool that enables quantification of environmental interventions and evaluation of the improvement options throughout the life cycle of process, product or activity.

The stringent environmental legislation, especially in developing countries has warranted the need for intensive research in this field. Moreover, the capital cost for mitigation of emissions have put enormous pressure on the industries to reduce the overall process economic performance. This has not exempted the Pulp and Paper industry, being the producers of highly variable emissions quality and quantity are the prime candidates for the application of the technique.

The application of the LCA in process selection has been necessitated by the fact that sometimes a technology intended to reduce wastes has created unanticipated impacts in other media and/or stages of the life cycle. Thus, LCA has been developed as a means to identify and deal with these impacts before they can occur. It differs from other pollution prevention techniques in that it views all the resource and energy inputs to a product (Life Cycle Inventory), as well as the associated wastes, health and ecological burdens (Impact Assessment), and evaluates opportunities to reduce environmental impacts (Improvement Analysis) from cradle to grave. LCA is often confused with other assessment tools, such as life cycle cost (LCC) or sometimes referred to as "environmental life cycle costing."

This study was conducted at Mondi Packaging South African-Piet Retief Mill, a producer of linerboard, since this site has ample opportunity to minimse the environmental burden presented by operation of both Copeland Reactor and Boilers with significant emissions of SO_x and NO_x, and water effluent. The current mill strategy that is based on tight procurement specification of raw material is unsustainable. The environmental and economic performance analysis for this study followed from a mass balance of the pulp plant, power station, and paper machine as well as black liquor incinerating plant, and it was found that the most significant emissions come from pulp and steam generating processes. These emissions can be reduced by improving the mill energy efficiency and optimizing the Copeland scrubber absorption efficiency. The optimization of the Copeland scrubbing system will surely lead to improved environmental performance, however, the furnace stacks have to be modified to include the scrubbing system for absorption of SO_x and NO_x.

STATEMENT OF AUTHORSHIP

Life Cycle Assessment (LCA) technique as a holistic tool for environmental and economic analysis of a co-pulping process.

By

K.D. Mokebe

I, *Kozana David Mokebe* (2312605), declare that this dissertation and the associated report is my own work (except where formally acknowledged in the section headed "Acknowledgments").

Student No: 2312605

Date: September 07

Name: Kozana David Mokebe

Signature:……………………..

"*During the next quarter century, the most significant net contribution to a greener world will be made by industry…. Not every company is there yet but most are trying. Those that aren't trying won't be a problem because they won't be around in a long term."* Ed Woolard, former chairman of DuPont

"*'Factor four, doubling wealth-halving resource use," in a nutshell means that resource productivity can-and should-grow four-fold. The amount of wealth extracted from one unit of natural resources can quadruple. Thus we can live twice as well-yet use half as much*" Amory Lowins, CEO of Rocky Mountain Institute, USA.

"Profitability which use to be trustworthy financial measure, has multiplied into a triple bottom line by blurring together economic, social and environmental performance" Clem Sunter Chairman of the Anglo American Chairman's Fund

"Actual and target: "We want to compare the heat we are actually using with the heat we ought to be using. It is easy to find the amount of heat we are buying; it is fairly easy to estimate the amount of steam we are making; it is not so easy to find out how and where this steam is being used. But it can be done with fair accuracy with few instruments. All this information is, however, of little use until we know how much heat and resources we ought to be using." By Oliver Lyle Author of "The efficient use of steam", 1947

Dedicated to my late fiancé and mom.

It is a pleasure to thank a number of very special persons and organizations that contributed immensely during my study at the University of Pretoria:

- Thanks to Professor Thokozani Majozi for setting high standard and rigor in investigating meaningful engineering problems. I would also like to pass my gratitude to him for reviewing first draft of this thesis and providing thorough and insightful comments.
- Thanks to Dr. B. Pillay (former lecture at University of Natal) for his encouragement and motivation.

- Dr. N. S Tlale of CSIR (Head of Robotics and Automation Group) for his input about writing and presentation of dissertation.

- Professor C. Buckley and Mr. I. Kerr of the University of Natal and Mr. D. Mercer (Enviros Consulting) for their elaborated response on the questions asked.

- We gratefully acknowledge the financial support provided by MPSA- Piet Retief, under the leadership of Mr. Bruce Strong and Management Committee ("Mancom").
- I would like to thank both Mr. Riaan Swart (former Mill Manager at Piet Retief) and Mr. Graham Burch (former Technical Manager) for always reminding me that "*An engineering compromise between a rigorous description and getting an answer that is good enough is always required*".

- University of Pretoria Research Committee for allowing this project.

- I would like to thank my parents, PJ Kabini and NV Mokebe *(late)*, for their continuing support throughout my undergraduate and graduate studies.

- NB Mkhabela, my late fiancé for being the source of love and inspiration.

TABLE OF CONTENTS

Appendix:

Abbreviations	Full Name
AA	Alkaline Charge
AP	Acid Rain Potential
AHP	Analytical Hierarchy Process
AR	Aboitic Resources
AQ	Anthraquinone
Alum	Aluminum hydroxide
ADt	Air dried fibre @ 8% moisture
BAT	Best available Technology
BPEO	Best Practicable Environmental Option
BDt	Bone dry fibre @ zero percent moisture
COD	Chemical Oxygen Demand
CP	Norwegian Cleaner Production method
CC	Evaporator Combined Condensate
CML	Chain Management Life Cycle Assessment Method
CML Method	LCA method of University of Leiden in Netherlands
CMLCA	Chain Management Life Cycle Assessment of University of Leiden, Netherlands
DP	Degree of Polymerization
DME	Department of Energy and Minerals
DEAT	Department of Environmental and Tourism
EA	Environmental Audit
EIA	Environmental Impact Audit
ECA	Environmental Conservation Act, 1989
EL	Environmental Index
EP	Euthrophication Potential
GL	Gigalitres
GWP	Global Warming Potential
HW	Hardwood
HP	High Pressure steam $(\geq 1500 kPa)$
HBL	Weak Black Liquor $(\approx \pm 52\%..solids)$
ISO	International Standard Organization
LCDP	Life Cycle Process Design
LP	Low pressure steam $(\leq 400 kPa)$

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCImA	Life Cycle Improvement Analysis
NSSC	Neutral Semi Sulphite Chemical Pulping
NSSC-AQ	Neutral Semi Sulphite Chemical Pulping with anthraquinone
NS-AQ	Neutral Sulphite Anthraquinone
NEMA	National Environmental Management Act, 2004
NWA	National Water Act, 1998
NO_x	Oxides of nitrogen
OCC	Old Corrugated Container
ODP	Ozone Depletion Potential
PM4	Mondi Packaging South African Machine Number 4
POCP	Smog Formation Potential
WSA	Water Service Act, 1997
WBL	Weak Black Liquor $(\approx \pm 19\%..solids)$
ROI	Return On Investment
RONA	Return On Net Assets
RMEE	Relative Mass-Energy-Economic
SETAC	Society for Environmental Toxicology and Chemistry
SBL	Strong Black Liquor $(\approx \pm 30\%..solids)$
S.A	South Africa
SO_2	Sulphur Dioxide
SW	Softwood
TRS	Total Reduced Sulphur
VOC	Volatile Organic Compounds

Symbol	**Definition**
q	Heat flow (MW)
BPR	Boling liquor temperature raise (OC)
E	Total energy used(MW.h)
To	Surrounding temperature for exergy calculation (^{O}C)
T	Stream temperature for exergy and energy calculation (^{O}C)
C_p	Stream heat capacity (kJ/kg.k)
CV	Coal Calorific Value (MJ/kg)
K3	Waste paper from converters(tons)
H	Stream enthalpy (kJ/kg)
K4	Common waste from supermarket(tons)
x_i	Stream concentration in terms of consistency (%)
F_t	Total stream flow rate (t/hr)
F_i	Fibre flow(t/hr)
F_w	Water flow (t/hr)
W_b	Amount of water blown down in a cooling tower (tons)
W_e	Amount of water lost due to evaporation
W_m	Freshwater makeup in the mill (tons)
λ	Latent heat of vaporization (kJ/kg)
ΔP	Pressure difference(kPA)

Name	***Definition***
Acidification potential	Acidifying substances cause a large number of diverse impacts on soil, groundwater, surface water, organisms, ecosystem and materials (buildings). Examples are recent dying of fish in the Vaal river, forest decline and crumbling of building materials.
Cleaner production	The continuous application of an integrated preventative environmental strategy applied to process, products and services to increase eco-efficiency and reduce risks to humans and the environment
Contaminant	The undesirable constituent of a process stream
CML LCA Methodology	Life cycle impact analysis technique (LCIA) that is directly applied in South Africa developed at the University of Leiden in Netherlands by Heijungs et al. (1992b)
Dry heating cylinders	The type of heat exchanger used on paper machine for paper drying. The steam is fed in the rotating cylinder and the paper wraps around the cylinders
Depletion of abiotic resources	The decrease of abiotic resources, the "dead" material resources such as iron ore, fossil fuels etc. that occur as inflows in LCA
Eco-efficiency	This is an environmental approach developed by the World business Council for sustainable development (WBCSD). It is about producing more with less resources and less pollution whilst encouraging business to become more competitive, more innovative, and more environmental responsible

Eco-points	Life cycle impact analysis technique (LCIA) that is normally applied in South Africa and has been developed by BUWAL in Switzerland
Eco-indicators 95	Life cycle impact analysis technique (LCIA) that is also occasionally applied in South Africa and has been developed by Pre Consultants in Netherlands
EPS	Life cycle impact analysis technique (LCIA) that is occasionally applied in South Africa developed by Chalmers University of Technology in Sweden.
Ecotoxicity	Eco-toxicology impacts are the effects of toxic substances on aquatic, terrestrial and sediment ecosystems
Effluent	Liquid waste generated by human activity
Eutrophication potential	Euthrophication includes all impacts due to a too high level of macronutrients in the environment. Nitrogen (n) and phosphorus are most important eutrophicating elements. This enrichment may case an undesirable shift in the composition of a species and an increased production of biomass with aquatic and terrestrial ecosystems.
Environment	The environment is the combination of both the system and the surrounding under consideration. In simple terms the thermodynamic universe.

Global warming potential	The effect of emissions as a result of human activities on the radioactive forcing (heat radiation absorption) of the atmosphere. This, in turn ca result in adverse effects on ecosystem health, human health and material welfare. Most of these emissions enhance the radioactive forcing, resulting in a rise in the earth's temperature. This is popularly referred to as the "Greenhouse effects".
Hazardous waste	Any waste, other than radioactive waste, which by virtue of its chemical reactivity, co-toxicity, and explosive character, corrosively, carcinogenic qualities, or other characteristics, may cause significant danger to, or impact adversely on human health or the environment.
Human toxicity Potential	The impact category contains the effects of toxic substance in the environment on humans
Heat transfer driving force	The temperature difference between hot and cold streams
Hypo number	The TAPPI used method for measuring the residual lignin content of pulp.
Impact categories	The actual environmental categories directly or indirectly affect by different human activity of emissions.
ISO 14040	ISO principles and framework procedure
ISO 14041	Goal and scope definition and inventory analysis
ISO 14042	Life cycle impact assessment methodology

ISO 14043	Life cycle interpretation procedure
ISO 14048	Data documentation format
ISO 14047/9	Examples of application
Landfill	The term refers to a commonly used method of solid waste disposal that includes placing in a specially designed site and covering the site.
Land use	
Life-cycle analysis	A science involving the listing of various positive and negative environmental aspects of specific product or service or process from its raw material extraction to the disposal. The type of information derived from this analysis is useful in process or product design stage to indicate what aspects can be changed or eliminated to improve overall environmental performance
Photo oxidant formation Potential	Photo-oxidant formation is the formation of reactive substances (mainly zone), which are injurious to human health and ecosystems, and which may damage crops.
Pollution	This term refers to the introduction into the environment of any substance caused the action of man which has, or results in, significant harmful effects to man or the environment
Process integration	A holistic approach to process design, retrofitting and operation which emphasis process unity

Recycling	This term refers to the use of water or raw material from one process as feedstock to another process
Regeneration	The reduction of contaminated mass load in an effluent stream
Reuse	The term refers to the use of water from one process to the other, without regeneration
Sink process	The process that consumes waste be either water or pulp from another process
Source process	The process that supplies water to another process
System	The system is the matter contained in the operating unit(s) on which the engineer wishes to focus
Surroundings	Everything not in the system is in the surroundings
Ozone depletion potential	The breakdown of stratospheric ozone as a result of human emissions. Because of the thinning of the zone layer, a larger fraction of the sun's UV-B radiation reaches the earth's surface.

1.1 Water in South Africa

Most companies regard water as one of the least expensive raw materials, which does not require much attention. It is used and dispensed without much consideration of the disposal costs. This even applies to domestic water users; nevertheless the trend is gradually changing in South Africa due to the scarcity of fresh water. This can be seen from the recent fresh water restriction in different provinces such as Western Cape and Mpumalanga due to low dam level.

The actual country's water demand depends on the level of economic activity and development, whereby in developed regions of the world, people use far less water per capita than in developing regions (Hinrichen et al., 1998). On a worldwide basis, agriculture accounts for about 69% of all annual water withdrawals, while industry about 23% and domestic uses only cater for only 8% (Azapagic & Clift, 2004). Table 1.1 shows that water demand and utilisation in South Africa is well aligned with the usage of developing countries, as the country's economic activity is developing rapidly (World Resource Institute, 2001).

To encourage for the responsible and reasonable freshwater use and extraction, the S.A Government have promulgated different water regulations, such as Water Services Act (1997), and National Water Act (NWA) (1998), which are all aimed at regulating both water supply management and conservation respectively. These acts make it compulsory for industries to apply to the local authority for water supplies (National Water Act Section 22(1) (b)), effluent minimisation (NWA Section 19(1-8) and waste disposal (Environmental Conservation Act (ECA) Section 20(1-6). Currently, the application process is arduous, forcing many companies to operate technically illegal with expired permits. The acts are also enshrined in Section 24(a, b) of the Bill of Rights of the Constitution. The water management approach used in S.A is similar to that applied in other countries such as Mexico, Chile and Australia (Majozi, 1998).

Country	Agricultural	Industries	Domestic and Commercial
	%	%	%
China	*77*	*18*	*5*
Egypt	*86*	*8*	*6*
India	*92*	*3*	*5*
France	*12*	*73*	*15*
Norway	*3*	*68*	*27*
Germany	*0*	*86*	*14*
South Africa	*72*	*11*	*17*

Table 1.1: Sectoral use of fresh water in selected countries (World Resource Institute, 2001)

1.2 Waste generation and disposal in S.A.

Common with a number of other industries, the Pulp and Paper industry is obliged to improve the overall environmental performance. The reduction of atmospheric emissions, releases of substance to watercourse, as well as minimisation of power consumption continues to be a key focus.

The sustainability of South Africa's Pulp and Paper industry is not just a matter of the kind of products produced, but also an issue of access to international markets, which have very stringent environmental legislation requirements. The continued search for new products and markets will also be accompanied by a dynamic and proactive research effort into better, cleaner and more competitive ways to make pulp products.

Presently, water consumption, condensate reuse, total reduced sulphur (TRS), sulphur dioxide (SO_2), Chemical Oxygen Demand (COD) levels and power consumption are the most common used environmental performance indicators to show the process's environmental friendliness. Nevertheless their impact and severity needs to be quantified, so that more environmental friendly substances can be used in future production. Besides, there has also been an increase in the use of old corrugated container [OCC (K4)] and Mixed Waste (Common Mix) in the manufacture of liner and fluting world wide, either to supplement virgin fibre or for use in 100% recycled product. This is a good step as it is inline with the new drafted Integrated Environmental Management, which could lead to the amendment of Section 20 of the

Environmental Conservation Act (Act 73 of 1989). This piece of legislation is based on a number of principles including the "Duty of Care", "Polluter Pays" and the " Cradle to Grave" principles.

Table 1.2 gives the brief overview of the existing national regulations governing the activities of different industrial sectors in South Africa. The legislative framework was established to:

- Protect the health and the well being of every person in S.A.
- Protect the environment for the benefit of the present and future generations, which is in line with the cleaner production initiatives
- Promote resources conservation
- Prevent any form of pollution and ecological degradation; as well as
- Secure ecological sustainable development and use of natural resources while promoting justifiable economic and social development.

However, the reality facing many different industries is that there is no easy quantifying technique that shows the overall environmental gains due to massive environmental investments. The environmental benefits can be quantified by applying LCA on the overall process and further used for selection of better treatment technology (Azapagic, 1999).

Clem Sunter in his book, *Beyond Reasonable Greed: Why sustainable business is much a better idea (2002*) argues that the reporting of economic performance for industry is not sustainable, and soon companies are going to be required to report on the so called the triple bottom line- the means and the ultimate measure of corporate success in the 21st century. The triple bottom line involves economic performance, environmental performance and social responsibility. This shows the necessity for companies to start performing the LCA on their processes to identify and quantify their environmental impact on the global scale.

Act	Legislative framework
National Environmental Management Act, 1998	•To promote cooperative governance •To provide for control of activities that may have a detrimental effect on the environment •To converts the constitutional environmental right to more concrete reality. •Section 24 ensure effects of activities on the environment receive adequate consideration before actions are taken
Environmental Conservation Act, 1989	•To provide for the effective protection and controlled utilisation of the environment •Section 22 prohibition on undertaking of identified activity ▪No person shall undertake an identified activity unless issued with a written authorisation ▪Authorisation may only be issued after considering the EIA report. ▪Unauthorised commencement is an offence.
National Water Act, 1998	•Covered is Section 11
National Environmental Management: Air Quality Act (Act No. 39 of 2004)	•To protect, restore and enhance the air quality in SA •Reduce risk to human health by: ▪Promoting pollution prevention and cleaner production ▪Promote reduction to harmless levels of pollutants likely to impair air quality ▪Promote reduction of pollutants at source.
National Energy Bill, September 2004	•To provide for sustainable development and use of energy resource •To provide for renewable resources •The target has been set for use of renewable energy resources by 2013 to about 10000 GWh per annum.
Integrated Pollution and Waste Management for South Africa, 2000	•Currently a discussion document

Table 1.2: South African legislative framework governing the operation of processes (Friend, 2003; Scotcher, 2005)

1.3 Sustainable forestry policy

The South African government published a white paper in 1997 on sustainable forest development in S.A., which deals with the scope of the relationships between people and forest resources. The overall goal of that policy was to promote a thriving forest sector to be utilised for the lasting benefit of the nation, and protect the environment in turn. This cannot be confined narrowly to matters relating to forest industries.

The forest sector in South Africa provides many benefits and is well positioned to contribute further to economic growth. However, the opportunities offered by industrial forestry need to be enhanced by pursuing greater competitiveness in the sector, and linking it more strongly to rural development objectives, and urgently pursuing wider access to these benefits.

1.4 Contribution of forest products to the economy

The forest industries, i.e. all those industries using wood and wood products as raw material, constitute a significant part of the South African economy, contributing about 7,4% to the total output of the country's manufacturing sector in 1993/94(1). The sector earned about R 2 billion in net foreign exchange, which amounts to 35% of the total foreign earning for 1994/95. Its relative contribution to the country’s economy has grown steadily in the past 20 years. The sector consumes about 19 million m^3 of wood a year (1993/1994), of which 43% is hardwood and the rest is softwood (PAMSA Report, 2001).

Sixty percent of the total timber consumed is used in manufacture Pulp and Paper, 25% in sawn timber, and about 15% as a mining timber. Pulp consumption is growing at rate of about 3% per year, and saw timber at 2%, but mining timber consumption is declining (DEAT Report, 1997). Investments in the forest products industry are valued at about R12 billion, of which 90% is in the Pulp and Paper mills. Figure 1.1 shows the land cover and use in South Africa with most of the forest plantation being on the eastern part of the country due to favourable climatological conditions.

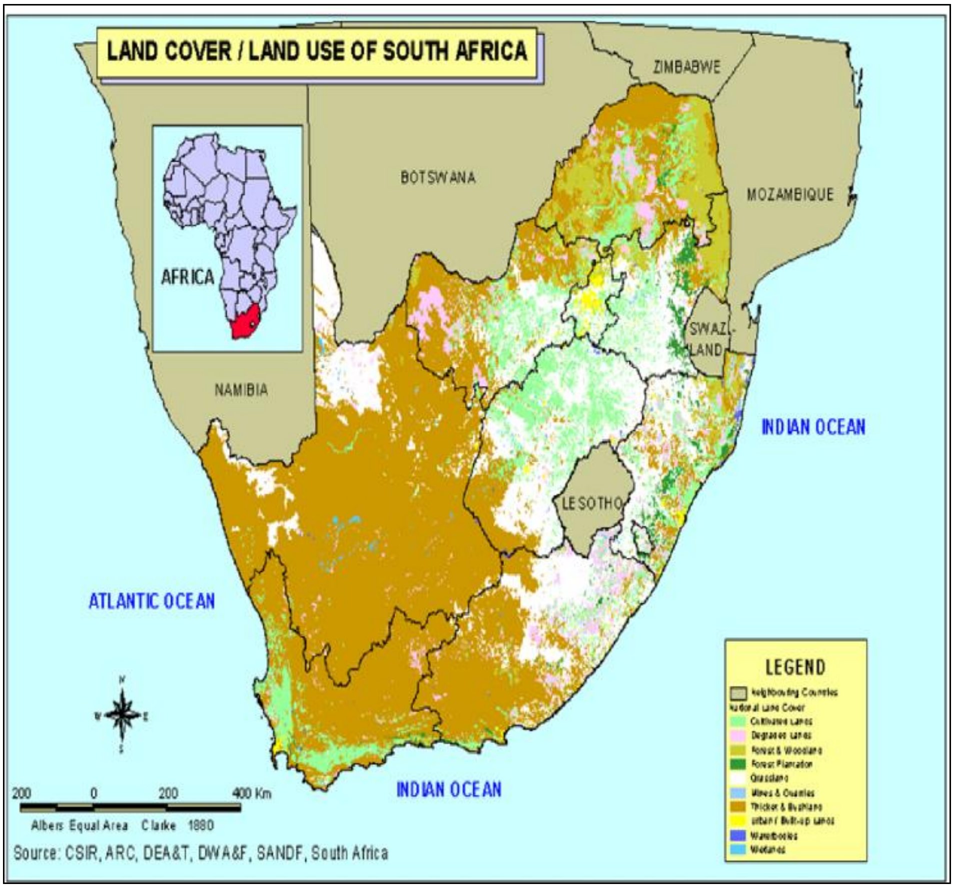


Figure1.1: Land cover/land use of South Africa (DEAT, 2001)

1.5 Exports

Most pulp produced locally (more than 60%) is destined for export, as well as wood chips. Of the total round wood consumed, about 35% was destined for export in 1992. In 1994 alone, Pulp and Paper and board industry contributed more than R2 billion in net foreign exchange earnings, whereas the timber and wood chips contributes to R700 million, which is equivalent to 6 *Gl* of round wood and 4 *Gl* sawn timber by volume.

1.6 Objectives of the study

This study was aimed at using Life Cycle Assessment (LCA) technique as a holistic tool for environmental and economic analysis of a co-pulping process. In a co-pulping process both hardwood and softwood are pulped together in a continuous digester to low hypo number before blending with other recycle material for production of finished product. Co-pulping process forms the basis for a case study wherein LCA was used to quantify and compare economic and environmental performance of a number of different co-pulping ratios of softwood and hardwood pulping aimed at reducing waste and improving the product performance.

1.7 Thesis structure

Chapter 2 gives an overview of LCA methodological framework and compares both ISO-14040 series and SETAC approach. It further gives a literature review on the application of LCA into chemical process design and technology selection using both environmental index (EI) and the plant economic performance indicator such as return on investment.

Chapter 3 presents the history of wood pulping process. It further gives an overview about the wood anatomy and fibre characteristics that make it ideal for papermaking. The section further reviews different pulping technologies that are used in the industry.

Chapter 4 presents the environmental issues pertaining Pulp and Paper industry. It also gives the overview of the application of cleaner production as an optimisation tool in the Pulp and Paper industry. It further discusses some possible alternative solutions for environmental issues.

Chapter 5 presents an overview of the case study for the application of LCA as a holistic environmental tool for co-pulping process. Different sections of the mill are discussed in great depth to outline the challenge faced by respective process engineers about prioritisation of environmental projects.

Chapter 6 develops the process-by-product input-output life cycle assessment methodology. LCA tools are used in the form of Chain Management Life Cycle (CML) methodology in context of environmental evaluation of case study in order to take into account the inputs generated by the upstream process that provide the inputs used by the operation. The process of pulp making, steam generation, black liquor incineration and effluent treatment have been used to demonstrate the method of LCA for possible use as a project screening tool. The LCA methodology has been broken down in detail, and major environmental impact categories that are used to evaluate environmental impacts are discussed.

Chapter 7 provides the recommendation and conclusions from this case study.

1.8 References:

1. Azapagic A, Life Cycle assessment and its application to process selection, design and optimization, Chemical Engineering Journal 73(1999), 1-21
2. Azapagic A and Clift R, Sustainable Development In Practice: case Studies for Engineers and Scientists, John Wiley and sons, Ltd, 2004, Chapter 3 - 12
3. Friend JFC, Environmental Management Course, Department of Chemical Engineering, University of Pretoria, 2003.
4. Food and Agriculture Organisation of the United Nations (FAO): water Resources, development and Management services, 2001. Statistics on water Resources by Country in FAO's AQUASTAT Programme (http://earththrends.wri.org
5. Hinrichsen D, Robey and Upadhyay(1998), How water is used? Population Reports. Volume XXVI, Number 1, September 1998. The Johns Hopkins School of Public Health, Baltimore, Maryland, USA, www.infoforhealth.org/pr/m14/m14chap2-2.shtml
6. Majozi T, van Schijndel P, Sustainable Engineering for Science technology, a short Course, Department of Chemical Engineering, University of Pretoria, 2005
7. Majozi T, Application of Pinch Technology as a strategic tool for waste management in an agrochemical industry, M.ScEng dissertation, University of Natal, 1998.
8. Ministry of Water Affairs and forestry, Pretoria S.A, Sustainable development S.A, white paper march-1997
9. Paper Manufactures Association of South Africa Report (2001), S.A Pulp and Paper statistical Data, 2001
10. Scotcher J, Cleaner production audits, implementation and training in Pulp and Paper industry, Department of Water Affairs seminar, 2005
11. Visser W, Sunter C, Beyond Reasonable Greed: Why sustainable business is a much better idea! Human &Rousseau Tafelberg, July 2002, page 11-190.
12. UN (2003b) Water for People-Water for life: United Nations water development Report. United Nations, New York.

2.1 Introduction

This section gives the overview of the LCA methodological framework. It also gives the comparison and discusses the difference between ISO-14040 series of standards and the SETAC general methodological approach for conducting LCA. It lastly, present a comprehensive literature review about the application of LCA analysis tool into chemical process design and technology selection using both Environmental Index (EI) and the plant economic performance indicator such as Return On Investment (ROI).

2.2 Background

Today's LCA originate from 'net energy analysis' studies, which were first published in the 1970s and considered only energy consumptions over a life cycle of product or a process. As a result, in 1990s, SETAC initiated activities to define LCA and develop a general methodology for conducting LCA studies. Soon afterwards, the International Standard Organization (ISO) started similar work on developing principles and guidelines of the LCA methodology (Consoli et al., 1993; Fava et al., 1991). Although both SETAC and ISO methodology were developed independently, a general consensus on the methodological framework between the two bodies has started to emerge, with the difference being mainly in the details. The ISO methodology is still being shaped, while the SETAC technique is widely accepted among many LCA practitioners. The later is described in the following section with reference to ISO methodology where appropriate.

2.3 Methodological framework for LCA

The series of standards, namely ISO 14040-14043, have been created in order to develop a consistent approach in conducting LCA studies. These procedures set four compulsory stages, which have to be part of any LCA study. The steps are:

- i Goal and Scope definition,
- ii Inventory Analysis,
- iii Impact Assessment and
- iv Interpretation.

It follows that the life cycle of a product or process or any activity must start extraction of raw material to final disposal. Figure 2.1 shows the typical flow of product which includes manufacturing, transport, use, re-use, maintenance and recycling. The approach is generally known as "cradle-to-grave" philosophy in the LCA system analysis (Friedrich, 2003).

The main advantage of LCA over other site-specific methods for environmental system analysis, such as Environmental Impact Assessment (EIA) or Environmental Audit (EA), lies in broadening of the system boundaries to include all burdens and impacts in the life cycle of a product or a process, and not just focusing on the emissions and waste generated by specific plant or manufacturing site.

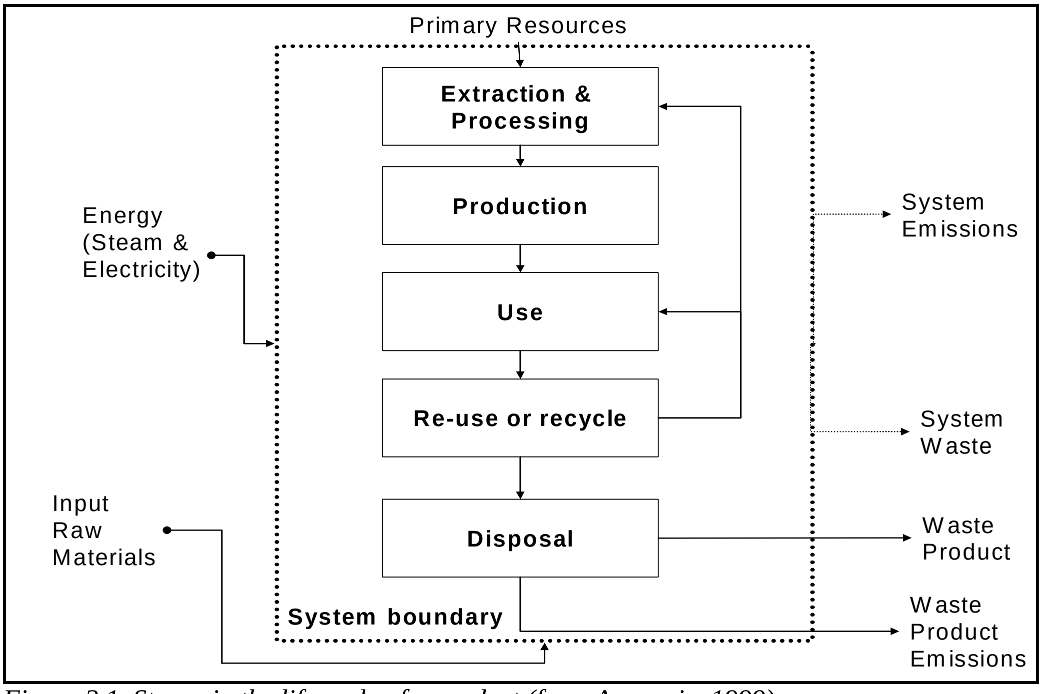


Figure 2.1. Stages in the life cycle of a product (from Azapagic, 1999)

2.4 Comparison between ISO 14040 series and SETAC method

Table 2.1 gives a comparison between ISO-14040 and SETAC method with emphasis on the four main stages of conducting the LCA:

SETAC (Fava et al.,1991)	ISO 14040 series (Consoli et al.,1993)
Goal definition & scoping	Goal definition & scoping: ISO-14041
Inventory Analysis	Inventory Analysis: ISO-14041
Impact Analysis	Impact Analysis: ISO-14042
Improvement Analysis	Improvement Analysis: ISO 14043

Table 2.1: Comparison of SETAC and ISO series method

As can be seen from Table 2.1, the methodological framework proposed by ISO 14040 series is similar to that defined by SETAC with the considerable difference being in the final implementation phase, as discussed in Section 2.6.

The actual interaction among the LCA stage is shown in Figure 2.2. It is based on the kind of thermodynamic and system analysis which are central to process engineering (Azapagic et al., 1994). Therefore, the first step in the analysis is always the definition of the system under study. In LCA, this is done under the Goal Definition and Scoping phase. The environment is then interpreted in the thermodynamic sense as 'that which surrounds the system', i.e. the whole universe except the system under study. Thus for these purposes, the environment is defined along with the system boundary, by exclusion. On this basis, Figure 2.3 shows schematically the general problem of environmental system analysis. Everything that surrounds the 'economic system' is considered as the environment, which the system has either negative or positive impact. The LCA is sued to quantify this impact in the holistic manner using the world data.

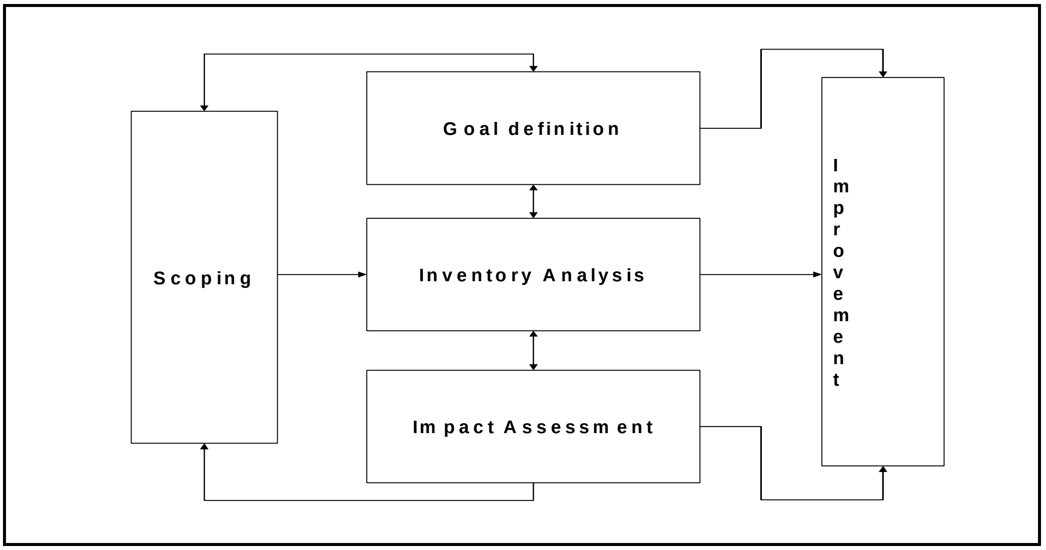


Figure 2.2: Interactions between LCA stages (from Azapagic et al, 1999)

Figure 2.4 illustrates the general approach for environmental system analysis. The system of interest exists because it produces products or services of an interest, which is treated together as outputs. To generate these outputs, inputs in form of energy and material is required. In a site-specific environmental analysis, such as Environmental Impact Assessment (EIA) or Environmental Assessment (EA), the system is the plant or manufacturing site and the inputs are related to the inputs of material and energy to that specific plant. However, in the LCA context, the system boundaries are drawn from *cradle to grave* or *cradle to gate* and this includes all burdens and impacts in the life cycle of a product or a process, so that the inputs into the system become primary resources.

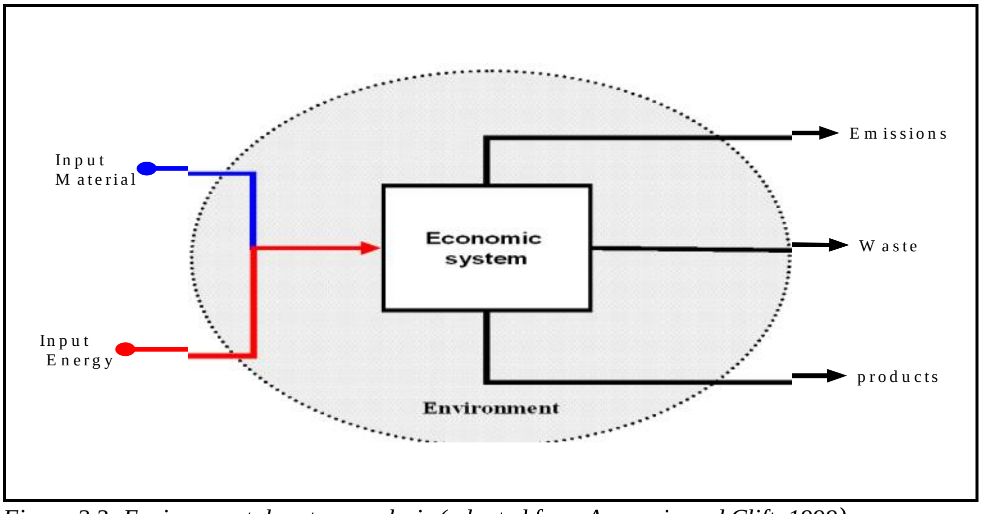


Figure 2.3: Environmental system analysis (adapted from Azapagic and Clift, 1999)

The system function is specified within the *goal definition* and *scoping phase*, expressed in terms of the functional units, which is a measure of the function that the system delivers. In setting the system boundaries, it is useful to distinguish between "foreground" and "background" systems (or strictly subsystems) (Ekvall, 1995). The foreground system is defined as the set or processes that are directly affected by the study delivering a functional unit specified in *goal and scope definition*. Whereas, the background system is that process or system that supplies energy and materials to the foreground system, usually via a homogeneous market so that individual plants and operations cannot be identified. Differentiation of foreground and background systems is imperative in deciding on the type of data to be used. The foreground system should be described by specific process data, while the background system is normally represented by data for a mix or a set of mixes of different technologies or processes.

2.5 Inventory Analysis

In the second phase (Inventory Analysis stage), material and energy balances are performed and the environmental burdens quantified. The burdens are defined by material and energy used in the system and emissions to air, liquid effluent, as well as solid waste discharged into the environment. Inventory Analysis includes the following steps:

- Detailed definition of the system under study.
- Data collection;
- Allocation of environmental burdens in multiple systems; and
- Quantification of the burdens

Aggregation of the burdens into a smaller number of impact categories or classification as is known and evaluation of their potential impacts (characterization) is part of the third phase, while the Impact Assessment phase is last stage.

A number of methods have been suggested for classification and quantification of environmental impacts, however, the problem-oriented method, developed by Heijungs et al. (1992), is the widely used. In this approach, the burdens are aggregated according to the relative contributions to specific potential environmental effects, such as global warming potential of other related gases, such as CH_4 and other volatile organic compounds (VOC). Detailed system characterisation involves disaggregation into a number of interlinked subsystems. Environmental burdens are then quantified for each subsystem according to the formula:

$$B_j = \sum_{i=1}^{n} bc_{j,i} x_i \qquad \text{(eq.2.1)}$$

Where:

- B_j Is the associated environmental burden (e.g. Global warming potential provided etc)
- $bc_{j,i}$ is the burden j from process or activity i
- and x_i is a mass or energy flow associated with that activity.

Then the associated environmental potential is found by using eq 2.2.

$$E_k = \sum_{j=1}^{n} ec_{k,j} B_j \qquad \text{(eq.2.2)}$$

Where:

- E_K is the any environmental potential (e.g. global warming or resources depletion)
- B_j is the associated environmental burden
- $ec_{k,j}$ is the relative contribution of the burden B_j to impact E_k as defined by problem-oriented approach.

If the system under consideration produces more than one functional output, then the environmental burdens from the system must be allocated among these outputs (Azapagic and Clift, 2004). In the LCA content recycling process, wastewater treatment and co-product processing are termed multiple-function systems. Allocation is not trivial matter, as the process of assigning to each function of a multiple-function system only those environmental burdens that each function generates. The simplest approach is to use either mass or economic basis, allocating the burden in proportion to the mass output or economic value of each product. More sophisticated and realistic allocation requires mathematical modelling and allocation based on physical causality, which reflects the underlying physical relationship between the functional units (Azapagic and Clift, 1999).

To guide the choice of the correct allocation method, ISO recommends a three-step allocation procedure (ISO 14041, 1997), which is:

1. Where possible, allocation is to be avoided by subdividing the process by analysis at a greater level of detail, or by system expansion. System expansion is more commonly applicable. Figure 2.5 below illustrates the principle. In simple if process 1 produces product A and B. Product A can be produced by process 2, which does not produce B. Allocation of environmental impacts from process 1 between products A and B is avoided by expanding the system to include process 3 which produces only product B, at a rate equal to that from process 1. The two processes now produce the same outputs and can be compared directly (Tillman et al., 1994).

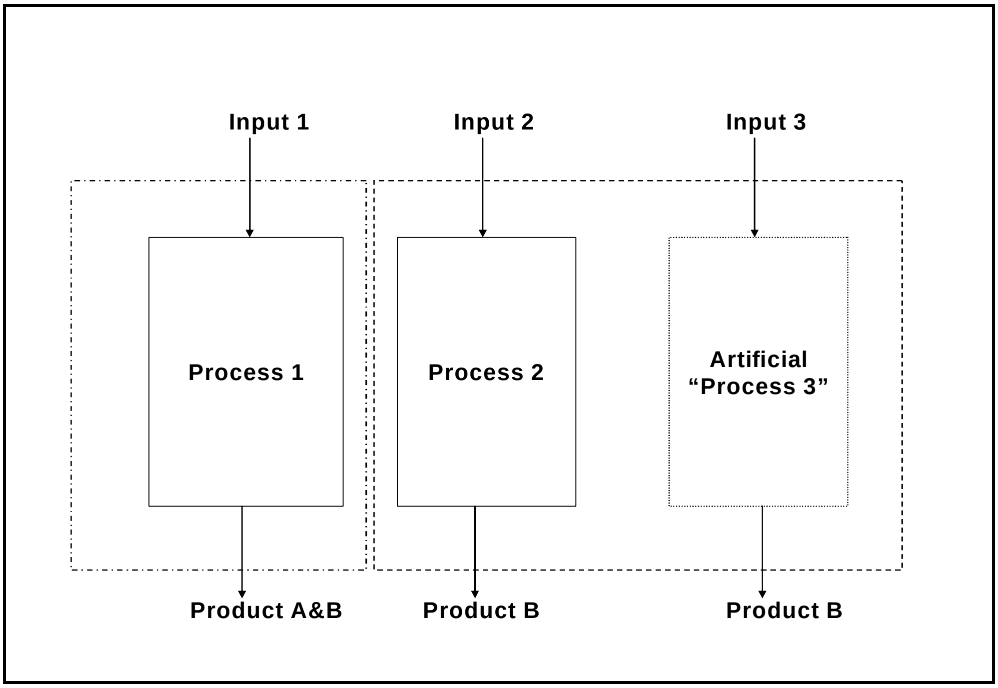


Figure 2.4: The ISO allocation procedure (ISO 14041, 1998a)

2. Where allocation cannot be avoided, the environmental impacts should be partitioned between the system’s different products or functions in a way which reflects the underlying physical relationship between them (ISO 14041, 1998a).

This means the allocation should reflect the way the system under analysis actually functions by allocating an environmental impact to a functional output according to how much the impact change in that output approach (Azapagic et al., 1999)

3. If neither of these approaches is possible, allocation should be on a basis that reflects other relationships between the products. This default is the most commonly necessary when two or more products must be produced together in fixed proportions.

A principal difficulty with system expansion lies in the selection of the additional processes. Should this be the average of the current process making B, or the current best processes, or likely future processes, or the least economic processes? Appropriate selection of the expanded system depends on the goals and scope of the LCA study (Weidema, 2001)

2.6 Impact Assessment

Environmental burdens quantified in “Inventory Analysis” are then translated into the related environmental impacts (Figure 2.6). This is carried out in the following steps in the “Impact Assessment” phase:

i Classification
ii Characterisation
iii Normalisation; and
iv Valuation

Classification involves aggregation of environmental burdens into smaller number of impact categories to indicate their potential impacts on human and ecological health and the extent of resource depletion. The aggregation is done on the basis of the potential impacts of the burdens, so that one burden can be associated with a number of impacts; for example, volatile organic Compounds contribute to both global warming and ozone depletion. The approach used most widely for the classification of the impacts is known as ‘problems-oriented’, whereby the burdens are aggregated accordingly to their relative contributions to the environmental effects that it may have. The impacts most commonly considered in LCA are shown in Figure 2.6.

The identification of the impact of interest is followed by their quantification in the characterisation phase. The impacts are then normalised with respect to the total emissions or extraction in a certain area over a given period of time. This assist in access the extent to which an activity contributes to the regional or global environmental impacts.

The final stage is valuation in which each impact is assigned a weight, which indicates its relative importance. This step has proven to be most contentious part of LCA because it implies subjective value judgments in deciding on the importance of different impacts (Azapagic et al., 1999; Azapagic and Clift, 2004). Valuation is typically not based on natural science but on expressing preference either by decision makers. At present, there is no consensus on how to aggregate the environmental impacts into a single environmental impact function or even on whether such aggregation is conceptually and philosophically valid (Kniel, et al., 1996).

The final stage in the SETAC methodology is known as improvement assessment phase, which is the stage used for improving the overall system performance by different technology selection or process modification. In the ISO methodology, this phase is known as *interpretation* and in addition to improvements and innovations, it covers identification of major stages in the life cycle contributing to impacts, sensitivity analysis and final recommendation. In the SETAC methodology, these additional steps are included within Goal Definition and Scoping phase and Inventory Analysis. Consequently, while these techniques are being developed, the use of LCA continues to increase.

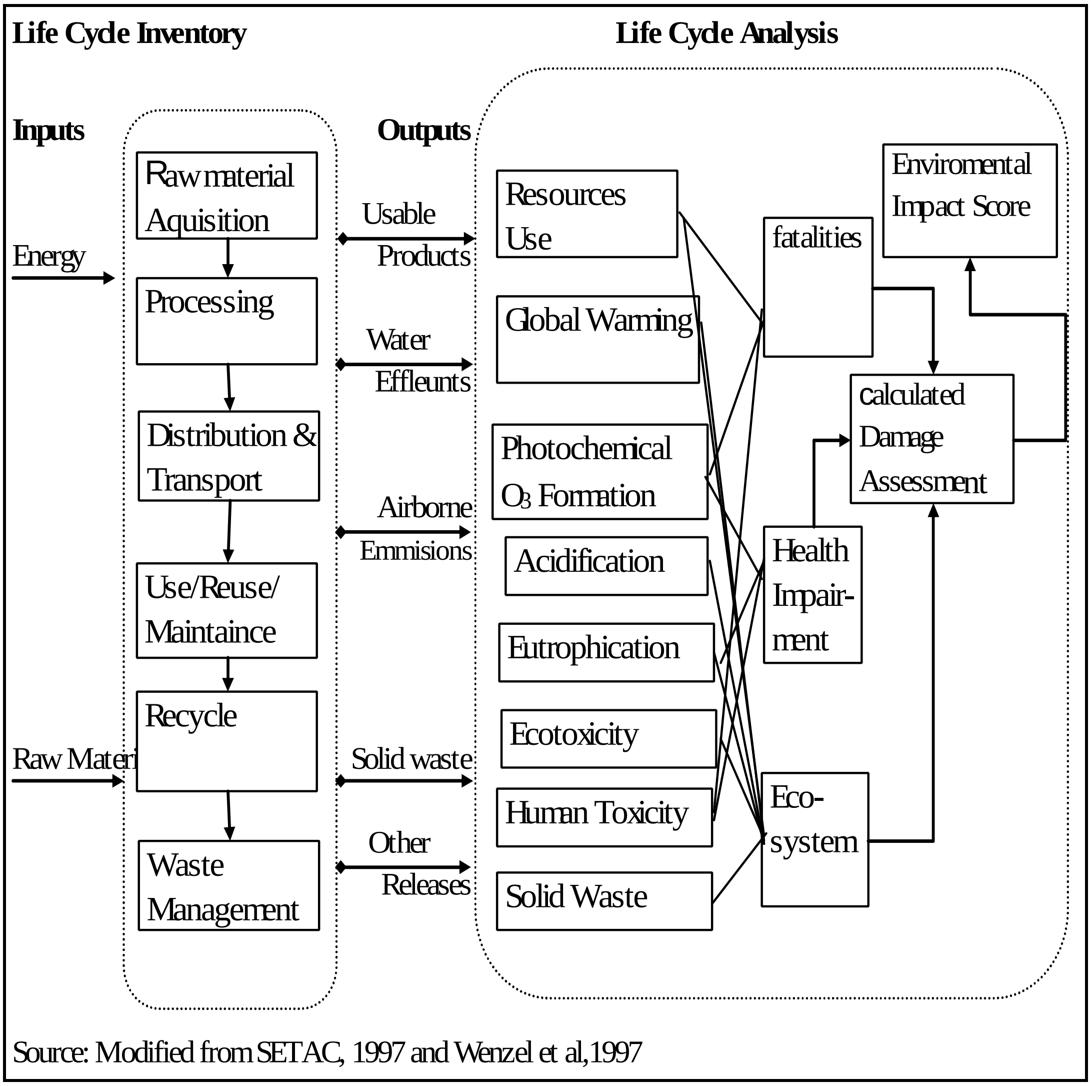


Figure 2.5: An overview of environmental life cycle assessment (Friedrich, 2003)

2.7 Economic consideration

Presently, the trend is industry when selecting between alternative technologies or plant modification is both capitals and operating expenditure. The main performance criteria used to judge alterative investment the project break-even point or return on net assts for existing plants.

2.8 The economic evaluation criterion

In order to make a satisfactory decision, three types of economic analysis technique are used, horizontal, vertical and ratio analysis:

i) *Horizontal analysis*: is a technique appropriate to evaluate data on a whole series of financial statements over a time horizon. The objective being to determine which changes took place, and then expresses the changes as a percentage.

ii) *Vertical analysis*: is a technique accordingly to which financial information is expressed as percentage.

iii) *Ratio analysis*: entails the identification, measurements and evaluation of financial relationships or ratios of the financial position and results.

These ratios are used for analysing financial position of an entity and they are grouped into the following category (Peters M.S, Timmerhaus, 1991; Coulson and Richardson, 1981; Faul and Pistorius, 1999):

- Profitability or rate of return
- Liquidity
- Solvency and
- Financing structure.

2.9 Return on Net Assets

The financial performance indictor considered in this study to evaluate the economic performance is the ratio analysis, which is the system return on net assets (RONA) (eq.2.3). This gives an overall company performance over the employed capitalised assets

$$RONA(ROI) = \frac{Income}{Net\_Assets} \qquad \text{(eq.2.3)}$$

Where:

- Income is the net income profit before tax.
- Net assets are the actual value of itemised assets less depreciation.

2.10 Trends in incorporating environmental issues in design

Early forms of LCA were used in the United States in the late 1960s for defining corporate environmental strategy, and later in the 1970s by government agencies as an aid for developing public policy. In the late 1990s, LCA emerged as a worldwide environmental management tool in the form of the ISO 14040 series [2,3].

Despite its relatively limited use in South Africa (Friedrich, 2003), there is a considerable potential for utilization in both public and private sectors. LCA is mainly used to provide a scientific basis for developing sound environmental strategies and policies in industry. Currently, LCA resources in South Africa are limited, but several tertiary institutions (e.g. University of Pretoria, University of Kwazulu Natal) have gradually developed the capacity to engage in scientific research, technical consultancy and training in this field.

Jensen et al. (1997) presented some of the new emerging applications for LCA worldwide and in South Africa in particular (Table 2.3). These applications differ from the original uses of LCA technique, which were mainly for decision support tool capable of distinguishing between different products and activities on environmental criteria. The range of applications of the LCA methodology in S.A differs from those seen overseas. The difference is due to the fact that there is no pressure in South Africa for publishing the LCA data, even though companies are legally required to report on there environmental performance. Consequently, this is gradually changing as South Africa is becoming a vital globally player.

Application overseas	**Application in RSA**	**Most used level of detail in LCA**		
		Conceptual	**Simplified**	**Detailed**
Generation of enviromental profiles	Sasol, ISCOR, ESKOM ,Impala Platimun Mondi Paper		X	Y
Design for envioroment	SASOL	X	Y	X
Product development	Not applied	X	Y	X
Product Improvemnet	Not applied		Y	X
Enviromental Claims	Not applied	X		
Ecolabeling	Not applied		Y	
Enviormntal declaration	Not applied		Y	X
Organisation Marketing	Not applied		Y	X
Strategic planing	SASOL	X	Y	
Green Procurement	Not applied	X	Y	
Deposit/refund scheme	Not applied		Y	
Enviromental Taxes	Not applied		Y	
Choice between systems	CSIR	X		Y
Y indicates most frequenly used level				
Source: Modified after Jensen t al,1997				

Table 2.2: Some of the application for LCA and the level of detail required.

2.11 Previous work in the application of LCA for process design

Many industries have made attempted to reduce pollution by implementing cleaner technologies and processes. Many times it has been observed that the efforts made to optimise the waste treatment process reduces the quality and/or quantity of waste discharge at the end-of the-pipe, but increases the total environmental burden and impacts (Azapagic,1999; Azapagic et al.,1999; Hernandez et al., 1998; Kniel at al.,1996; van Berkel, 2000).

It is therefore important to consider the environmental burden and adverse caused due to any change or modification in the process and allied facilities in a holistic manner. This is only possible when there is a vivid comprehension of the relationships among operating and design parameters with environmental impacts for a complete life cycle of the process. Few new attempts have been made in this direction.

Van Berkel (2000) provided an overview of the current status of LCA methodology, and reviews of LCA case studies from the primary resources industries against this background. The paper explores the potential application for cradle-to-gate LCA approaches in minerals sector. It then concludes that LCA has a significant potential for supporting environmental improvement and innovation in the mineral sector.

Khan et al (2001) presented a holistic and integrated methodology (namely Green Pro I and Green Pro-II) for process and product design by combining the traditional LCA approach with multi-criteria decision-making methods. His work has been focused on the development of process selection and design methodology considering assessment and minimization of risks and impacts of the process system by embedding the convectional LCA principles within process design and decision making framework. It has implications to process synthesis as it includes environmental objectives together with technical feasibility and economics at the design stage to determine cost efficient solutions. The new technique differs from their earlier work, GreenPro I, in that it is good and effective in design, but its application is restricted at the early design stage due to extensive computational and large data requirements.

Both Green Pro I and Green Pro II are simple and applicable at the early design stage and more robust against uncertainty in the data. Their applicability has been demonstrated through a urea production case study. The method overcomes many of the problems faced in the conventional approaches and establishes a link between the environmental risks and impacts, cost and technical feasibility of the processes.

El-Halwagi and Monusiouthakis (1989) introduced the concept of mass pinch as a tool to derive cost optimal mass exchanger networks with minimum emissions waste. Using the concept, Wang and Smith (1994) developed a method to obtain design target for minimum water generation in process plants. In their latest publication El-Halwagi and co-workers (1998 and 1999) have proposed interval based targeting procedure for waste minimization considering energy and mass inputs. The waste minimization was achieved by recycling of the target stream or species back to the process or selecting a replacement of it with less serve one

Flower et al (1993) introduced the idea of graphical mass balance- a visual means of mass balance manipulation for an initial screening of process not complying with environmental regulations. Hallale (2001) introduced a new graphical method for targeting freshwater and waste minimization. The approach is based upon a representation of water composite curves and the concept of water surplus. This method has several advantages over existing techniques, such as being able to deal with wider range of water using operations as well as having more convenient and familiar representations.

Kniel (1996) presented the LCA case study of nitric acid process considering environmental and economic constraints. The article uses the combined cost benefits analysis and LCA graphical technique to arrive at the cost optimal solution for proposed modification of the plant. Though the article emphasis the use of LCA in the design stage but it does not provide any details of the methodology and steps involved. This includes the valuation phase of the LCA, which is always fraught with difficulty when apportioning the weights.

Hernandez et al (1998) proposed a mathematical model to minimize the environmental impacts that are subsequently used for deciding the optimal degree of pollution abatement (12). Azapagic and Clift appreciably advocated for the LCA based design and decision-making. They showed the application of the LCA method in various processes and product selection and decision-making. Azapagic (1999)] and Azapagic and Clift (1999) then discuss the application of LCA in the evaluation of process performance for various Boron products. The study shows that a newly emerging Life Cycle Process Design (LCPD) tool offers potential or technological innovations in process concept and structure through the selection of best material and process alternatives over the whole life cycle. This approach provides a potentially powerful decision making tool which may help to identify more sustainable solutions in the process industries.

Ekvall et al (2005) presents the normative ethics and methodology for LCA. Prospective LCA provides information on the environmental consequences of individual actions, whereas Retrospective LCA provides information about the environmental properties of the life cycle investigate and its subsystems. The two approaches differ in details and the quality of data used, but conclusions cannot be drawn that one approach is superior to the other.

Kjaerhein (2005) describes the difference between the Norwegian Cleaner Production (CP) and the LCA technique, as well as presenting the results and experiences from application of CP technique over the past 12 years. It is concluded that CP as a stand-alone option is unlikely to succeed to create a sustainable society, but integrating the approach to quality systems and environmental management systems is believed to important step in the right direction, provided that sufficient funds are available.

LCA is normally performed to show where in the life cycle of a given product or process the most important environmental problems arise, whereas CP techniques has historically and still focuses on improvements to individual production sites. Kliopova et al. (2005) presented a case study about the evaluation of CP performance in Lithuanian industries. Some studies included the application of CP technique in different chemical industries.

2.12 Conclusions

As an environmental tool for process management, LCA has two main objectives. The first is to quantify and evaluate the environmental performance of a process from 'cradle to grave' and also help to choose a more sustainable option or improvements in the process industry. Another objective is to provide a basis for assessing potential improvement in the environmental performance of a system.

Two main problems associated with these objectives are, firstly, in many cases there will be a number of options and possibilities for improvements and it may not be obvious which of them represents the optimum solutions. Therefore, some kind of system optimisation will be necessary. Secondly, the may exist more than one optimum solutions for improving the overall system's performance, in which case the issue becomes that of choosing the best compromise option from a number of optimum solutions. LCA has profound implications for process synthesis by combining including environmental objectives together with technology and economic at the design stage so as to determine cost efficient solutions, right at the early design stage.

It application to different process in the literature review demonstrates it as a potentially useful tool for: (1) identifying optimal levels of waste generation and abatement by properly accounting for the trade-offs between input and output waste, and (2) optimising the process designs for best practical environmental options and thus developing cleaner and greener processes. This approach provides a potentially powerful decision making tool which will help process industries in identifying sustainable process for the future. It must be mentioned that LCA can be used in conjunction with other waste minimisation techniques such as cleaner production methodology and waste water pinch analysis technique for improving the system environmental profile. The only limitation for the pinch techniques reviewed in this study is that they are mostly applicable for single stream contaminant.

2.13 References:

1. Azapagic A, Life Cycle assessment and its application to process selection, design and optimization, Chemical Engineering Journal 73(1999), 1-21
2. Azapagic A and Clift R, Allocation of environmental burdens by whole-system modelling-The use of linear programming. In: G. Huppes F, Schneider , (Eds), allocation in LCA, SETAC, Brussels, 1994, pp 54-60.
3. Azapagic A and Clift R, Sustainable Development In Practice: case Studies for Engineers and Scientists, John Wiley and sons, Ltd, 2004, Chapter 3 - 12
4. Azapagic A and Clift R, The application of life cycle assessment to process optimization, Computers and Chemical Engineering Journal 23(1999), 1509-1526
5. Consoli F, Allen D, Boustead I, Fava J, Franklin W, Jensen A.A, de Oude N, Parrish R, Perriman R, Postlethwaite D, Quay B, Seguin J, Vigon B, Guidelines for Life-Cycle Assessment: A ‘Code of Practice’, SETAC, Brussels,1993.
6. Coulson JM, Richardson JF, Sinnot RK, Chemical Engineering Design, Vol 6, Pergamon Press, Chapter 1,6.
7. Ekvall T, Tillman Anne-Marie, & Molander S, Normative ethics and Methodology for LCA, Journal of Clearner Production (2005), www.elsevier.com/locate/jclepro.
8. El-Halwagi M.M, Manousiouthakis V (1989), Synthesis of Mass-exchange networks, AICHE Journal, 35(8), 1233-1244.
9. El-Halwagi M.M, Spriggs H. D, Employ mass integration to achieve truly integrated process design, Chemical Engineering Progress, August, 22-44
10. Faul MA, Pistorius CWI, van Vuuren LM, Vorster Q, Swanevelder JJ, Accounting- An Introduction, Interpak Natal Pietermaritzburg, 1999, Chapter 1, 24-33
11. Fava J, Dennison R, Curran, Vigon B, Selke S, Barnum(Eds), A technical Framework for Life Cycle assessment, SETAC and SETAC Foundation for Environmental education, Washington, DC, 1991.
12. Flower J.R, Bikes S.C, and Johnson S.W (1993), The graphical mass balance in the early design of clean processes. Transactions of the IChemE, Part B, 71,194-198.

13. Friedrich E, The environmental Life Cycle Assessment as a holistic tool, Chemical Technology, January 2003, 9-11.
14. Glazewski Jan, The Legal Framework for Renewable Energy in South Africa, University of Cape Town
15. Hallale, N. A New Graphical Targeting Method for Water Minimisation. *Adv. Environ. Res.* 2002, *6*, 377.
16. Heijungs R(ed)(1992) Environmental Life Cycle Assessment of products-Guide, Center for environmental Science, University of Leiden, Leiden, the Netherlands.
17. Hernandez, O.R, Pistikopoulos, Livingston A. (1998), Waste treatment and optimal degree of pollution abatement, Environmental Progress, 17(4), 270-276.
18. ISO/TC 207/Sc 5/ WG 2 N 112, ISO/DIS 14041: Environmental Management- Life Cycle Assessment- Part 2: Goal and Scope Definition and Life Cycle Inventory Analysis, Voting draft, 1997.
19. Jensen A.A., Elkington J, Christiansen k, Hoffmann L, Moller B.T, Schmidt A, van Dijk F, (1197) Life Cycle Assessment (LCA)- A guide to approaches, Experiences and information Sources, Report to the European Environmental Agency, Copenhagen, Denmark.
20. Khan F.I, Natrajan B.R, Revathi P, GreenPro I: a new methodology for cleaner and greener process design, Journal of Loss Prevention in the Process Industries 14(2001) 307-328
21. Khan F.I, Natrajan B.R, Revathi P, GreenPro-II: a risk-based life cycle assessment and decision-making methodology for process plant design, Environmental Modeling and Software 17(2002) 669-692
22. Kjaerheim G, Cleaner production and Sustainability, Journal of Cleaner production 13(2005), 329-339.
23. Kliopova I, Staniskis K. J, The evaluation of Clearner production performance in Lithuanian industries, Journal of Clearner Production (2005), www.elsevier.com/locate/jclepro
24. Kniel G.E., Delmarco K, Petrie J.G., Life Cycle Assessment applied to process design: Environmental and economic analysis and optimization of a nitric acid plant, Enviro.Prog. 15(4) 1996 221-228
25. Lyle O, The efficient use of steam, Millbank, London, July 1947.

26. Meier M, Evaluation and reporting Guidelines for LCA Case Studies, Final Report of the SETAC-Europe Case studies working group (CSWG), April 1997
27. Ministry of Water Affairs, and Forestry, Pretoria, S.A, Sustainable Forest development in S.A, white paper march-1997
28. Peters M.S, Timmerhaus K.D, Plant Design and Economic for Chemical Engineers,McGraw_Hill International editions, 1991, Chapter 1-10.
29. Seborg D.E., Edgar T.F, Mellichamp D. A, Dynamics and Control, John Wiley and Sons
30. Tillman AM, Ekvall T, Baumann H, Rydberg, Choice of System Boundaries in Life Cycle Assessment. J. Cleaner Production. 2(1),21-29,1994.
31. van Berkel R, LCA for environmental improvement of Mineral production, Environmental Workshop, Mineral Council of Australia, 29 Oct-1Nov 2000, Perth WA.
32. Wang Y, and Smith R (1994), Waste water minimization, Chemical Engineering Science, 49(7), 981-1006.
33. Weidma B, Avoiding Co-product Allocation in Life Cycle Assessment, J.Ind. Ecol., 4(3), pp 11-33, 2001.

3.1 Introduction

This section presents the history of wood pulping process. It further gives an overview about the wood anatomy and fibre characteristics that make it ideal for papermaking. Different pulping technologies that are used in the industry are discussed.

3.2 History of the pulping process

Papyrus was the world's first writing material invented by the Egyptian from antiquity, and was made by beating and pressing together thin layers of the stem of the papyrus plant (Biermann, 1996). The squeeze ensured that natural glues in the reed held the layers together. There was, however, no complete defilibriation of fibers, which is the main characteristic of true papermaking (Smook, 1992).

Ts'ai Lun of China made the first authentic paper around 105 AD using hemp rags, ropes, fishing nets and other domestic articles, which were beaten in a mortar and drained on a piece of loosely woven cloth (Clapperton ,1952). Within the next couple of years, he produced paper by treating the bark of mulberry trees with lime, bamboo and cloth. The process was then developed into a highly skilled art by the Chinese during next few hundred years, during which it was kept a closely guarded secret (Calkin, 1957). Then came the Arabs who actually disseminated the art of papermaking through Middle East and later Europe, where cotton and linen rags became the most widely used raw materials (Biermann, 1996; Smook, 1992). The beginning of the 15th century saw the establishment of small paper mills in Spain, Italy, Germany and France.

Freidrich Keller introduced ground wood pulping concept around 1843, after watching children grind cherry pits against a wet stone with a piece of wood, which was gradually fiberised under the influence of water and pressure (Kocurek, 1983). As a result, groundwood mills sprung up throughout Germany and other European countries. In the late eighteen century (1869), Behrend introduced the concept of steaming logs before grinding(Kocurek, 1983). Thus the basis was laid for the development of modern mechanical and thermomechanical pulping processes (e.g. Mondi Merebank).

Chemical pulping came into being an independent pulping process in the mid-1800s. In 1851 Watt and Burgess found that it was possible to dissolve lignin, which binds wood fibres together, from wood at elevated temperatures using strongly alkaline solutions based on sodium hydroxide (Gullichson , 1999; Stephenson, 1950). In 1854 Burgess setup a mill in the USA in which poplar chips were cooked with sodium hydroxide, called the soda process (Stephenson, 1950). In 1866 Tilghman invented the sulfite process, and the sulfate or kraft process was developed by Dahl in 1879 (Grant, 1958). Numerous refinements of these three processes in the twentieth century have led to the rapid growth and adaptation of paper not only for writing and printing, but also for wrapping, packaging and a variety of disposable products.

3.3 Wood Chips

The basics of papermaking depends on the understanding of wood anatomy, wood chemistry and wood structure as this discussed below.

3.4 Wood anatomy

Within trees, wood trunk performs the support, conduction and storage function. These support roles allow the tree trunk to remain erect despite the height to which a tree grows. Because of the difference in heights for different wood species, the trunk also performs the role of water transportation, which is the absorption of water from the ground roots to the upper parts of the tree branches. Finally, it stores fruits in certain parts until they are required by both man and animal alike.

3.5 Wood Chemistry

There are 4 major chemical components of wood: cellulose, lignin, hemicelluloses and extractives. The major component of wood is cellulose, and it accounts for more than 40% of the total dry body mass, depending on the species (Smook, 1992). Cellulose is a semi-crystalline, microfibrillar linear polysaccharide of $\beta-1,4$- linked D-glucopyranose with a chain length or degree of polymerization (DP) of between 10000-15000 units, depending on species (Smook ,1992). The actual chemical structure of a cellulose molecule is shown in Fig. 3.1. It constitutes the fibrous part of wood (and other plant material) and is white colour. Cellulose highly water insoluble and other organic solvents, and has a relatively high tensile strength.

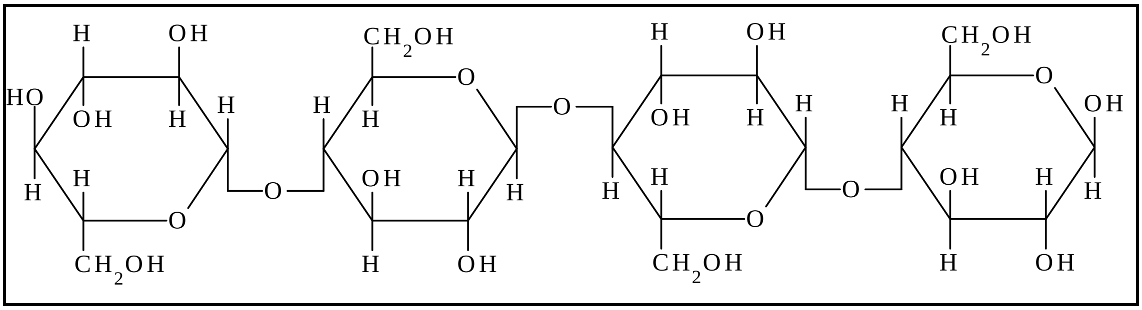


Fig. 3.1: Chemical structure of a cellulose molecule (Smook, 1992).

Hemicelluloses are similar to cellulose only in that they are polymers of sugar monomers such as pentoses, hexoses, deoxy-hexoses and hexuronic acids. They are short-chained polymers (DP 150-200) and are often branched. Their function is the plant is poorly understood. The total hemicelluloses content of wood varies from about 15 to 18 % (in softwoods) to about 22 to 34 % (in hardwoods) (Smook, 1992). The simplified structures of the major hemicelluloses in wood are shown in Fig. 3.2.

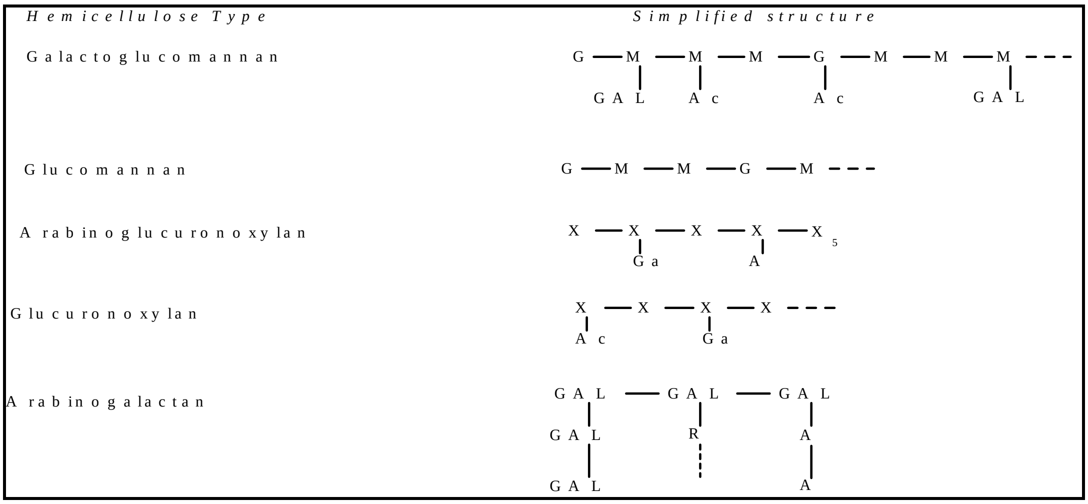


Fig 3.2: The types and simplified structures of the major hemicelluloses in wood (Smook, 1992).

Abbreviations:

G	- Glucose	X	- xylose

GAL	- galactose	A	- arabinose
M	- mannose	Ac	- acetyl group

Ga - 4-O-methyl-glucoronic acids R- usually galactose

For practical purposes, cellulose in wood pulp has traditionally and is still classified according to its solubility in an alkali solution (Inguerber,):

- α-cellulose are non-soluble in aqueous 17,5 % NaOH, whereas
- β- cellulose are soluble in above mentioned solution, precipitates after neutralization
- γ– cellulose is only fractionally soluble after neutralization

It was then suggested that a 17,5 % NaOH solution dissolves chains up to a DP of 200 (Smook, 1992). Since the DP of hemicellulose in wood ranges between 50 and 300, a large part of the beta- plus gamma-cellulose in can be classified as hemicellulose and not cellulose chains shortened during the pulping process. The terms α-, β- and γ cellulose are however still used despite this discrepancy.

Other types of cellulose have also been defined according to the method by which they were isolated, e.g. holocellulose and Cross and Bevan cellulose (Ingruber, 1985). This cellulose differs in degree of purity, i.e. the amount of other wood material, mainly lignin and hemicellulose, isolated together with the cellulose.

The third macro molecular component of wood is lignin. The cells in wood are bounded together by a group of molecules called lignins. These are aromatic complex compounds structure. There prime purpose of chemical pulping is to remove as much lignin from the wood as possible, thereby liberating the cellulose fibres from the wood. Lignin is not limited to the boundary between fibres but also present between the cellulose fibrils. Three building units of lignin are p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol and are shown in Fig. 3.3.

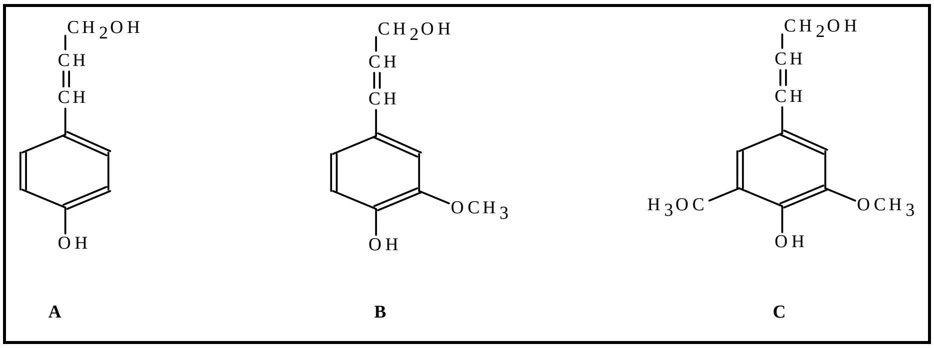


Fig. 3.3: The building units of lignin: A: p-coumaryl alcohol, B: coniferyl alcohol and C: sinapyl alcohol (Hunt, 1999a).

These units are linked together in many different ways, mainly by oxygen (ether) bridges connecting the α or β carbons of the side chain of one unit with the phenyl ring of the other. These bonding are well explained Smook (1992).

The final group of chemicals found in wood is called extractives. These are volatiles components of wood. They are normally removed by the time pulp is ready for papermaking. They are however nuisance is that they are a main cause of pitch build-up on the paper machine and pipes, especially during the rainier season where 'greenwood' is used. To counteract this problem papermaker requires that wood be left in the forest for about 12-15 weeks after harvesting.

3.6 Cell wall structure

Cellulose molecules are aggregated into threadlike structures approximately 3.5 nm in diameter, containing both crystalline and amorphous regions (Biermann, 1996). These are encased in a shell of hemicelluloses molecules called microfibrils (Kellomäki ,1999). The microfibrils occur in small bundles or "macrofibrils". These thin sheets or "lamellae" gives the wall a layered texture (Kocurek, 1983). Fig. 3.4 illustrates a typical fibre, showing transverse face of softwood trachea. A cementing layer, which is the middle lamella holds the individual fibres together and is composed mainly of lignin.

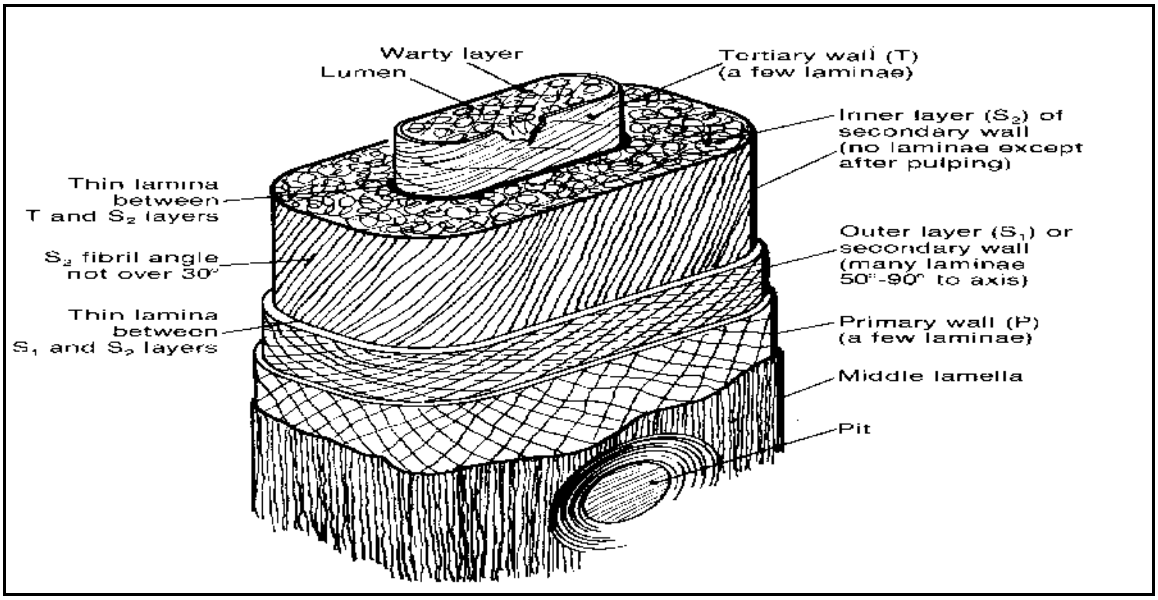


Fig. 3.4: Diagrammatic sketch of a typical fibre (softwood trachea) (14).

The fibres cells in all plants grow from the outside inwards. When growth of an individual cell begins, the primary cell wall is formed filled with liquid. The layer about 0,1 µm thick and has a netlike structure of microfibrils in an interwoven pattern. The microfibrils are orientated at an angle of 85 ° with the cell axis. The primary wall is has about 10 % cellulose embedded in an amorphous plastic matrix of hemicellulose, extractives and lignin (Smook, 1992).

The multi-layered secondary wall is formed after further growth. The outer layer of the secondary layer, called the S_1-layer, is about 0,1 to 0,2 µm thick with a microfibril angle between 50 -70 °. The S_1-layer is rich in lignin and closely resembles the primary wall to which it is closely attached, therefore it is also known as the transition layer. The central secondary wall, the S_2-layer, is attached much less firmly to the S_1-layer. A continuous envelope of hemicellulose between these layers is thought to cause this lesser cohesion. The S_2-layer contains more cellulose and less lignin than the S_1-layer, whilst the microfibril angle is between 10 and 30 °. It forms the bulk of the fibre and is about 2 to 6 µm thick (Hunt, 1999a).

The tertiary wall is the innermost component of the cell wall and the surrounds the central canal called the lumen. The tertiary wall is very thin, about 0,1 µm, and is rich in hemicellulose (Hunt, 1999a, Smook, 1992).

3.7 Wood classification

Trees types are classified into two major categories, namely softwoods (gymnosperms) and hardwoods (angiosperms). The botanical basis for classification is whether or not the tree seed is naked (softwoods), or covered (hardwoods). The major difference with regard to wood anatomy is the presence of vessels in hardwoods. Vessels are structures composed of cells created exclusively for the conduction of water. Softwoods lack vessels but have cells termed longitudinal tracheids, which perform a dual role of conduction and support. In general, softwood fibres are more than twice as long as hardwood fibres (Hunt, 1999b).

3.8 Softwood anatomy

The anatomy of softwoods is a lot less complex than that of hardwoods. The two main cell types, which constitute softwoods, are *tracheids* and *parenchyma*. Tracheids are long, tapering cells, which are orientated in the longitudinal direction, i.e. parallel to the vertical axis of the tree (Smook, 1992). Depending on species, most softwood has tracheids ranging from 2,5 mm to 7 mm in length (Hunt, 1999a). The tracheids are a lot longer in length than the parenchyma cells, and constitute 90 % or more of the volume of wood in the tree. The tracheids perform the roles of water conduction and support within a tree (Smook, 1992).

Parenchyma are responsible for storing various extractives, including starch, polyphenols, oils, fats, etc., as well as inorganics, e.g. K, Mg, Mn, Ca and Si. The parenchyma cells are orientated in the transverse direction, at right angles to the vertical tree axis, and are very short, chunky, thin-walled Fibres. Ray tracheids, which are similar in size to parenchyma, and longitudal parenchyma cells, are found in small quantities in some softwood species.

3.9 Hardwood anatomy

Hardwoods have a more complex anatomy since more than two kinds of cells are present. Specific characteristics of the hardwoods are a lack of radial alignment of cells, variable size and composition of cells, abundance of rays and the presence of pores or vessel elements (Smook, 1992). The four major cell types are fibres, vessel elements, tracheids and parenchyma cells. The relative quantities of the different types of cells vary significantly from tree to tree, and give each species its specific characteristics.

Vessels perform the role of water conduction in hardwoods. They are structures composed of vessel elements stacked on top of each other. Vessel elements are short, thin-walled cells with large diameters and perforated ends. They occupy a large cross-sectional area, and can often be detected with the unaided eye (Hunt, 1999a).

Fibres occupy 40 – 75% of the wood volume, and perform the role of supporting a tree. They are orientated in the longitudinal direction, and are thick-walled, elongated cells with closed pointed ends. Fibre lengths are in the order of 0.9 mm to 1.5 mm (Smook, 1992). The term fibre is also commonly used for all woody cells used in the pulp and paper industry (Hunt, 1999b).Hardwood tracheids occur in small amounts in some species. These are small, longitudal conducting cells, which act as transition elements between major cell types (Ingruber, 1985).

Longitudal and ray parenchyma cells are present in hardwoods (Smook, 1992). They constitute a larger volume (about 20 % on average) than do softwood parenchyma cells. These cells perform the storage role in a tree, as is the case with softwood parenchyma.

3.10 Wood growth rings

Growth rings, or annual increments, are detectable due to differences in the wood produced early and late in the growing season. Growth in a tree occurs at the cambium layer, which is a thin layer of tissue situated between the bark and the wood of a tree. The rate of cambial growth varies during the growing season, causing deposition of thin-wall Fibre cells in the early season and more dense thick-walled fibres towards the end of the growing season (Smook, 1992). The cambium layer is dormant outside of the growing season. The wood produced early, called early wood or springwood, and is considerably lighter in colour than the wood termed latewood or summerwood, which is produced, late in the growing season. The colour difference is due mainly to the different kinds of cells produced either early or late in the growing season.

The inner portion of wood in a tree eventually dies and is called heartwood. Heartwood is generally drier than the outer part of the trunk, which contains living cells, called sapwood.

3.11 Reaction wood

"Reaction wood" forms because of external mechanical forces, caused by wind and geotropic erection, as well as the presence of branches. The anatomical, physical and chemical characteristics of reaction wood differ from the normal wood tissue. Reaction wood is formed as a self-regulating response to provide support and reorientate the deviated growth of the tree due to the above external forces.

Hardwood trees form tension wood, while compression wood is the reaction wood of softwoods. Compression wood develops typically on the underside (compression side) of leaning or malformed stems, branches and beneath branch insertions. The main characteristics are its dark colour and high density as compared to normal wood. This is caused by relatively high lignin content and a modification of the cell wall. The tracheids are 30-40 % shorter and the cell walls are considerably thicker. Compression wood in a mechanical pulping process leads to inferior paper properties due to the inability of the fibres to fibrillate under normal refining circumstances. In chemical pulping, the high lignin content causes the yield to be lower and the chemical requirements to be higher than for normal wood from the same tree (Smook, 1992; Hunt 1999a).

In hardwoods, the reaction wood tissue is commonly located on the upper side of branches and leaning stems. The structural characteristics of tension wood are less definitive than those of compression wood (Smook, 1992). A prominent feature of tension wood is its increased fibre volume and above average cellulose content.

Another feature is an additional, loosely attached cell wall layer at the fibre lumen. This layer, called the *G-layer*, is composed of almost pure cellulose and has a microfibril angle close to the Fibre axis. In mechanical pulping, the thickened Fibre walls and lower lignin content promote defibration and enhance sheet properties. Chemical pulp from tension wood has a high yield because of the high cellulose content, but the strength is inferior to that of pulp from normal wood from the same tree (Hunt, 1999b).

3.12 Typical fibre Characteristics

Two factors should be taken into account when wood is considered as a source for producing pulp and paper, namely the fibre yield per ton of a given weight, and the quality of the resulting fibre (Virkola et al., 1981). The former depends on the characteristics of wood prior to pulping and the process employed in its conversion to pulp, while the latter is mainly a result of morphological features of the individual fibres and their modification due to the pulping process.

Fibre quality is also a variable quality in the sense that interpretations of the quality aspects of fibres depend on the specific requirements of the final product to be made from the pulp. The question of wood pulp quality is still further complicated by the lack of agreement among the technical people and producers of pulp products on the interpretation of the qualitative features of fibres, and by the difficulties encountered in determining these features in a practical way (Smook, 1992). The qualities of the resulting fibres depend on the wood structure, i.e. the types of cells, and to a lesser extend on the chemical composition of the cell wall material.

The fibre variables responsible for determining the physical characteristics and quality of pulp and paper are classified under fibre morphological aspects. The most important of these variables are cell wall thickness and fibre length (Hunt, 1999b). Other variables include fibre coarseness, fibre strength and interfibre bonding.

3.13 Individual fibre Characteristics

The property of the final paper product is also determined by individual fibre properties such as fibre wall thickness and fibre length.

3.14 Fibre wall thickness

Thick walled cells, such as found in the latewood of softwoods, resist the compacting forces and tend to maintain their original cross-sectional shape during sheet formation. This results in open, absorbent and bulky papers. Strength properties associated with Fibre bonding, such as bursting and tensile strength are appreciably reduced, whilst tearing resistance is relatively high. Thin walled cells on the other hand, collapse readily to form dense, well-bonded papers, low in tear but high in burst, tensile and other strength properties.

3.15 Fibre length

The actual fibre length is vital because certain average length is required to provide sufficient bonding surface between different fibres. The distribution being between 0.5-1mm and less than 0.9 mm for both soft and hard wood respectively (Smook, 1992). Paper made from fibres that are too short will have insufficient common bonding area, resulting in weak points within the sheet and the sheet will have low mechanical strength properties.

The tearing resistance of a sheet is virtually proportional to fibre length, i.e. the longer the fibres, the higher the tearing resistance (Hunt, 1999b). Bursting and tensile strength properties are also affected by both fibre length and fibre bonding (Hunt, 1999b). Long fibres with a high coarseness (weight per unit length of a fibre) do not collapse easily during refining and sheet formation, giving bulkier, more open structures with less bonded contact area and lower burst and tensile strengths (Smook, 1992). Therefore, burst and tensile strength are more dependent on fibre coarseness than on fibre length.

Another important factor is the degree of variation in fibre lengths found in pulpwood. Although the longer fibre lengths are an important factor, as far as strength is concerned, their significance is affected by the fact that any portion of a tree will contain a range of fibre lengths, with many short fibres included. These short fibres have a negative influence on the strength of the paper. Short fibres are also essential for surface properties and sheet printability.

3.16 Types of pulping processes

Table 3.1 give four different type of pulping technology used in the world, namely chemical, semi-chemical, chemi-mechanical and mechanical pulping which all produce pulp of different fibre properties. In chemical pulping, lignin is dissolved in cooking liquor. Whereas, mechanical pulping separates the fibre bundles through shear forces provided by an abrasive grinding stone or metal discs. This resulting in different fibre yields with mechanical pulping giving yields above 80% by mass.

•Classification	•Process Name	•Wood used	•Hypo numbers	•Typical yields (%)
•Mechanical	•Stone ground wood •Thermo mechanical	•Softwood (mostly) •Softwood	•Greater than 200	•90-95 •90-95
•Semi-mechanical	•Cold soda	•Hardwood		•85-90
•Semi chemical	•NSSC •High yield Sulphite •High yield frat	•Hardwood •Softwood (mostly) •Softwood (mostly)	•170-185	•65-80 •55-75 •50-70
•Chemical	•Kraft •Sulphite •Soda	•Both •Both •hardwood	•Less than 150	•40-50 •45-55 •45-55

Table 3.1: Summary of major pulping process (Smook, 1992)

3.17 Difference between chemical and mechanical pulping

The fibres from chemical pulping are slightly longer, flexible and stronger than those from mechanical pulping, due to the fact that they fibres undergo less physical damage during processing. The average pulp yield of a chemical pulping process is about 45 to 55% depending on the final residual lignin measured in terms of hypo number or kappa number. Whilst the fibre yields mechanical pulping usually varies between 90-95%. The fibre yield is defined as the mass fraction of moisture free pulp produced divided by the total weight of moisture free wood used for its production.

The operating yield for each mill is determined practically, as the hypo number and the fibre yield correlates very well. Hypo number is used as measure of residual lignin on the pulp in industry (Smook, 1992; Hunt, 1999a). Digesters operating at high hypo number are classified as either semi-chemical or chemi-mechanical pulping due to intermediate pulp yields of about 60% to 85%, while pure chemical pulping operates at very low hypo number and yield. The actual operating regime for each digester is determined by the quality of the final product produced (Smook, 1992).

Chemical pulping is categorized as either sulphite or alkaline pulping, depending on the actual cooking chemicals. Alkaline pulping uses both soda ash and sodium sulphite as cooking chemicals, and soda pulping uses caustic soda as the active cooking ingredient.

Semi-chemical pulping combines both chemical and mechanical pulping. The pulping process occurs in two stages. Where in the first stage, chips are chemically treated to weaken inter-fibre bonding, and in the second stage the fibres are mechanical broken down through raffinators and refiners.

3.18 Sulphite pulping

Sulphite pulping process was developed in 1866 by an American (Benjamin Chew Tilghman) (Ingruber, 1985), whilst inspecting wooden wine vats in Paris, Tilghman observed that the wine barrels became fiberised on the inside after repeated use and disinfections with sulphur dioxide. After considerable experiments using sulphurous acid and wood, he found that fibers could be isolated if the mixture was kept at a high temperature and under pressure. To prevent the formation of free sulfuric acid and consequent damage to the pulp, lime was added to the cooking liquor.

The alkaline sulphite process was developed and resulted in a far superior pulp quality compared with the kraft process, giving pulp that is easy to bleach. These developments meant that the sulphite processes provide a better pulp grades required for paper-making.

3.19 Semi-chemical pulping

Semi-chemical pulping emerged in late eighties, but its implementation was however delayed, because of a lack of demonstrated use of the pulp and suitable equipment for defibering. Semi-chemical pulping involves partial cooking and mechanical defibering to break bundles and liberate the fibre for papermaking process.

Sodium is the most predominantly used base in semichemical pulping due to its low relative cost, compared to ammonium which was more prevalent in the sixties. Ammonia does not leave any residual that would require additional processing after the burning of spent liquor. It was however found not to be cost, thus they are no ammonium base NSSC mills were left (Ingruber , 1985). The increase in the paper and paperboard requirements ensures steady growth in semi-chemical pulping, because of its unrivalled compression strength that hardwood imparts to corrugated containers (10). Since the mid-seventies, many NSSC mills have been converted to none sulphur (sodium carbonate and sodium carbonate) semi chemical pulping in order to reduce environmental impacts (e.g. Mondi Piet Retief Mill).

Sodium sulphite is the most active delignification ingredient, whilst sodium carbonate is used as a buffer to control pH by neutralizing hexunoric acids released during pulping process. In essence the soluble HSO_3^- ions are formed in a solution of sodium sulphite and water in the following manner, resulting in the sulfonation process.

$$Na_2SO_3 \rightarrow 2Na^+ + SO_3^{2-}$$

$$SO_3^{2-} + H_2O \rightarrow HSO_3^- + OH^-$$

In sulfonation reaction, sulphonic acid (HSO_3^{-}) reacts with lignin to makes it more hydrophilic. This converts water insoluble lignin (hydrophobic) to a more water-soluble lignosulfonate (hydrophilic). The second step of the reaction is termed hydrolysis, which breaks down the lignin bonds so that new and smaller water dissolvable lignin fragments. Fig. 3.5 illustrates sulfonation and hydrolysis reaction steps of the lignin molecule with sulphonic acid ion (Ingruber, 1985).

.

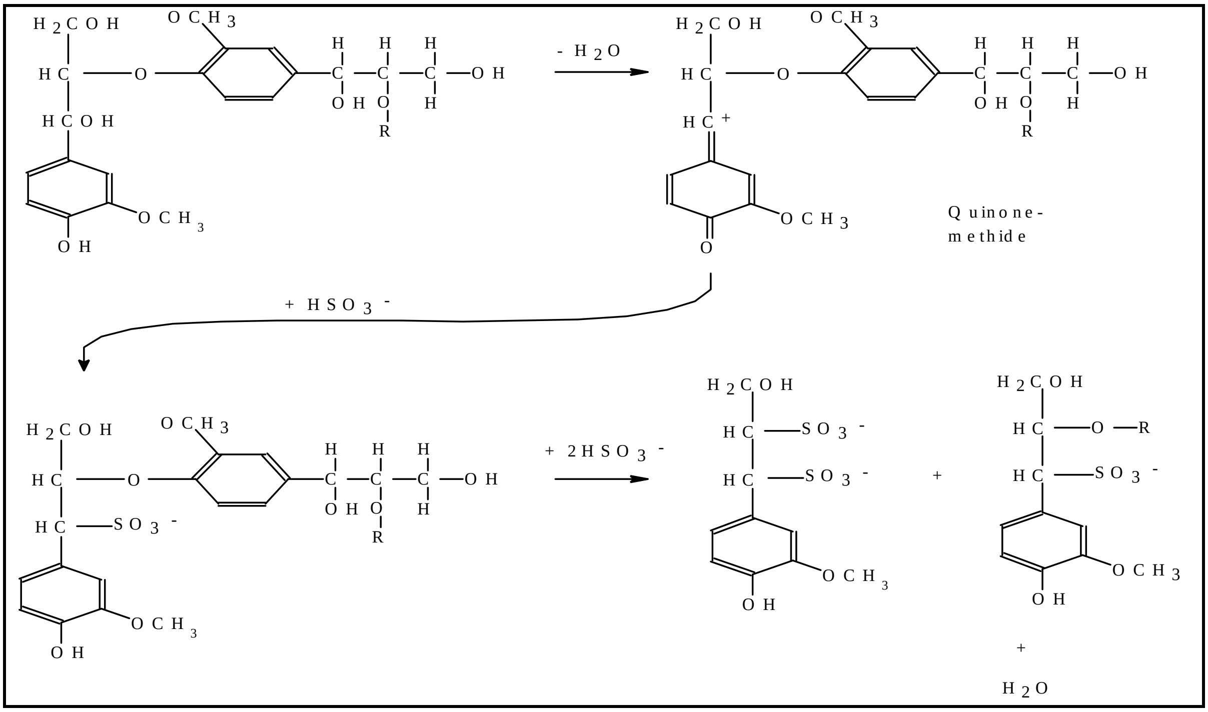


Fig. 3.5: Sulfonation and hydrolysis of lignin in neutral sulphite pulping (Hunt, 1999a).

3.20 Mechanical pulping

Mechanical pulping is widely used in mills that makes newsprint papers (e.g. Mondi-Merebank) for many different reasons such as higher yield, environmental consideration, cheaper pulp, lower effluent, ease printing, good ink absorbency and easier recycle. The raw material requirements for mechanical pulping are softwood only, the reason is that hardwood is not pliable enough, tree age of 12-16 years as younger trees are difficult to process and old trees contain more latewood thicker cells) and heartwood, log length must be same as width, log diameter must be 100 to 350mm as too long and small results in control problems and finally the moisture must be below 50%.

The typical process flow for mechanical pulping includes wood yard, slasher, wood disc, screens, bull screen, screens, Decker, water cooler, chemical and storage. The important stage in the ground wood grinding is the operation of the grinder, with the following typical operating conditions:

Condition	Values
Speed @ 5Hz	300
Diameter (m)	1.8
Width (m)	1.2
Capacity (t/day)	45
Freeness (CSF)	80 to 100
Specific Shower water m^3/min @ $50^{O}C$	2
Pit temperature (^{O}C)	70
Consistency (%)	1.2 to 2.0
Specific Input Energy (mWh/t)	2.5

Table 3.2: Typical grinder operating condition (19)

The overall energy requirements for ground wood pulping are 25 to 30% less that thermo mechanical puling. The fibre fractions are similar with strength properties between ground wood and thermo-mechanical pulping being similar. The last form of mechanical pulping is refiner pulping where discs are used for defibrillation of fibres. This process is explained in details in the next section as is used in Mondi-Piet Retief.

3.21 Chemical pulping variables

The following pulping process variables are important in any chemical pulping operation, digester temperature control, liquor to wood ratio, chemical charge and the control of catalyst used for improving of the deliginification rate.

3.22 Temperature

The digester temperature affects the overall cooking rate by a factor of 2 for every ten degrees increase in temperature (Hunt, 1999a). High temperature has profound effect on the fibre selectivity, i.e. the relative amounts of lignin and polysaccharides removed from the wood, although cellulose losses are not excessive. The selectivity for neutral sulphite pulping is more temperature dependant than that of Kraft pulping, in which case it the selectivity stays relatively constant if the temperature is increased (Ingruber, 1985). The neutral sulphite process is more selective in its action than Kraft pulping, removing a larger portion of lignin at an equivalent yield. This causes NSSC-AQ pulp to have a higher yield than Kraft pulping at a similar residual lignin level (Ingruber, 1985; Hunt, 1999a).

Continuous digesters temperature control is a very complex situation due to high level of interaction between related control loops. The trim the temperature control has been advocated but it still remains just a concept. The neutral sulphite delignification rate rigidly obeys the Arrhenius equation $K = Ae^{-Ea/RT}$. The H-factor is a mainly used variable that combines time and temperature into a single variable. It was developed by Vroom (Smook, 1992), and has been successfully employed in different kraft pulping (Ingruber, 1985).

3.23 Liquor to wood ratio

The actual ratio of liquor to wood in the digester generally ranges between 1.5:1 and 4:1 (10). When a low liquor ratio is used, chips are not probably impregnated resulting in poor cooks. Low liquor to wood ratio saves steam, since less external energy is required to heat up the digester charge to cooking conditions; however it is highly undesirable due to safety concern. The correct liquor to wood ratio is determined by the chemical charge on the dry wood chips, and the chemical concentration.

3.24 Alkali charge (AA)

The production of corrugating medium requires the actual sodium sulphite charge of 8 to 15 % as Na_2O on oven dry wood basis. The residual sodium sulphite on the extraction liquor is kept between 5 to 10 g/l of black liquor. The residual charge is required to avoid dark pulp being produced(Ingruber, 1985; Antonides, 2000).

Sodium sulphites to sodium carbonate a ratio is varied between 10:1 and 2.56:1 with the ratio expressed as g Na_2O (10). At about 80 –85 % sodium sulphite and 15 – 20 % sodium carbonate or sodium hydroxide (all chemicals expressed as g Na_2O) in the cooking liquor, maximum pulp yield of softwood cooks is obtained with minimum lignin content and carbohydrate degradation (Ingruber, 1985).

A concentration range of 54-82 g sodium sulphite per litre is used, with the anthraquinone (AQ) dosage rate being maintained at 0.5 % (on o.d. wood). The cooking times are varied to obtain yields of 50 and 80 %. Virkola et al .(1981) discovered during softwood NS-AQ cooking trials on the laboratory and industrial scale that the most important factors influencing the result of NSSC-AQ cooking are total alkali charge, alkali ratio and amount of AQ on wood. The sodium sulphite charge had a greater influence on delignification rate than the total alkali charge. All the properties of the NSSC-AQ pulps are quoted as being exceptional compared with conventional sulphite pulps, whilst one of the most interesting aspects of the NSSC-AQ process was found to be the very high pulping yield.

Sodium carbonate is counteracting a fast drop in pH at the beginning of a cook, which is due to the neutralization reaction of acetyl groups in wood (Smook, 1992; Ingruber, 1985, Hunt, 1999a). A minimum amount of buffer chemical, just sufficient for a spent liquor pH of 7 produces the brightest pulp, whilst pH greater than 9 provides faster pulping. Some mills pulp mills discharge spent liquor of pH low than 6 to save on buffer chemicals and to enhance pulp drainage (Ingruber, 1985). The actual residual pH of spent liquor is the matter of pulping variable cost control.

3.25 Anthraquinone (AQ) as a catalyst

AQ is known to accelerate the rate of delignification for a pulping process (Ingruber, 1985; Hunt, 1999a; Mokebe, 2006). At a constant residual lignin level, NSSC-AQ pulps have higher yields than the conventional NSSC pulps, due to AQ being able to protect the carbohydrate portion of wood during pulping. Mechanical strength properties for NSSC-AQ pulp have been found to be significantly higher than that of NSSC pulps (Ingruber, 1985). Virkola et al. (1981) has also found that mechanical properties of the NSSC-AQ pulps were exceptional compared to conventional sulphite pulps, whilst resulting in higher yields.

A mill in New Zealand is said to have achieved a 25 % increase in its production throughput with just the introduction of AQ (Ingruber, 1985). This shows that will increase the overall deliginifcation are, AQ also protects the fibres. AQ can be used in a number of ways in the mill, including the decrease to the overall cooking time, and reduction in the total alkaline charge [19].

The essential factor influencing the result of NSSC-AQ cooking is the total alkali charge, alkali ratio and amount of AQ on wood. Sodium sulphite charge has a greater influence on delignification than the total alkali charge. This was found during softwood NSSC-AQ cooking trials on both laboratory and mill scale.

The most prominent feature for bulk delignification in neutral sulphite anthraquinone (NS-AQ) cooks is its good selectivity (In Gruber, 1985). This was shown during trials on neutral sulphite anthraquinone cooking of pine and birch chips (0, 1 % AQ on wood) to produce paper pulps. A 0.1% AQ on oven dry wood basis is commonly used, though dosages as low as 0.05 % to 0.08 % AQ on wood has been successfully. For a 0.5 % AQ dosage, used in neutral sulphite pulping of pine (*Pinus Radiata*), the kappa number dropped by half under given pulping conditions. For loblolly pine, the optimum AQ charge was found to be 1 % (Smook, 1992; Ingruber, 1985; Antonides, 2000).

AQ is believed to enhance delignification during the initial phases of sulphite-AQ pulping by promoting the cleavage of free phenolic Beta-aryl ether linkages (Ingruber, 1985). It is reduced in the pulping process to anthrahydroquinone (AHQ), which ionised and dissolves as the AHQ anion with a dark red colour, as shown in Fig. 3.6.

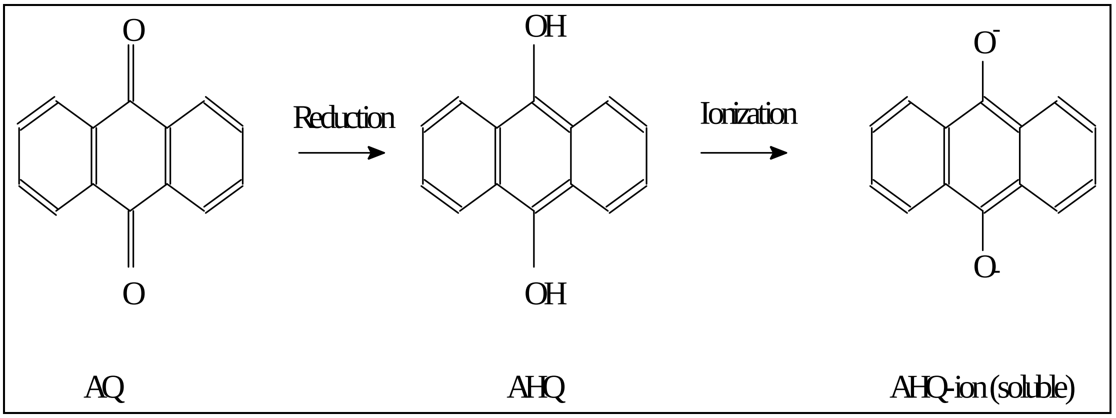


Fig. 3.6: Reduction of anthraquinone to anthrahydroquinone and subsequent ionization (Ingruber, 1985).

3.26 Simultaneous pulping of hardwood and softwood- Novel Approach

Little information is available on simultaneous pulping of hardwood and softwood, as is technically not preferable to both soft hardwood and softwood. There are however, a varies circumstances, which make it preferable economically to enhance both surface and mechanical properties of the sheet, which depend on the ratio of softwood and hardwood ratio's in the blend (Ingruber, 1985; Antonides, 2000).

Some investigations into the simultaneous pulping of hardwood and softwood species pulping have been reported. But a long-term mill operating experience has shown that hardwood and pine can be successfully mixed pulped by the counter current soda-AQ process. During simultaneous pulping of hardwood and softwood with Soda-AQ pulping process, it was found that hardwood was severely overcooked in all cases. This is because hardwoods pulp are more easy to pulp than softwoods, because of the different chemical nature of the lignin of the two species, as well as the lower lignin content of hardwood (Hunt, 1999a).

A way to minimize the overcooking of HW chips is by manipulating the chip thickness, especially the pine chip thickness (Antonides, 2000). Increasing the hardwood chip thickness or decreasing that of the softwood decreases the difference of the extent of delignification of the two species. This can easily be done in the laboratory, but on the large-scale plant it is intricate, as of fines lot of fines are generated during the chipping process. This novel approach of pulping both hardwood and softwood simultaneously is covered in Chapter 5.

3.27 Conclusions

The pulp and papermaking technology has not experienced any radical changes in the last thirty years since the introduction of NSSC pulping method. The changes that have occurred have been on the equipments development side with many companies moving away from batch to continuous digestion due to increased fibre demand. Other developments have been on the development of specialised pulping chemicals because of the need for improved fibre quality and reduced input cost. Many Kraft mills have also been closed due to increased environmental pressure. Attempts have been made as well for simultaneous pulping of both hardwood and softwood together, but there are still some challenges in this area.

3.28 References

1. Antonides F., Simultaneous pulping of both softwood and hardwood in continuous digester, MScEng Dissertation, University of Natal, 2001.
2. Biermann, C.J., *Handbook of Pulp and Papermaking*. 2nd ed. 1996: Academic Press.
3. Clapperton, R.H., *Modern Papermaking*. 3rd ed. 1952: Basil Blackwell.
4. Calkin, J.B., ed. *Modern Pulp and Papermaking*. 3rd ed. 1957, Reinhold Publishing Corporation: London.
5. Hunt J, *Paper Making Technology Notes *(1999a), University of Natal, South Africa*.
6. Hunt J, *Wood Pulping Technology Notes *(1999b), University of Natal, South Africa*.
7. Gellerstedt, G., *The Reactions of Lignin during Sulfite Pulping.* Svensk Papperstidning, 1976. **79**(16).
8. Grant, J., *Cellulose Pulp and Allied Products*. 3rd ed. 1958: Thomas Reed and Company limited.
9. Gullichson, J.F., C-J. ed. *Chemical Pulping*. Papermaking Science and Technology. Vol. 6A. 1999, Fapet Oy.
10. Ingruber, O.V., Kocurek, M.J. & Wong, A., ed. *Sulfite Science and Technology*. 3rd ed. Pulp and Paper Manufacture. Vol. 4. 1985, The Joint Textbook Committee of the Pulp and Paper Industry.
11. Kellomäki, S., ed. *Forest resources and Sustainable Management*. Papermaking Science and Technology. Vol. 2. 1999, Fapet Oy.
12. Kocurek, M.J.S., C.F.B., *Pulp and Paper Manufacture*. 1983: The Joint Textbook Committee of the paper Industry.
13. Mokebe, KD, *Surfactant Enhanced AQ Applied To Semi Alkaline Sulphite-AQ Process.* SAiCHE Symposium Sasol Auditorium, 11 May 2006.
14. Smook, G.A., *Handbook for Pulp & Paper Technologists*. 2nd ed. 1992, Vancouver: Angus Wilde Publications Inc.
15. Stephenson, J.N., ed. *Preparation and Treatment of Wood Pulp*. Pulp and Paper Manufacture. Vol. 1. 1950, McGraw-Hill Book Company.
16. Virkola, N., Pusa, R. & Kettunen, J., *Neutral Sulfite AQ Pulping as an Alternative to Kraft Pulping*. Tappi, 1981. **64**(5).

4.1 Introduction

This section gives an overview of the environmental issues pertaining Pulp and Paper industry and include some example of cleaner production application as a waste minimisation tool in the Pulp and Paper industry. It further discusses the energy situation in S.A, as this is deemed necessary for all future expansions and sustainability projects implementation.

4.2 Cleaner Production

Cleaner production is defined by the United Nations Environmental Program as the continuous application of an integrated preventative environmental strategy applied to process, products, and services to increase eco-efficiency and reduce risks to humans and the environment (Barcaly et al., 2005). This is accomplished by conserving raw materials, energy, minimising "waste" load raw materials, such as plastics and trash, and improving the purity of the incoming raw materials, and reducing and improving both the quantity and quality of all emissions and wastes streams.

The derived benefits from such an undertaking can only be comprehensively quantified with an environmental analysis tool such as LCA during the environmental performance assessment of the process (Azapagic, 1999). Thus, most of the current environmental protection methodology focuses more on what to do with wastes and emissions after they have been created which is the main drive of cleaner production [CP)]for trying to reduce waste at source.

Cleaner production is internationally recognised as a crucial means to reconcile the environmental burdens and economic goals involved in the move towards sustainable development (Majozi, 1998; Majozi and van Schijndel, 2005&6). Its long-term benefits are to:

i) Reduce waste costs management
ii) Increase on-site reuse
iii) Improve overall environmental performance
iv) Increase profitability

v) Promote a positive public image through reduced emissions to the atmosphere

vi) Reduce liabilities

vii) Improve housekeeping

viii) Improve health and safety of employees and public alike, and

ix) Increase operating efficiency

All the above mentioned benefits show that CP is the means of accomplishing economic growth without compromising the environmental standards. Even though there is an improvement of the site environmental performance because of the site usage application of CP. LCA still has to be applied to quantify the site environmental profile, as it with the assist with the prioritisation of environmental projects aimed at decreasing environmental burdens.

4.3 Cleaner Production application in Pulp and Paper industry

The Department of Environmental Affairs and Tourism [DEAT] initiated a project to demonstrate Cleaner Production application in the South African by choosing two Pulp and Paper Mills for pilot project. The project was funded by Norwegian Research Development [NORAD] as part of the Norway-South Africa Environmental Cooperation Programme. The main aim of this project was to conduct CP Audits, and train the employees on the implementation of audit recommendations.

A team of Consultants led by Susan Barclay cc was appointed by DEAT, to undertake a project on Cleaner Production Audits, Implementation and Training in the Pulp and Paper Industry. Other project team members included: BECO Institute for Sustainable Business (BECO), University of KwaZulu-Natal (UKZN), Enviros Consulting and the Durban Institute of Technology (DIT).

Two mills were chosen to participate in this project, namely MPSA- Piet Retief and Sappi-Springs Mill. Each Mill was required to for its own team for investigation of CP projects and implementation, as well as determining the expected saving scope using the Norwegian cleaner production methodology (Barclay et al., 2005). The actual implementation according to the Norwegian implementation plan is:

- Planning and Organisation

- Pre-assessment phase
- Detailed assessment
- Identification of opportunities using monitoring and targeting techniques.
- Feasibility analysis for project justification
- Implementation
- Maintaining of the program

This program was implemented according over a period of 18 months with the following main findings:

- Upgrading of existing chemical mixing plant to avoid excessive spillage of sodium sulphite and sodium carbonate.
- Investigating the usage of extracted black liquor for heating of digester wash water.
- Improving of Condensate return system, and
- The possible usage fibre save all on the papermachine.

But it must be said that only few of this option have been implemented due to financial constraint. The most important stage for CP implementation project is the monitoring and targeting, as this help to identify the areas of improvements.

4.4 Energy Sector

Most of S.A electricity is mainly (89 %) produced from coal, with balance being produced from nuclear, hydro, wind and solar power. Currently, S.A has a surpassed its surplus limit and this creates problems with power outages. This will remain a problem for a while as building large power plants normally requires at least 10 years of planning, and new plants of a smaller scale with less financial risk will be needed. South Africa Government will need other means of electricity source this sustain the rapidly growing economy. Figure 4.1 shows the sectorial energy demand with the overall industry accounting for about 49% of 22GW (approximately 190.4 TW.h) per annum.

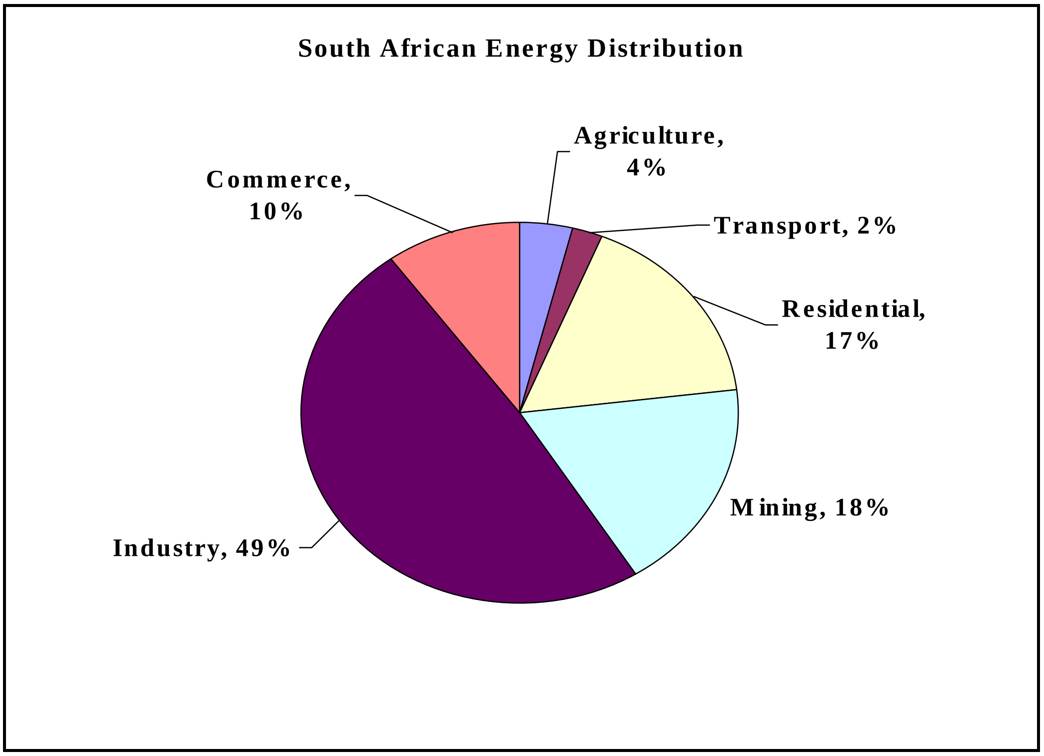


Figure 4.1: South African Energy distribution in S.A. (DME report, 2001b &2002b)

It is the S.A government strategy to provide electricity to all citizens before 2010, which implies filling the gap of about 3 million non-electrified households (Winkler et al., 2003). This will be an additional load of the current overloaded national grid. Eskom has in a prognosis stated it will be spending about R200 billion on the upgrading and bring back the power stations that were mothballed over the next 20 years to ensure adequate electricity supplies, and the cost of electricity is set to double or triple during this period at a rate of 5,7 % yearly (Winkler et al., 2003).

The S.A government has set a 10-year target for renewable energy use. The strategy is to produce about 1.1GW (approximately 10,000 GW.h) of renewable energy per year by 2013. This translates to about 2 % of the current net energy demand of 44 GW per annum. Figure 4.2 shows the actual sectorial energy demand with industry accounting for 49%, mining 18%, residential about 17% and the rest going to transport, agricultural activities and commercial purposes.

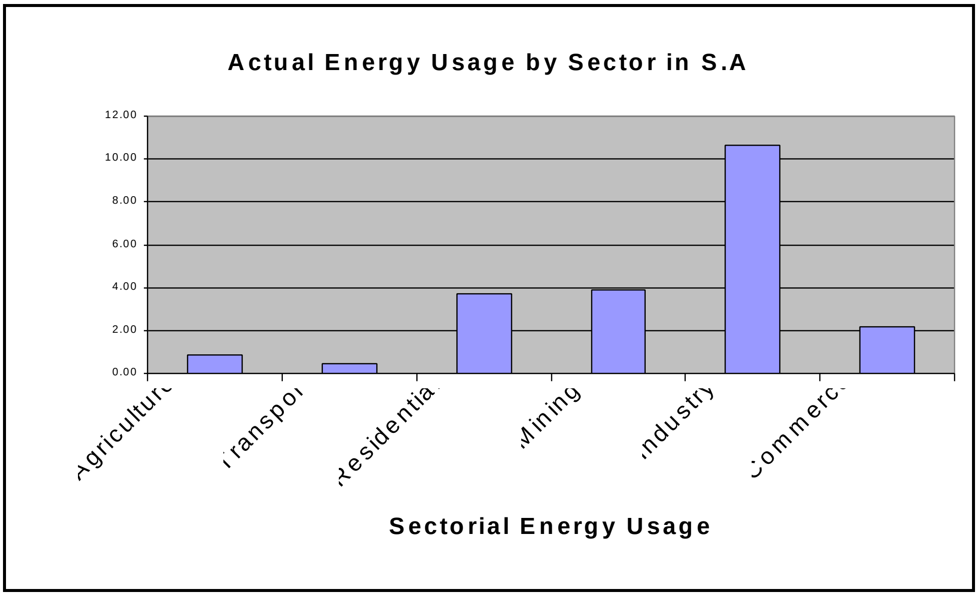


Figure 4.2: The actual energy usage by sector in S.A. (DME report, 2001b &, 2002b)

4.5 Energy situation in Pulp and Paper industry

Figure 4.3 shows the actual industrial energy distribution with the Pulp and Paper industry accounting for mere 5.36 % of total slice (10.83 GW). The chemical industry accounts for 23%, basic metal industry about 41%. On the grand scale MPSA- Piet Retief uses only about 0.1% (10.83 MW) of this net energy demand. The actual energy usage and distribution for MPSA-Piet Retief is elucidated in the next Section 5.7.

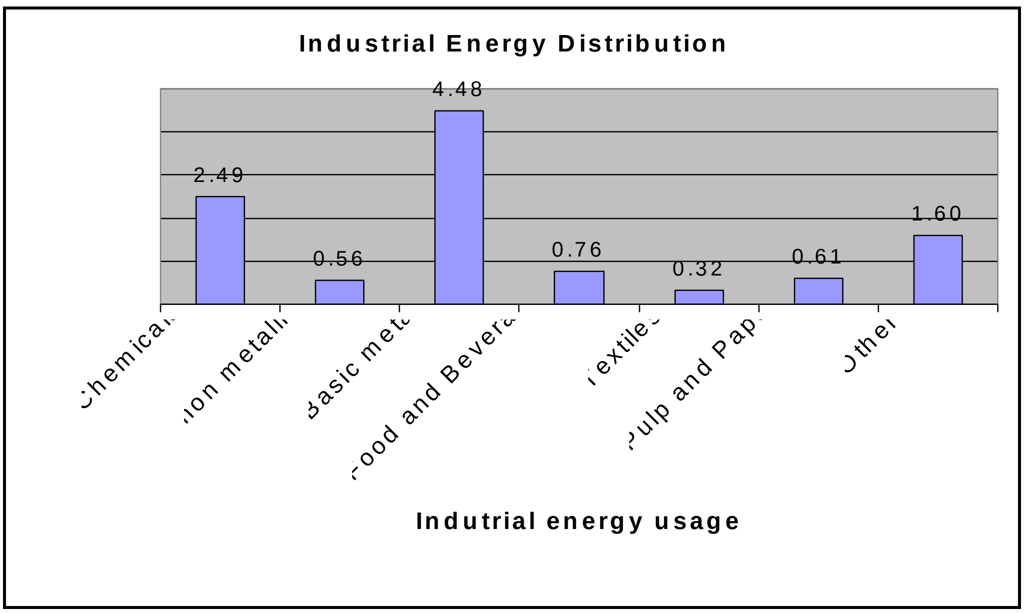


Figure 4.3: Industrial energy distribution in S.A. (DME report 2001b & 2002 b)

4.6 Peak energy demand

The main problem facing S.A is the peak energy demands that happen in the early hours of the morning and the afternoon. The grid energy demand is reported to increase by more than 32 MW (Eskom report, 2006), with both industry and residential usage accounting for more than 70%. This trend has to be reversed or the existing energy supply facility would soon exceed its capacity leading to economic crisis in the long term. This can be taken from recent experience in the Cape Town and Durban.

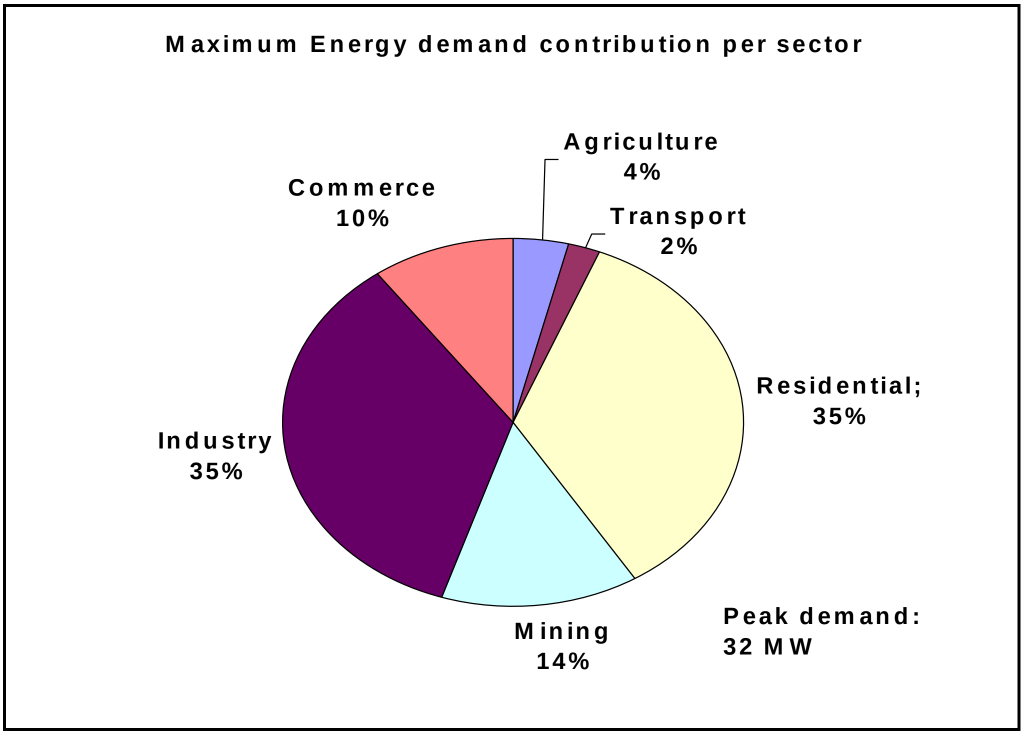


Figure 4.4: Summary of peak energy demand by sector (Eskom, ref 6)

4.7 Conclusions

The application of CP in the Pulp and Paper industry has proved to be a very successful initiative as some benefits in terms of cost saving has started to be realised. The application of LCA as a process engineering tool for projects screening in the whole CP methodology is applicable under the feasibility analysis phase. LCA can then be used to determine the project feasibility in terms of both economic and environmental benefits.

There energy situation in S. A is also critical as the demand now also most exceed the supply. This is crucial for industry to understand as the implementation of any project is also depended on the energy availability. With S.A economy increasing so rapidly the supply grid is bound to experience problems. In house power generation and energy conservation is highly in this recommended.

4.8 References

1. Barclay S, Kothuis b, Bull E, Buckley C, Kerr I, Mercer D, Pauk J, Cleaner Production audits, Implementation and Training in the Pulp and paper industry, Assessment report, Mondi –Piet Retief, April 2005.
2. Barclay S, Kothuis B, Bull E, Buckley C, Kerr I, Mercer D, Pauck J, Cleaner Production audits, implementation and training in the pulp and paper industry, feasibility assessment report, Mondi Piet Retief, received July 2005.
3. DME (Department of Mineral and Energy) 2001a.Annual Report 2000-2001.Pretoria.
4. DME (Department of Mineral and Energy) 2001b, South African National Energy Balance 1999.Microsoft Excel Spreadsheet Pretoria, available on website.
5. DME (Department of Mineral and Energy) 2002b, South African National Energy Balance 2002b. Pretoria, DME. www.dme.gov.org
6. Eskom report, Analysis of current Demand Supply Management (DSM) effort & ESCO activity against electricity consumption patterns. www.eskom.co.za
7. Majozi T, Application of Pinch Technology as a strategic tool for waste management in an agrochemical industry, M.ScEng dissertation, University of Natal, 1998.
8. Majozi T, Sustainable Engineering for Science technology, a short Course, Department of Chemical Engineering, University of Pretoria, 2006
9. Majozi T, van Schijndel P, Sustainable Engineering for Science technology, a short Course, Department of Chemical Engineering, University of Pretoria, 2005
10. Ministry of Water Affairs, and Forestry, Pretoria, S.A, Sustainable Forest development in S.A, white paper march-1997
11. Smil Vaclav, Energy in the Twentieth Century: Resources, Conversion, costs, Uses and Consequences, Energy Environ, 2000.25:21-51
12. Winkler H, Davidson O, South Africa's energy future: Visions, driving factors and sustainable development indicators, Energy and development Research centre, University of Cape Town, August 2003.

5.1 Introduction

This section presents an overview of the case study for the application of LCA as a holistic environmental tool for co-pulping process. Different sections of the case study are discussed in detail, where Fig. 5.10 to 5.12 shows the relevant block diagrams of the processes analysed.

5.2 Mondi- Piet Retief Overview- Chip preparation

Figure 5.10 shows the flow of chips from the chipper to the slab storage as pulp. Hardwood logs are delivered to the mill from the forests by road. These logs have already been debarked when delivered, as bark consumes more cooking chemicals (± 3 %) than necessary resulting in inferior pulp quality. Hardwood logs are then chipped in a Norman chipper and stored in chip piles. There mill operates 30 t/hr chipper running at 700 rpm speed and consuming the overall power of about 522 kW. Softwood chips are from local sawmills, and piled in different heap pile before being conveyed through the hopper into the chip bin. The loading chips into the chip bin are done by front end loaders. Two different screw feeders transport the chips from the chip bins onto two vibrating screens, where undersized and oversized chips are removed. The actual feed ratio of hardwood to softwood is controlled by adjusting the relative speeds of the screw feeders. These screws are controlled at the set flow of about 20 t/hr, with the average rejection rate of about 1 % at the shaker screens. The rejects are then collected and sent for incineration as a biomass fuel in the boilers.

From the chip hopper the chips go through a chip meter and a low-pressure feeder into a low pressure-steaming vessel operating at about 150kPa. The steaming vessel in the form of a screw-type conveyer is used to impregnate the chips with low steam at 150 kPa. The main purpose for pre-steaming is to remove entrained air from the chips. The process uses about 10% of high-pressure (HP) steam and the balance being flash steam from the pulping process. When the steam-impregnated chips are exposed to the high pressure inside the digester, the steam collapses, and subsequently takes up less volume. This causes the cooking liquor to effectively be sucked into the chips to fill the volume left by the collapsed steam, resulting in more effective liquor impregnation.

5.3 Pulping process

From the steaming vessel the chips go via a chip chute into a high-pressure feeder. Circulating cooking liquor from the digester top separator is used to transport the chips from the high-pressure feeder into the continuous digester; this circulation flow is normally referred to as *C4* system. The C4 temperature is maintained at about ± 100°C. The top separator has a separating basket for filtering the liquor and chips. It is a vertically mounted variable speed screw conveyor that feeds the chips into the digester. The excess cooking liquor from the high-pressure feeder is pumped through a sand separator and an inline strainer to remove solid materials (sand grits). This leads to the introduction of fresh cooking liquor as well as AQ dispersion from mixing tanks through the C4 line.

Mondi-Piet Retief uses the Kamyr continuous digester, which is a hydraulic base. This type of digester is divided into three active zones, namely the impregnation zone, the cooking liquor zone and the counter current washing zone. The impregnation zone starts in the top separator, where chips are impregnated with the cooking liquor. The chips then descend down is a plug flow to the cooking zone. External energy is supplied by high-pressure steam at 11 to 13 bars and 220 to 250 °C, and is injected to the top of the digester, and is used for maintaining the cooking zone temperature at ± 180 °C. The top digester temperature is controlled by modulating the inlet steam flow rate, and manipulating the pressure relief valve and realising all excess steam to flash vessel for secondary energy recovery or cooling water condensers.

The digester have three distinct sets of extraction screens where weak black liquor *(WBL)* is extracted. WBL from the top extraction screens is circulated through a C6 heat exchanger and pumped back to the top of the digester to maintain the constant cooking temperature. Excess spent liquor is extracted from the middle and bottom extraction screens at the temperature of ± 165 °C, and is passed through the flash cyclone before being sent to the storage tank. Flashed steam is then recycled to the steaming vessels or sent to the condenser. The passing of WBL through flash cyclone increases the *WBL* solids before storage.

The pulp-washing zone starts just below the bottom extraction screens. The pulp cooking reaction stops in this zone due to rapid extraction of the spent cooking liquor. Wash water from pulp washers is pumped into the digester through nozzles located below the washing zone extraction screens to provide counter current washing. The normal washing zone temperature is maintained at ± 60 °C. After the washing zone pulp is blown out through the blow unit and the bottom scrapper.

The actual pulp throughput is controlled by adjusting the bottom scrapper speed. It is then passed through the contra-shear for thickening before dumping in the semi pulp chest. This pulp is then washed in the co-current washers and thickened on the press to operating consistency of about 55%. This high consistency pulp is then stored on the slab for usage on the paper machine.

5.4 Stock preparation and washing

Figure 5.11 shows the flow of pulp from the storage until the final sheet has been produced and stored in the warehouses. Pulp from the slab is fed into the Grubbens pulper at operating consistency of 5%. It is then pumped through raffinators for breaking fibre of chip bundle before storing in the pre-refining chest. From the pre-refining chest, pulp is passed through a series/parallel combination of refiners for fibre fibrillation that improve the final sheet properties. The degree of fibrillation is measured in terms of freeness, which is a measure of the pulp drainer-ability on the wire.

Freeness is a measure or an indication of the rate at which water drains through pulp under prevailing conditions. It is used as determining factor for setting of machine speed for good formation. Virgin pulp from the refined chest is mixed with other recycled feedstock into the blending chest. The operating ratio of virgin pulp to waste paper pulp is maintained at 45:50 with 5% broke. After blending the mix is then pumped to the machine chest as feedstock for paper making (Section 5.1.5).

5.5 Papermaking

Two systems are used for supplying top and bottom stock to the head boxes for production of twin-ply sheet. The stock is pumped via the fan pump to the head box before lying fibres on the fourdrier for sheet formation. Vacuum system is used on the forming boards for sheet consolidation before pressing. The sheet is then passed to the pressing section for fibre consolidated. After the press section the sheet moisture is maintained at about 45 to 50%. Felts on the press section are used for water removal and sheet consolidation.

The sheet is then guided through the first set of cylinders dryers by drying screens, as the sheet is still wet and does not have sufficient mechanical strength (measured in terms of burst-strength). From the second to the last (fifth) stage the sheet is dried by direct contact with the steam heated cylinders to the product moisture of less than 8%, before calendaring for surface properties consolidation (e.g. smoothness). The sheet is then rolled on the spools before being sent to the winder for cutting. These spools carry between 15 to 20 tons of paper depending on the actual sheet grammage. At winder the paper is cut into required size and sent to either customer by road or warehouse.

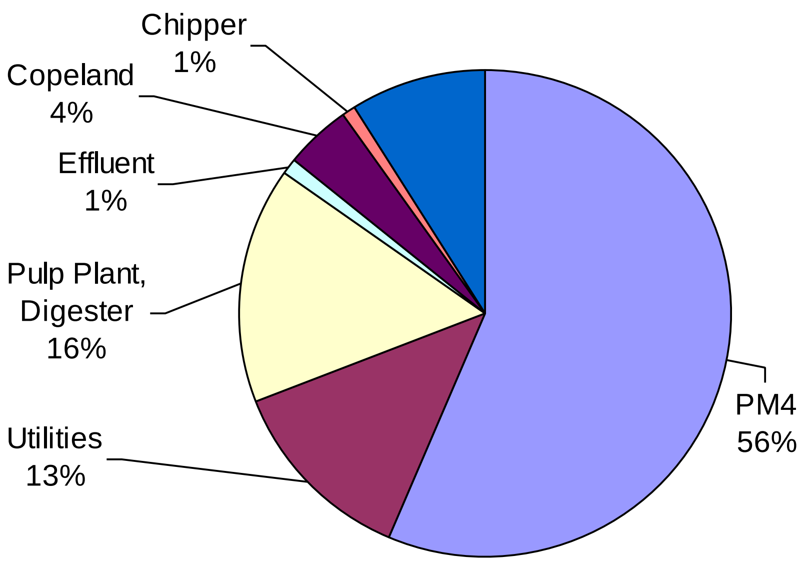
5.6 Spent liquor treatment process

Figure 5.12 shows the treatment process for WBL from the digester extraction until incineration in the Copeland Reactor. WBL liquor is subsequently pumped through a fibre filter to remove grits. The resulting filtered liquor is then concentrated in five stages counter-current evaporators from the feed solids of 19% to about 30 %. Low solid concentration is always avoided in practice for WBL due to foam tendency. The concentrating of WBL results in production of resulting concentrated black liquor *(*SBL*)* is stored in an intermediate storage tank. SBL from storage tank is pumped through a venturi scrubber, where it is concentrated to 50 % solids by the Copeland reactor flue gases. This forms heavy black liquor (HBL) that is very rich is organics (approximately 50%) and acts as reactor fuel and it is stored in the HBL tank.

Heavy black liquor is exothermically incinerated at 700^{O}C to produce salt cake (Sodium carbonate and Sodium sulphate salt) that is sold as a by-product. This combustion process is carried in the fluidised bed reactor (known as Copeland Reactor) producing about ± 50 tons. HBL is introduced in the fluidised bed through a conical spray with air disperser. A multi stage turbo compressor that fluidises the bed supplies the required oxygen for combustion process. All the dissolved organic components of black liquor are converted to carbon dioxide, water vapour and various other forms of pyrolysis products gasses, while the inorganic are oxidised to Na_2SO_4 and Na_2CO. The flue reactor gas is passed through the venturi scrubber for absorption soluble gases such as SO_2, NO_x that is reduced to 200 mg/l before releasing to the atmosphere.

5.7 Energy usage at Mondi Piet Retief

Figure 5.3 shows the total electrical energy distribution for MPSA Piet Retief with most of the energy used in the paper machine. The actual analysis for the energy usage on the machine is shown in Figure 5.4. The figure shows that most of the energy is used on the refiners, vacuum system and the paper machine dryers. The total energy usage on the paper machine accounts for 56% of the total site usage.



Figre 5.1 : Mondi Piet Retief Electricity Usage 2004
Total usage was 101,400MWh

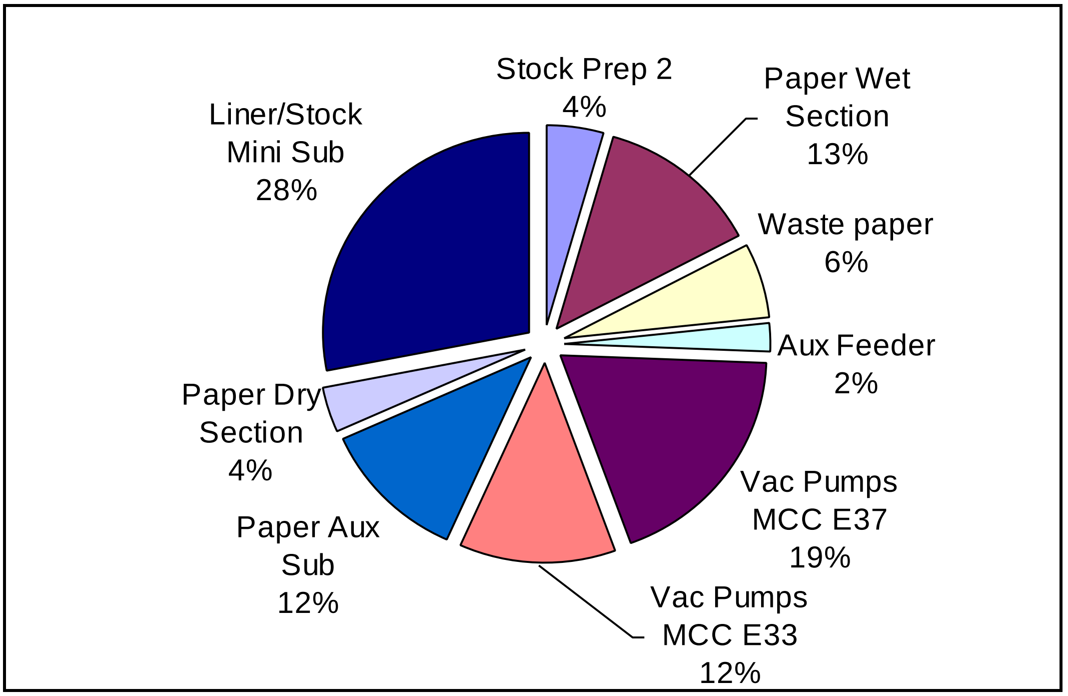


Figure 5.2: Actual energy breakdown on the papermachine

5.8 Electricity performance

Figure 5.3 and 5.4 shows the energy base load for both the pulp production section and the site electricity performance, the no production power for the pulp plant is 30% of the site energy usage, whereas site has 65%, this shows that the pulp and paper industry is energy intensive.

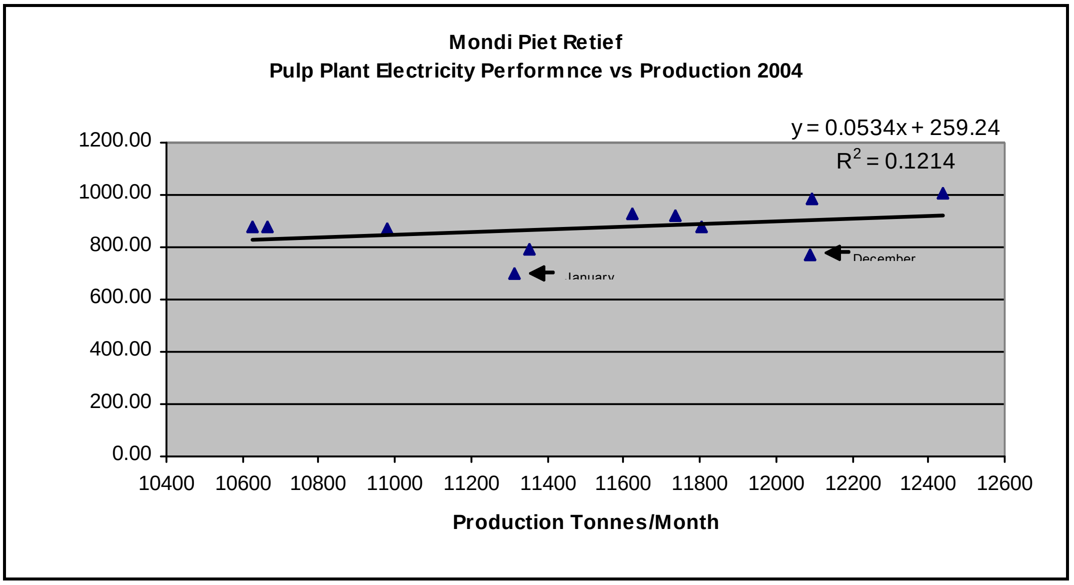


Figure 5.3: Pulp Plant electricity performance vs production rate

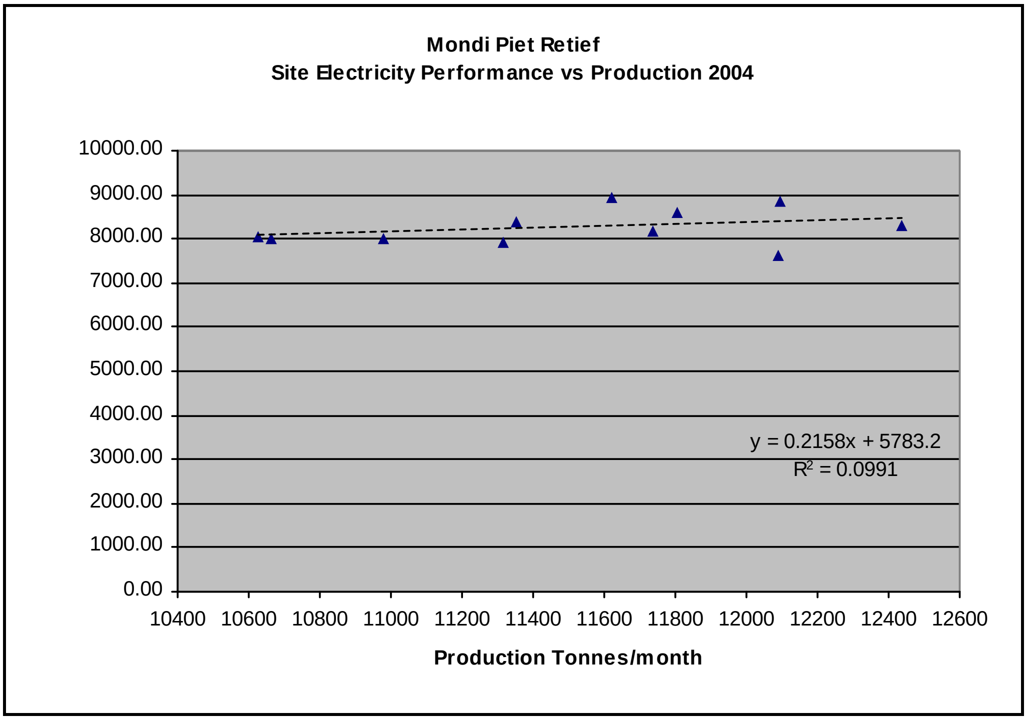


Figure 5.4: MPSA-Piet Retief electricity performance vs production rate

5.9 Steam performance

The site steam performance analysis was done with Figure 5.7 depicting the total site steam breakdown. Paper machine uses about 66% of the steam generated and the pulp plant only accounting for 16% for pulp production.

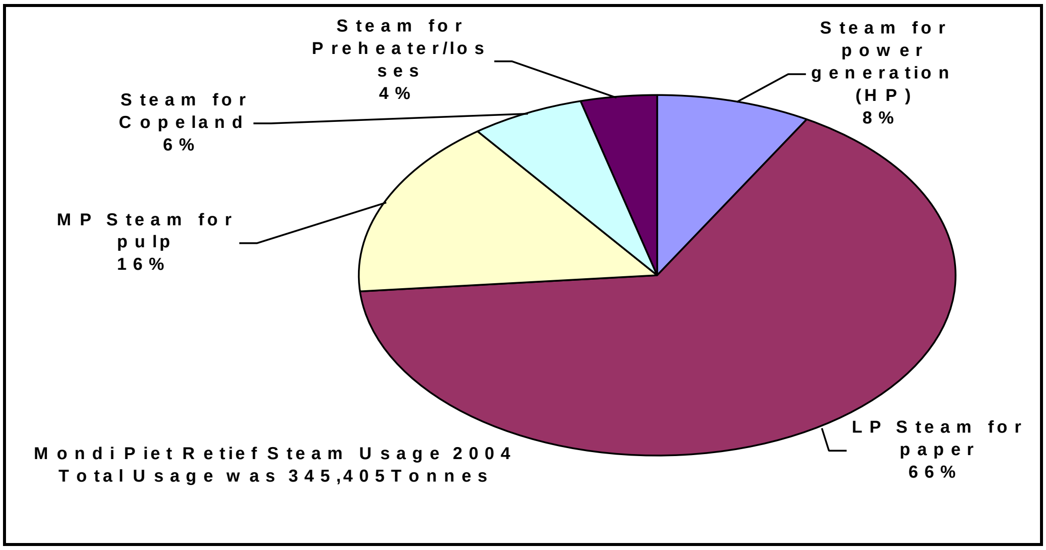


Figure 5.5: MPSA steam distribution

Figure 5.6 and 5.7 illustrates the paper machine and pulp production steam usage and the actual steam base load of 76 % and 79 % respectively. The base steam load is required irrespective of the equipments producing or not, the energy is requires to keep the equipments at operating temperature for both the digester and the paper machine.

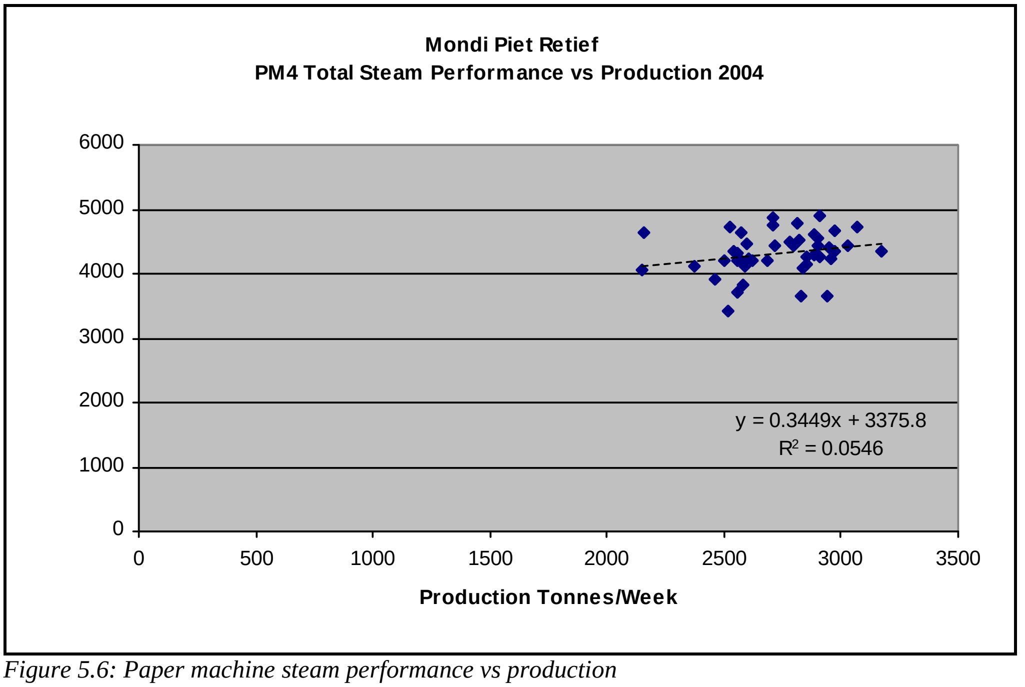


Figure 5.6: Paper machine steam performance vs production

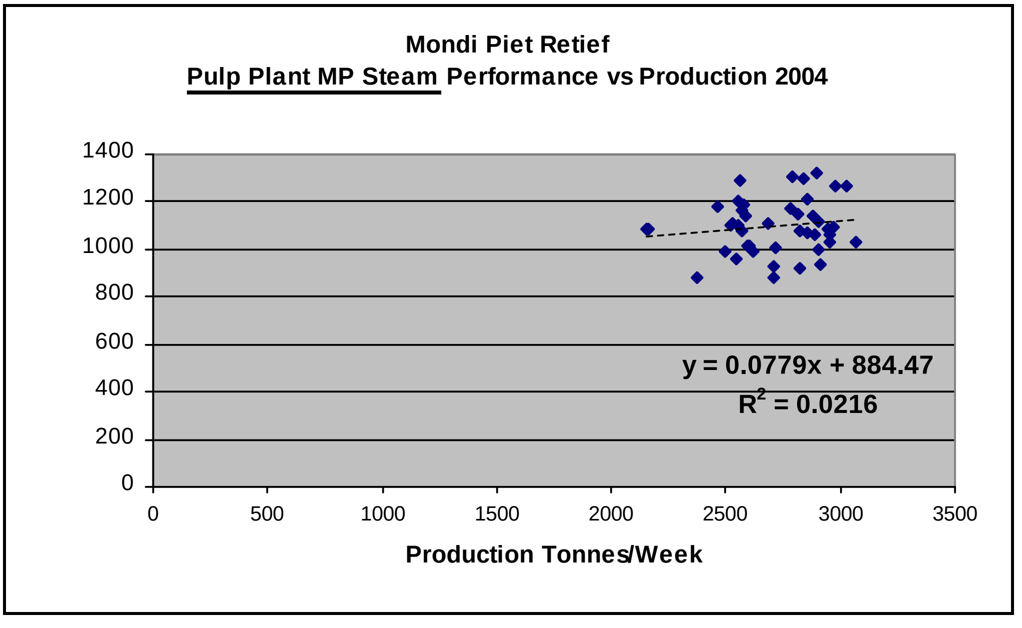


Figure 5.7: Pulp Plant steam performance vs. production

5.10 Conclusions

The most energy intensive stage in the Pulping and Papermaking process is the digestion and sheet formation stages. Both processes have also a high base load energy points and this increase both the process operating cost and environmental performance. This can be seen from figure 5.6 and 5.7 where the paper machine accounts for about 56% and digester alone uses about 16% of the imported energy with the balance driving the axillaries equipments.

5.11 References:

1. Barclay S, Kothuis B, Bull E, Buckley C, Kerr I, Mercer D, Pauck J, Cleaner Production audits, implementation and training in the pulp and paper industry, feasibility assessment report, Mondi Piet Retief, received July 2005.

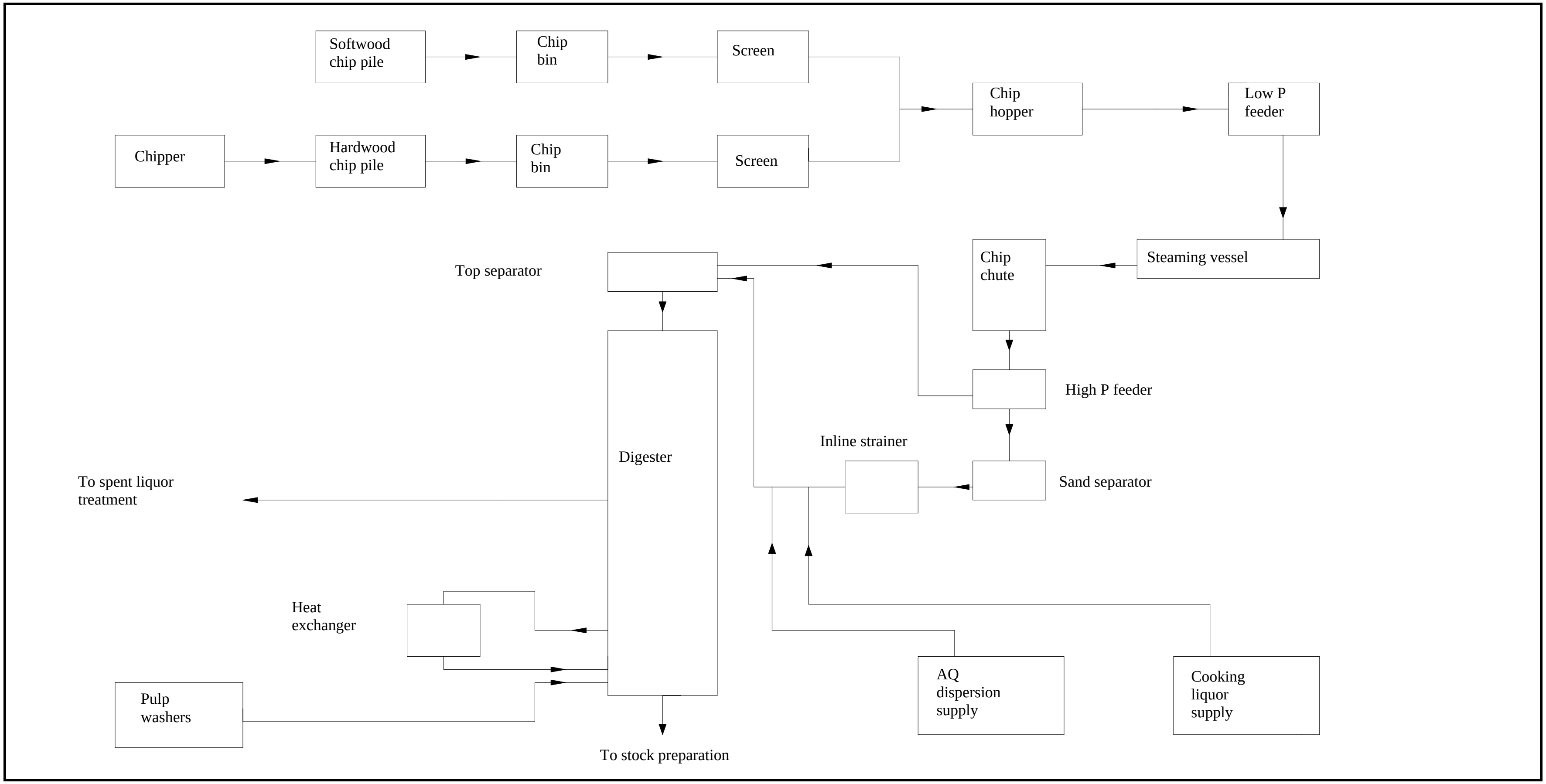


Fig 5.8: Block diagram of chip preparation and pulping at Mondi Kraft, Piet Retief.

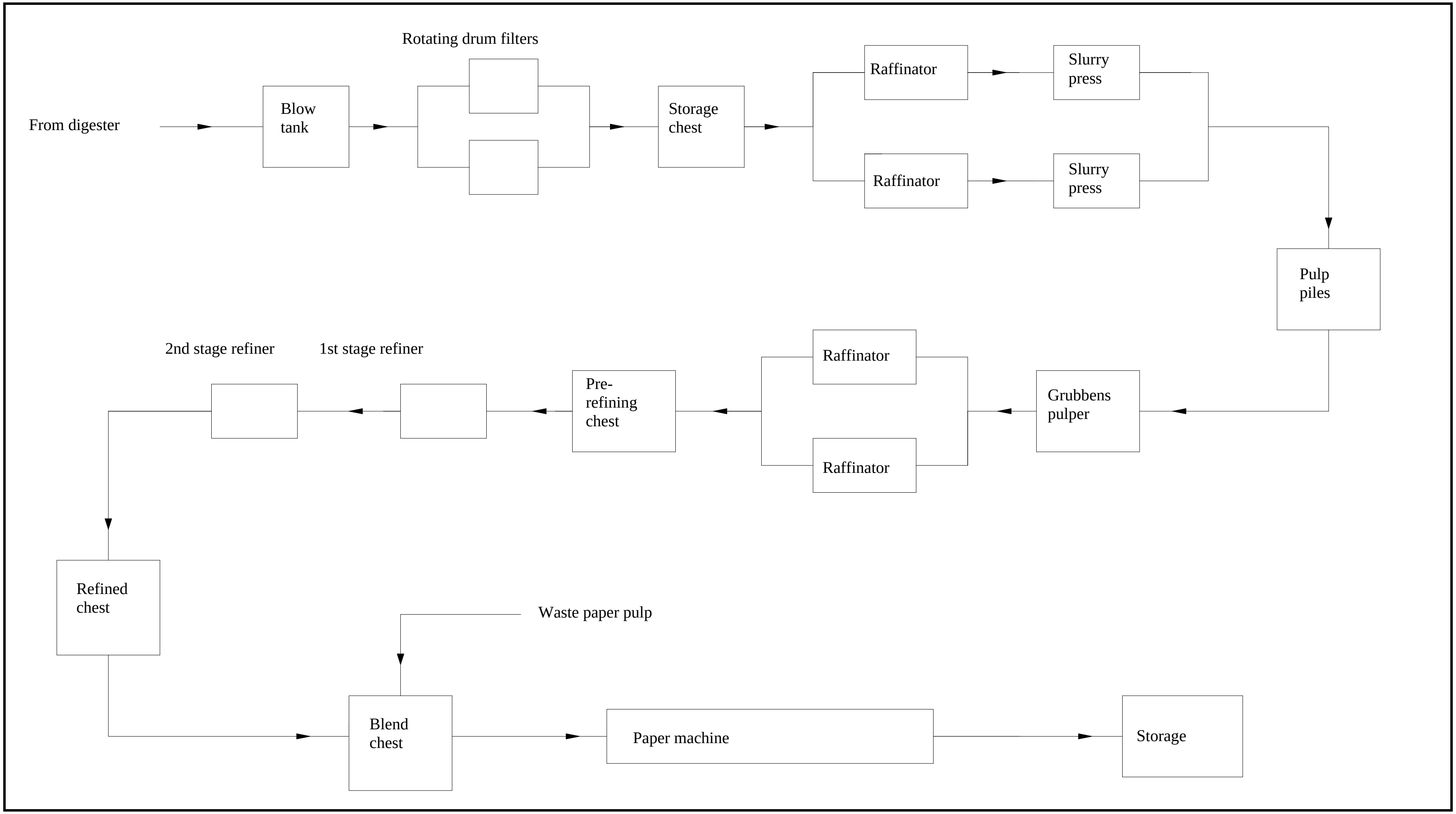


Figure 5.9: Block diagram of stock preparation and linerboard making at Mondi Kraft, Piet Retief

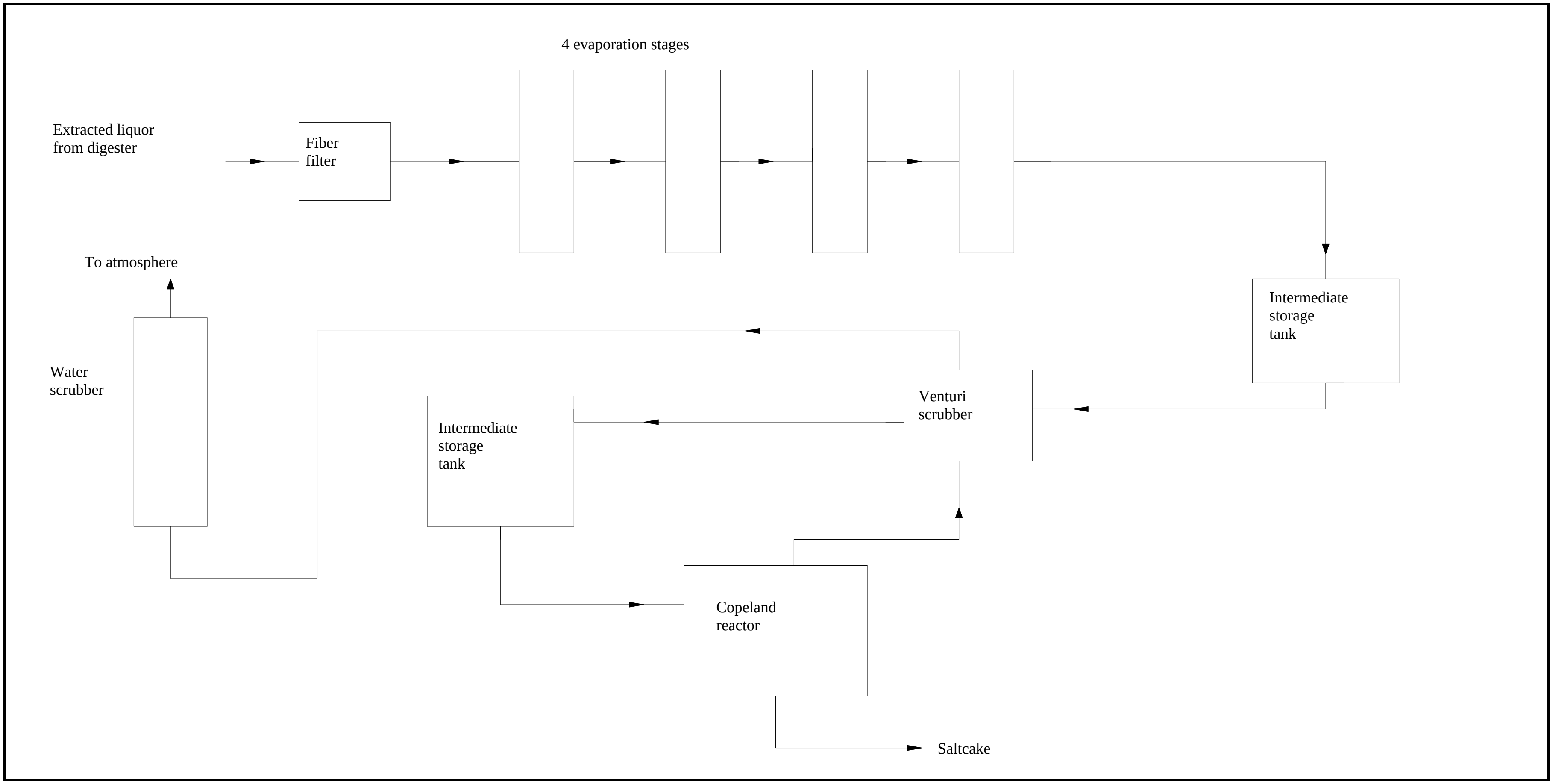


Fig 5.10: Block diagram of chip preparation and pulping at Mondi Kraft, Piet Retief

6.1 Introduction

This section develops the process-by-product input-output life cycle assessment analysis of co-pulping process; using the LCA technique in the form of the Chain Management Life Cycle (CML) methodology of Heijungs (1992). The analysis focused on the following processes (i) pulp process, (ii) steam generating processes, (iii) black liquor incineration and (iv) effluent treatment into consideration.

6.2 Co-pulping process in Paper industry

Co-pulping process is unique in that both softwood and hardwood are pulped simultaneously at different ratios in the continuous digester improve mechanical (strength properties (e.g. burst, tensile, tearing etc), structural properties (e.g. porosity etc), appearance (e.g. smoothness, shives, dirt etc), barrier and resistance (water absorbents) and permanence (e.g. smoothness, porosity). This is not a norm in the Pulp and Paper industry, as both the softwood and hardwood are pulped separately then blend together in the right proportion at the later stage (i.e. Mondi Richards Bay, Sappi Tugela and Ngodwana).This leads to optimal development of fibres to enhance the sheet characteristic by improving overall surface, and strength properties. But, it has a high capital requirement, as an additional digester will be required or alternative pay a penalty by importing pulp separately.

6.3 Pulping process

Hardwood logs are delivered from local saw mills suppliers with softwood chips being received from local chip suppliers. These logs are then chipped on site and stored in stock pile before being fed into the chip bins at the volumetric flow of 50% hard and softwood respectively. The chips are then screened at the shaker screen were about 10% (m/m) of fines is lost in the process. The chips classification is done using the screen mesh analysis were everything above 40mm is classified as overlarge and rejected, whereas anything less than 15 mm is characterise as fines and also rejected.

The chips are then screw conveyed at the controlled rate for the required production rate of about 150 bones dry tons per day. The chips mix with black liquor in the C4 circulation line for pneumatic conveying to the top separator and screened. Chips are then fed into the digester at a high-pressure 9.2 bar (gauge) at the operating temperature of 180^{O}C. Sodium sulphite, sodium carbonate and anthraquinone (AQ) are added as digestive cooking chemicals. This allow the chips to be cooked to the required hypo number of 175- 185 while maintaining the fibre yield of about 70%-75% by mass.

The blown out pulp is passed through a series of washing screens for removal of residual lignin such that it is maintained below 7.5 kg of Na_2SO_4 per bone dry per ton of pulp produced. This pulp is then pressed to the final moisture consistency of 45-50% before being conveyed to the slab. Another additional softwood pulp is imported from Swaziland's Usutu Mill for blending as a top sheet.

6.4 Black Evaporator liquor incineration

The weak black liquor extracted from the digester is stored in the WBL tank and fed to the counter-current evaporator stage. This weak black liquor is concentrated from 16% to 25% solids with the overall steam usage of 2.1 tons per hour, and defoamer is added at the rate of about 0.03 litres per cubic meter of WBL to prevent WBL from foaming. The problem with black liquor at high solids concentration is precipitation of calcium salt that forms a very hard scale, the actual tube surface scaling is minimised by operating at about 50% solids concentration.

The SBL (~26% solids) is stored in the SBL tank, where about 2% of flash steam is flashed to the atmosphere further concentrating the mother liquor to 30%. The SBL (at 30%) is then pumped to the scrubber as quench medium for the reactor flue gas and absorption of both SO_2, and NO_x. This mother liquor is then concentrated further to 50% and it is called heavy black liquor, which is very rich in organic content. The HBL is exothermically burnt in the Copeland reactor forming salt cake that is sold as by product. The mill specific salt cake production is 0.1 tons of salt cake per ton of paper produced. The main environmental concerns from black liquor incineration are the release of SO_2, NO_x and the carbon dioxide to the atmosphere.

6.5 Boiler and energy generation

The mill has four water tube boilers with only three operational, producing 55 tons of high-pressure steam per hour translating to a specific steam demand 3.28 tons of steam per ton of paper produced. These boilers are operated the different steaming ratio, which is defined as the ratio of actual steam produced per maximum capacity rating of the boiler. Boiler 1 &2 are each operated at the steaming ratio of about 90% while boiler 4 is maintained at about 80%. It must be mentioned that this method of measuring boiler efficiency does not lead to easy optimisation and efficient operation of boiler; because it is only based on the mass balance around the system and it does not take consideration the applicability of second law of thermodynamics.

High-pressure steam is then passed through a back-pressure turbine to reduce the exhaust pressure from 3000 to about 4 bar (gauge), giving about 1.5 MW of electricity in the process. The actual turbine efficiency for the mill is about 58.6 %, which is low than the values for properly designed turbines or expander that are usually in the range of 70 to 80% (Smith and van Ness, 1996). The additional energy is used for powering of critical auxiliary units during the production process, such as compressor and the Copeland Reactor. The source of energy for these boilers is a lower sulphur coal (~1.69% m/m), but the absence of any scrubbing medium on the stacks is still a concern, as combustion results in an unacceptable emission of NO_x, SO_2 and other nuisance gas. A new grit arrest has recently been installed for lowering of particulate emissions from 509.96 mg/m^3 to acceptable 200 mg/Nm^3, as a legal limit for particles emissions is stipulated for any boiler operation to kept below 300 mg/Nm^3.

Figure 6.1 shows the summary of the mill's steam distribution with the overall steam loss of about 15% mainly due to condensate losses, especially on the paper machine and pulp mill, steam traps, flash losses, and general site leaks.

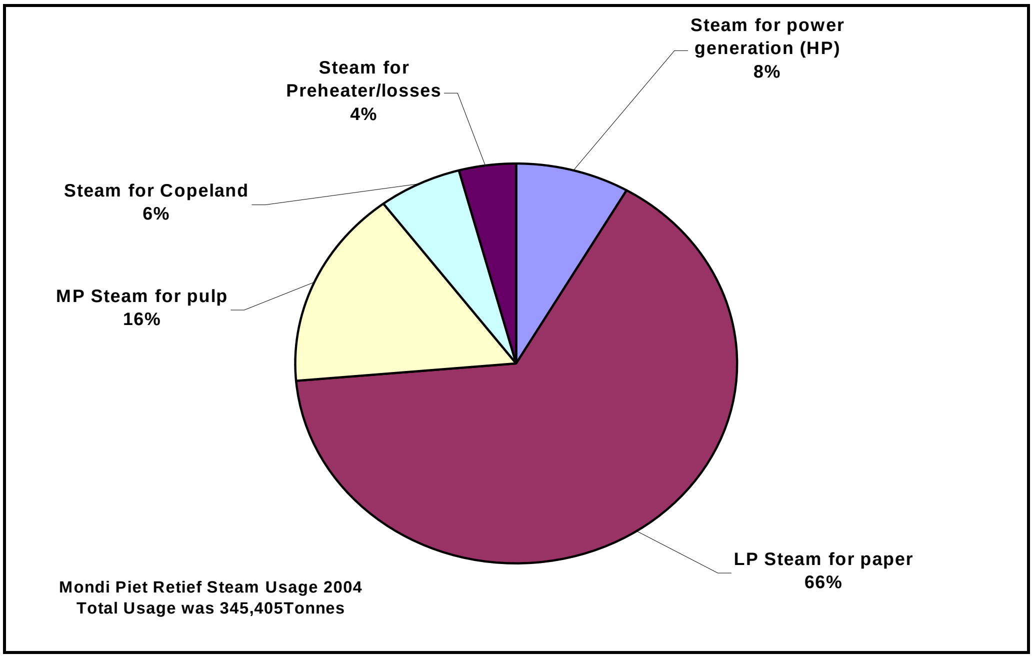


Figure 6.1: The mill steam distribution and usage

6.6 Papermaking process

Waste paper and NSSC pulp are both mixed in the blending chest and diluted to lower consistency through a series of dilution stages to a head box operating consistency of 0.09% (m/m). The fibres is then laid on the fourdrier and passed through a serious of felts for dewatering. The sheet ex-press moisture is maintained at about 50% (m/m). It is passed through a serious of steam-heated cylinders to the final dry sheet moisture of 92%. This sheet is then calenderer for surface properties consolidation and development before being stacked on spool. It is then sent to the rewinder for cutting and loading on trucks for transportation to different destination.

The sheet fibre and chemical retention is controlled at about 95% first pass retention; this retention rate is calculated by measuring the head box operating consistency and the backwater consistency. The ratio of the two consistencies is referred to as the first pass wire retention and it is controlled by adjusting the polymer flow to the machine headbox to aid with flocculation. Alum [Al $(OH)_3$] is also added on the machine to control the backwater pH. Black and brown dyes are used on the machine for controlling the sheet colour and shade.

Starch and polymer (which are organic sugar molecules) are added on the sheet for improving the overall sheet mechanical properties, such as bursting strength, tensile and tear. Biocide (which is chlorine based) is dosed on the backwater system, which is normally referred as the machine short water circuit for controlling of both slime and algae. Slime normally forms on the head box due to favourable condition that prevails. The circuit operates at about 30-40^{O}C and there is also abundance of starch. It must be mentioned that different chemicals are added on the paper machines to try and improve the sheet properties and control sticks, but their environmental impact is not well understood. Under this circumstance, LCA analysis provides a holistic view on the impact of these different chemicals; and the selection and use of different chemicals added on the machine puts a strain on the process engineers working in the section due to the absence of a holistic quantification approach.

6.7 Application of LCA methodology in the case study

Figure 6.2 shows an overview of LCA technique applied in this case study, which consists of three overlapping steps, namely: Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA) and; Life Cycle Improvement Analysis (LCImA). The first step in this LCA analysis was to set down the goals and scope of the study. It must be mentioned that LCA is an expansive systems analysis methodology and the analysis must be carefully focused in order to acquire meaningful outcome. Therefore, the concept of LCA has a goal definition and scoping as its center, and it is imperative before any analysis can begins. The aim of this case study was to evaluate both economic and environmental performance of the co-pulping process from gate to gate.

The second phase was the LCI which is an inventory of resource, materials and energy consumed, as well as environmental releases produced for each stage in the life of a product, from raw material preparation to ultimate disposal – which is what is meant by the terms, "cradle to grave" and "dust to dust" so often used in the LCA field. For existing process the process is slightly modified and is from raw material receiving to final product production and this is what is known as "gate to gate" approach.

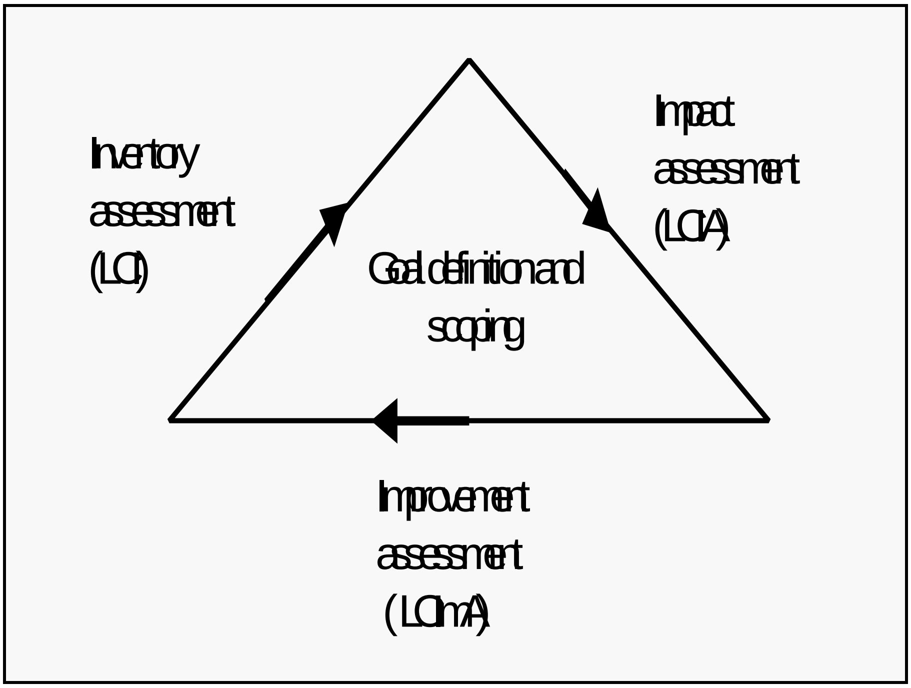


Figure 6.2: A typical Algorithm for conducting LCA

After collecting the required data, an LCIA of the environmental and health effects related to resource consumption and environmental releases was conducted. In fact, the LCIA begins to develop before the LCI is completed as impacts of priority concern are rapidly identified. The procedure is quantitative and qualitative in nature, as it categorizes, characterize and value environmental impacts to form a basis for comparison between dissimilar impacts (e.g., global warming vs. ozone depleting chemicals etc).

As the LCIA shapes up, the basis for the LCImA was formed, which identifies and provides a preliminary assessment of the changes needed to reduce environmental burdens of the subject product or process. The findings of this analysis are discussed later on and future recommendations are made about the financing of environmental projects for sustainable plant operation.

Figure 6.3 shows a typical procedure that was followed when conducting the case study's LCA. The step that is mostly left out in most LCA studies is cost benefit analysis, however the trends are gradually. LCA is now used as design and analysis tool for process improvements (9-10).

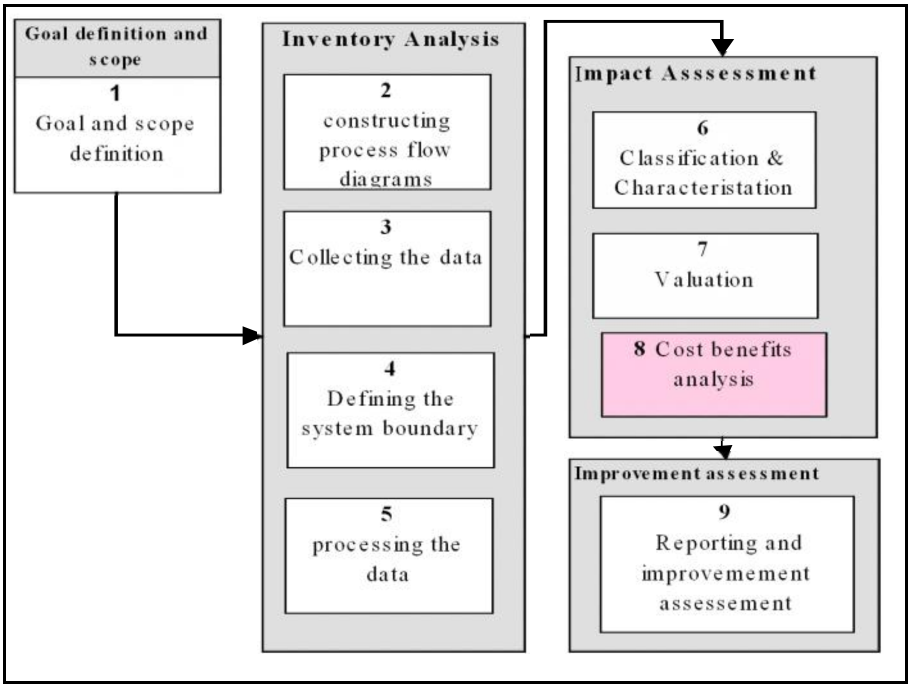


Figure 6.3: A summary of stages that are followed when conduction LCA

6.8 Goal and scope definition

Prior to undertaking the LCA study, its purpose must be clearly articulated. LCA's are comparative by nature and are best used when either evaluating a potential alternative to an existing activity, or in seeking to identify what choices (such as identifying or choosing between Best Available Technology (BAT)) are available and evaluating them. When a problem, such as an undesirable environmental impact, has been identified, or when there is a general interest in improving or upgrading a system, the questions being asked determine the goal and scope of the study. The process is concise, nonetheless critical because LCA is a systems wide approach that needs to be focused in order to avoid unnecessary investment in time and resources to activities that will not contribute to the final decision. In this case study, the LCA was conducted for a baseline Pulp and Paper production at MPSA-Piet Retief site, which includes a typical waste, NSSC, and broke combinations.

The purpose of this analysis was to apply the LCA methodology as a holistic tool for analysing of the NSSC co-pulping process with emphasis to both economic and environmental performance. The technique was further used to investigate the applicability of the LCA as a tool for process optimisation and evaluation

(Azapagic, 1999). Co-pulping process used at Piet Retief site formed the basis for the evaluation; as plant was constructed in 1965 before the recent technological developments tat are taking place. The capital and operating costs of the plant were obtained from the balance sheet. Whereas, other operating costs, commodity prices and working capital were obtained from the mill financial information or estimated from standard reference texts [Peters M.S, Timmerhaus, 1991; Faul and Pretorius, 1999].

It was assumed in this analysis that other raw materials such as AQ, sodium sulphite, sodium carbonate, and paper machine and pulp mill as well as power station additives are available at no environmental penalty (Ekvall et al, 2005). These processes form the background system that supplies energy and materials to the foreground system, by means of a homogeneous market so that individual plants and operations cannot be identified. The functional unit for this analysis was defined as a "Production of one ton of Linerboard." This description is adequate as a functional unit must describe the main function fulfilled by a product system and also indicate how much of this function is considered (Majozi and van Schijndel, 2005&6).

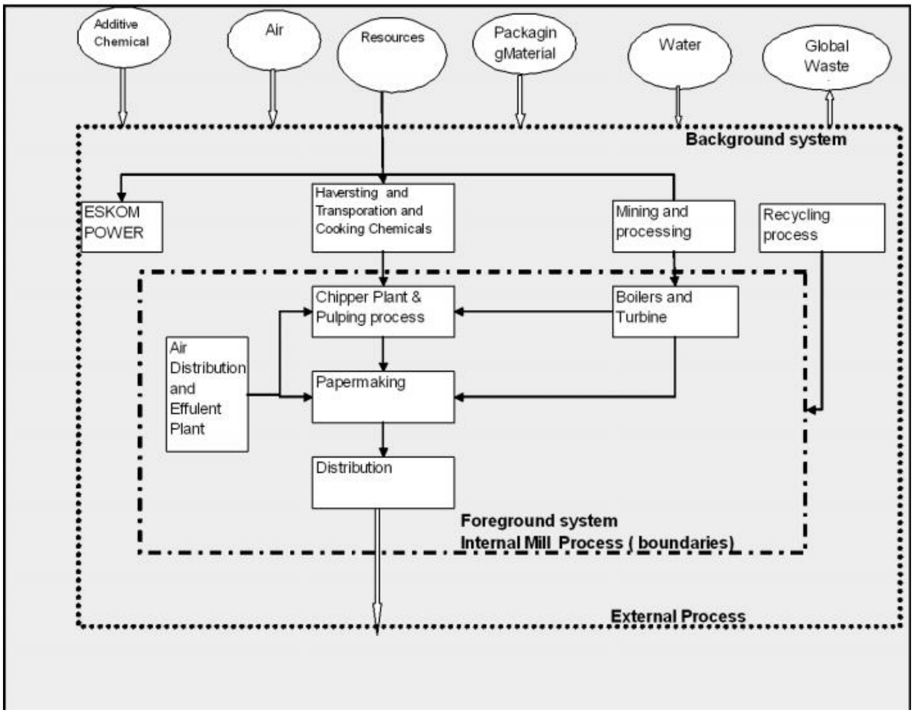


Figure 6.4: Gate to gate cycle of linerboard process for co-pulping process

6.8.1 LCA usage

Vyzi and Azapagic (1998), Azapagic (1999) demonstrated, for instance, how LCA can assist in process selection in the context of Best Practicable environmental option (BPEO) by comparing the three most common flue gas desulphuring (FGD) processes: wet limestone/gypsum, double alkali and sodium carbonate process. Their analysis showed LCA as a newly emerging Life Cycle Process Design (LCPD) tool that offers a potential for technological innovation in process concept and structure through the selection of best material process alternative over the whole life cycle. The most common methods used in industry for improving the overall company environmental profile are really based on heuristic rules, such as those used by Rocky Mountain Institute in the recent workshop at Anglo Platinum (RMI report, 2003)]. These techniques are based on the general waste minimisation principles or elimination. The “Seven wastes scenarios” which are normally considered under this heuristic rules are minimisation or eliminate:

1. Waste from overproduction
2. Waste of time,
3. Transport waste (energy),
4. Processing waste
5. Inventory waste
6. Waste of motion and
7. Waste of poor quality. All the steps above have their basis on the application of LCA, but applied as stand alone their results cannot be quantified easily.

6.9 Inventory analysis

In order to accomplish the goals of the LCA, data must be collected or calculated. The LCI methodology collects or calculates data by focusing on material and energy balances of each operation within the system or for the entire life cycle of the system. The LCI has to be as complete as possible in order to provide the data relevant to the final decision. In instances where estimates have to be made, they must be conservative and clearly noted.

Data quality vary upon the source and care was taken in order to ensure the data used is the best available and that the sources are contemporary. For liner-boarded production, the LCI involved collection of environmental and utility data that describe the production system, including the raw materials used, water and energy, air emissions, liquid wastes, and solid wastes. A simplified process diagram of the production of the linerboard was presented in Chapter 5, with some details given above.

6.10 Data gathering

Data with respect to the NSSC pulping process was mainly obtained through two methods.

- Mass and related energy balance for the following subsystem were performed to determine the flows and corresponding percentage loss. This includes: boilers, steam distribution system, evaporators, Copeland reactor system, digester plant and the paper machine.
- South African literature and international publication where South African data could not be obtained, with particular emphasis on the type of ecosystem associated with the region where pulping and papermaking is assumed to take place.
- Lastly the economic data was obtained from the company financial reports.

6.11 Data quality

Data quality is vital in any LCA study as it affects the quality of the output. Data quality is normally analyses in terms of validity, i.e. representative of the life cycle system, and reliability, i.e. the completeness, variability and uncertainty of the data (Raynolds et al., 2000). Although the data used is representative of the life system, there is still uncertainty about its completeness.

Forestry operation which affects the quality of chips supply vary accordingly to age and location and geographical conditions, i.e. the resources-use for pulp production is depended on the regional and climatologically conditions. Also, a comprehensive survey or element analysis of each process stream is required to ensure completeness and reliability. This is obviously not possible c because of trading secrets and difficulty in establishing the active ingredient of some special chemicals used. Real time data was used in this analysis is as it was taken from operating plant.

6.11.1 Modelling of the emissions data

Mass and energy balance were performed for different sections of the mill to establish the actual loss and emissions to the atmosphere. The data was compared with the field metering information and the difference was mainly attributed to leaks and losses to the surrounding environment. The accuracy of the metered information is good because most of the metering units in the mill are calibrated annual. To check for consistency and completeness the data was compared to similar studies (Vyzi, 1998; Kniel, 1996).

A. Allocation of environmental impacts

Figure 6.3 shows the outline of an existing pulping process at Piet Retief site. The overall plant energy requirements are supplied by a combined heat and power stream system and external power. Table 6.1 show details of the present steam use, raw material preparation and cooking chemicals consumption. The balance for this calculation is based on the daily pulp production of 150 BDt/day.

The plant specific steam usage is 1.8 tons of steam per ton of pulp with the wash water extraction rate of 1.2 m^3/ton of pulp. The heat exchanger circulation rates are kept at 0.3 and 0.15 m^3/bdt. These settings are normal operating condition for maintaining both the cooking and wash water temperature. The cooking digester zone is maintained at $180^{O}C$ by using high-pressure steam and the digester chip moisture is maintained at 39% (m/m). Wet chip leads to pitch deposit and dry chips do not form a good plug flow in the digester, causing channelling problems. Digester steam and chip losses are estimated to be about 4% and 10% respectively. These losses are due to leaking glands, and inefficient screening process and steam vents to the atmosphere. Table 6.1 shows the summary of the mass and energy balance for the pulp production process and the process losses contributing to different environmental categories are shown in Appendix A. The losses were estimated by comparing the mass balance figure with the actual metered readings and the differences was due to losses. As for the fines chips the actual number of skips taken offsite were counted.

The process uses about 8.6 tons of 50% moisture of both soft and hardwood respectively. With the average operating yield of 70-75% producing 6.2 ton of fibre with the black liquor extraction rate of 25.4 tons per hour. The WBL is then burnt in the Copeland Reactor. Black liquor is made of 34% inorganic salts, such as sodium carbonate and sodium sulphite and other form of impurities such as sodium chloride and silica. Sodium chloride is must be kept below 0.5 ppm due to its impact in the operation Copeland reactors.

HEAT AND MASS BALANCE EXISTING			
	tph	t / bdt pulp	MJ / hour
INPUT			
Chips - wood @ 39% moisture	8.6	1.45	372.9
Chips - water	5.7	0.95	699.7
Rejects - wood	0.2	0.04	28.5
Rejects - water	0.7	0.11	219.6
LP Steam + flash	0.7	0.11	1814.0
C5 heat exchanger **	0.0	0.00	0.0
C6 heat exchanger **	1.3	0.22	832.2
C8 heat exchanger **	1.6	0.26	18.9
MP steam direct	11.2	1.88	31215.8
Brown liquor	7.5	1.25	2536.8
White liquor	6.3	1.05	1962.8
Heat of reaction			11207.9
TOTALS	40.9	6.8	50908.9
OUTPUT			
Pulp and rejects	6.2	1.04	912.6
Liquor with pulp	6.2	1.04	2523.0
BL to EDA	25.4	4.25	10015.6
BL heat exchanger cooling water **	0.0	0.00	0.0
Vapour to terp cond ex pre steamer	0.2	0.03	542.9
Vapour to terp cond ex cycl 1	0.5	0.09	1435.0
Vapour to terp cond ex cycl 2	2.9	0.49	7792.1
Vapour to atmosphere	0.2	0.03	526.7
TOTALS	41.7	7.0	23748.0

Table 6.1: Summary of the mass and energy balance for pulping process

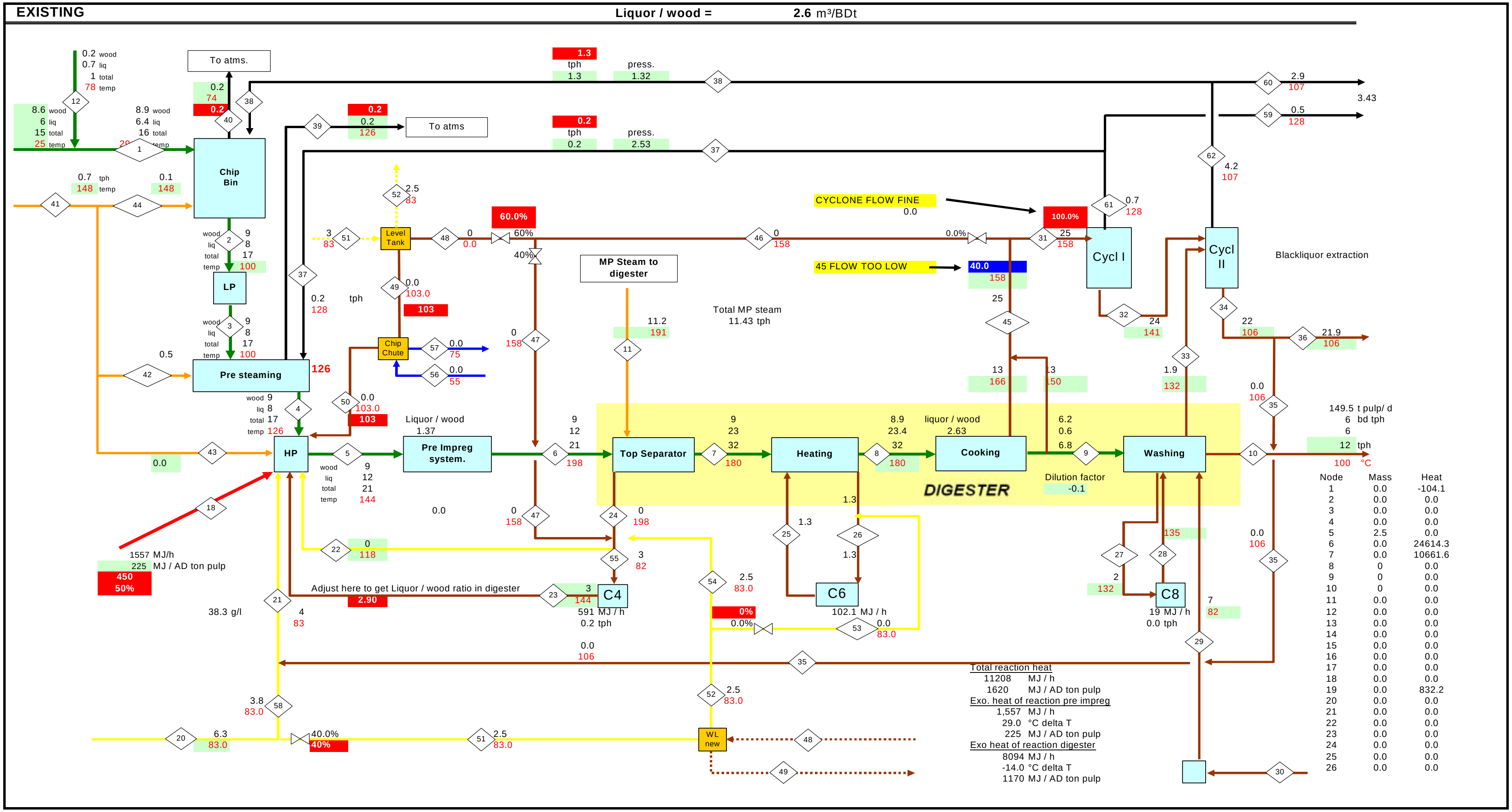


Figure 6.5: Summary of the mass and energy balance for pulping process at MPSA-Piet Retief

B. Evaporator process

Figure 6.6 (Appendix B) shows the outline of an existing evaporator's section where weak black liquor is concentrated from 16.1 % solids to about 23.97%. These evaporators are counter-current flow configuration with the total steam usage of about 3.61 tons per hour. About 33 t/hr of weak black liquor is processed to produce about 23.1 tons per hour of SBL using 3.61 tons of low-pressure steam at 400 kPa (gauge) at the saturation temperature of 121^{o}C.

Table 6.2 presents the summary results of the flows for the evaporator section. All the section gland water is lost to the sumps and some black liquor due to leaking glands and tank overflows. Combined condensate (produced from evaporation) is used for floor washing as well as making up of the washing system. The balance does not include evaporation losses and cooling tower drift losses. The basis of calculating these flows is given in Appendix AI, with the operating inlet flow of 550 l/min. To calculate the stage evaporation rate, the product solids were experimentally determined using the density method. This stage product solid becomes an input to next stage. The energy balance for each stage was calculated using methods given in standard reference texts (Kenneth, 1990; Kern, 1958).

Inputs	**Units**	**Used**
LP Steam	t/hr	3.61
HP Steam	t/hr	0.5
Defoamer	l/day	40
Gland water	m^3/day	277
WB liquor	t/hr	33.00
Biocide	kg/day	8.33
Outputs	**Units**	
Waste H_2O		277
SBL liquor		23.10
Steam losses		0.00
Solid Waste	kg/min	1.38
CC loss	t/day	0.19
Return Condensate loss	t/day	0.11
Black liquor	t/day	0.66
HP steam loss	t/day	0.5

Table 6.2: Summary of the mass and energy balance for evaporation process

C. Copeland Reactor

Table 6.3 presents the summary of the results obtained from the combustion of 205 litres per minutes of black liquor with 660.04 kg/min of air. About 35.76 kg/min (51 tons per day) of salt cake is produced during this highly exothermic reaction at about 700°C. The flue gas from the reaction contain carbon dioxide, nitrogen dioxide, excess oxygen which is required for avoiding the generation of poisonous carbon monoxide and water vapour. This flue gas is scrubbed to remove soluble gases from the plume.

Inputs	**Units**	**Used**
Air		
Nitrogen	kg/min	520.11
Oxygen	kg/min	138.61
Other gas	kg/min	1.32
Black liquor	kg/min	205
HBL liquor		
Sodium	l/min	15.147
Potassium	l/min	1.683
Sulphur	l/min	3.366
Carbon	l/min	31.977
Hydrogen	l/min	3.366
Oxygen	l/min	27.7695
Chlorine	l/min	0.42075
Water	l/min	
Other	l/min	1.025
Steam	t/hr	0.5
Charcoal	kg/min	1000
Paraffin	m^3/min	4
Quench water	l/min	40
Outputs	**Units**	
Salt Cake		
Na_2S	kg/min	7.79
Na_2SO_4	kg/min	0.75
Na_2CO_3	kg/min	23.13
NaCl	kg/min	0.69
K_2CO_3	kg/min	2.97
Other	kg/min	0.42
Emissions		
Flue gas	kg/min	
CO_2	kg/min	112.874
N_2	kg/min	520.114
O_2	kg/min	122.890
H_2O vapour	kg/min	151.144
Other gas	kg/min	1.320

Table 6.3: Summary of the mass and energy balance for Copeland Reactor process

D. Boilers

Figure 6.7 (Appendix C) shows the outline of an existing power plant. The power plant air usage and emission gases were calculated based on the four main gas reactions occurring in the combustion chamber:

$$C + O_2 \rightarrow CO_2 ....\Delta H(kJ/mole) = -393.509$$
$$S + O_2 \rightarrow SO_2 ....\Delta H(kJ/mole) = -296.83$$
$$2H_2 + O_2 \rightarrow 2H_2O.............\Delta H(kJ/mole) = -241.818$$
$$C + O_2 \rightarrow CO......................\Delta H(kJ/mole) = -110.525$$

The three boilers supplies a total steam tonnage of about 54.84 tons of steam and 54.23 MW of energy to different sections of the mill. Based on the average hourly paper production rate of 16.7 tons per hour the specific steam usage on the machine is about 1.98 tons of steam per ton of paper. These boilers are operating at the maximum combustion efficiency of 92.8 % and the overall steaming efficiency of about 25%, which despite improvements in equipment design, the efficiency of conversion is still relatively low (values greater than 35% are uncommon), as consequence of the second law (Smith and Van Ness, 1996; Seider,1998). All the emissions associated with the combustion process are not treating on site and are directly released to the atmosphere, except the fly ash and unburnt coal that is controlled below the legal required 200 mg/Nm3 with an aid of grit arrestors. Other emissions are abated through procurement process, as only low sulphur content coal is only acceptable on site. This is not sustainable in the long term due to the energy prices fluctuations. The full energy and exergy analysis for improvement of energy usage at Piet Retief mill is given in Appendix D, including the summary of direct emissions to the atmosphere.

Exergy analysis is imperative in any energy distribution system as it is a guiding tool for optimisation of the system overall energy efficiency (Gaggioli et al., 1991; Petit et al., 1980; Sama et al., 1988). The steam distribution system exergy analysis was performed using methods given in standard reference texts (Petit, 1980; Sama, 1989; Smith and Van Ness, 1996; Seider, 1998). It is very clear from the analysis that both turbine 1 and 2 are underutilised, as the maximum energy that can be recovered from them is 2.5 MW and 4.99 MW respectively. But they are both operating at 1.5 MW and 2 MW respectively, which translates to 58% efficiency. Also there is a significant exergy lost across the pressure reducing control valves that are used to regulate the pressure at different manifolds. The is about a loss of about 2.48 MW exergy lost on the LP header mainly due to mixing of two or more streams of material that differ in temperature, pressure and quality. This mixing leads to significant increase in entropy, but it may be unavoidable in some instance.

The second law thermodynamic efficiency of the mill steam distribution system is about 44.94 %, based on total inlet exergy of 20.27 MW and the output exergy of 9.11 MW to different section of the mill. This is accordance with much industrial process thermodynamic efficiency, which is in the range of 25-30% (Seider, 1998). However economic analyses have shown that it is worthwhile to seek ways to improve this efficiency to at least 60%. The system thermodynamic efficiency can be increased by returning turbine 2 online as 2.5 MW of useful energy will be available. This will increase the current thermodynamic efficiency of the system to about 57.27%.

E. Paper machine

The mass balance on the paper machine is based on the daily production rate of 400 tons per day; with different chemical specific consumption of both mechanical, chemical properties development. The chemicals added on the machine are for chemical properties development, namely alum and size for sizing, which is the alteration of sheet property for moisture resistance. Polymer is used for the first pass retention on the four drier that is maintained at more about 96%. High retention is necessary for sheet surface consolidation and smoothness as well as printability. Betonite (clay) is added for actual improving of the sheet surface and lastly black and brown dye for shade and colour.

The machine uses about 30 tons per hour of low-pressure steam (400 kPA) and 3 tons of high-pressure steam for actual drying of paper with total electrical consumption of about 157.60 MWh for driving of different section (Chapter 4). The actual raw material used for sheet production is NSSC, waste that is divided into K4 and K3. The trend in the market is to move to 100% recycled paper due to fibre shortage and the new market is the east. Figure 6.8 (Appendix E) shows the paper machine air, waste and effluent emissions based on the global mass balance of the paper machine. All the internal streams were not considered in the balance, as they are deemed not necessarily, as they do not contribute to different environmental categories because the streams are treated internally.

6.12 Boundaries setting of the case study

The actual uses and final disposal of sheet is not included and the lie cycle, this study is therefore a gate-to-gate assessment of the actual manufacturing stages of the Linerboard at Piet Retief site (Section 6.4). All the process that serve to provide input streams into the product cycle, and which are included in the boundaries of the study, are determined by the relative mass, energy and economic value of the input streams compared to the functional unit (Raynolds et al., 2000).

Accordingly to the Relative Mass-Energy-Economic (RMEE) method, unit process with a mass and energy and economic ratio less than 0.05 compared to the functional unit will contribute less than 5% of the overall environmental impacts of the life cycle system, that is a cut-off ratio of 0.05 has a means of 99.38% of the total environmental burdens with a confidence interval of 95%.

The functional unit of this study does not have an actual energy value. In case of the energy comparison, the contribution of an input stream to the overall input of the linerboard life cycle system is considered, i.e. an energy ratio of less than 0.05 compared to the whole system is again used as the cut off criteria. It must be noted that predicaments have been associated with cut-off procedures in the life cycle studies. However, for the simplified case study, the RMEE technique is assumed adequate to determine the most vital process that contributes to the impacts of the overall system.

6.13 Inventory Data

The values of the unit process of sections have been altered accordingly to the produced functional unit and they are summarised in Table 6.1 (Appendix A), i.e. the input and output parameters of the unit process are determined by calculating from the gate (bottom of the table) to the gate activities (top of table).

The following process have been omitted from the life cycle system and the completeness of the inventory data is thereby reduced (section 6.5.4)

- Effluent treatment plant. The costs (30 cents per m^3) of effluent treatment programs are significant in terms of the RMEE method and the supply thereof should be included in the study but little is available for the effluent. However, the actual emissions are included as effluent loading on the paper machine.
- Demineralised water treatment plant. The actual mass flows are significant (1.25 m^3 per ton of paper). The environmental burdens associated with these unit process are not considered as important as those directly related to the production system, but should be included in the future expansion of a detailed Kraft liner life cycle.
- Chemical material. The RMEE method excludes the required materials (except any chlorine component) from the study. E.g. dyes, detergents, acids, etc, but the true environmental impacts associated with the production of these materials should be considered in a detailed study.
- Solid waste site operation. The local authority of S.A differs when the solid waste from sheet production is classified in terms of national regulation. Also impact associated with the final disposal of the solids waste are dependent on the type of landfill site specified by local authorities. Due to these uncertainties the landfill site operations and its related environmental burdens have been excluded from the case study. Furthermore, the release of pollutants from properly managed disposal sites are presumed to be considerable less compared with the direct process realises to ambient environment.
- Impacts associated with general operations of the manufacturing facilities, infrastructure, i.e. air conditioning, lightening, on site transportation, and fuel, labour impacts, etc have not been included in the simplified life cycle inventory.

6.14 Classification

Classification is the process of assigning and aggregating results from the inventory into relatively homogeneous impact categories. The process involves identifying stressors and organizing them by impact on the ecosystem. For example, carbon monoxide, chlorine and methane are all stressors with the potential to impact the environment under the following different categories global warming, acidification etc. Classification involves the creation of complex stressor/impact chains, because a single pollutant can have multiple impacts, and a primary impact can result in secondary (or greater) impacts as one impact results in another along the cascading impact chain (Chapter2). For linerboard production, nine impact categories were selected for characterization: smog formation potential (POCP), ozone depletion potential (ODP), acid rain potential (AP), global warming potential (GWP), human health inhalation toxicity, terrestrial toxicity, aquatic toxicity, land use, and natural resource depletion. It must be note that this type of contribution analysis also serves as a focus for the sensitivity analysis (RMI Report, 2003).

6.15 Perturbation analysis

In a perturbation analysis, the effects of small changes in the parameters that describe the system are studied on the overall results of an LCA (RMI Report,2003). The effects of these small changes are calculated simultaneously for all the flows of a system, i.e. economic flows and environmental interventions. The analysis may be performed at different levels of aggregation: inventory tables, indicator results, normalised indicator results or weighting factors. All the factors used to calculate the aggregated result are included in the perturbation analysis.

6.16 Sensitivity and Uncertainty analysis

If LCA is to be usefully employed as a decision making tool, the robustness of the results must be clear. A basic distinction must be made between accuracy and precisions. This is always a difficult task to ascertain in most industrial operations, as some data are precise but inaccurate and other are accurate but not precise. The result of calculations is sensitivity to several source of uncertainty, such as uncertainty in data, variable data. To smoothen data and reduce uncertainty the specific chemical consumption for individual process are measured over a year period.

6.17 Life Cycle assessment Impact analyses (LCIA) results

In the characterisation step, the in-and outputs are attributed to all relevant impact categories and the contribution to the different impact categories calculated based on the characterisation factors/methods chosen. All in-and outputs are taken to contribute to these categories to their potential full amount, which means that we do not account for the possible occurrence of parallel impacts (= the contribution of the substance to one impact category diminishes the contribution to another) to occur. The characterisation factors used in this study are listed in Appendix H, and they are based on the CML method.

Characterisation results of the chain management life cycle assessment (CMLCA) methodology for linerboard production are shown in Figure 6.6. The processes that mainly contribute to production of linerboard impact categories of the CML procedure are the pulping process, energy and steam generation, Copeland reactor, evaporators and Paper machine (PM4). The solid waste emissions are the result of the reject chips, waste paper and salt cake. Human toxicity is due to the emissions of SO_2, NO_x and salt cake dust, especially in the Copeland area and boilers house. Global warming potential contribution of the Piet Retief site is due to the total CO_2 produced from the Copeland Reactor and the boilers section. Eutrophication potential is due to the total mill's total COD load in the wastewater. Lastly, aboitic resource depletion potential is mainly due to coal usage. Copeland reactor and the boilers are the main contributes to the number CML categories.

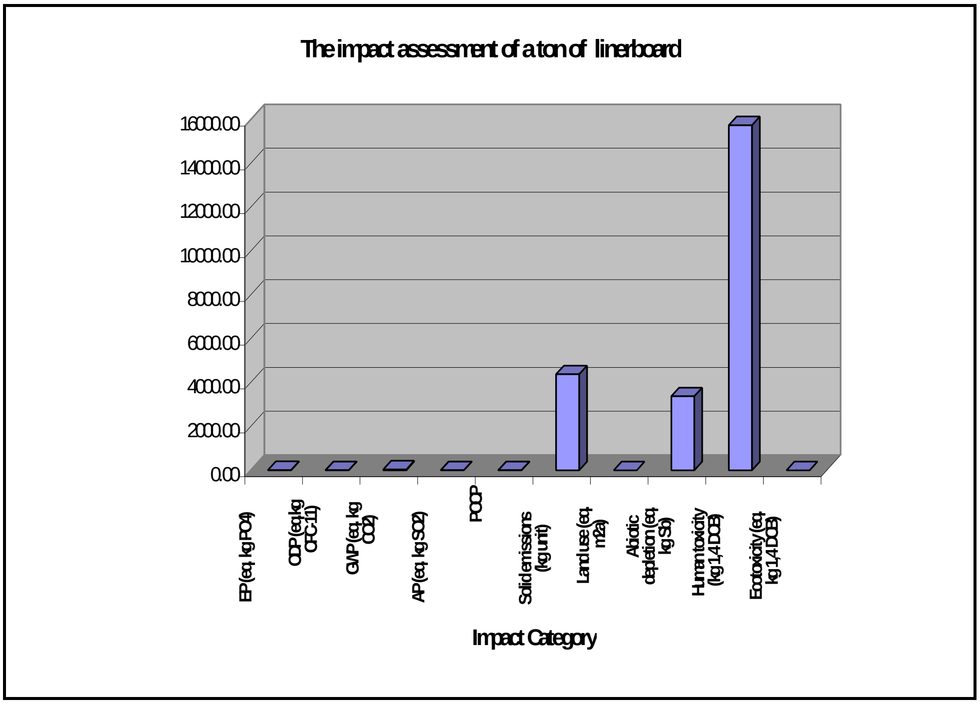


Figure 6.6 Characterisation results of the CML LCIA procedure

In the normalisation stage, the indicator result per impact category is given as a fraction of the reference contribution of a certain region or person, over a particular interval of time, to this impact category. Among these reference contributions (normalisation data) one find the annual contribution to the impact categories under consideration per the entire world. This step makes it possible to compare the contributions of the different impact categories, since they are now in the same dimensions: e.g. a fraction of the annual worldwide contribution to this category. As a step towards grouping and weighting, normalisation is often indispensable (Gorree et al., 2000). In this study, the results are normalised based on the contribution of the world in 1990 to all categories.

Normalisation results of the CMLCA method for linerboard production are shown in Figure 6.7. The normalisation procedure shown in the Figure 6.7 is based on the actual or calculated world inventory data of the CMLCA. Using the world data show that Aboitic Resource Depletion Potential, Ozone Depletion Potential are the most important environmental category accordingly to the CML method. This is the cause for concern for the mill with the ever-increasing energy price and decline quality of coal.

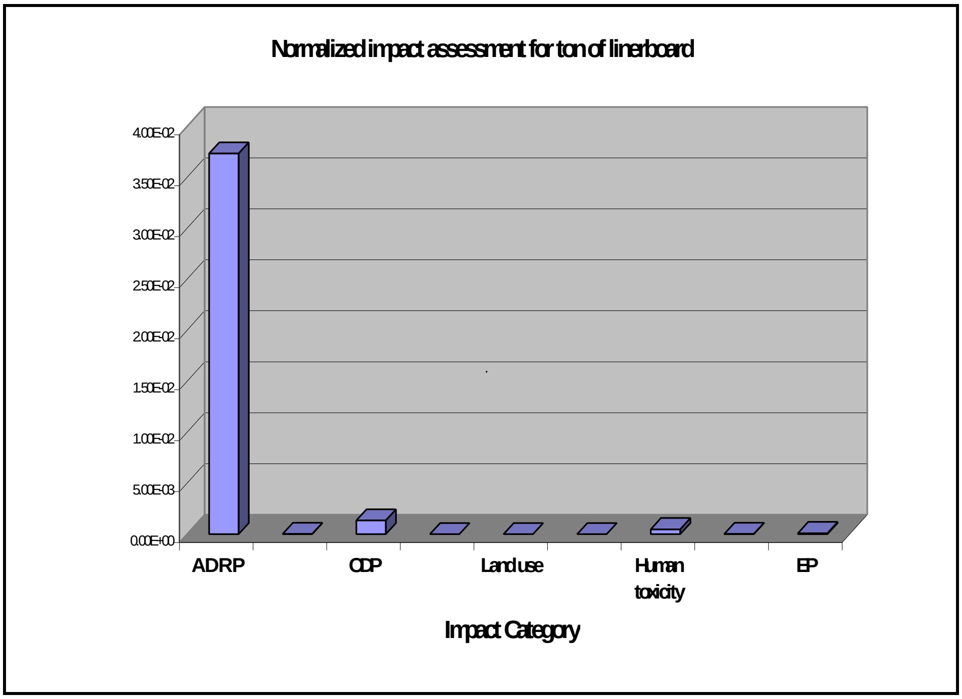


Figure 6.7: Normalisation results of the CML procedure

6.18 Valuation and economic performance

Valuation phase involves assigning relative values or weights to different impacts, economic and performance measures, so that a total score for all decision criteria should be determined. The valuation method used in this study is the Analytical Hierarchy Process (AHP) (de Vaal, 2005). The AHP process involves a structured description of the hierarchical relationships among the problem elements, beginning with an overall goal statement and developing a decision tree, where the branches of the tree include major and minor decision criteria. Assignment of weights was done as a group exercise, where a four-member team was asked to reach a consensus on the weight factors prior to their being entered into the model. Because the team included one process engineer, one environmental engineer, a production foreman, and an ecologist, the valuation team mix, and the resulting weights, were considered reasonable. Table 6.4 shows the summary of the weights the team agreed on. These weights were then used to calculate the actual site environmental index and use it in the economic model.

Impact Category	Impact Weighting
A R	0.05
POCP	0.04
ODP	0.10
GWP	0.25
Land use	0.15
Ecotoxicity	0.12
Human toxicity	0.12
AP	0.17
EP	0.00
Total Score	1.00

Table 6.4: Mondi Packaging South Africa environmental weighting for production of a ton of linerboard based on AHP method

6.19 Economic vs. Environmental performance

The site environmental performance index and annual rate of return for the production of linerboard process is shown in Figure 6.8. The plant had the lowest rate of return in 2004 because of the high inventory stock. But 2005 was a better year with an average annual rate of return increasing drastically due to high throughput and minimum stock inventory, it is worth noting that the capital cost for both years remain constant (*Appendix K*). As anticipated form the environmental profiles, the environmental index for the two year running remain relative the same showing that the environmental performance of the plant had been changed significantly.

Comparing the overall performance of the linerboard production with the Nitric acid plant study by Kniel (1996), it can be seen that the linerboard production process has both better annual rate of return and environmental index.

The results demonstrate the potential benefits of holistic waste minimisation approach over ‘end of pipe’ solutions to a problematic waste steam. It also shows that the reduction of waste at source provide both an environmental benefit and a payback on capital investment through increased process efficiency. High sulphur content burners, however, provides only a financial liability and penalty.

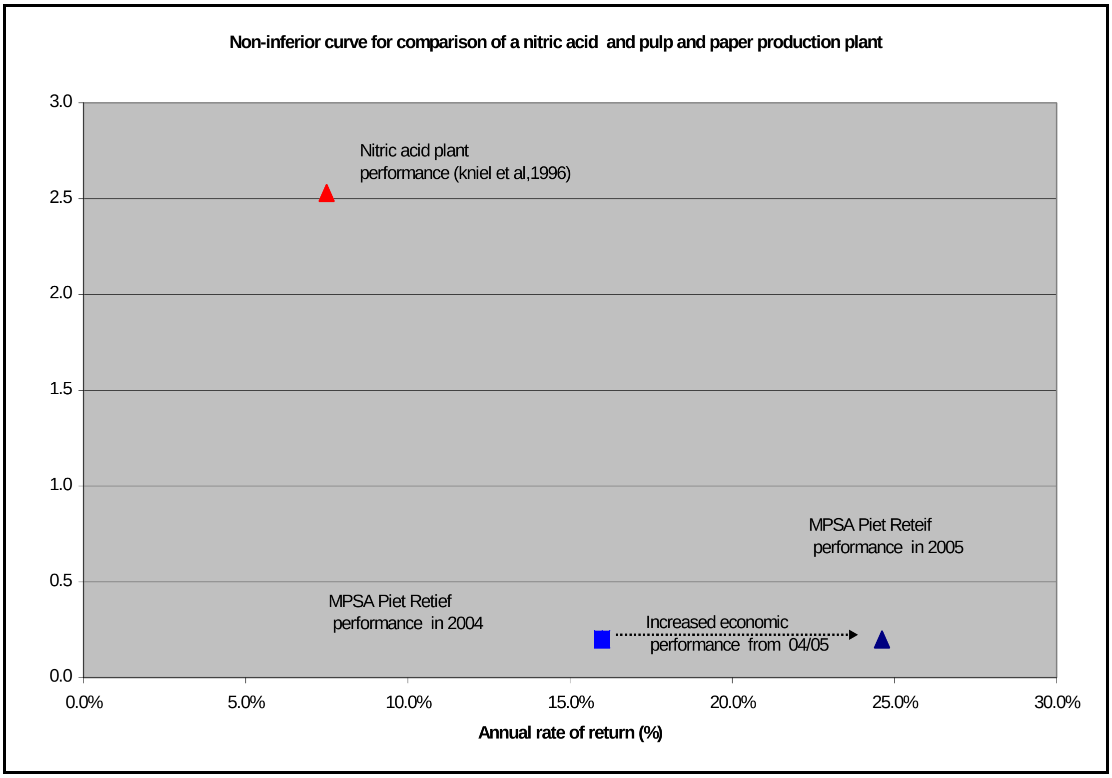


Figure 6.8: Economic and environmental performance of linerboard production and nitric acid plant

6.20 Life cycle improvement

The impact valuation scores for the baseline linerboard system indicated that the impact categories of greatest concern are ozone depletion potential, acid rain potential, and human inhalation toxicity. The ozone depletion potential impact is primarily due to the chlorine based compounds in air emissions associated with manufacturing of paper and pulp. The acid deposition impact is primarily due to the SO_2 air emissions associated with manufacturing steam and black liquor incineration. The human inhalation toxicity impact potential is primarily due to the chlorine air emissions associated about equally with manufacturing pulp and coal combustion. On the basis of the LCIA, it was determined that the alternatives with the best potential for reductions in these impact categories were the substitution of a investigation of scrubbing unit of boilers and investigation of chlorine free biocides.

6.21 LCA as a tool for screening projects

Figure 6.8 above can be used for preliminary screening of projects as the throughput of the plant will have to increase and the corresponding environmental performance index simultaneously decrease for the process to be both economically viable and environmental friendly (Azapagic, 1999). Table 6.5 shows the summary of strategic projects undertaken at Mondi for 2006 and these projects can easily be expressed through Figure 6.8 as being both economically and environmental viable. As most of this projects result in an increased throughput that translates to increased annual rate of return, while having the opposite effect on the overall site emissions.

MPC	Description	Total Cost
1	Pulp washing upgrade	2,000,000.00
2	Clarifier	9,000,000.00
3	New warehouse	14,000,000.00
4	Installation of better control units in chemical mixing	3,000,000.00
5	Long and short fibre fractionation	2,000,000.00
6	Pulp Mill heat integration	2,000,000.00
7	Replace Digester top separator	8,000,000.00
	Total Value	**40,000,000.00**

Table 6.5: Summary of strategic projects undertaken at MPSA-Piet Retief

6.22 Conclusions

The following conclusions can be drawn from this case study:

- Environmental issues are emerging as one of the major driving force for change in the chemical industry. A review of a product and process design that views the environment as an objective and not just one of the constraints on the operation leads to the discovery of design or product alternatives with improved economic and environmental performance.
- Life cycle assessment is a systematic tool that quantifies the environmental burden of products or services, and when used it can lead to big advantages in decision making, possibly leading to improved performance in terms of environmental and economic performance.

- Application of LCA tools must be used for the design of future process. The study results can also be used as marketing tool to show environmental improvements in terms of environmental performance index.
- Applying LCA methodology to linerboard production process resulted in a series of discoveries concerning upstream and downstream impacts, problems in the field not previously known to the designers, variances in procedures and potential improvements for the system.
- The study shows that LCA should be used for environmental performance evaluation of a process, especially with the new reporting requirements in industry that forces companies report on the overall environmental performance, economic performance and social responsibility.
- The results of this study emphasised the potential advantage of waste minimisation techniques over typical “end of pipe” solutions to effluent and gas emissions problems. The links provided by LCA were exploited to optimise both the environmental and financial performance and thus provide a potentially powerful decision making tool for management about resource allocation.
- A more subjective means of valuation and derivation of weighting factors were described and applied in form of AHP technique.
- It was found that the main process contributing to abiotic depletion resources potential, ozone depletion potential and human toxicity are the Copeland reactor operation and the power generation plants; due to the high sulphur dioxide and nitrogen oxide emissions. It was also shown that good economic performance does not therefore translate to favourable environmental profile and both acquisitions of new technology and specialties chemicals must be done with great consideration.

6.23 Recommendations for future work

- MPSA- Piet Retief must considered alternative fuel resources in the near future, as bark boiler.
- There is a need to explore the installation of a common stack scrubber at power station to reduce soluble gases.
- LCA should be the first phase in any project review stage.

- All new chemical considered must be evaluated through LCA to quantify their environmental impact.

6.24 References

1. Azapagic A, Life Cycle assessment and its application to process selection, design and optimization, Chemical Engineering Journal 73(1999), 1-21
2. BP Amoco.2000. BP Statistical Review of World Energy 1999. London: BP Amoco. www.bp.com/worldenergy
3. Coulson JM, Richardson JF, Sinnot RK, Chemical Engineering Design, Vol 6, Pergamon Press, Chapter 1, 6.
4. de Vaal P.L, An introduction to the application of neural networks in process Control, Analytical Hierarchy Process, Multivariable Controls system design 700/707, University of Pretoria, 2005.
5. Ekvall T, Tillman Anne-Marie, & Molander S, Normative ethics and Methodology for LCA, Journal of Clearner Production (2005), www.elsevier.com/locate/jclepro
6. Faul MA, Pistorius CWI, van Vuuren LM, Vorster Q, Swanevelder JJ, Accounting- An Introduction, Interpak Natal Pietermaritzburg, 1999, Chapter 1, 24-33
7. Faul MA, Pistorius CWI, van Vuuren LM, Vorster Q, Swanevelder JJ, Accounting- An Introduction, Interpak Natal Pietermaritzburg, 1999, Chapter 1, 24-33
8. G.E. Kniel, K. Delmarco, J.G. Petrie, Life Cycle Assessment applied to process design: Environmental and economic analysis and optimization of a nitric acid plant, Enviro.Prog. 15(4) 1996 221-228
9. Gaggioli R. A., Sama D. A., Sanhong Qian, El-Sayed Y. M., Integration of a New Process Into an existing Site: A case study in the application of exergy analysis, Journal of engineering for gas turbines and power, Vol113, April, 19991, page 170-183.
10. Gorree M., Guinee J.B., Huppes G., van Oers L., Environmental Life Cycle Assessment of Linoleum (final report), Centre of Environmental Science-Leiden University (CML-UL), June 2000.
11. Kenneth R. Stone, Life Cycle Assessment Team Leader, National Risk Management Research Laboratory, .S. Environmental Protection Agency
12. Kern D, Process Heat Transfer, McGraw~Hill, 1958, Chapter 1 to 11.
13. Majozi T, Sustainable Engineering for Science technology, a short Course, Department of Chemical Engineering, University of Pretoria, 2006

14. Majozi T, van Schijndel P, Sustainable Engineering for Science Technology, A short Course, Department of Chemical Engineering, University of Pretoria, 2005
15. Ministry of water affairs, and forestry, Pretoria, S.A, Sustainable Forest development in S.A, white paper march-1997
16. Peters M.S, Timmerhaus K.D, Plant Design and Economic for Chemical Engineers,McGraw_Hill International editions, 1991, Chapter 1-10.
17. Petit P, and Gaggioli R.A., 1980," Second law procedures for evaluating processes," Thermodynamics: Second law analysis, Am Chem. Soc. Sympsosium Series, Vol.122, pp. 15-18.
18. Raynolds M., Fraser R., Checkel D.,(2000): The relative mass-energy-economic (RMEE) method for system boundary slection. Part 1: A means to systemenatically and quantitively select boundaries. International Journal of Life Cycle assessment, 5(1), pp 37-48.
19. Rocky Mountain Institute, Anglo Platinum. Innovation Lab Workshop, Rustenburg, 2003
20. Sama D.A, Qian S, Gaggioli R.A, 1989, "Common-sense second law approach for improving propcess efficiencies," Thermodynamic Analysis and improvement of energy systems, International academic Publishers, Beijing. Page 520-531(Pergamon Press, Oxford-New York).
21. Seider W.D, Seder J.D, Lewin D.R, Process Design Principles: "Syntheses, Analysis and Evaluation", John Wiley & Sons, Inc, 1998, pp 207-238.
22. Smil Vaclav, Energy in the Twentieth Century: Resources, Conversion, costs, Uses and Consequences, Energy Environ, 2000.25:21-51
23. Smith J.C., Van Ness H.C., Abboit M.M., Introduction to Chemical Engineering Thermodynamic, 5th Ed, MaGraw~Hill, New York, 1996.
24. Vyzi E., Azapagic A., Life Cycle assessment as a tool for identifying Best Pacticable Enviromental Option (BPEO), Research report, University of Surry,1998.

7.1 Conclusions

- Environmental issues are emerging as one of the major driving force for change in the chemical industry. A review of a product and process design that views the environment as an objective and not just one of the constraints on the operation can lead to the discovery of design or product alternatives with improved economic and environmental performance.
- Life cycle assessment is a systematic tool that quantifies the environmental burden of products or services, which can lead to big advantages in decision making, possibly leading to improved performance in terms of environmental and economic performance.
- Application of LCA tools must be used to design future process and regulations. The results can also be used as marketing tool to show environmental improvements in terms of environmental performance index.
- Applying LCA methodology to linerboard production process resulted in a series of discoveries concerning upstream and downstream impacts, problems in the field not previously known to the designers, variances in procedures and potential improvements for the system.
- Integrating LCA for design purpose has significant potential for savings on cost and environmental impacts by making design a fully integrated process throughout the product life cycle.
- The study shows that LCA should be used for environmental performance evaluation of a process, especially with the new reporting requirements in industry that forces companies report on the overall environmental performance, economic performance and social responsibility.
- This feature has been used to both compare environmental performance of linerboard production site and to establish an objective link to economic performance via mass and energy flows in the process. LCA offers a systematic way to incorporate the entire material and energy supply chain into strategic planning and policy development.

- Results of this study emphasised the potential advantage of waste minimisation techniques over typical “ end of pipe” solutions to effluent and gas emissions problems. The links provided by LCA were exploited to optimise both the environmental and financial performance and thus provide a potentially powerful decision making tool for management about resource allocation.

- A more subjective means of valuation and derivation of weighting factors were described and applied in form of AHP technique.
- It was found that the main process contributing to Abiotic depletion resources potential, ozone depletion potential and human toxicity are the Copeland reactor operation and the power generation plants; due to the high sulphur dioxide and nitrogen oxide emissions. It was also shown that good economic performance does not therefore translate to favourable environmental profile and both acquisitions of new technology and specialties chemicals must be done with great consideration.

7.2 Recommendations for future work

- MPSA- Piet Retief must considered alternative fuel resources in the near future, as bark boiler.
- There is a need to explore the installation of a common stack scrubber at power station to reduce soluble gases.
- LCA should be the first phase in any project review stage.
- The entire new chemical supplied must be evaluated through LCA to quantify their environmental impact.