

Optimisation of South Africa's Biomass to Bio-Ethanol Supply Chain Network



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by

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PLAGIARISM DECLARATION

This work has not been previously submitted in whole, or in part, for the award of any degree. It is my own work. Each significant contribution to, and quotation in, this dissertation from the work, or works, of other people has been attributed, and has been cited and referenced.

Mildred Mutenure,

Signature: Signed by candidate Date: 15-02-2016

For I know the thoughts that I think toward you, saith the Lord, thoughts of peace, and not of evil to give you an expected end.

(Jeremiah 29 verse 11)

But my God shall supply all my needs according to his riches in glory by Christ Jesus.

(Philippians 4 verse 19)

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May God bless you!

EXECUTIVE SUMMARY

This study is about the optimisation of bio-ethanol supply chains for economic and environmental objectives, using a mathematical programming approach. A superstructure presented as a Mixed Integer Linear Programme (MILP) model that adequately captures the key variables in South Africa's bio-ethanol supply chain network is developed. The MILP model accounts for food demand, geographical distribution of biomass cultivation areas and biomass diversity, feedstock, product and by-product distribution, product demand and tax subsidies. The study focuses on the use of sugarcane, bagasse and crop waste from maize, wheat, barley and sorghum in the production of bio-ethanol.

In the supply chain, one processing technology for ethanol production is considered and one mode of transportation for both feedstock and products is considered. A detailed profitability analysis of the optimised MILP model is also provided. To account for the environmental impact of the supply chain, the model is integrated with life cycle analysis through multi-objective optimisation. The ϵ -constraint method is used to solve the multi-objective optimisation problem and Pareto analysis is done to check the trade-offs between the economic and environmental objectives, which is measured mainly by greenhouse gas emissions. In addition to greenhouse gas emissions, other impact categories namely eutrophication, human toxicity, acidification and global warming potential were also considered.

Bio-ethanol production has been a subject of many studies. It is a renewable and potentially environment-friendly product, which after blending with petrol can be used as a fuel in the transport sector. The use of bio-fuels has the potential to relieve pressure on fossil-based fuels, and achieve a reduction in the emissions of greenhouse gases. The use of bio-fuel results in net savings in carbon dioxide gas emissions as plants absorb the carbon dioxide released during bio-fuel production during biomass cultivation. The bio-fuel industry worldwide, however, faces many challenges, which compromises its economic viability and commercialisation, especially where lignocellulosic biomass is to be used in bio-fuel production. These

challenges include the uncertainty or discontinuous availability of biomass, fluctuations in market prices, high logistics and high maintenance costs of the processing equipment. The high logistics costs arise from the low density of the feedstock and from distribution of the feedstock, which is usually scattered over a wide area thereby making the process energy intensive. To overcome these challenges, an optimised supply chain network is required.

The mixed integer linear program superstructure developed in this study comprises three nodes, namely farms, processing facilities and blending facilities. Each farm has the potential to supply feedstock to any processing facility, and the blending facilities can each receive ethanol from any of the processing facilities. One of the objectives of this study is that the processing facilities should be located in such a way that transportation distances for both feedstock and product are minimal.

In South Africa, the bio-fuel industry has been identified as a source of economic and social development for underdeveloped areas (Letete & von Blottnitz, 2012). The South African government, through its bio-fuels industrial strategy, has been trying to encourage the commercialisation of the bio-fuel industry. A target market penetration of 2% energy content bio-fuel in the transport sector was set for the year 2013 by the SA government (DME, 2007). Due to the sustainability challenges faced by the bio-fuel industry, a large scale bioethanol commercial plant has yet to be set up in South Africa (DME, 2007). In the position paper on bio-fuels, as a measure to lure investment into the bio-fuels industry, mandatory blending of bio-fuels into the national liquid fuel supply was to be implemented by 1 October 2015 (Government Gazette, 2013). Apart from the bio-fuels industrial strategy, there have been other efforts to accelerate the development of the bio-fuel industry. However, these efforts have proven to be lacking. This fact, together with the emergence of advanced software for process parameter optimisation, prompted the undertaking of this study, in an effort to develop a model that minimises the overall cost of the biomass to bio-energy supply chain and determine the associated environmental impact.

The study aims to contribute to the body of knowledge in the development of South Africa's bio-fuel industry through use of simplified models to represent key nodes of the supply chain network. In South Africa, most sugarcane farms and sugar processing mills are located in the KwaZulu-Natal (KZN) and Mpumalanga provinces. Studies done in the United Kingdom and Italy have shown that the use of mathematical based models in the optimisation of bio-ethanol supply chains results in reduced costs. Two case studies, using three provinces in South Africa, namely KZN, Eastern Cape and Mpumalanga, are used to demonstrate the proposed optimisation approach.

The methodology for data collection and analysis makes use of mapping and geographical information systems (GIS) software, ArcGIS, to establish the quantities of feedstock available in each location. A routing software known as Google Earth[®] was used to find the actual transportation distances between nodes in the superstructure/supply chain network, using existing infrastructure. Land cover data from two sources was used in this study for the purpose of comparison, giving rise to two sets of data that are referred to as Case 1 and Case 2. The amount of feedstock obtained, using this data collection approach, tallied with those reported in the literature on crop production in South Africa, which validates the method. The optimal solution to the MILP model developed for the supply chain network and applied to the case study showed that it is economical to establish bio-ethanol processing facilities at current sugar mill locations, using bagasse and sugarcane as feedstocks. If current mill supply areas are maintained, production will mainly be from bagasse, which is preferred over sorghum, maize, barley and wheat residues due to no purchasing cost. However, with use of a bigger feedstock supply area, more sugarcane will be used to produce bio-ethanol, thereby increasing the ethanol output. Because of the nature of data involved in bio-ethanol supply chains, there is a large number of variables in the model developed. To reduce the number of variables in the model, crop fields falling within a cell in the grid measuring 30 by 40 km, were grouped together to form one farm, which is then represented as one binary variable.

Economic analysis of the optimised model at a discount rate of 8% predicts an annual economic potential of ZAR188 million for Case 1 and ZAR7,296 million for Case 2 for

annual production of 467,808 t of ethanol for Case 1 and 1,516,317 t of ethanol for Case 2. A profit margin above 45% and a net present value above ZAR21,000 million for the plant life of 20 years at a discount rate of 8% was obtained. This came about as the main choice of feedstock was bagasse was assumed to have no feedstock cost and low transportation cost. Furthermore, the payback period was 4 years for Case 1 and 3 years for Case 2. This is within the acceptable time of less than five years for the supply chain for both cases, where fourteen plants are located at the sugar mills. A rate of return above 20% was estimated at the end of the plant life. According to the analysis, the biomass-to-bio-ethanol supply chain for the 2 cases considered in the study is economically viable and will meet the 2% target demand of blending bio-ethanol into the national liquid fuel supply.

From the multiobjective optimisation the environmental impact at the optimal economic points for the two cases mentioned above is 4,580 kt CO₂ equivalent in Case 1 while for Case 2 it is 3,644 kt CO₂ equivalent. Since approximately 7% of avoided greenhouse gas emissions were obtained from the use of a petrol-ethanol blend that is obtained from mixing of the bio-ethanol produced in this study with petrol, it can be said that the biomass-to-bio-ethanol supply chain considered in this study is environmentally viable. The green house gas emissions comparison was done on an energy basis. However, it is important to note that such low quantities of emissions are only obtained because emissions due to direct and indirect land use changes were not considered. The criteria used for multiobjective optimisation is not simultaneous optimisation but an indication of the environmental emissions at a particular economic optimal point.

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NOMENCLATURE

Abbreviations

GAMS	General Algebraic Modelling system
GIS	Geographical Information Systems
GHG	Greenhouse gas
LCIA	Life Cycle Impact Assessment
MILP	Mixed Integer Linear Program
MP	Mathematical Program

General notation

CO ₂	Carbon dioxide
Conv	Conversion
D	Distance
fix	Fixed component of a cost function
inv	Investment cost
L1	Layer 1
L2	Layer 2
L3	Layer 3
L4	Layer 4
L5	Layer 5
LO	Lower bound
UP	Upper bound
Stor	Storage
tr	Transportation
op	Operating costs
tech	Technology
var	Variable component of a cost function

Sets

I	Set of biomass farms
M	Set of locations of sugar mills and storage facilities
N1	Set of locations of pre-treatment facilities
N2	Set of locations of processing facilities
J	Set of locations of product demand centres
P	Set of resources and products
W	Set of transportation modes
T	Set of technologies
tp	Set of time periods

Subsets

RE(p)	Set of feedstocks
PI(p)	Set of intermediate products on level 2
PM(p)	Set of intermediate products on level 3
PD(p)	Set of direct products
PP(p)	Set of produced products
PR(p)	Set of products
kp(p)	Set of key products
elhe(p)	Set of products (electricity and heat)
T ₂	Set of technologies at the second level at location m
T ₃	Set of technologies at the third level at location $n1$
T ₄	Set of technologies at the fourth level at location $n2$
T ₅	Set of technologies at the fifth level at location j

Indices

i	biomass farm
m	location of sugar mill and storage facility
$n1$	location of pre-treatment facility
$n2$	location of processing facility

j	product demand centre location
p	resource and product
w	transportation mode
t	technology
tp	time period
re	feedstock
pi	intermediate product at level 2
pm	intermediate product at level 3
pd	direct product
pp	produced product
pr	product
kp	key product
$elhe$	electricity and heat
$t2$	technology on the second level at location m
$t3$	technology on the third level at location $n1$
$t4$	technology on the fourth level at location $n2$
$t5$	technology on the fifth level at location j

Multidimensional sets

ret	Index set of pair (re, t) for technology t and each feedstock, re
pit	Index set of pair (pi, t) of technology t for each intermediate product, pi
pmt	Index set of pair (pm, t) of technology t for each intermediate product pm
ppt	Index set of pair (pp, t) of technology t and each produced products pp
$repi$	Index set of pairs (re, pi) for intermediate products pi from each feedstock re

$repd$	Index set of pairs (re, pd) for direct products pd from each feedstock re
$pipm$	Index set of pairs (pi, pm) for intermediate products pm from each pi
$pmpp$	Index set of pairs (pm, pp) for produced products pp from each intermediate pm
pdt	Index set of pairs (pd, t) for direct products pd from technology t
ppt	Index set of pairs (pp, t) for produced products pp from technology t
tkp	Index set of pairs (t, p) for key products p from each technology t

Scalars

n	Capacity exponent for plant size
TP	Number of time period
NI	Number of linearization intervals
Pl	Plant life in years

Parameters

$alimit(i, re)$	Maximum available amount of feedstock in each farm
$C_t^{fix.inv,L2}$	Fixed investment cost of technology t at level 2, ZAR million
$C_t^{var.inv,L2}$	Variable investment cost of technology t at level 2, ZAR million/t
$C_t^{fix.inv,L3}$	Fixed investment cost of technology t at level 3, ZAR million
$C_t^{var.inv,L3}$	Variable investment cost of technology t at level 3, ZAR million/t
$C_t^{fix.inv,L4}$	Fixed investment cost of technology t at level 4, ZAR million
$C_t^{var.inv,L4}$	Variable investment cost of technology t at level 4, ZAR million/t
C^{re}	Cost of feedstock re , ZAR/t
$C_t^{op,T,L2}$	Operating cost for technology t , at level 2, ZAR/t
$C_t^{op,T,L3}$	Operating cost for technology t at level 3, ZAR/t,
$C_t^{op,T,L4}$	Operating cost for technology t at level 4, ZAR/t
C_p^{pd}	Direct product price, ZAR/t or ZAR/MJ or ZAR/MWh
C_p^{pp}	Product price, ZAR/t or ZAR/MJ or ZAR/MWh
$C_{re,t}^{prep,L2}$	Preparation cost for feedstock at level 2, ZAR/t

$C_p^{fix.stor,L2}$	Storage cost for feedstock, on level 2, ZAR/t
$C_{p,t}^{var.sto,L2}$	Variable cost of storage for feedstock on level 2, ZAR/t
$C_{re}^{tr,fix,L1,L2}$	Fixed transportation cost for feedstock from level 1 to level 2, ZAR/t
$C_{re}^{tr,var,L1,L2}$	Variable transportation cost of feedstock from level 1 to level 2, ZAR/(t.km)
$C_{pp}^{tr,fix,L4,L5}$	Fixed transportation cost of produced product from level 4 to level 5, ZAR/t
$C_{pp}^{tr,var,L4,L5}$	Variable transportation cost of produced product from Layer 4 to Layer 5, ZAR/(t.km)
$C_{pd}^{tr,fix,L4,L5}$	Fixed transportation cost of direct product from Layer 4 to Layer 5, ZAR/t
$C^{fixinvtot}$	Total fixed capital investment costs, ZAR million
$C_{pd}^{tr,var,L4,L5}$	Variable transportation cost of direct product from level 4 to level 5, ZAR/(t.km)
$D_{i,m}^{L1,L2}$	Distance between farm at location i on level 1 and demand centre at location m on level 2, km
$D_{m,n1}^{L2,L3}$	Distance between facility at location m on level 2 and facility at location $n1$ on level 3, km
$D_{m,j}^{L2,L5}$	Distance between facility at location m on level 2 and demand centre at location j on level 5, km
$D_{n1,n2}^{L3,L4}$	Distance between facility at location $n1$ at level 3 and facility at location $n2$ on level 4, km
$D_{n2,j}^{L4,L5}$	Distance between facility at location $n2$ on level 4 and demand centre at location j on level 5, km
$e_{truck,re}^{L1,L2}$	Environmental impact of transportation of feedstock from level 1 to level 2 by truck
$e_{truck,pi}^{L2,L3}$	Environmental impact of transportation of intermediate product pi from level 2 to level 3 by truck
$e_{truck,pd}^{L2,L5}$	Environmental impact of transportation of direct produced product from level 2 to level 5 by truck
$e_{truck,pp}^{L4,L5}$	Environmental impact of transportation of produced products from level 4 to level 5 by truck

$ei_{re,pd,t}^{L2}$	Environmental impact due to processing of biomass to direct products at technology t on level 2
$ei_{re,p}^{L1}$	Environmental impact due to production of biomass at level 1
$ei_{pm,pp,t}^{L4}$	Environmental impact at the processing facility with technology t at level 4
E^{imptot}	Total environmental impact of the supply chain
$f_{re,pi,t}^{conv,T,L2}$	Conversion factor of resource re to intermediate product pi through technology t at level 2
$f_{re,t}^{conv,T,L2}$	Conversion factor of resource re through technology t on level 2
$f_{pi,pm,t}^{conv,T,L3}$	Conversion factor of intermediate products pi to intermediate products pm by technology t (pre-treatment) at level 3
$f_{pm,pp,t}^{conv,T,L4}$	Conversion factor of intermediate products pm to produced products pp at level 4 through technology t
$I_{m,ni,t}^{L2,T}$	Fixed capital cost for technology t for direct products at level 2 in linearization interval ni , ZAR million
$I_{n2,ni,t}^{L4,T}$	Fixed capital cost for technology t for produced products at level 4 in interval ni , ZAR million
I_t^T	Fixed capital cost for the technology t , ZAR million
$I_t^{T,1}$	Fixed capital cost for reference capacity of plant using technology t , ZAR million
L_{re}	Harvesting loss, %
$M_{t,dp,ni}^{T2,L2}$	Investment cost of technology at level 2 in the interval between $ni+1$ and ni , ZAR million/t
$M_{t,pp,ni}^{T4,L4}$	Investment cost of technology at level 4 in the interval between $ni+1$ and ni , ZAR million/t
$q_t^{1,T4,L4}$	Reference capacity of technology t at level 4, t/y
$q_{t,dp,ni}^{T2,L2}$	Capacity of technology t producing direct products at level 2 in interval ni , t/y
$q_{t,kp,ni}^{T4,L4}$	Capacity of technology t producing key product kp at level 4 in interval ni , t/y

$\Delta q_{n2, kp, tp, ni}^{T4, L4}$	Difference between capacities of process technology t in an interval at level 4 within a time period
$q_{1, t, kp}^{1, t, L2}$	Reference capacity of process technology t at level 2, t/y

Variables

$C^{inv tot}$	Total investment cost, ZAR million
$C^{tr tot}$	Total transportation cost, ZAR million
$C_{re}^{tr, L1, L2}$	Transportation cost of biomass from Layer 1 to Layer 2, ZAR million
$C_{pi}^{tr, L2, L3}$	Transportation cost of intermediate product pi from Layer 2 to Layer 3, ZAR million
$C_{pd}^{tr, L2, L5}$	Transportation cost of direct produced products pd from Layer 2 to Layer 5, ZAR million
$C_{pm}^{tr, L3, L4}$	Transportation cost of intermediate product pm from Layer 3 to Layer 4, ZAR million
$C_{pp}^{tr, L4, L5}$	Transportation cost of produced product pp from Layer 4 to Layer 5, ZAR million
C^{re}	Feedstock cost, ZAR/t
$C^{op, T}$	Total operating cost for technology t
$C^{op, L2}$	Operating cost for technology t at level 2, ZAR/t
$C^{op, L3}$	Operating cost for technology t at level 3, ZAR/t
$C^{op, L4}$	Operating cost for technology t at level 4, ZAR/t
C^{Pctot}	Total production cost of the supply chain, ZAR million
$C^{preptot, L2}$	Total preparation cost for feedstock at level 2, ZAR million
C^{stor}	Storage cost for product p , ZAR/t
E^{imptot}	Total environmental impact of the supply chain
$I_{m, t}^{L2, T}$	Capital cost for technology t for produced product at L2, ZAR million
$I_{n2, t}^{L4, T}$	Capital cost for technology t for produced product at L4, ZAR million
$pbtax$	Profit before tax
$q_{i, re, tp}^{L1}$	Feedstock production rate at farm, t/y
$q_t^{T4, L4}$	Capacity of technology t at level 4, t/y

$q_t^{T2,L0}$	Minimum capacity of technology t at level 2, t/y
$q_{t,tp}^{T2,L0}$	Minimum capacity of technology t at level 2 within a time period tp , t/y
$q_{t,dp}^{T2,L2}$	Capacity of technology t producing direct products at level 2, t/y
$q_{m,n1,pi,tp}^{L2,L3}$	Quantity of intermediate product pi that is taken from level 2 to level 3
$q_{t,tp}^{T3,L0}$	Minimum capacity of technology t at level 3 within a time period tp , t/y
$q_{n1,pi,pm,t,tp}^{T3,L3}$	Quantity of intermediate product pi at level 3 that is to be converted to intermediate product pm at level 3 within time period tp , t/y
$q_{t,kp}^{T4,L4}$	Capacity of technology t producing key product kp at level 4, t/y
$\Delta q_{n2,kp,tp}^{T4,L4}$	Difference between capacities for technology t at level 4 within a capacity interval, which is given by distance between two points on the x- axis of a piecewise linearization graph
$q_{i,re,tp}^{L1}$	Quantity of feedstock that is produced at level 1 in time period tp
$q_{m,j,pd,tp}^{L2,L5}$	Quantity of direct product produced at level 2 that flows to level 5, t/y
$q_{i,m,re,tp}^{L1,L2}$	Quantity of direct feedstock produced at level 1 that flows to level 2, t/y
$q_{m,n1,pi,tp}^{L2,L3}$	Quantity of intermediate product, pi , produced at level 2 that flows to level 3, t/y
$q_{n1,n2,pm,tp}^{L3,L4}$	Quantity of intermediate product, pm , produced at level 3 flows to level 4, t/y
$q_{n2,j,pm,pp,tp}^{L4,L5}$	Quantity of intermediate produced product pp at level 4 that flows to level 5, t/y

Binary variables

$y_m^{T,L2}$	Existence of technology at location m (storage, crushing and sugar mill)
$y_{m,tp}^{T,L2}$	Existence of technology at location m (storage, crushing and sugar mill) in time period tp
$y_{n2,tp}^{T,L4}$	Existence of technology at location $n2$ (fermentation - CHP) in time period tp
$y_{n1,t}^{T,L3}$	Existence of technology at location $n1$ (storage –pre-treatment)
$y_{n1,t,tp}^{T,L3}$	Existence of technology at location $n1$ (storage –pre-treatment) in time period tp

$y_{n1,t,ni}^{T,L3}$

Existence of technology t at location $n1$ in interval ni

$y_{n2,t,ni}^{T,L4}$

Existence of technology t at location $n2$ in interval ni

$y_{m,t,ni}^{T,L2}$

Existence of storage on level 2 at location m in interval ni

CHAPTER 1. INTRODUCTION

1.1 Background to Bio-fuel Production

The continuous increase in energy demand as well as the need to reduce the greenhouse gas emissions resulting from use of fossil fuels led to research on renewable sources of energy. Bio-based materials are a viable option to improve energy security and reduce emission of greenhouse-gases by approximately 86% (Wang et al., 1999). Bio-fuels, which are produced from plants (food crops and non-food crops) and agricultural waste are considered to be among the best alternatives for the petroleum-based fuels used in the transportation sector. The use of food crops as a source of fuel results in high food prices and therefore the need to develop second-generation techniques for bio-energy production (Bonomi et al., 2011). However, second-generation techniques in isolation are not financially viable, hence the need to integrate them with first-generation techniques (Akgul et al., 2012). Bio-ethanol and bio-diesel, which are blended into gasoline and diesel respectively, are the two main types of bio-fuels. In 2011, a total of 85.13 million cubic metres of ethanol was produced globally, with the USA contributing 62%, while Brazil contributed 24% (Lichts, 2015).

According to reports by Lichts (2015), the major bio-ethanol producers worldwide in the year 2012 were Brazil and the United States (US). These two countries produced approximately 89% of the total ethanol produced in that year, which was 107.32 million cubic metres. Africa contributed approximately 0.15% to the world ethanol production in the same year (Lichts, 2015). Bio-ethanol production continues to increase with forecasts done in the year 2013, showing an increase of 2.5% in the major producers and an increase of approximately 8% in Europe, the third largest bio-ethanol producer worldwide. In 2014, global bio-fuels production increased by 7.4% (+4.9 million t of oil equivalent) from the previous year. This growth was driven by increases in the US (+5.6%), Brazil (+5.5%), Indonesia (+40.4%) and Argentina (+30.9%) (BP plc, 2014). However, the growth was below the average growth in bio-ethanol production for the previous years.

To date, more than 210 bio-ethanol plants have been commissioned all over the world with the first cellulosic ethanol producing plants set up in the US. Approximately 95% of the ethanol produced globally is produced through fermentation and 5% is synthetic ethanol (Berg, 2008). Synthetic ethanol is readily synthesised from natural gas, coal and ethylene, a by-product of petroleum (betalabservices, 2015). Although the cost of producing synthetic ethanol from coal is almost half the cost of ethanol produced from sugarcane, synthetic ethanol is less environmentally favourable compared to fermentation ethanol (CARENESA, 2008).

1.2 Sugarcane and Grain Production in South Africa

In April 1989, the South African government approved a series of constructive expansion and deregulation proposals for the sugarcane industry (Dewey, 1989); and in August 1989 it decided to approve in principle the production of ethanol from sugar (Lewis, 1989). An ethanol refinery, estimated to cost ZAR120 million to build, was most likely going to be erected at Richards Bay in KZN. The effect of these decisions was to allow growers to expand the area under sugarcane production by over 30,000 hectares and to produce in excess of 1 million extra tonnes of cane (Lewis, 1989).

On average 22 million tonnes of sugarcane are produced each season from 14 mill supply areas, extending from Northern Pondoland in the Eastern Cape to the Mpumalanga Lowveld (SASA, 2014). Currently, up to approximately 2 million tonnes of sugar are produced per year from an area of 430,000 hectares in South Africa. Of this, 60% is marketed in the SACU (Southern African Customs Union). The remainder is exported to Africa, Asia and the Middle East. The industry makes an important contribution to local employment and generates an annual estimated average direct income of R8 billion. This constitutes R5.1 billion in the value of sugarcane production. Approximately 1 million people (2% of the country's population) depend on sugarcane for a living (SASA, 2014).

According to Grain SA (2013), approximately 10 million tonnes of maize are produced in South Africa from approximately 3.1 million hectares of land annually. Of this, 8 million tonnes are consumed in South Africa and the rest is exported. In the year

2012/2013, approximately 45% of the maize produced in South Africa came from the Free State, while 21% was produced in North West province (Grain SA, 2013). In the same year, according to the same report, maize produced from Mpumalanga and KZN constituted 24.7% of the annual maize production.

Sorghum is mainly produced in the Free State. In the year 2012/2013, a grand total of 147,000 t were produced in South Africa with the Free State contributing approximately 47%. Mpumalanga province produced approximately 29% to the total sorghum harvest of the same year. KZN and Gauteng together contributed a total of 1.9% to the total amount of sorghum that was harvested in the year 2012/2013.

Wheat is mainly grown in the Western Cape. For the year 2012/2013, of the 1,870,000t of wheat produced in South Africa, 48% came from the Western Cape (Grain SA, 2013). According to the same report, Free State and Northern Cape contributed 19% and 14.5%, respectively, with the remaining 18.6% coming from the other six provinces. The Western Cape also produced approximately 75% of the country's annual barley production (Grain SA, 2013).

In this study, in addition to sugarcane and its residue, maize, sorghum and wheat residue that are produced in Mpumalanga, KZN and the Eastern Cape are considered as feedstock for bio-ethanol production.

1.2.1 Feedstock availability for bio-ethanol production in South Africa

Although sugarcane is mainly used in the production of granular sugar, in South Africa the resource will be able to cater for the sugar and bio-ethanol industries due to the availability of cheap sugar imports from Brazil (Cargill South Africa, 2014). The availability of land for cultivation of more sugarcane also ensures that there is no competition between food and fuel cropland. According to Marrison and Larson (1996), the available area for new cropland and energy crop cultivation for the year 1990 was estimated to be 104,417,000 ha and only 2% of this would be needed for food crop production by the year 2025. The availability of land for bio-ethanol feedstock production is also confirmed by the bio-fuels industrial strategy, which states that only

1.4% of underutilised arable land in South Africa (which is approximately 14% of the total arable land) would be required to meet a 2% target bio-fuel penetration in the national liquid fuel supply by 2013 in South Africa. This shows that there is much land available for biomass cultivation. Sugarcane production will only utilise a small portion of this vast land due to its high energy yield (van Zyl & Prior, 2009). Approximately 85% of the sugarcane produced nationwide comes from (KZN), which receives good rainfall and has fertile soil. This study will focus on production of bio-ethanol in this area. KZN, which is around 94,361 km², constitutes approximately 7.7% of the total land area of South Africa (approximately 120 Mha) (Brand South Africa, 2014).

On average, the ratio of cellulosic residue to the grain, seeds or sugar is approximately 1:1 (Lynd et al., 2003). The residue from grains and sugarcane plays a role in maintaining soil fertility in addition to being used as an animal feed. On average, between 13-70% of the residue can be removed from the cultivation areas depending on soil fertility. In most cases, the selling price of the straw and stover includes compensation to the farmers for nutrients lost, which they will replace with other fertilisers (Perlack et al., 2003).

Maize residue availability in South Africa was estimated to be 6.7 million tonnes per year by Lynd et al. (2003), who based their estimates upon crop data from NDA crop production reports. Wheat straw output was estimated to be 1.6 million tonnes per year according to the same studies. In South Africa, Batidzirai et al. (2012) estimated the amount of residue that can be collected after meeting animal feed demand and soil organic carbon demand (SOC) to be 5.7 million tonnes for maize and 603,000 t for wheat. Residue from maize, sorghum and wheat crops that are also produced in Mpumalanga and KZN, will be considered as feedstock in this work in addition to sugarcane and its residue.

1.3 Bio-fuel supply chain

A bio-fuel supply chain comprises the following activities; biomass cultivation, harvesting, collection, transportation, storage, bio-fuel production, blending and distribution of product. It is a multi-echelon network consisting of biomass cultivation

sites, ethanol production facilities and demand centres (Akgul et al., 2009). Application of supply chain optimisation to such systems requires consideration of all the aforementioned nodes in the chain as well as the transport of biomass and ethanol between the nodes (Gold et al., 2011). The bio-fuel supply chain needs to be optimised so that maximum possible benefits can be realised. These benefits include rural development, job creation, boost in agricultural activities as well as a reduction in greenhouse gas emissions. This study focuses on optimisation of economic and environmental objectives in the bio-ethanol supply chain network in South Africa. Figure 1.1 below shows a bio-ethanol supply chain comprising alternative modes of transportation such as road and rail for the movement of biomass and bio-ethanol within the network.

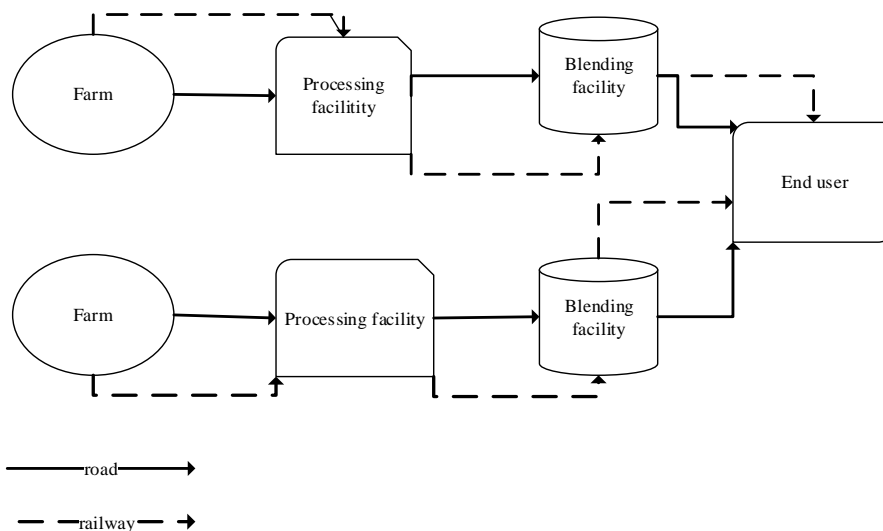


Figure 1.1: Biomass to bio-ethanol supply chain diagram

1.3.1 Biomass cultivation, harvesting and geographical location of feedstocks

Sugarcane is one of the most efficient crops in converting sunlight energy to chemical energy for fuel (Tew & Cobill, 2008). According to Bonomi et al. (2011), sugarcane planting is done through semi-mechanised and mechanised planting. In the semi-mechanised planting method, furrows are opened mechanically and filter cake mud – if present – is applied together with NPK ($N-P_2O_5-K_2O$) (Bonomi et al., 2011). The quantities of fertilizer applied depend on crop needs and soil fertility. Harvesting,

cutting and distribution of the sugarcane setts (stem cuttings or sections of the stalks) are done manually. Approximately 10 t of seed are required to plant one hectare of land and up to 25 labourers per hectare are used in the planting operation (SCGA, 2013). Insecticides, micronutrients, hormones and growth promoters are applied during the closing of the furrows (Bonomi et al., 2011).

On average, sugarcane takes approximately 12-14 months to mature. In South Africa, sugarcane grows at an average rate of 5-7 t per month per hectare; maturing at approximately 12-14 months at the coast and 20-24 months inland (SCGA, 2013). The duration of a ratoon varies between 11-12 months for irrigated cane in the Pongola valley and the Mpumalanga Lowveld; to 12-14 months at the north coast of KZN; 14-18 months at the south coast; and 18-24 months in the Midlands of the KZN. When harvested, one hectare of cane yields from 60-90 t at the coast and 90-120 t inland, dependent on rainfall and husbandry (SCGA, 2013). Sugarcane yield can be estimated, using the ACRU-Thompson Model given by Equation 1 below:

$$Y_{sc} = 9.53 \left(\frac{E_{an}}{100} \right) - 2.36 \dots \dots \dots (1)$$

Where: Y_{sc} is the annual sugarcane yield in t. ha⁻¹
 E_{an} is the annual total evaporation (sugarcane water use), mm

The equation above estimates the yield for a twelve-month period; thus to obtain a yield for a crop of sugarcane the tonnage estimated has to be adjusted to account for the duration of a particular growing period (Water research, 1984).

Harvesting can be done either manually or mechanically. The type of method employed may depend on the topography of the area. In hilly areas, only small areas lend themselves to mechanisation; hence the reliance on labour-intensive practices (SCGA, 2013). The cane is harvested by labourers who work as cane cutters, using cane knives. On average, a cutter can cut and stack 3 t of trashed (un-burnt) cane and approximately 4 t of burnt cane per day. This stack is loaded onto a tractor-drawn trailer and hauled to a loading zone. The less hilly farms are able to harvest the cane

and directly load into a trailer, using a mechanical loader. In this case, a cane cutter can harvest approximately 8 t per day as he is not required to create a stack or bundle (SCGA, 2013).

1.3.2. Biomass storage and transportation

Sugarcane in South Africa is normally transported by road in trucks of 25 t or 50 t capacity or by rail. It has a high density, but low energy content. Biomass storage should not exceed three days, as the sugarcane will become stale, which will make it difficult to process due to conversion of sucrose to dextran by bacteria. This calls for an efficient way of transporting the biomass from the farms to the bio-ethanol processing facilities. The distance between farms/storage sites and bio-ethanol plants/blending plants, as well as the mode of transportation, plays a key role in determining the economic and environmental impact of bio-ethanol supply chains. If minimised, the transportation distance will result in lower cost as well as lower greenhouse gas emissions from the transportation of feedstock and product.

1.3.3. Biomass pre-treatment and bio-ethanol production

A key component of the supply chain network being considered in this study is the processing of biomass to produce bio-ethanol. The process of converting biomass to bio-ethanol involves pre-treatment to remove lignin, thereby freeing up sugars followed by enzymatic saccharification and fermentation. The biomass is pre-treated in order to separate lignin and break the structure of lignocellulose. Pre-treatment is a key process in the conversion of lignocellulosic materials into bio-ethanol (Yang & Wyman, 2008). This is one of the most expensive steps in the process of converting biomass to fermentable sugars (Binod et al., 2012). The goal of pre-treatment is to increase the accessible surface area, decrystallise cellulose, modify the lignin structure and solubilise the hemicellulose structure (Bordeur et al., 2011). To date, there are a number of pre-treatment methods that have been investigated and employed. These can be broadly classified into four categories, which are: physical, physicochemical, biological and chemical methods.

1.3.4 Bio-ethanol production technologies and facilities

This study considers autonomous, annexed facilities and stand-alone second-generation plants for bio-ethanol production. Autonomous plants process sugarcane solely for bio-ethanol production, while annexed plants process sugarcane, bagasse and straw to produce both sugar and bio-ethanol within the same premises.

This work considers an integrated approach in which two or more different feedstocks are converted to products from the same facilities that exist in annexed plant configuration. The advantage of this integrated approach, where lignocellulosic material is used in addition to food crops as feedstock (for ethanol production in first-generation technology) for bio-ethanol production, is the reduced investment cost. This is due to the sharing of processing equipment and infrastructure such as cogeneration facilities, fermentation, distillation, concentration and storage facilities between first- and second-generation technologies (Bonomi et al., 2011).

1.3.5 Bio-ethanol transportation and storage

Bio-ethanol can be transported in pipelines as well as by road and rail. In Brazil and the US, pipelines have been used to transport bio-ethanol. Transporting bio-ethanol in pipelines however, can be problematic, because it is corrosive due to its high oxygen content and it also absorbs water and impurities easily, which causes problems. If bio-ethanol is transported via multiproduct pipelines, there is the danger of potential contamination of jet A1 oil in the pipeline (DME, 2014). Thus, in some studies, options considered for the transportation of bio-ethanol from production facilities to blending sites/depots are either road tankers or rail tankers. Transportation of feedstock and raw materials by road and railway contributes to the overall environmental impact of the supply network through greenhouse gases that are emitted during this process. Development of models that can be used to determine optimum locations for the processing facilities can reduce the transportation distance of the product from the production facilities to the blending facilities. This would contribute to a reduction in the distribution distance thereby minimising the overall cost and environmental impact of the bio-ethanol supply chain.

1.3.6 Bio-ethanol blending

Due to its corrosive nature, ethanol is blended with petrol before use in motor vehicle engines. All vehicles can use ethanol blends such as E-10 (gasoline blended with 10% ethanol). Only a small number of vehicles (called flex fuel vehicles) can use higher blends such as E-85 (Ekşioğlu et al., 2009). According to the Department of Energy (DoE, 2014), the actual process of blending could occur at either the petroleum refinery or depot level. Blending at petroleum refinery level, however, requires that bio-fuels be transported a considerable distance from their source of manufacture to each of the six refineries in South Africa. In this study, the depot level blending, *not* the petroleum refinery level blending, is included in the supply chain superstructure. The two depots used already exist in Durban.

1.4 Environmental Analysis of Biomass to Bio-Ethanol Supply Chain

The use of renewable energy is highly beneficial as it has a better environmental performance compared to the fossil-based fuel that it replaces (Botha & von Blottnitz, 2006). A number of “well to wheel” studies have been conducted to compare greenhouse gas emissions over the entire life cycle of bio-ethanol and petrol as the activities in the biomass-to-bio-ethanol supply chain also result in greenhouse gas emissions. To account for and reduce the environmental impact of the supply chain on the global warming potential, You et al. (2011) incorporated greenhouse gas emissions into their supply chain optimisation framework as a measure of the environmental impacts. Similarly, this study incorporates greenhouse gas emissions into the optimisation framework, which has an environmental objective of minimising greenhouse gas emissions in the biomass-to-bio-ethanol supply chain. The emissions are measured through a farm to wheel lifecycle analysis of the bio-ethanol.

1.5 Problem Statement

South Africa produces synthetic ethanol and to date, there are no commercial bio-ethanol/fermentation plants in operation. The government of South Africa, through the DoE, has attempted to encourage investment into the bio-fuel industry through the

Bio-fuel Industrial Strategy. According to the government white paper on bio-fuels (DME, 2007), bio-ethanol production is identified as a source of economic and social development for under-developed areas in South Africa. In the white paper on bio-fuels (DME, 2015), sugarcane, which is mainly grown in KZN, Mpumalanga and the Eastern Cape, is among the crops that can be used for bio-ethanol production in South Africa. In these provinces where all the sugar mills are located, maize, sorghum and wheat are also cultivated. The wastes from these crops can be utilised in bio-ethanol production since the Bio-fuels Industrial Strategy excludes seed from maize and other food crops from the list of bioethanol feedstocks (DME, 2007). Since the cultivation areas are scattered over a wide area and the possible bio-ethanol feedstock has high density and low energy content, it is necessary to locate the processing facilities in strategic positions such that logistic costs and greenhouse gas emissions due to transportation are minimised. This is because it is hypothesised that the economic and environmental viability of biofuels is improved by optimally locating bioprocessing facilities.

The problem statement for this study is summarised as follows:

Given are different kinds of biomass, a set of biomass cultivation centers, a set of possible processing facilities locations, a set of sugar mills, a set of blending facilities locations and a set of transportation modes and processing technologies. It is required to determine the size and location of the processing facility, the source, type and quantity of biomass that has to be shipped to each selected processing facility. It is also required to determine the selected processing facilities which will supply each ethanol demand center and the quantities of ethanol to be supplied so as to make the overall supply chain both economically viable.

1.6 Objectives

The aim of this research is to develop a model that can be used to establish the quantity of ethanol, profits and the environmental impact associated with bio-ethanol supply chains in South Africa when the following agricultural materials are used as

feedstock in the bio-ethanol production: sugarcane, bagasse and crop waste material in the three provinces of South Africa mentioned above.

1.7 Key Questions

The key questions to be answered in this work are:

- Which location and size of processing facility should be established in order to obtain an economically and environmentally viable supply chain?
- Which farms should supply feedstocks to the proposed processing facilities so as to obtain an optimal network both in terms of economics and environmental impact without upsetting sugar and food demand?
- What should be the optimum quantity of product to be supplied by each selected processing facility to the selected blending facility in order to obtain an economically and environmentally viable supply chain?

1.8 Scope and Methodology

The model is to be applied to the case study area and optimised for both economic and environmental objectives. The economic objective in this study is to maximise the profit of the bio-ethanol supply chain network, while the environmental objective is to minimise environmental impact from the supply chain network. These two objectives are to be optimised through multi-objective optimisation.

The scope of the work includes the selection of optimum plant locations, selection of feedstock sources, determination of transportation distances for both product and feedstock and profitability analysis of the optimised bio-ethanol supply chain. A superstructure for the supply chain is developed and presented as a mixed integer linear programming model. The mathematical model is used to optimise the economics and environmental performance of the biomass to bio-ethanol supply chain in South Africa, using KZN, Mpumalanga and Eastern Cape as a case study. Actual road routes are determined for the transportation of feedstock and products in the case study. In this study, the geographical information systems software (GIS), ArcGIS

version 10.3.1 for desktop, is used as a tool for data analysis. A routing software, Google Earth®, is used for data gathering and an optimisation software, General Algebraic Modelling Systems (GAMS) is used as the solver environment.

1.9 Thesis Structure

Chapter 2 presents theoretical background information and a literature review that is relevant to bio-ethanol supply chain optimisation. It covers modelling and optimisation in general before reviewing models that have been used to optimise the bio-energy supply chain. The studies conducted by Čuček et al. (2014) and Akgul et al. (2012) are closely reviewed as the scope of this work is quite similar to their studies.

Chapter 3 details the methodology used for this study and a description of the system under study. Data used in the study are presented in this chapter as well as the different scenarios that are considered for the supply chain. The model equations are also presented in this chapter.

Chapter 4 presents the results and discussion for the economic and environmental objectives presented in Chapter 3. The environmental objective is dependent on the output of the economic objective.

Chapter 5 presents the conclusion and recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Supply Chain Optimisation

There has been much discussion on optimisation of the bio-energy supply chain to improve its financial viability. Some studies looked at economic viability simultaneously with environmental viability. Other studies even included the social impact of the bio-fuel network. Most studies used a mathematical programming approach to develop models to optimise part of the bio-energy supply chain, which they solved by using various software, with the mostly used software being the General Algebraic Modelling Systems (GAMS). A few studies focused on optimising the whole supply chain. However, most of the studies highlighted the importance of the location of the processing facility.

The location of a bio-ethanol processing plant has a significant influence on its viability and the scope for future expansion. Therefore, a study must be carried out to identify and evaluate the crucial factors affecting the site selection decision in order to prescribe the appropriate choice. Many considerations may be made when selecting a site for erecting a new plant. All factors affecting the selection of plant location are weighed carefully. Several methods, including the factor-rating systems, centroid method and transportation method, have been employed to select the best location option for siting a bio-ethanol plant (Bartness, 1994). Dantzig (1963) developed a shipment model, using the transportation method to optimise the distribution of products to warehouses. The transportation method, when used together with other methods, can narrow down the number of nodes in the supply chain, thereby reducing the number of variables in the model. One such method could be the Kepner Tregoe (K-T) decision-making criteria, which prioritize and evaluate information. Using the (K-T) analysis, influential factors affecting the location of the plant are evaluated. These factors are ranked in order of importance with respect to their effect on the decision of siting a bio-ethanol production plant. These are ranked from 1 to 100, with the most crucial factor taking the highest rank of 100. The performance of each site with respect to the chosen site is evaluated. Geographical information systems can also be used

for location precision, thereby improving the accuracy of the solution obtained from the model (Panichelli & Gnansounou, 2008). The site with the highest final score is the final choice. Such a bio-ethanol production location would be at a sugar mill when considering the sugarcane-to-bio-ethanol supply chain. The production of sugar and bio-ethanol in one location will reduce the overall cost of the bio-ethanol supply chain and improve the revenue competitiveness of sugar production (Tongaat Hulett, 2013).

Another advantage of locating bio-ethanol facilities at sugar mills is the possibility of energy integration, which can result in reduced energy costs and reduced greenhouse gas emissions. Additionally, cogeneration of heat and power allows sugar producers to meet their internal energy requirements and drastically reduce their operational costs, in many cases by as much as 25% (bio-energy consult, 2015). Most of the sugar mills are designed to produce heat and electricity from bagasse, thereby making them energy independent. Currently, Malelane and Komati mills, which are South African sugar mills owned by Transvaal Sugar Beperk/Limited (TSB), are self-sufficient in power and sell surplus electricity to the grid under power purchase agreements (Tongaat Hulett, 2013). Thus, locating bio-ethanol facilities at the current sugar mill locations will result in reduced costs for the supply chain. In cases where the electricity generated from biomass is not enough to cater for the energy demand, additional electricity is bought. Čuček et al. (2014) included additional electricity in their MILP model.

Brazil and India produce sugar, electricity and ethanol from sugar mills. The mills in India produce more electricity than ethanol, while the mills in Brazil produce more ethanol than electricity (Tongaat Hulett, 2013). According to the same report, Brazil has had a growth of approximately 60% electricity production from sugarcane and India had an electricity production capacity of 5,000 MW from the sugarcane industry. Other countries such as Thailand, Mauritius and Australia are also transforming to co-produce sugar, ethanol and electricity from sugarcane (Tongaat Hulett, 2013).

In South Africa's neighbouring country, Zimbabwe, there is the Triangle plant that produces sugar and bio-ethanol. This plant is owned by Tongaat Hulett, which

operates six of the sugar mills in South Africa. Triangle plant has a capacity to produce 40 million litres of bio-ethanol per year (i.e. a 48-week production). On average, it produces 740,000 litres of fuel-grade ethanol per week and 24 million litres per year due to lack of demand. Zimbabwe currently blends ethanol into petrol at a ratio of 1:9 to produce E-10 petrol.

A multi-objective model of bio-ethanol and bio-diesel supply chains in the South African context was developed by Letete (2009). The framework for Letete (2009) included three objectives, which are an environmental objective, an economic objective and a social objective. Location and capital costs of the production facilities is not covered in the work of Letete (2009). From the findings of the study, Letete (2009) recommended the production of both biodiesel and bioethanol. This recommendation could have been influenced by the simplification in the transportation distance and costs of the supply chain network considered in the study. The biomass to bio-diesel supply chain in South Africa was also optimised for “value added,” location, plant size and cost by Becker (2012). The author concluded that small sized facilities were economical for biodiesel production due to tax subsidies. Another study was done by Čuček et al. (2014) using corn, wheat, straw and other energy crops as feedstocks, for a region in Europe. The authors’ approach entailed the use of an MILP model, which was solved, using GUROBI solver in GAMS. Wheat and wheat straw were also used as feedstock for studies carried out in the UK by Akgul et al. (2013) and Zamboni et al. (2009). The studies’ objectives were economic and environmental, while satisfying food demand.

2.2 Bio-Ethanol Production

A key component of the supply chain network considered in this study is the processing of biomass to produce bio-ethanol. Bio-ethanol can be produced from the conversion of biomass through thermochemical conversion, which involves gasification and pyrolysis and biochemical technologies that make use of microorganisms during the fermentation process (Hamelinck et al., 2005). *Saccharomyces Cerevisiae* is the most employed microorganism for fermenting the

hydrolysates of lignocellulosic biomass (Cardona et al., 2009). This yeast ferments the hexoses contained in the hydrolysate, but not the pentoses (Cardona et al., 2009). If fermentation and hydrolysis/saccharification of lignocellulosic biomass takes place in separate vessels, the process is known as separate hydrolysis and fermentation (SHF). This configuration allows each step to be performed at its optimal operating conditions (especially temperature and pH) (Cardona et al., 2009).

To increase the amount of sugars converted into ethanol genetically modified organisms that can ferment both glucose and xylose simultaneously are used (Mosier et al., 2005). Sequential fermentations are employed and both fermentations are performed independently (co-fermentation) (Cardona et al., 2009). Biomass utilisation rates are lower than those of microorganisms that only assimilate hexoses (Cardona et al., 2009).

When fermentation and saccharification take place in the same vessel, the process is known as simultaneous saccharification and fermentation (SSF). This process reduces equipment costs, as no hydrolysis reactors are required. However, this process is difficult to control due to the different optimal operating conditions of hydrolysis and fermentation (Claassen et al., 1999). To improve the bio-ethanol yield, this process is combined with co-fermentation and the process is called simultaneous saccharification and fermentation (SSCF) (Mosier et al., 2005). In this study, it is assumed that the SHF process is employed and the yeast *Saccharomyces Cerevisiae* is used during fermentation.

Pre-treatment is a key process in the conversion of lignocellulosic materials into bio-ethanol (Yang and Wyman, 2008). The effectiveness of pre-treatment depends on the type and composition of the biomass. Table 2.1 presents the chemical composition of sugarcane bagasse reported by different authors.

Table 2.1: Chemical composition of sugarcane bagasse (Karp et al., 2013).

Component	Quantity reported by authors (%)		
	Soccol et al. (2011a)	Rocca et al. (2011)	Bertoti et al. (2009)
Cellulose	32.0-44.0	45.5	47.5-51.1
Hemicellulose	27.0-32.0	27	26.7-28.5
Lignin	19.0-24.0	21.1	20.2-20.8
Extractives	-	4.6	0.8-3.0
Ashes	4.5-9.0	2.2	other compounds

Physical pre-treatment methods include milling, pyrolysis and microwave. The mode of action of these methods involves reduction of size to increase the surface area of particles that is exposed to hydrolytic agents in downstream processing without the use of chemicals. Ball milling is the most commonly used milling method. In pyrolysis and microwave pre-treatment methods, heat is used to break down the hemicellulose part of lignocellulose biomass into H₂, CO₂ and char (Kumar et al., 2009). Microwave method has the advantage that it has short reaction times and homogeneous heating of the reaction mixture, which results in energy and time savings. (Balcu et al., 2011). Physicochemical methods use physical properties such as temperature and pressure in combination with other reagents that are added to the lignocellulosic biomass. These include ammonia fibre explosion (AFEX), steam explosion, liquid hot water (LHW) and supercritical fluid (SCF) pre-treatment.

Biological methods involve the use of microorganisms such as fungi to degrade the hemicellulose and lignin parts of the lignocellulosic biomass. Although biological pre-treatments are low cost methods, the pre-treatment time is long and they have low rates of hydrolysis (Sun et al., 2002). Chemical pre-treatment methods loosen the crystalline structure of the lignocellulose network (Canilha et al., 2012). These methods include acid-based, alkaline-based, wet oxidation, ozonolysis, organosolv and ammonium pre-treatment. Acid-based pre-treatment processes have proved to be effective in delignification on a wide range of lignocellulose substrate, but are relatively expensive (Mosier et al., 2005b) due to the cost of the acid and the energy

required in the process. However, if operated at low to medium temperatures, less energy is required and the process becomes economical. It is assumed that chemical pre-treatment technology is employed in this study because of its effectiveness on a wide range of lignocellulosic material. A summary of various pre-treatment methods, their advantages and/or disadvantages, pre-treatment conditions and yields are shown in Table 2.2 below.

Pre-treatment process	Conditions	Advantage	Disadvantage	Biomass/treatment	Yield (%)	Reference
Acid treatment	Dilute/concentrated acid/few minutes/high and low temperature	Increase in porosity/increased enzymatic hydrolysis	Synthesis of furfural/hydroxymethyl furfural/need for recycling/costly	Olive tree biomass/170 °C and 1.0% acid	48.6% Reducing sugar	Cara, et al. (2008)
				Corn fibres/0.5% sulfuric acid, 5% biomass and at 140°C	56.8% Reducing sugar	Noureddini and Byun (2010)
				Sugarcane tops/25% w/w biomass, 3% sulfuric acid for 60 min	68.5% Reducing sugar	Sindhu, et al. (2011)
Alkaline treatment	Alkali treatment at NTP	Removal of lignin/hemicellulose hydrolysis	Formation of salts of calcium and magnesium	Corn stover/0.5 g Ca(OH) ₂ /g, 55 °C for 4 weeks with aeration	91.3% Glucose, 51.85% xylose	Kim and Holtzapple (2005)
				Spruce/3% NaOH/12% urea and -15 °C	60% Glucose	Zhao, et al. (2008)
				Switch grass/0.5% KOH, at 21°C and after 12 h treatment	58.2% Reducing sugar	Sharma, et al. (2012)

Ammonia treatment	Ammonia at elevated temperatures	Removal of lignin/decrystallizing cellulose	Removal of ammonia/costly	Corn stover/first stage 190 °C, 5.0 mL/min, 30 min for hot water treatment and 170 °C, 5.0 mL/min, 60min for aqueous ammonia treatment	78% Glucan, 3.6% xylan	Kim and Lee (2006)
				Barley hull/15–30% aqueous ammonia, at 30–75 °C for 12 to 77 days	83% Glucan, 63% xylan	Kim, et al. (2008)

Table 2.2: Summary of various pre-treatment processes, their advantages/disadvantages, pre-treatment conditions and percent yield. Taken from Chartuverdi and Verma (2013)

After pre-treatment, ethanol is then produced from the biomass through fermentation. Figure 2.1 below shows production of anhydrous ethanol from sugarcane.

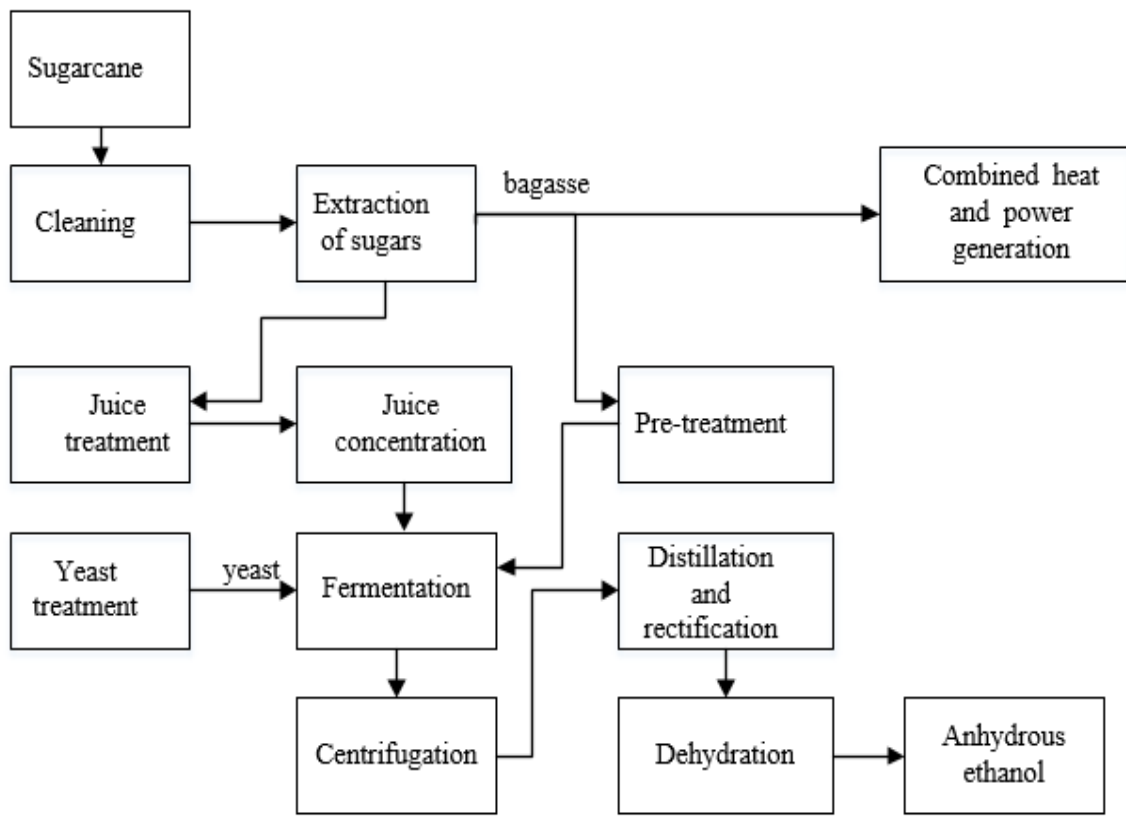


Figure 2.1: Block flow diagram of anhydrous bio-ethanol production process from sugarcane autonomous distillery adapted from Dias et al. (2010).

2.3 Sugar Production

The energy demand in a sugar mill can be met by burning bagasse, the fibrous part of the cane that remains after juice extraction. About 280 kg of bagasse is produced for every tonne of cane crushed (Tongaat Hulett, 2008; Mtunzi et al., 2012). “Per kilogram of sugar produced, the milling of the cane also results in about 0.3 kg of molasses as secondary product, and about 1.25 kg of fibrous residue (dry basis), known as bagasse, which is used to provide the energy requirements of the process” (Botha & von Blottnitz, 2006).

At the Triangle plant in Zimbabwe, approximately 13.5 MW of electricity is generated from 640,750 tonnes of bagasse annually (Mthunzi et al., 2012). If the bagasse is

incinerated efficiently, there is potential to double the amount of electricity produced from bagasse (Mthunzi et al., 2012). The net calorific value for bagasse is 7.85 MJ/kg (Mthunzi et al., 2012). According to Mthunzi et al. (2012), 1 kg of bagasse produced 2,064 kg of steam. The electricity demand per tonne of cane – according to the work of Mthunzi et al (2012) – was 43 kWh per tonne of cane crushed. Lower consumption values of 28 kWh per tonne of cane crushed and steam demand per tonne of cane crushed of 240-500 kg have also been reported (Seabra et al., 2010; Ogden et al., 2013). Electricity and/or steam is required to drive shredders, cane knives and crushers. Steam is also required in feed pumps, drying, dewatering, steam turbines and other equipment that require use of steam. Steam and electricity are produced from combined heat and power plants within the processing facilities.

2.4 Combined Heat and Power (CHP) cogeneration technologies

The process by which electricity is produced together with heat from a single source of such as coal, biogas, biomass or oil, is known as cogeneration or combined heat and power (CHP) (EPA, 2008). Use of CHP from bagasse and other waste material has several merits, which include reduction in greenhouse gas emissions, as environmentally friendly fuel is used and less fuel is burnt to produce each unit of electricity. No losses are incurred during transmission and distribution if the energy is produced and used on site. CHP also cushions the plant against outages from the national grid as the plant generates electricity on site. If the plant generates excess electricity, that is sold to the national grid and the company benefits economically. CHP cogeneration techniques vary and the amount of electricity and heat produced depends on the technique, turbine type and size among other factors.

2.4.1 Biomass integrated-gasifier/gas turbine combined cycle (BIG/GTCC) cogeneration technology

In the (BIG/GTCC) design, existing conventional cogeneration equipment is used to provide and meet process steam requirements. The steam from this boiler is expanded to 2.5 bar in back-pressure steam turbines that run mechanical equipment in the factory. A small amount of electricity is also generated from this process. In parallel to

the 22-bar boiler is the gasification equipment as shown in Figure 2.2. Fuel to the gasifier is dried up to 10% moisture content through the use of a small amount of bagasse that is burnt in a furnace. From the drier, the fuel goes into a gasifier, then into a gas cleaner. The fuel is then compressed and fed to a gas turbine generator. Hot gases produced are used to drive the steam turbine generator. The diagram below shows a partial BIG/GTCC cogeneration technology.

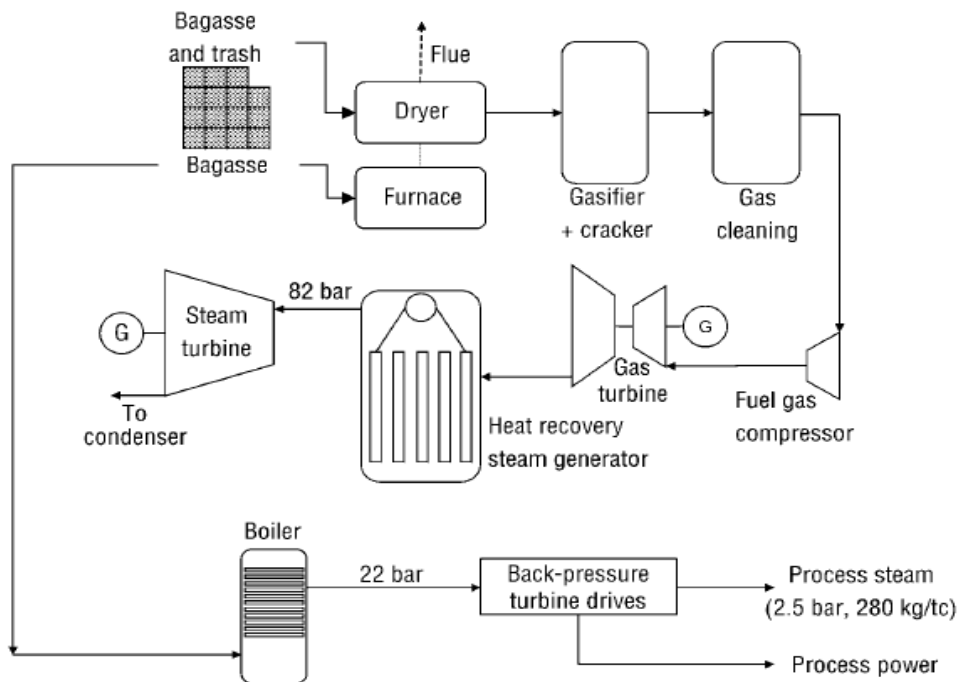


Figure 2.2: Partial biomass integrated-gasifier/gas turbine combined cycle. Adapted from Larson et al. (2001).

2.4.2 CHP Cogeneration costs

The cost of generating electricity varies considerably depending on plant size, technology, location and pricing policy (Khatiwada et al., 2012). Electricity production from bagasse cogeneration at the processing facility that uses sugarcane as feedstock is cost competitive due to low or absence of biomass transportation costs. The investment cost for a bagasse cogeneration plant was found to be 1,000 \$/kW in Mauritius and Reunion (Mbohwa et al., 2003). These cogeneration costs are not consistent. In some cases CEST is cheaper than the backpressure cogeneration system, whilst in other cases it is vice versa. For the year 2004/2005, Marcovitch (2005) gave estimates for Brazil cogeneration technologies producing 40 kWh per

tonne of sugarcane as 500-600 \$/kW for conventional cogeneration during harvest period and 600-800\$/kW for CEST producing 150 kWh per tonne of cane crushed for the whole year. For a biomass integrated gasifier/gas turbine (BIG/GT) producing 517 kWh per tonne of cane crushed, the cost was estimated to be 2,500 \$/kW. According to the work done for Hippo Valley Estates by Mtunzi et al. (2012), the cost of cogeneration, using a back pressure turbine system, was approximately 579 \$/kW for a 20 MW steam turbine. Larson et al. (2001) estimated the cost of CEST to be 1,500 \$/kW for a 33 MW plant; and for a 60 MW plant the installed cost for BIG/GTCC was estimated to be 1,480 \$/kW. CHP cogeneration costs for biomass systems in Brazil were also estimated, by the EPA to be 4,630 \$/kW and 4,000 \$/kW for a back-pressure system for plants with capacities 600 and 900 tonnes per day, respectively. For a power-only CEST, the cost was lower; 1,860 \$/kW and 1,630 \$/kW for the two plants.

2.5 Other By Products from Bio-Ethanol Production

In addition to heat and electricity, other products such as molasses and vinasse are produced depending on the biomass type. Molasses is a dark brown liquid that remains after crystals are made from sugarcane juice that contains approximately 4% of sucrose, 11% of reducing sugars (fructose, glucose) and many minerals (Tongaat Hulett, 2008). Molasses is used in ethanol manufacture and in animal feed. In South Africa, molasses is mainly used as an animal feed, while vinasse is used as a fertilizer. For every 100 kg of cane crushed, 4 kg of molasses is produced (Tongaat Hulett, 2008). Most of the animal feed production facilities are located within the mill facilities. These include Voermol foods, located at the Maidstone mill and Molatek that is located at Malelani mill.

Second-generation biomass produces lignin cake during the delignification stage of pre-treatment. The yield of lignin cake after hydrolysis ranges from 0.43 kg/kg of bagasse up to 0.48 kg/kg of bagasse hydrolysed (Palacios-Bereche et al., 2012). In this study, the lignin cake yield is taken to be 50% of the bagasse that is fed to the pre-treatment unit. In the methodology of this study, in line with the studies conducted by Kadam (2002), Botha and von Blottnitz (2006), it is assumed that the lignin cake will

be dried and burnt together with bagasse to produce heat and electricity to meet plant energy needs. In the South African context, Botha and von Blottnitz (2005) compared the environmental merits of using bagasse for electricity generation and for bio-ethanol production, using a cradle to gate lifecycle assessment. They concluded that it is more environmentally friendly to produce electricity than to produce bio-ethanol. However, for this work, an economic value, equivalent to the heat and electricity that would have been produced from the lignin cake was assigned to the lignin cake, since the current model does not include product recycle, which will be incorporated in future studies.

2.6 Capital Costs and Plant Sizing

Capital costs of a bio-ethanol processing facility constitute the greater part of the overall costs of the supply chain. Most researchers in the field used the six tenth rule for estimation of fixed capital costs of processing facilities. Nguyen and Prince (2006) developed a model for optimising plant capacity for bio-ethanol plants. In their study, the relationship between transportation costs and capital costs was investigated with the aim of finding a relationship that minimises total costs for the supply chain. In the power rule for capital cost estimations, Nguyen and Prince (2006) used a value of 0.7, although most studies use 0.6. Their model showed that transportation costs increase with plant size and capital costs decrease with increase in plant size (economies of scale). Čuček et al. (2014) used the six tenths rule to determine the capital cost of the bio-fuel plants in Europe. Other methods that can be used to estimate fixed capital cost include the factorial method and the Lang factor approach, which was used by Amigun and von Blottnitz (2009) in their analysis of costs for bio-ethanol plants. The capital cost expression is a source of non-linear equation in a mathematical programming model. This nonlinearity can be overcome by use of linearization techniques such as the Taylor series expansion, which can be used to linearize the investment term. Some studies have used the piece-wise linearization approach (Bergamin et al., 2008; Čuček et al., 2014).

2.7. Storage of Feedstock and Products

To avoid deterioration of its content, sugarcane must be processed as soon as possible to avoid its sugar content deteriorating. Most sugarcane is delivered within 24 hours of harvesting (Shell, 2014). For this study, since the demand for ethanol at the fuel depots/refineries was calculated as 10% of the annual output of the depots, additional storage facilities would be required to store the ethanol prior to blending, i.e. for a scenario where the petroleum refineries do not have enough storage space to cater for the new product.

2.8 Life Cycle Assessment / Environmental Impact Assessment

Life cycle assessment (LCA) is a multi-step procedure for calculating the lifetime environmental impact of a product or service. According to the International Organization for Standardization (ISO) 14040 and 14044 standards, a Life cycle assessment is carried out in four distinct phases. These are often interdependent as the results of one phase form a basis for the completion of other phases. These phases are:

- (i) goal and scope definition;
- (ii) inventory analysis;
- (iii) impact assessment; and
- (iv) interpretation (ISO 2006a; ISO 2006b).

The **goal and scope definition** step defines the reason for executing the LCA and also describes the product, the stages of the product life cycle and the purpose of having the product. It also defines the system boundaries as well as the functional unit. The Life Cycle Impact Assessment (LCIA) procedure requirements, as well as the interpretation to be used, is also covered under this step (PRé, 2013).

In the **inventory analysis** step, the inputs and outputs of the system as well as the emissions to the environment related to each of these inputs and outputs are identified and quantified. It is possible to use databases that come with LCA software (PRé,

2013). These include ecoinvent v3. 0 and the U.S. Life cycle inventory database among others.

In the **impact assessment** step, data from the inventory analysis is evaluated and translated into a set of potential environmental impacts. It is mandatory for LCIA to select impact categories and characterise the environmental impacts from the inventory step. Impact categories include climate change, acidification, eutrophication and human toxicity. Category indicators are also selected such as global warming potential (GWP), which is indicated by greenhouse gas emissions (such as N₂O, CO₂, CH₄) measured in kg of CO₂ equivalent are also selected. The total environmental impact for each of the categories is obtained by summing the equivalence of each of the contributing emissions.

There are many life cycle impact assessment methods that can be used to categorise the elementary flows from the inventory step after characterisation. These methods include the Institute of Environmental Sciences, Leiden University Impact Assessment (CML-IA) baseline method. The CML-IA method classifies environmental impacts into ten categories. These are: global warming potential (kg CO₂ eq), eutrophication (kg PO₄ eq), acidification (kg SO₂ eq), human toxicity (kg 1,4-DB eq), abiotic depletion (kg Sb eq), ozone layer depletion (kg CFC-11 eq), photochemical oxidation (kg C₂H₄ eq), marine aquatic ecotoxicity (kg 1,4-DB eq) and terrestrial ecotoxicity (kg 1,4-DB eq) (PRé, 2013).

For simplification of results interpretation, normalisation and weighting are used. These are optional steps in ISO 14040/44 as they contain additional subjective steps (PRé, 2013). The extent of an impact category indicator is compared to a reference, thereby making it possible to compare the environmental impact of different categories, which have different units. Normalisation shows the extent to which an impact category indicator result has a relatively high or relatively low value compared to a reference. Normalisation also solves the incompatibility of units. The results are weighted against subjective criteria whose weighting factors may be biased. Weighting

is a controversial step in LCA, since it is not based on natural science. As such, it is only used in comparisons for internal decision-making (PRé, 2013).

The interpretation step is the final step of the LCA, where the results from the previous steps are analysed in line with the goal of the LCA and conclusions and recommendations are drawn. During the analysis, the impact category contributing the highest environmental impact as well as the LCA stage that has the highest environmental impact are identified and significant issues are noted. These issues are then used in the evaluation of the data that was used in the LCA. Checks are done for completeness, sensitivity and reliability of the data (Günther Seliger, 2012).

2.9 Mathematical Modelling

Mathematical modelling is a process of developing a model that describes a system using mathematical language and concepts. These models help to explain the system, study the effects of different components. The models also make predictions about behaviour of the system. Experimentation is possible with a model, whereas it is often not possible or desirable to experiment with the object being modelled (Williams, 2001). The operation of the system is represented by simulation. Simulation is the imitation of the operation of a real-world process or system over time. Simulation is also used when the real system cannot be engaged, if, for example, it is not accessible, dangerous or unacceptable to engage, being designed but not yet built, or simply non-existent (Williams, 2001). In this study, modelling is used as there are no commercial bio refineries that have been erected yet in South Africa. This work is meant to build confidence in investors by providing options that are financially and environmentally feasible for bio-ethanol production from sugarcane, bagasse, sugarcane leaves and crop residue material.

There are several types of mathematical programming models; these include linear programming (LP) models, mixed integer linear programming (MILP) models, nonlinear programming (NLP) models and mixed integer non-linear programming (MINLP) models. Linear programming is an optimisation tool that is used to achieve an optimum solution based on some set of constraints, using a linear mathematical

model. MILP models determine the values of decision variables that optimise (maximise or minimise) an objective function among all sets of values that satisfy the given constraint (De Meyer et al., 2014). An objective function is the quantity or quality to be minimised or maximised, while a constraint defines the boundaries of the parameters.

A MILP model arises if some or all the variables in an LP model assume integer values. Such models are more difficult to solve compared to those that include fractional values (Williams, 2001). Models that incorporate nonlinear terms are known as NLP models. For such models, solutions reported by a solver environment such as GAMS may not always be the optimum (McCarl et al., 2003). This occurs since the solvers and GAMS generally do not try to verify whether the conditions for true global optimality exist, the verification is left to the user (McCarl et al., 2003). Global optima is a selection from a given domain, which provides either the highest value or the lowest value depending on the objective when a specific function is applied (Williams, 2001). Other optimisation programming models include stochastic programming, which is mostly used where there is uncertainty and probability is employed to specify the required data.

All mathematical programming models involve optimisation. Optimisation problems are formulated as follows:

$$\begin{aligned}h(x, y) &= 0 \\ \text{Min } Z &= f(x, y) \\ \text{subject to } &g(x, y) \\ x &\in X, Y \in (0, 1)\end{aligned}$$

Where $f(x, y)$ is the objective function (e.g. cost), $h(x, y) = 0$ are the equations that describe the performance of the system (e.g. material and energy balances) and $g(x, y)$ are constraints of the system. These constraints can be 'equal to', 'less than or equal to', or 'greater than or equal to' a certain value. The variables x are continuous and generally correspond to state variables (e.g. flow rates, temperatures, compositions, etc.), while variables y are binary variables, that are restricted to take

values of 0-1 (Floudas, 1995). The discrete variables represent decision variables, e.g. selection of plant location, routing tankers for the distribution of crude and refined products, sizing and layout of a pipeline and designing equipment and an entire plant (Edgar & Himmelblau, 1988).

Mathematical programming models involve large amounts of data that cannot be handled and processed manually. Solvers are employed to solve and compute the models developed. In this study, GAMS version 22.4 is used as the solver environment. This computer package does not require huge computer memory and task execution is generally fast. The size of the model also determines the time it takes to solve. The larger the model, the more computer processing unit (CPU) seconds it takes to solve. To this effect, in this study, reasonably sized models are developed to reduce solving time. Akgul et al. (2010) solved the mixed integer linear programme model developed in their study of optimisation based bio-fuel supply chains, in less than 15 seconds, using a CPLEX solver in GAMS. Čuček et al. (2014) solved large models in a few hours, using GUROBI solver in GAMS.

2.9.1. Modelling and optimisation

Mathematical optimisation models can be classified as single objective and multi-objective optimisation models (Čuček et al., 2014). Single objective models seek to find one solution that is considered as the best option, which corresponds to the minimum or maximum value of a single objective function that lumps all different objectives into one. This provides decision-makers with insights into the nature of the problem, but usually cannot provide a set of alternative solutions that trade different objectives against each other (Savic, 2002). Multi-objective optimisation considers more than one objective function and if the objective functions are conflicting, there is no single optimal solution. The interaction among different objectives gives rise to a set of compromised solutions, largely known as the trade-off, non-dominated, non-inferior or Pareto-optimal solutions (Savic, 2002). Multi-objective optimisation is considered to be an application of single-objective optimisation for handling multiple objectives (Kalyanmoy, 2001).

Ekşioğlu et al. (2009) developed MILP models to optimise biomass (corn and wood) to bio-energy supply chain, using economics as the objective. The primary goal of the work of Ekşioğlu et al. (2009) was to improve energy sustainability, job creation in rural areas, and to reduce the consequences of climate change. Some similarities can be drawn between the studies of Ekşioğlu et al. (2009) and the present study in that the driving force for bio-ethanol production in South Africa includes bridging the economic gap between the first and second economies. The environmental impacts associated with the supply chain are also investigated in this study. However, the model developed by Ekşioğlu et al. (2009) only covered the supply chain up to the bio-refineries, leaving out the product distribution network aspect. Dal Mas et al. (2010) developed a MILP model that takes into account uncertainty of product market. The model was optimised for the financial objective.

Biomass availability is one of the major factors affecting the delivery cost of ethanol (Ekşioğlu et al., 2009). Transportation costs increase when biomass has to be shipped from afar. Ekşioğlu et al. (2009), concluded that when biomass availability is low and transportation costs are high, smaller size bio-refineries become economical. The results from their study indicated that constructing two or three small-sized bio-refineries instead of one centrally located bio-refinery of a large size would decrease the overall supply chain costs by decreasing transportation distances and corresponding costs. Although it is generally assumed that economies of scale should result in reduced total production costs, Ekşioğlu et al. (2009) found that the economies of scale due to operating large-sized facilities are overcome by the increase in transportation costs. Paradoxically, at higher ethanol demand, building a centralised ethanol production facility would result in reduced costs due to economies of scale (Lin et al., 2014). In this study, smaller sized optimally located bio-refineries have been considered. The government in the position paper on bio-fuels (2014) stated that subsidies would be given for the production of bio-ethanol up to a maximum of 158,000 m³/y. This is also taken into consideration during the sizing of the bio-processing facilities in this study.

Huang et al. (2009), in their study of strategic planning of future bio-ethanol systems, developed a multi-stage mixed integer linear programming model to optimise the whole bio-ethanol supply chain from biowaste source to the consumers. The multistage model for cost minimisation was solved, using commercial solver AMPL-CPLEX (Huang et al., 2009). Their model integrated facility spatiality and time variation of demands. They also determined the best sequence of opening and expanding bio-refineries. In their model, they included a penalty cost for outsourcing of ethanol when ethanol demand is not met. They introduced a constraint that allows for the expansion of the bio-refineries catering for increase in demand. The model in the present study does not include such a constraint as it is not a demand-based model. The size and location of the bio-refineries will be designed to utilise as much biomass as possible within a geographical location. Throughout their analysis, Huang et al. (2009) found that the competitiveness of bio-ethanol highly depends on the optimisation of the entire supply chain over the whole planning horizon. They also concluded that optimising a portion of the supply chain would not accomplish the goal. Performing a full supply chain optimisation would provide a better understanding of the many trade-offs involved in both temporal and spatial dimensions. Yu et al. (2009) concluded, from their studies on biomass supply, that transport costs were significant. They suggested ways of minimising the transport costs of biomass such as locating processing facilities in areas close to the farms with high biomass cultivation rate. Similarly, transport costs from the distribution of the bio-ethanol and by-product also contribute to the overall cost of the supply chain. This was confirmed by a study by Morrow et al. (2006) on the distribution of ethanol blends in the US. The transport costs may also vary with topography. In this study, transportation of both biomass and product are optimised.

Akgul et al. (2012) developed a MILP model to address the sustainability issues associated with the supply chain. These issues include land use requirements of second-generation crops, the use of food crops in bio-fuel production and competition for biomass with other sectors. The objective of the model developed in the work of Akgul et al. (2012) was to minimise the total daily cost of the supply chain. The constraints in their model were bio-fuel demand, bio-fuel production (minimum and maximum capacity of plant and location of plants), biomass cultivation rate (minimum

and maximum amount of local biomass) and sustainability. They also contained a sustainability constraint aimed to reduce the competition for biomass between food and fuel production. The proposed models were solved in GAMS 22.8 by using CPLEX 11.1 solver in a 3.2 GHz, 3.49 GB RAM machine.

Akgul et al. (2012) investigated two demand scenarios based on the UK domestic target of 3.4% by energy content and the European Union target of 10% by energy content for the years 2011 and 2020, respectively. From the first scenario, they found that integrating first- and second-generation technologies resulted in reduced production costs. This is due to a less distributed network structure in terms of biomass flows and activated biomass cultivation sites (Akgul et al., 2010). From the 2020 scenario, they concluded that utilisation of set-aside land for energy crops resulted in reduced dependency on biomass imports, thereby enhancing the security of energy supply. This study shows that use of hybrid technologies results in an efficient utilisation of biomass.

Čuček et al. (2014), in their work on synthesis of optimally integrated biomass and bio-energy supply network, developed a MILP model that was converted to a MILP model by linearizing the nonlinear investment terms. Their study had a single optimisation objective, which was to optimise profits focusing on land utilisation in the production of first-, second- and third-generation bio-fuels. They concluded that it was profitable to produce second- and third-generation bio-fuels if land dedicated to energy crops was increased. Akgul et al. (2012) also investigated land use and came to the same conclusion. The work of Čuček et al. (2014) also demonstrated that producing bio-fuels was economically more attractive than producing food.

The collection of biomass from farms is a process that can add substantial costs to the overall cost of the supply chain if not carefully planned. Čuček et al. (2014), in their biomass supply chain optimisation model, included central storage facilities where biomass from farms that are far from the processing facility is stored whilst awaiting transportation. Akgul et al. (2012) used Von Neumann and Moore's 8N and 4N's "neighbourhood approach" for biomass flow from farms to ethanol processing facilities

in order to optimise the flow of material from the processing facility's surrounding farms. They also introduced a constraint called the number of transport units in their optimisation model to increase the biomass flow rate to the processing facilities. They found that the optimisation of biomass flow resulted in reduced transportation costs.

Several methods have been employed in determining the transportation distance between locations in a supply chain. Google Earth® (Google Earth, 2014) has been employed to determine distance between two points based on existing infrastructure. You et al. (2012) used google maps to obtain distances between the centre points of counties in their study. This gives good approximations of the transportation distance. However, most studies used straight line distances which have to be multiplied by a tortuosity factor for the particular mode of transport to get the actual distance (Akgul et al., 2010; Čuček et al., 2014; Becker, 2012; Zamboni et al., 2009).

Some studies have used mapping software to get improved estimates of location and distances used in supply chain models (You et al., 2012). Lin et al. (2012) used ArcGIS to determine transportation distances that were used in their model. Besides getting improved location and distance estimates, the use of mapping software such as ArcGIS helps to incorporate spatial information in studies where specific locations are to be determined. Zhang et al. (2011) in a study to find optimal location of a biofuel plant used GIS and a transportation cost model. County boundaries and county based biomass distribution were used in their GIS analysis. The use of political boundaries can have a disadvantage in that these boundaries may change with time. To overcome this a fishnet based approach is used in the current study (ISO 19131., 2013). In this approach a fishnet, which is a collection of rectangles arranged in a manner similar to a rectangular grid, was superimposed on the map covering the area under study. In the context of this study, each rectangle in the fishnet/grid is referred to as a cell. A similar approach was used by Zhang et al. (2011) in the second stage analysis of their study in which a transportation model is employed to identify the optimal location of bio-ethanol processing facilities.

Lin et al. (2012), developed a model, which was formulated as a mixed integer linear program to optimise the location, size and number of biofuel processing facilities so that the overall cost of the supply chain could be minimised. The model was solved using CPLEX solver in GAMS. They used GIS tools to generate data for the model. This data was stored in a spreadsheet format. Similar to the work of Lin et al. (2012), GIS tools were used in this study to generate data that was stored and used as excel spreadsheets. You et al. (2012) integrated GIS with mathematical programming to determine the location of biorefineries and also to optimise biofuel supply chains (You et al., 2012).

While most objectives are complementary to financial objectives, environmental objectives are often contradictory. When profits are increased, the environmental impact is also increased. To circumvent this problem, a compromise is made on both financial and environmental objectives in such a way that there is a balance between the two objectives. The best scenario would be one in which profits are at a maximum and the environmental impact is at a minimum. Pareto analysis is employed to achieve this balance.

Although there has been much research conducted in this field of bio-ethanol supply chain optimisation, very few authors have focused on more than one objective in optimising the supply chain. Figure 2.3 below shows a Pareto curve that was used to find an optimal solution for the optimisation of a bio-refinery for environmental and economic objectives (Santibañez-Aguiler et al., 2011).

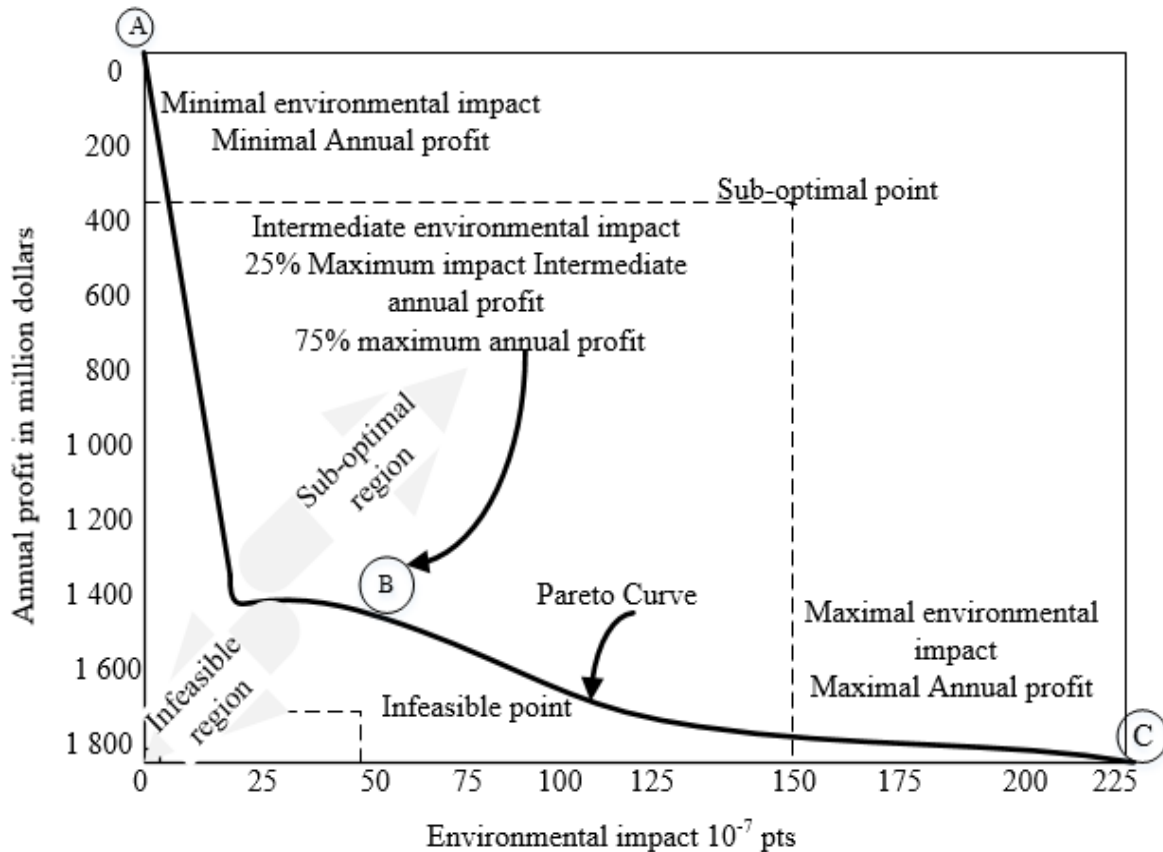


Figure 2.3: Pareto solution (Santibañez-Aguilar et al., 2011)

Santibañez-Aguilar et al. (2011), in their research on optimal conversion of biomass to bio-fuels, looked at the selection of processing technologies, feedstock and products. The objective of their work was to maximise profits and minimise environmental impact simultaneously. They measured environmental impact through the eco indicator 99 based on LCA analysis, which looks at damage to human health, ecosystem and resources. In the linear programming model that was developed for a case study in Mexico, they did not consider the economies of scale for transportation costs because the distances between the feedstock source and demand centres were short. Pareto curves were constructed, using the ϵ -constraint method as explained by Diwekar (2003). These were used to select the most favourable option of 80% profits and 25% of environmental impact. The linear programming models developed were solved in a matter of seconds in GAMS, using CPLEX solver. A similar approach was adopted in this study for multi-objective optimisation. However, economies of scale for transportation is taken into consideration.

The ϵ -constraint method was also used in the multi-objective optimisation of cellulosic bio-fuel supply chains by You et al. (2012). A Pareto analysis was done to see the trade-offs among three objectives namely, social, economic and environmental. A MILP model was developed, which included Aspen-based process models for biochemical and thermochemical conversion pathways for biomass to bio-ethanol. The number of jobs created was used to measure the social impact, while greenhouse gas emissions were combined to form one environmental indicator expressed in carbon dioxide equivalent emissions.

In the South African context, the three objectives mentioned above were also used in optimising the model developed for bio-fuel supply chains by Letete (2009). The author investigated the effect of changes in land use to produce crops for bio-ethanol production and also explored crop combinations that would maximise the economic objective. For bio-ethanol production, Letete (2009) concluded that the economic objective would be maximised by a combination of sugarcane and maize as feedstocks, while for bio-diesel, canola and sunflower should be combined. In terms of carbon debt repayment, sugarcane had the favourable timeframe amongst all the crops that were considered in the study. To avoid food shortages and because of its exclusion from the government list of usable crops for biofuel production, maize is not included as a feedstock in this study.

Pareto analysis of the results of the investigation performed by Giarola et al. (2011) gave the optimum technology as integrated grain stover processes, which is a first/second-generation hybrid technology. Thus, in order to optimise the biomass to bio-energy supply chain, it is more favourable to use hybrid first- and second-generation technologies than to use the technologies separately. Giarola et al. (2011) and Giarola et al. (2012), in their study to optimise the financial and environmental performances of bio-refineries and bio-fuel supply chain respectively, found that first-generation technologies are more economically competitive, but are not environmentally sustainable (10% greenhouse gas savings instead of a minimum of 35% as stipulated by the European Union). The EU targets for greenhouse gas savings for bio-fuels were 35% for the year 2010 and 50% for the year 2017 (Green

Paper, 2000). They also found that second-generation technologies are environmentally competitive. However, second-generation technologies on their own are not economically viable. This is due to the high cost of setting up facilities and a heavy dependency on subsidies and incentives.

In a comparison of bio-fuel production technologies, Bonomi et al. (2011) investigated the environmental impact (global warming potential, eutrophication potential and human toxicity potential) of standalone ethanol production plants and integrated sugar and ethanol production plants. They found that environmental impact in the ethanol production process could be reduced by making use of annexed plants, which are flexible.

2.10 Sensitivity Analysis

Models developed for bio-ethanol supply chain optimisation should be able to measure the effect of changes in the operating environment. A sensitivity analysis of the effect of changes in demand and yield on the supply chain was done by Lin et al. (2014). The authors found that a reduction in biomass yield of 50% would result in an increase in the total supply chain cost by 11%. They highlighted the need to increase central storage and pre-treatment (CSP) facilities in a supply chain in order to meet higher demand. Although a high demand of product reduces total unit production cost due to economies of scale, as mentioned previously, Ekşioğlu et al. (2009) found that the economies of scale due to operating large-sized facilities are negated by the increase in transportation costs.

2.11 Uncertainty

The bio-fuel industry is greatly affected by uncertainty. Uncertainty in supply is mainly due to weather conditions during the actual growing of the crop and during the harvesting month (De Meyer, 2014). Papastolou et al. (2011) cited the challenges that could be encountered during model formulation as uncertainty and unavailability of data. Kostin et al. (2011), in their study on optimal design and planning of integrated bio-ethanol-sugar supply chains, considered financial and environmental objectives

under demand uncertainty. Zamboni et al. (2009) developed MILP models to optimise financial and environmental impact of bio-ethanol supply chains. They used different scenarios to analyse the effect of demand on the supply chain. However, the models developed were too large and took long to solve. Akgul et al. (2010) introduced use of a neighbourhood flow approach to reduce computational time for large models. The uncertainty mentioned above, together with the high cost of setting up and maintaining the bio-fuel processing facilities, makes the bio-fuel industry unattractive to investors. However, the government – through favourable policy – can encourage investors to venture into the industry. Papastolou et al. (2011) investigated two scenarios, a high cost and low cost scenario. The low cost scenario benefitted from land support schemes, subsidisation of feedstock cultivation and tax incentives from the government. The high cost scenario comprised many imports due to lack of support from the government.

2.12 Government Policy

The provision of incentives and fuel subsidies by the government of South Africa will help support the bio-fuel industry by making it financially viable. The government will provide incentives to the bio-fuel industry for 20 years starting from the first year of providing financial support to the first manufacturer of bio-fuels (DME, 2014).

In South Africa, in order to accommodate as many players as possible in the bio-fuels industry, the maximum annual volume that will qualify for incentives per manufacturer will be capped to the most efficient plant capacity assumed in the Bio-fuels Pricing Reference Models, (2014). For bio-ethanol, it is 158,000 m³/y and for bio-diesel, it is 100,000 t/y or 113,600 m³/y (DME, 2014). A constraint on capacity of the processing facilities will be introduced in the optimisation framework of this study. This is because any production above the specified maximum capacities will not receive any subsidies for the bio-ethanol produced in excess or above the maximum volumes set by the government. However, there is a need to determine if lack of subsidy for the volume exceeding the subsidised capacity will result in increased production costs or economies of scale will cater for the extra unsubsidised production cost.

2.13 Conclusion

This chapter covered the following main areas:

- The South African government's position on bioethanol
- Geographical distribution of feedstock in South Africa
- Bioethanol production and supply chain
- Optimisation and modelling techniques
- Previous studies on bioethanol and biofuel modelling and the different objectives investigated.

The major findings are:

- There are a variety of bioethanol supply chain optimisation techniques, however most of the advances in recent years have focused on single objective optimisation with a few focussing on multiobjective optimisation of low value feedstock.
- The South African government is putting effort in commercializing biofuels especially through policy and incentives.
- There is considerable complexity in modelling systems for multiple objectives.
- The production of biofuels is highly dependent on government subsidy to make it viable economically.
- Small biofuel processing plants are more economically feasible than large plants (Becker, 2012).
- Transportation contributes considerably to the total cost of the supply chain.
- Location of processing facilities is of significance to both the profitability and environmental sustainability of the biofuel supply chains.

CHAPTER 3 METHODOLOGY

The literature presented in the previous chapter introduced a need to develop a multi-objective optimisation model that will optimise the whole biomass to bio-ethanol supply chain incorporating the different modes of transport for biomass, bio-ethanol and by-products, hybrid first- and second-generation ethanol production and annexed sugar and ethanol production facilities. This is important for South Africa has yet to erect a commercial bioprocessing facility.

In this work, the supply chain network of biomass to bio-ethanol is modelled to give an optimum location for bio-ethanol processing facilities in South Africa. The system modelled also determines the farm and biomass source (including quantities) that should be supplied to the processing facilities. Only locally available biomass is considered in the system. Use of sugarcane, sugarcane bagasse and residues from food crops that are currently produced in three provinces of South Africa, namely KZN, Mpumalanga and Eastern Cape is investigated in this study. The bio-ethanol produced is transported to petroleum refineries/blending facilities. The model developed in this work also determines, which of the identified processing facilities should supply bio-ethanol to the blending facilities.

The models developed in this study have some similarities to the work of Čuček et al. (2014). However, the results obtained in this study for total costs, supply chain profile and associated environmental impact differ from those of Čuček et al. (2014) due to differences in geographic characteristics, the type of land area data used as well as the mode of capture and availability of biomass in the regions considered. The work of Čuček et al. (2014) also included seasonality, different processing technologies and more than two key products that are not considered in this study. Other scenarios covered by Čuček et al. (2014) are product recycle and heat integration. These other scenarios are recommended in this study as future work. The proposed model includes constraints on capacity to cater for the incentives being offered by the South African government, which should result in reduced production costs. A detailed

environmental analysis will show the effects of the bio-fuel industry on the climate, human health as well as on land and water bodies.

Figure 3.1 below shows an overview of the model developed in this study. It is divided into layers comprising the following activities; biomass cultivation, harvesting, collection, transportation of biomass from the farms to the processing facilities, the processing of the biomass to produce bio-ethanol, and distribution of product to the refineries for blending.

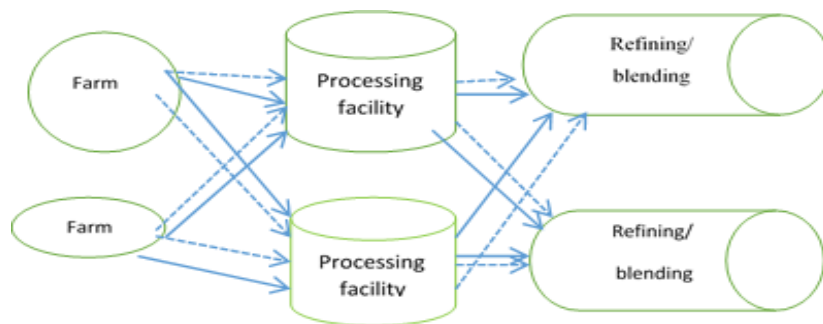
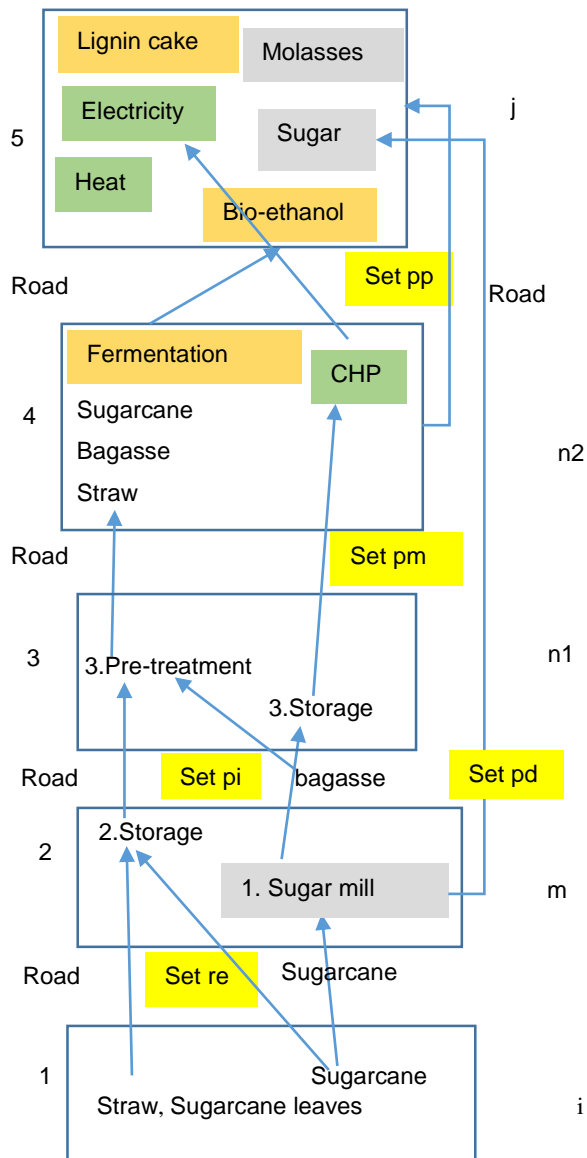


Figure 3.1: Overview of the biomass to bio-ethanol supply chain network used in this study

Due to the complexities involved in solving supply chain optimisation models to global optimality, the processes involved in the supply chain model of this study are represented as black boxes. Figure 3.2 below shows the details of the processing facility layer of Figure 3.1.

The processing facility node of the supply chain portrayed in Figure 3.2 is split into three stages (sugar mill, pre-treatment and ethanol production) in order to cater for food demand. This is also done to simplify the formulation of the model. Figure 3.3 below shows the flow of material in the supply chain and product demand centres modelled in this study.



Demand locations

Engen, Sapref, Umzikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Felixton, Umfolozi, Pongola, Komati, Malelani, Animal feed centre, Sugar warehouse

Processing facilities

Umkikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Felixton, Umfolozi, Pongola, Komati, Malelani, 15, 16, 17, 18, 19, 20

Storage/sugar mill

Umkikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Felixton, Umfolozi, Pongola, Komati, Malelani, 15, 16, 17, 18, 19, 20

Storage/sugar mill

Umkikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Felixton, Umfolozi, Pongola, Komati, Malelani, 15, 16, 17, 18, 19, 20

Farms

1*220

Figure 3.3: Material flow in the supply chain network

The feedstocks that are not directed to sugar milling technology were assumed to be directed to storage on the second level m . Together with bagasse from the sugar milling technology, these materials are referred to as intermediate products denoted by pi . Sugar and molasses, which are direct products from sugar milling denoted by pd are taken to level 5. The intermediate products pi , when taken to the third level, $n1$ are pre-treated to produce another intermediate product pm . This intermediate product pm is then sent to the corresponding technology on level 4. Bagasse is sent to CHP to produce heat and electricity, while sugarcane juice and the sugars obtained from the acid hydrolysis and delignification process is sent to fermentation for conversion to bio-ethanol. The produced products from this level were referred to as p or pp in the model and were sent to demand centres on level 5 denoted by j . The bio-ethanol produced was transported to depots for blending and the lignin cake is stored and sold from warehouses within the processing facility premises.

The flow of material through the layers and available technologies can also be represented as shown in the Figure 3.4 below.

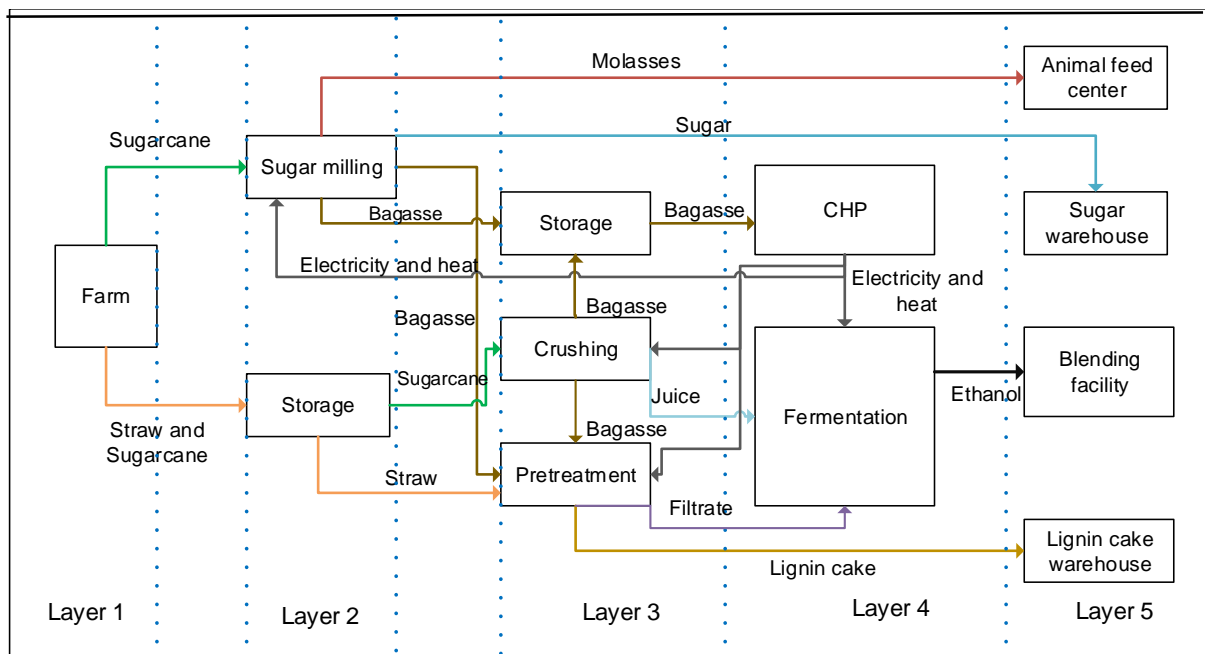


Figure 3.4: Flow diagram of the supply chain

3.1 Model Formulation

The model is formulated as a MILP according to the material flow shown in Figure 3.3. The notation used is given in the nomenclature section. The activities in the supply chain are addressed according to the layers shown in Figure 3.3. The model has cost functions, mass balances for every layer or level, production constraints and environmental impact functions. The production constraints include the limit on farm capacities and on plant sizes. The farm capacities have been pre-calculated, using the fishnet approach where a single cell in the grid is considered as a farm and the maximum amount of feedstock that can be obtained from that cell is the capacity constraint on the farm.

3.1.1 Material balance and production constraints

In this section, the activities occurring in each layer are discussed. A mass balance is performed on the feedstock and product movement for each layer of the superstructure. In Layer 2 feedstock from Layer 1 is converted into direct produced products and intermediate products. In Layer 3 the intermediate products which include bagasse and straw from storage, are converted into another intermediate product. In Layer 4, the intermediate products from Layer 3 are converted into products (bio-ethanol, electricity and heat) which are referred to as produced products in the context of this work. Conversion factors are used to determine the amount of product that can be obtained from the feedstock and intermediate products. The material balance will be done for a time period, which is one year in this context and for the entire plant life, which is 20 years.

Layer 1 to Layer 2

After harvesting, biomass is collected from the farms at location i , Layer 1, and transported to technology at location m in Layer 2. The $q_{m,pi}^{L2,L3}$ maximum amount of biomass of type re that can be collected at farm location i is constrained by the farm production capacity, $alimit(i, re)$, and the biomass production rate.

$$q_{i,re}^{L1,L2} \leq alimit(i,re) \quad \forall i \in I, re \in RE \quad (3.1)$$

$alimit(i, re)$ is the product of the available cultivation area in cell i and the average biomass yield. This was pre-calculated, using the cultivation area per farm as analysed by ArcGIS and only the maximum production per zone is shown in the GAMS model.

$$alimit(i, re) = biomass\ yield \left(\frac{t}{ha} \right) * Cultivation\ area \quad (3.2)$$

The total amount of biomass re that can be transported from Layer 1 to demand centre m in Layer 2, L2, within a time period tp should be equal to the biomass production rate at farm i , $q_{i,re,tp}^{L1}$. This is shown in Equation 3.3.

$$q_{i,re,tp}^{L1,L2} = \sum_{m \in M} q_{i,m,re}^{L1,L2} \quad \forall i \in I, m \in M, re \in RE \quad (3.3)$$

At level 2, there are two technologies: storage and sugar milling as shown in Figure 3.3. The biomass is split in such a way that biomass demand for food production is satisfied before directing the remaining biomass to bio-ethanol production technologies at this level, which are storage and crushing. It is assumed that harvesting loss, L_{re} , of biomass is 5%. The amount of biomass that is sent to technology t at level 2 within a time period tp , is given by Equation 3.4:

$$\sum_{m \in M} q_{i,m,re,tp}^{L1,L2} (1 - L_{re}) = \sum_{(re,t) \in RE,T_2} q_{m,re,t,tp}^{T2,L2} \quad \forall m \in M, re \in RE, t \in T_2, tp \in TP \quad (3.4)$$

The feedstocks, re , are converted to intermediate products, pi , at level 2. At this stage, the intermediate product obtained is bagasse and all the other feedstocks sent to storage do not change their form. A conversion factor denoted $f_{re,pi,t}^{conv,T2,L2}$ is used to calculate the flow rate of intermediate product produced at each technology as shown in Equation 3.5. $q_{m,re,pi,t,tp}^{T2,L2}$ is the quantity of intermediate feedstock that is produced from the conversion of feedstock re , at location m in Layer 2.

$$q_{m,re,t,tp}^{T2,L2} \cdot f_{re,pi,t}^{conv,T2,L2} = q_{m,re,pi,t,tp}^{T2,L2} \quad \forall m \in M, t \in T_2, tp \in TP, (re, t) \in RET, (re, pi) \in REPI \quad (3.5)$$

The amount of biomass, re , that goes to a selected technology at level 2 is greater than the minimum capacity $q_{t,tp}^{T2,LO}$ of the processing technologies at level 2. The minimum capacity of a technology on level 2 within the entire plant life is given by Equation 3.6. $y_m^{T,L2}$ is a binary variable that indicates the selection of that technology at level 2

$$\sum_{(re,t) \in RET} \sum_{(re,pi) \in REPI} \sum_{(tp \in TP)} q_{m,re,pi,t,tp}^{T2,L2} \geq q_t^{T2,L2,LO} \cdot y_m^{T,L2} \quad \forall m \in M, t \in T_2, (re, pi) \in REPI \quad (3.6)$$

Equation 3.7 shows the capacity of the technology at level 2 within time period tp where $y_m^{T,L2}$ is a binary variable for selection of technology at level 2 in time period tp and $q_{t,tp}^{T2,L2,UP}$ is the maximum capacity of the facility within a time period tp

$$q_{t,tp}^{T2,L2,UP} \cdot y_m^{T,L2} \geq \sum_{(re,t) \in RET} \sum_{(re,pi) \in REPI} \sum_{(t,pi) \in TPI} \sum_{tp \in TP} q_{m,re,pi,t,tp}^{T2,L2} \quad \forall m \in M, t \in T_2, tp \in TP \quad (3.7)$$

The quantity of biomass that is directed to a selected technology t at level 2 within the entire plant life is less than the maximum capacity of technology t , $q_t^{T2,UP}$ at level 2 is given by Equation 3.8.

$$q_t^{T2,L2,UP} \cdot y_m^{T,L2} \geq \sum_{(re,t) \in RET} \sum_{(re,pi) \in REPI} \sum_{(t,pi) \in TPI} \sum_{tp \in TP} q_{m,re,pi,t,tp}^{T2,L2} \quad \forall m \in M, t \in T_2, tp \in TP, (re, \chi) \quad (3.8)$$

Layer 2 to Layer 5

In Layer 2, feedstock is processed to produce intermediate products pi and direct produced products pd . Direct produced products in this context come from the sugar milling processing technology at level 2 and are transported directly to level 5 without undergoing further processing at the other levels. Furthermore, the intermediate products pi in this study include bagasse, straw and sugarcane that are directed to

storage while the direct products are molasses and sugar that go straight to Layer 5. In Equation 3.9 below, $q_{m,j,pd}^{L2,L5}$ is the direct produced product pd that goes to Layer 5, while $q_{m,n1,pi}^{L2,L3}$ is the intermediate product that goes to Layer 3. The sum of the direct product produced and the intermediate products produced at Layer 2 is equivalent to the product of amount of feedstock at technology on Layer 2, $q_{m,re,t,tp}^{T2,L2}$ and the respective conversion factors namely $f_{re,pi,t}^{conv,T,L2}$ and $f_{re,pd,t}^{conv,T,L2}$.

$$\begin{aligned}
& q_{m,re,t,tp}^{T2,L2} \cdot f_{re,pd,t}^{conv,T,L2} + q_{m,re,t,tp}^{T2,L2} \cdot f_{re,pi,t}^{conv,T,L2} \\
&= \sum_{j \in J} \sum_{pd \in PD, (re,pd) \in (REPD)} q_{m,re,pd,tp}^{L2,L5} \\
&+ \sum_{n1 \in N1} \sum_{n1 \in N1} \sum_{pi \in PI, (re,pi) \in (REPI)} q_{m,re,pi,tp}^{L2,L3} \quad \forall e \in M, t \in T_2, tp \in TP, (re, pi) \in REP \quad (3.9)
\end{aligned}$$

Layer 3

On Layer 3, selection of technology is done by the binary variable $y_{n1,t,tp}^{T,L3}$, which represents the existence of technology t at location $n1$ on Layer 3 in time period tp , and $y_{n1,t}^{T,L3}$ is the existence of technology at location $n1$ on Layer 3 within the entire plant life. The intermediate product pi from Layer 2, is sent to the selected technology at plant $n1$ in Layer 3. In Equation 3.10, $q_{m,n1,pi,tp}^{L2,L3}$ gives the quantity of intermediate product pi that is moved from level 2 to level 3 within time period tp , while $q_{n1,pi,t,tp}^{L3}$ gives the amount of pi on level 3 within time period tp .

$$\begin{aligned}
& \sum_{m \in M} q_{m,re,pi,tp}^{L2,L3} \\
&= \sum_{(pi,t) \in (PIT), \forall t \in T_3, n1 \in N1} q_{n1,pi,t,tp}^{T3,L3} \quad \forall n1 \in N, pi \in PI, tp \in Tp, t \in T_2 \quad (3.10)
\end{aligned}$$

For the entire plant life, the quantity of pi on level 3 is given by $q_{n1,pi,t}^{L3}$ while the amount of intermediate product pi that is moved from level 2 to level 3 is given by $q_{m,n1,pi}^{L2,L3}$. Substituting these two terms into Equation 3.10 above would give the mass balance for intermediate products on level 3 for the entire plant life

The intermediate product pi from Layer 2 is converted into another intermediate product, pm in Layer 3, using the conversion factor $f_{pi,pm,t}^{conv,T,L3}$. The flow rate of the intermediate product, pm , will be equal to the flow rate of intermediate pi (from storage, crushing and sugar mill) to technology t at Layer 3, multiplied by the conversion factor. This is shown in Equation 3.11.

$$\begin{aligned} & q_{n1,pi,t,tp}^{T3,L3} \cdot f_{pi,pm,t}^{conv,T,L3} \\ &= q_{n1,pi,pm,t,tp}^{T3,L3} \quad \forall n1 \in N1, (pi, t) \in PIT, (pi, pm) \in PIPM, tp \in TP \end{aligned} \quad (3.11)$$

The capacity of the conversion technology $q_{n1,pi,pm,t,tp}^{T3,L3}$ on level 3 is greater than the minimum capacity $q_t^{T3,L3,LO}$ of the selected technology at level 3. This is given by Equation 3.12 in which $y_{n1,t}^{T,L3}$ is the binary variable for selection of technology on level 3.

$$\begin{aligned} & q_{t,tp}^{T3,L3,LO} \cdot y_{n1,t}^{T,L3} \\ & \leq \sum_{(pi,t) \in PIT} \sum_{(pi,pm) \in PIPM} \sum_{(t,pm) \in TPM} \sum_{tp \in TP} q_{n1,pi,pm,t,tp}^{T3,L3} \quad \forall n1 \in N1, t \in T_3 \end{aligned} \quad (3.12)$$

Equation 3.13 shows that the capacity $q_{n1,pi,pm,t,tp}^{T3,L3}$ of the conversion technology at the processing facilities within a time period tp is less than the maximum capacity $q_{t,tp}^{n1,T,UP}$ of the technology within that time period tp

$$\begin{aligned} & q_{t,tp}^{T3,L3,UP} \cdot y_{n1,t,tp}^{T,L3} \\ & \geq \sum_{(pi,t) \in PIT} \sum_{(pi,pm) \in PIPM} \sum_{(t,pm) \in TPM} \sum_{tp \in TP} q_{n1,pi,pm,t,tp}^{T3,L3} \quad \forall n1 \in N1, t \in T_3 \end{aligned} \quad (3.13)$$

In Equation 3.14, the capacity of the selected technology for conversion of intermediate products pi into intermediate product pm at level 3, is less than the maximum plant capacity of the technology for the entire life which is denoted by $q_t^{T3,UP}$

$$\begin{aligned}
& q_t^{T3,L3,UP} \cdot y_{n1,t}^{T,L3} \\
& \geq \sum_{(pi,t) \in PIT} \sum_{(pi,pm) \in PIPM} \sum_{(t,pm) \in TPM} \sum_{tp \in TP} q_{n1,pi,pm,t,tp}^{T3,L3} \quad \forall n1 \in N1, t \in T_3
\end{aligned} \tag{3.14}$$

Layer 4

Layer 4 houses the technologies for converting intermediate products into finished products, which are referred to as produced products, pp , in this context. These products are bio-ethanol, lignin cake electricity and heat. In this layer, the selection of technology t (fermentation and CHP), within a time period tp , is done through the use of a binary variable $y_{n2,t,tp}^{T,L4}$. The intermediate product, pm , from Layer 3 is sent to the selected technology on Layer 4.

$$\begin{aligned}
& \sum_{n1 \in N1} q_{n1,pi,pm,tp}^{L3,L4} \\
& = \sum_{(pm,t) \in (PMT), \wedge t \in T_4} q_{n2,pm,t,tp}^{L3,L4} \cdot y_{n2,t,tp}^{T,L4} \quad \forall t \in T4, pm \in PM, tp \in Tp
\end{aligned} \tag{3.15}$$

The intermediate product pm is converted into produced product pp , using the conversion factor $f_{pm,pp,t}^{conv,T,L4}$. The produced product pp , whose flowrate will be equal to the flow rate of intermediate pm (from storage and pre-treatment) to technology t at level 4, multiplied by the conversion factor.

$$\begin{aligned}
& q_{n2,pm,pp,t,tp}^{T4,L4} \cdot f_{pm,pp,t}^{conv,T,L4} \\
& = q_{n2,pp,t,tp}^{T4,L4} \quad \forall n2 \in N2, (pm,t) \in PMT, (pm,pp) \in PMPP, tp \in TP
\end{aligned} \tag{3.16}$$

The minimum capacity (represented as $q_t^{T4,L0}$) of a processing facility for a case where a particular technology is selected, is given by Equation 3.17 where $y_{n2,t}^{T,L4}$ is the binary variable for selection of technology at level 4

$$q_{t,tp}^{T,L4,LO} \cdot y_{n2,t}^{T,L4} \leq \sum_{(pm,t) \in PMT} \sum_{(pm,pp) \in PMPP} \sum_{(t,pp) \in TKP} \sum_{tp \in TP} q_{n2,pm,pp,t,tp}^{T,L4} \quad \forall n2 \in N2, t \in T_4 \quad (3.17)$$

Equation 3.18 shows the capacity of the facilities within a time period tp , where $y_{n2,t}^{T,L4}$ is a binary variable for selection of technology and $q_{t,tp}^{T,L4,UP}$ is the maximum capacity of the facility within a time period tp .

$$q_{t,tp}^{T,L4,UP} \cdot y_{n2,t}^{T,L4} \geq \sum_{(pm,t) \in PMT} \sum_{(pm,pp) \in PMPP} \sum_{(t,pp) \in TKP} \sum_{tp \in TP} q_{n2,pm,pp,t,tp}^{T,L4} \quad \forall n2 \in N2, t \in T_4, tp \in TP \quad (3.18)$$

Equation 3.19 shows the selection of the technology and the maximum capacity of the facility within the entire plant life.

$$q_t^{T,L4,UP} \cdot y_{n2,t}^{T,L4} \geq \sum_{(pm,t) \in PMT} \sum_{(pm,pp) \in PMPP} \sum_{(t,pp) \in TKP} \sum_{tp \in TP} q_{n2,pm,pp,t,tp}^{T,L4} \quad \forall n2 \in N2, t \in T_4 \quad (3.19)$$

3.1.2 Costing

The total annual cost of the supply chain comprises of the following:

- (i) Transportation costs;
- (ii) Annualised investment cost;
- (iii) Production costs (feedstock and operating costs).

Transportation costs

Transportation costs consist of a variable cost component, $C_{re}^{tr,var,L1,L2}$, that depends on transportation distance and a fixed cost component, $C_{re}^{tr,fix,L1,L2}$, which is due to loading, offloading and handling costs. In the supply chain model, biomass, re is transported from farms i , on level 1 to the processing facilities, m , in Layer 2. The

transportation distance between Layer 1 and Layer 2, $D^{L1,L2}$, was computed based on existing infrastructure, using Google Earth®. This eliminates the need to introduce a tortuosity factor in the transportation distance as is done in most studies. The biomass transportation cost formula is given in Equation 3.20 below.

$$C_{re}^{tr,L1,L2} = \sum_{ie I} \sum_{me M} \sum_{tp \in TP} (q_{i,m,re,tp}^{L1,L2} \cdot C_{re}^{tr,fix,L1,L2} + D_{i,m}^{L1,L2} \cdot C_{re}^{tr,var,L1,L2} \cdot q_{i,m,re,tp}^{L1,L2}) \quad \forall re \in RE \quad (3.20)$$

Where: the variable transport cost is in R/t.km and the fixed component is in R/t. $C_{re}^{tr,L1,L2}$ is the total transport cost of feedstock/biomass from Layer 2 which is the sum of the variable and fixed components of the transportation cost which are denoted by $C_{re}^{tr,var,L1,L2}$ and $C_{re}^{tr,fix,L1,L2}$ respectively.

Equation 3.21 gives the transportation cost for intermediate products pi that are transported from level 2 to level 3.

$$C_{pi}^{tr,L2,L3} = \sum_{m \in M} \sum_{ni \in N1} \sum_{tp \in TP} (q_{m,n1,pi,tp}^{L2,L3} \cdot C_{pi}^{tr,fix,L2,L3} + D_{m,n1}^{L2,L3} \cdot C_{pi}^{tr,var,L2,L3} \cdot q_{m,n1,pi,tp}^{L2,L3}) \quad \forall pi \in PI \quad (3.21)$$

The transportation cost for the direct produced product pd that goes from level 2 straight to level 5 is given by Equation 3.22.

$$C_{pd}^{tr,L2,L5} = \sum_{m \in M} \sum_{je J} \sum_{tp \in TP} (q_{m,j,pd,tp}^{L2,L5} \cdot C_{pd}^{tr,fix,L2,L5} + D_{m,j}^{L2,L5} \cdot C_{pd}^{tr,var,L2,L5} \cdot q_{m,j,pd,tp}^{L2,L5}) \quad \forall pd \in PD \quad (3.22)$$

The transportation cost for the intermediate product pi from level 2 to level 3 where it is converted to intermediate product pm is given by Equation 3.23 below.

$$C_{pm}^{tr,L3,L4} = \sum_{n1 \in N1} \sum_{n2 \in N2} \sum_{tp \in TP} (q_{n1,n2,pm,tp}^{L3,L4} \cdot C_{pm}^{tr,fix,L3,L4} \cdot D_{n1,n2}^{L3,L4} \cdot C_{pm}^{tr,var,L3,L4} \cdot q_{n1,n2,pm,tp}^{L3,L4}) \quad \forall i \quad (3.23)$$

The transportation cost for the produced product from processing facility $n2$ at level 4 to product demand centre j at level 5 is given by Equation 3.24.

$$C_{pp}^{tr,L4,L5} = \sum_{n2 \in N2} \sum_{j,j} \sum_{tp \in TP} (q_{n2,j,pp,tp}^{L4,L5} \cdot C_{pp}^{tr,fix,L4,L5} + D_{n2,j}^{L4,L5} \cdot C_{pm}^{tr,var,L4,L5} \cdot q_{n2,j,pp,tp}^{L4,L5}) \quad \forall pp \in PP \quad (3.24)$$

The sum of the transportation costs shown in Equations 3.20 to 3.24 gives the overall transport cost C^{trtot} for the supply chain and this is represented by Equation 3.25.

$$C^{trtot} = \sum_{re \in RE} C_{re}^{tr,L1,L2} + \sum_{pi \in PI} C_{pi}^{tr,L2,L3} + \sum_{pm \in PM} C_{pm}^{tr,L3,L4} + \sum_{pp \in PP} C_{pp}^{tr,L4,L5} + \sum_{pd \in PD} C_{pd}^{tr,L2,L5} \quad (3.25)$$

Production costs

The production cost, C^{Pctot} is the sum of the market price of the biomass and the cost of operating technology C^{op} . The cost of the feedstocks C^{re} is cost at gate of farm, which includes any compensation to the farmer for loss of nutrients.

$$C^{Pctot} = \sum_{m \in M} \sum_{i \in I} q_{i,m,re,tp}^{T2,L1,L2} \cdot C^{re} + \sum_{m \in M} \sum_{i \in I} q_{i,m,re,tp}^{T2,L1,L2} \cdot C^{prep,L2} + \sum_{i \in I} \sum_{m \in M} \sum_{(re,t) \in RET} q_{i,m,re,tp}^{T2,L1,L2} \cdot C_t^{op,T,L2} + \sum_{m \in M} \sum_{n1 \in N1} \sum_{(pi,t) \in PIT} q_{m,n1,pi,tp}^{T3,L2,L3} \cdot C_t^{op,T,L3} + \sum_{(pm,t) \in PMT} \sum_{(pm,pp) \in PMPP} \sum_{n1 \in N1} \sum_{n2 \in N2} q_{n2,pm,pp,t,tp}^{T4,L3,L4} \cdot C_t^{op,T,L4} \quad (3.26)$$

Where $C_t^{op,T,L2}$ is the cost of operating technology at level 2 in ZAR/t

$C_t^{op,T,L3}$ is the cost of operating technology at level 3 ZAR/t

$C_t^{op,T,L4}$ is the cost of operating technology at level 4 in ZAR/t

C^{re} is the biomass cost in ZAR/t.

$C^{prep,L2}$ is the feedstock preparation cost at level 2 in ZAR/t

Fixed investment cost

The investment cost is the sum of the cost of the processing facilities, pre-treatment facilities and the storage. At the product demand centres, additional storage space might be required for ethanol storage, but the costs are excluded from the total supply chain cost. If seasonality were to be considered in terms of availability of feedstocks, then storage costs would be substantial. However, we are assuming that there will be feedstock supply throughout the year such that storage will only be required for up to two weeks. Two linearization methods were used to linearize the investment term for the processing facility, with both methods using the six tenth rule as a basis, which is given below. Linearization is done to eliminate any non-linear terms in the model since the model was developed as an MILP. Bergamini et al (2008) used piece wise linearization to make the investment term linear. The same approach was taken by Holland and Wilkinson (1997), Čuček et al. (2014), You and Wang (2011) and Lin et al. (2014).

$$I_2 = I_1 \left(\frac{Q_2}{Q_1} \right)^n$$

Where:

I_2 = Capital cost of the project with capacity Q_2 ;

I_1 = Capital cost of the project with capacity Q_1 ;

The value of n is taken as 0.6 (the six tenths rule).

Equation 3.27 gives the fixed investment cost for the processing facility based on the first linearization method, which was based on the Taylor series linearization technique.

$$\begin{aligned}
C^{fixinvtot} = & \sum_{n2 \in N2} \sum_{t \in t} C_t^{fix.inv,L4} \cdot y_{n2,t}^{L4,t} + \sum_{n2 \in N2} \sum_{t \in T} C_t^{var.inv,L4} \cdot q_{n2,pm,pp,t,tp}^{T4,L3,L4} \\
& + \sum_{n1 \in N1} \sum_{t \in t} C_t^{fix.inv,L3} \cdot y_{n1,t}^{L3,t} + \sum_{n1 \in N1} \sum_{t \in T} C_t^{var.inv,L3} \cdot q_{n1,pi,pm,t,tp}^{T3,L2,L3} \\
& + \sum_{m \in M} \sum_{t \in t} C_t^{fix.inv,L2} \cdot y_{m,t}^{L2,t} + \sum_{m \in M} \sum_{t \in t} C_t^{var.inv,L2} \cdot q_{m,re,pi,t,tp}^{T2,L1,L2}
\end{aligned} \quad (3.27)$$

Where:

$C_t^{fix.inv,L4}$ is the fixed investment cost of technology at level 4 in ZAR;

$C_t^{var.inv,L4}$ is the variable investment cost of technology at level 4 in ZAR/t;

$C^{fixinvtot}$ is the total fixed investment cost in ZAR;

$C_t^{fix.inv,L3}$ is the fixed investment cost of technology at level 3 in ZAR;

$C_t^{var.inv,L3}$ is the variable investment cost of technology at level 3 in ZAR/t;

$C_t^{fix.inv,L2}$ is the fixed investment cost of technology at level 2 in ZAR;

$C_t^{var.inv,L2}$ is the variable investment cost of technology at level 3 in ZAR/t.

To derive the cost of capital per year, the total investment cost is multiplied by an annualisation factor. The annualisation factor is a function of discount rate i , and time n , which is the fixed period over which the capital has been borrowed. For biofuels economics in South Africa accelerated depreciation is recommended at rates of 50%, 30% and 20% according to the white paper on biofuels (DME, 2007). However, in this study simple straight line depreciation is applied in order to get an estimate of the average economic potential per year. Equation 3.28 gives the annualised capital cost of the supply chain when piece-wise linearization is used.

$$\begin{aligned}
C^{invtot} = & \frac{i(1+i)^n}{((1+i)^n) - 1} \\
& * \left[\sum_{n2 \in N2} \sum_{t \in t} I_{n2,t}^{L4,T} + \sum_{m \in M} \sum_{t \in t} I_{m,t}^{L2,T} + \sum_{m \in M} \sum_{t \in t} C_p^{fix.stor,L2} \cdot y_m^{m,T,L2} \right. \\
& \left. + \sum_{m \in M} \sum_{t \in t} C_{p,t}^{var.sto,L2} \cdot q_{m,re,pi,t}^{T2,L1,L2} \right]
\end{aligned} \quad (3.28)$$

where:

$I_{n2,t}^{L4,T}$ is the investment cost of the processing facility on level 4;

$C_p^{fix.stor,L2}$ is the storage cost in ZAR;

$C_{pm,t}^{var.prep,L3}$ is the variable cost of preparation in ZAR/t;

i is the interest rate

n is the fixed period in years over which the capital is borrowed which is assumed to be equal to the plant life in this study.

A graph of capacity against fixed investment costs is drawn from the power law model using the reference plant capacity costs with the capacity on the x-axis and the investment costs on the y-axis. The capacities are then divided into segments, in this case 5 segments. In each of the segments a linear approximation of the points in the segment is made and the slope of the line is calculated to give the variable component of the investment cost. The fixed component is obtained by approximating the investment cost on the y axis of the graph. This is done through drawing a line from the selected capacity point on the x axis up to the point where it intersects with the linear approximation of the power law model in that segment. This is then added to the lower bound of the capacity in the segment

The equations used are similar to those used by Čuček et al. (2014) and only a few are presented here. The capacities within a technology are divided into 5 intervals in which the fixed capital costs for the main points in the intervals are pre- calculated according to the equation below which was used for technologies on level 4.

$$q_{n2,kp,t,ni}^{T4,L4} = q_{n2,kp,t,ni-1}^{T4,L4} + \frac{q_t^{T2,UP} - q_{n2,kp,t,ni-1}^{T4,L4}}{|NI|-1} * (ni - 1) \quad \forall n2 \in N2, (t, kp) \in TKP, ni \in NI, ni \neq 1 \quad (\text{Čuček et al., 2014})$$

The corresponding fixed capital cost is calculated according to Equation 3.29 below.

$$I_{n2,t}^{L4,T4} = \sum_{ni \in NI} \sum_{(t,kp) \in TKP} I_{n2,t,kp,ni}^{L4,T4} \cdot y_{n2,t,ni}^{LAT4t} + \Delta q_{n2,kp,tp}^{T4,L4} \cdot m_{n2,kp,tp,t,ni}^{T4,L4} \quad \forall n1 \in N1, t \in T3, (t, kp) \in TKP \quad (3.29)$$

$$I_{n2,t}^{L4,T4} = I_1 \left(\frac{q_{n2,kp,tp,ni}^{T4,L4}}{q_{1,t}^{1,L4}} \right)^{0.6} \quad (3.30)$$

Where:

$q_t^{1,t,L4}$ is the reference capacity of plant used in the model;

I_1 is the investment cost of the reference plant;

$I_{n2,t,kp,ni}^{L4,T}$ is the fixed component of the investment cost in an interval

$q_{n2,kp,tp,ni}^{T4,L4}$ is the difference between capacities of process technology t in an interval at level 4 within a time period;

$y_{n2,t,ni}^{L4,t}$ is a binary variable for interval ni selection at level 4 and

$$\Delta q_{n2,kp,tp,ni}^{T4,L4} \leq \left(q_{n2,kp,tp,ni+1}^{T4,L4} - q_{n2,kp,tp,ni}^{T4,L4} \right) \cdot y_{n2,t,ni}^{L4,t} \quad \forall n1 \in N1, t \in T_3, (t, kp) \in TKP \quad (3.31)$$

Equation 3.31 shows that the capacity that lies within an interval should be less than a complete interval. The component, which is the investment cost per unit of capacity in the interval between ni and $ni+1$, which is denoted by $m_{n2,kp,tp,t,ni}^{T4,L4}$, is calculated according to Equation 3.32.

$$m_{n2,kp,tp,t,ni}^{T4,L4} = \frac{I_{n2,t,kp,ni+1}^{L4,T} - I_{n2,t,kp,ni}^{L4,T}}{q_{n2,kp,tp,ni+1}^{T4,L4} - q_{n2,kp,tp,ni}^{T4,L4}} \quad \forall n1 \in N1, t \in T_3, (t, kp) \in TKP \quad (3.32)$$

Similar to $I_{n2,t}^{L4,T}$, the fixed investment cost $I_{m,t}^{L2,T}$ is the sum of the investment cost of the technologies on level 2 for the size that lies within the linearization interval.

3.1.3 Economic objective function

The objective function is to maximise the economic potential of the supply chain. The expenses for the year are deducted from the revenue from product and by-product sales to give the profit before tax. Since straight line depreciation is considered in this work, the depreciation charge per year, which is less than the cost of capital, instead of subtracting the depreciation to get the profit before tax, cost of capital is deducted.

Consequently the “profit before tax” becomes a measure of the economic potential of the supply chain rather than an actual realizable profit. Equation 3.33 below gives the profit before tax for the supply chain.

$$\begin{aligned}
 \text{Economic Potential} &= \sum_{m \in M} \sum_{j \in J} \sum_{pd \in PD} q_{m,j,pd,tp}^{L2,L5} \cdot C^{pd} \\
 &+ \sum_{n2 \in N2} \sum_{j \in J} \sum_{pp \in PP} q_{n2,j,pp,tp}^{T4,L4,L5} \cdot C^{pp} - C^{trtot} - C^{invtot} - C^{Pctot}
 \end{aligned} \tag{3.33}$$

Where, C^{pd} is the selling price of the direct product and C^{pp} is the selling price of the produced product. C^{trtot} is the total transport cost, C^{invtot} is the cost of capital and C^{Pctot} is the total production cost.

3.1.4 Environmental objective function

The other objective for this model is to minimise the overall environmental impact, where greenhouse gas emissions are used as a measure. The greenhouse gas emissions at each stage of the bio-ethanol supply chain are to be considered. The stages are biomass cultivation, harvesting and transportation of both biomass and ethanol as well as during the ethanol production process. Optimising the transportation distance will reduce the total environmental impact due to a decrease in the greenhouse gas emissions from the transporting vehicles.

3.2 Case study

The model formulated above was applied to an area covering three provinces of South Africa, namely KZN, Mpumalanga and the Eastern Cape. Figure 3.5 below shows the area under study and the locations and boundaries for sugarcane cultivation centres. On the map, the purple dots denote possible locations for the processing facilities. Some of these locations are the current locations of the sugar mills. Figure 3.6 shows a larger cultivation area that includes grains in the biomass feedstock. The nodes of the supply chain, which are the farms, processing facility locations, and blending facility locations, are also shown on the map.

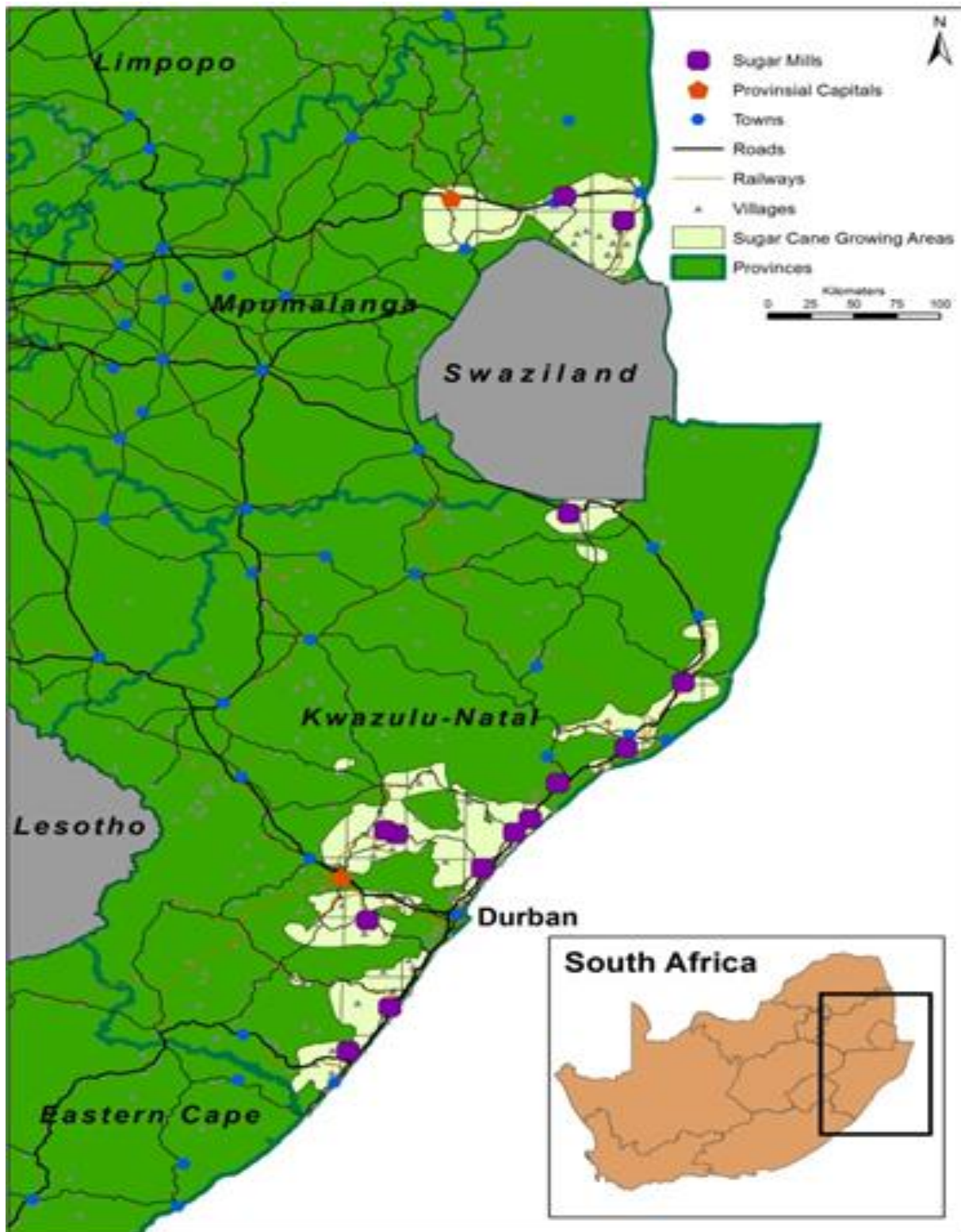


Figure 3.5: Map of South Africa showing sugarcane producing areas and sugar mill locations.

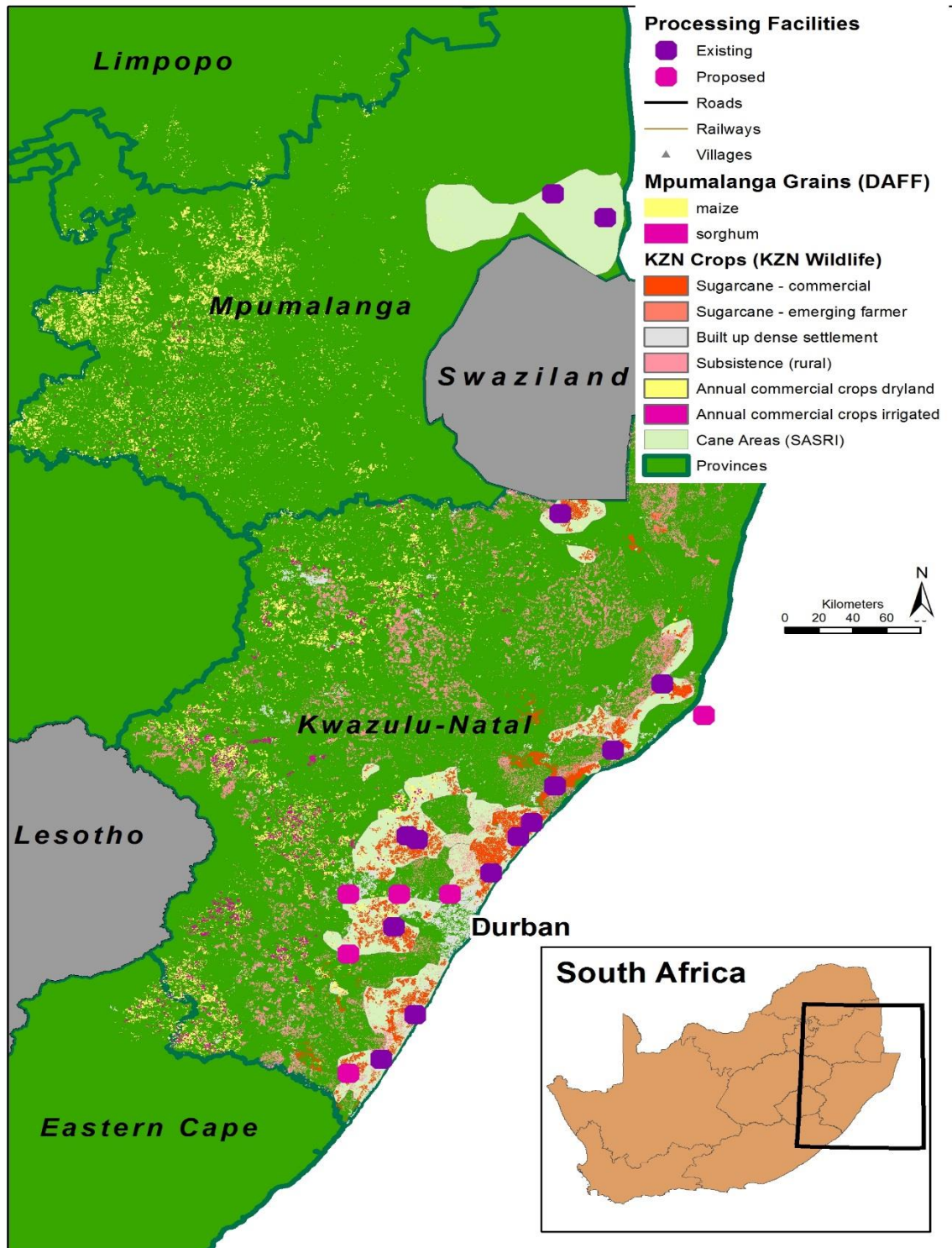


Figure 3.6: Map showing increased biomass cultivation areas for grains and sugarcane as well as locations for bio-ethanol processing facilities and petroleum refineries, namely Sapref and Engen.

The map in Figure 3.6, shows that most of the sugarcane and bagasse come from KZN and Mpumalanga, while sorghum and maize farms are mostly located in Mpumalanga and only in some parts of KZN.

3.2.1 Methodology

The methodology comprises data collection and data analysis of the processes that are in the supply chain model. These include biomass production, biomass conversion to bio-ethanol and transportation of biomass and products.

3.2.2 Data collection

Data was collected from the government Department of Agriculture, Forestry and Fisheries, the South African Sugar Research Institute (SASRI) and from Ezemvelo KZN Wildlife. Data for crop production per municipality, which was obtained from the work of Batidzirai et al. (2013), was also used, where land cover data was not sufficient. One of the challenges faced was insufficient data on the type of crop cultivated in some areas. This implies that in such cases, provincial data had to be intersected with the grids and shape files from Ezemvelo KZN Wildlife, which did not specify type of crop in each municipality except for sugarcane. Land cover data was used to classify the growing areas as commercial, subsistence, and so forth. This data was analysed, using geographical information system and the mapping software ArcGIS. This method has the advantage that the actual area under crop cultivation can be calculated.

Maps showing the cultivation area under study, as shown in Figures 3.5 and 3.6, were drawn, using ArcGIS mapping software. This method has the advantage of giving a good estimate of the feedstock cultivation area, which together with average annual feedstock yield per hectare, can be used to calculate the actual amount of feedstock that can be obtained from the cultivation area. The land area containing feedstock, for the purpose of the development of the optimisation code, was partitioned into rectangles measuring 30 x 40 km through a fishnet approach. A fishnet, which is a collection of rectangles arranged in a manner similar to a grid, was superimposed on

the map covering the area under study. In the context of this study, each rectangle in the fishnet/grid is referred to as a cell. The number of cells/rectangles containing feedstocks in the fishnet used in this study was 220. The central coordinates of these cells were taken as the collection point of the biomass from the fields in each cell. Due to the large number of fields in each cell, the fields in each cell were combined to make up one farm to reduce the number of variables in the model, ultimately reducing the size of the model. Thus, the number of cells was the same as the number of farms in the study. Figure 3.7 below shows an example of four cells in a region. In this context, all the cells that fall within the boundaries of the three provinces under consideration are combined to form a region.

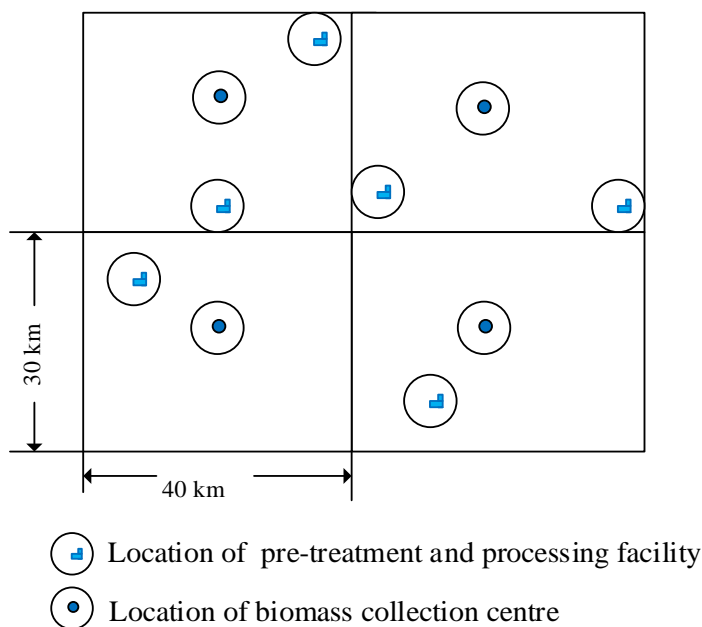


Figure 3.7: Distribution of collection centers and processing facilities in four cells.

For the bio-ethanol processing facilities, it is assumed that fourteen of the 20 possible locations are situated at the actual locations of the sugar mills. It is further assumed that the location for the other six potential bio-ethanol processing facilities is at the centre of the cell, just like the collection centres. The mill crushing capacities were taken from (sugartech, 2014). The coordinates of the sugar mills (processing facilities)

and petroleum refineries (product demand centres), which form the other two layers of nodes shown in Figure 3.1, were also noted and added to the map.

Other researchers in this field located the nodes in different points on the grid. Some placed the collection facilities at the centre and the pre-treatment facilities further away from the collection zone, at the edges of the cell/grid (Čuček et al., 2013; Becker, 2012). The number of cells also depends on the size of the region under study. Some researchers used fewer numbers of cells with bigger cell sizes. Akgul et al. (2011) divided the region under study in the UK into 34 square cells of 108 km in length. In South Africa, Becker (2012), in a thesis on bio-diesel supply chain network, used municipality boundaries to divide the region under study. Interregional transportation distances, based on distances between towns obtained from the Yellow Pages maps by TRUDON (2009) were used in the work of Becker (2012). The use of big cells results in a smaller number of variables in the model. However, transportation distances within the fields in each cell cannot be ignored when cell sizes are big, leading to more computational work.

3.2.3 Data analysis

Data analysis was done, using ArcGIS tools such as intersect, interpolate and join. Excel spreadsheets were generated showing cell numbers, shape length, area of farms in the cells and coordinates of the cells. This data was generated from the feedstock containing areas of the map, which was intersected with the fishnet as shown in Figure 3.5.

The coordinates of the processing facilities, otherwise referred to as feedstock demand centres in this study, were taken together with the coordinates of the farm locations (central coordinate of each cell containing crop) to create a routing spreadsheet. Similarly, the coordinates of the product/bio-ethanol demand centres and the processing facilities were also used to create another routing spreadsheet. These spreadsheets were used to find routes and distances between the nodes, using mapping/routing software Google Earth®. This software uses existing transport infrastructure (road and rail) to create a route between any given points and give a

good estimate of the distance between the points. It also gives the estimated time that could be spent covering the distance, depending on the selected mode of transport. A visual basic macro (Chandoo, 2009) was added to Excel to compute the distances, using Google Map Application Programming Interface (API).

3.2.4 Transportation distances

The cost of transportation for biomass per tonne were taken from literature. This transportation cost, as mentioned previously, was separated into two components, a fixed cost and a variable cost, which depends on the distance travelled. Most researchers in this field used straight-line distances, which are then multiplied by the tortuosity factor for the particular mode of transport to give an estimate of the actual transportation distance (Akgul et al., 2010; Čuček et al., 2014; Becker, 2012; Zamboni et al., 2009). In this study, ArcGIS could have been used to compute straight line distances, but this would require that the distances be multiplied by the respective tortuosity factor for each mode of transport. Table A1 in Appendix A1 shows the transportation distances between farms and processing facilities that were obtained from Google Earth®. Table 3.1 shows transportation distances from processing facilities to product demand centres.

3.2.5 Cultivation regions/farms

In the context of this work, a farm is a group of fields within a 30 km by 40 km cell. The farms under consideration are sugarcane and grain farms in KZN, Mpumalanga and the Eastern Cape. The farm numbers were allocated depending on the position of the cell in the grid/fishnet that covers the three provinces mentioned above.

Table 3.1 Road distance from facility at Layer m to product demand centres j in km

Sugar mill	Sapref	Engen	Animal feed centre	Sugar warehouse
Umzikulu	108	183	5	1
Sezela	77.1	152	5	1
Eston	55.4	33	5	1
Noodsberg	57	104	5	1
Maidstone	90	137	5	1
Union Cooperative Limited (UCL)	133	68	5	1
Gledhow	133	69	5	1
Darnall	99.6	147	5	1
Amatikulu	133	214	5	1
Felixton	171	218	5	1
Umfolozi	231	279	5	1
Pongola	396	442	5	1
Komati	750	682	5	1
Malelani	800	732	5	1
15	135	210	5	1
16	128	50	5	1
17	105	31	5	1
18	67	30	5	1
19	49	77	5	1
20	33	75	5	1

Table 3.2 below shows the maximum farm capacities of feedstock that is available in the cultivation centres in Case 1. The data used in Case 1 was based on the shape files from SASRI and the government Department of Agriculture. The data in Case 1 covered only current sugarcane producing areas and gave only the quantities of sugarcane that were currently obtained from these areas. The data for grains used in Case 1 is the same as the one that was used in Case 2 such that the same quantities of crop residue were available for use in the two cases.

Table 3.2 Amount of feedstock available at the farms in Case 1

Feedstock	Total amount of feedstock available, t/y
Sugarcane	23,093,175
Sugarcane leaves	3,463,976

Table 3.3 shows the maximum quantities of grain and sugarcane that could be obtained in another case (i.e. Case 2). The information for Case 2 was based on shapefiles and data obtained from Ezemvelo KZN Wildlife and Government Department of Agriculture. The data for Case 2 covered a bigger sugarcane producing area (possibly includes potential sugar cultivation area) compared to the one in Case 1. It is possible that the shapefiles in Case 2 included current sugar producing areas which are covered by Case 1 and in addition to that, potential sugar producing areas. Consequently, the approximate amount of sugarcane that could be obtained from this area is astoundingly large. However, this was included for comparison purposes. The amount of sugarcane obtained from Case 2 is approximately 15 times bigger than the one in Case 1. The maximum amount of feedstock that can be produced in each farm is shown in Tables A2.1 and A2.2 in Appendix 2.

The data was analysed as two cases because of the differences in the size of feedstock (sugarcane only) cultivation area in the land cover data obtained from SASRI and from Ezemvelo KZN Wildlife.

Table 3.3 Amount of feedstock available at the farms in Case 2

Feedstock	Total amount of feedstock available, t/y
Sugarcane	141,437,487
Maize straw	1,115,708
Wheat straw	47,515
Sorghum straw	29,990
Sugarcane leaves	21,215,623

The amount of sugarcane that was transported from the farms to the processing facilities, which is given in Table 3.3, was higher than the total amount of feedstock available according to the data used. This is because the available amount was multiplied by a factor of 1.114 to make the model feasible, since the available amount was not able to cater for sugar demand. Multiplying by this factor also ensured that the total amount of feedstock available tallied with data from literature on sugarcane production in South Africa. The discrepancy could have been due to different sugarcane yield estimates or a result of underestimation of the mill supply area.

3.2.6 Processing facilities

The processing facilities are located where the lignocellulosic biomass and sugarcane are processed to produce bio-ethanol as a main product through the fermentation process. The capital costs of the processing facilities/technologies were calculated, using the sixth tenth rule (Holland & Wilkinson 1997, Čuček et al., 2014, You & Wang, 2011) as previously illustrated.

In order to provide an almost equal opportunity at selection for all processing facilities and biomass types, the other six processing facilities' locations, which were not situated at the current sugar mill locations, were potentially located close to or within the sugarcane producing area. The locations were also selected based on field crop density. There is more biomass in these areas than in the surrounding region. It was assumed that processing of first- and second-generation biomass is done on separate lines within the same premises due to differences in the feedstock preparation and pre-treatment. The final product can be mixed, depending on the quantity of water in it. In the two case studies, it was assumed that the final product is anhydrous ethanol.

Table 3.4: Sugar mill processing capacities

Sugar mill	Crushing capacity in t/year
Umzikulu	1,400,000
Sezela	2,500,000
Eston	1,400,000
Noodsberg	1,344,000
Maidstone	2,365,440
UCL	775,000
Gledhow	1,512,000
Darnall	1,639,680
Amatikulu	2,069,760
Felixiton	2,496,000
Umfoloji	1,200,000
Pongola	1,400,000
Komati	2,500,000
Malelani	1,830,000

If a processing facility was to be located at the sugar mill, it would ensure that sugarcane demand at the mill was satisfied first before the production of bio-ethanol. During the sugar production process, the by-products produced are sugarcane within the mill in the production of animal feed. However, not all the sugar mills have animal feed production facilities. For simplicity, then, a monetary value was attached to the molasses. It was assumed that the molasses would be stored at the mill and that transportation cost would be incurred by the animal feed centre, thus excluding the production of animal feed from this work.

If second-generation feedstocks are used in the process, they undergo a pre-treatment stage, where lignin is separated from cellulose prior to the fermentation stage. Acid hydrolysis was the technology of choice in this work. The dissolved sugars from hydrolysis are directed to fermentation, while the filter cake, known as lignin cake, is dried in a furnace and burnt in boilers together with bagasse to produce heat and electricity, using the CHP technology. According to the flow of material in the proposed model, lignin cake is a produced product that has to be recycled into the process for electricity and heat production. Similar to molasses, a monetary value was assigned

to lignin cake, based on the amount of electricity and heat that can be produced from it. Similar to energy production from bagasse, the ratio of heat to electricity produced from lignin cake was taken to be 0.35:0.50

Table 3.5: Conversion factors for intermediate products and produced products.

Resource	Conversion factor to product per tonne of resource						
	Electricity MWh	Heat GJ	Ethanol (t)	Sugar (t)	Molasses (t)	Bagasse (t)	Lignin cake(t)
Sugarcane	-	-	0.071	0.1	0.04	0.28	-
Sugarcane leaves	-	-	0.0936	-	-	-	0.5
Sorghum straw	-	-	0.0392	-	-	-	0.5
Maize straw	-	-	0.0493	-	-	-	0.5
Wheat straw	-	-	0.0392	-	-	-	0.5
Bagasse	0.33	0.00177	0.096	-	-	-	0.5
Lignin cake	0.33	0.00177	-	-	-	-	-

3.2.7 Blending facilities

It was assumed that two oil refineries in Durban, namely Sapref and Engen Refinery will be used as the blending facilities. The oil refining capacities of the two refineries are 172,000 bbl/day (8,600,000 t/y) and 125 000 bbl/day (6,250,000 t/y), respectively. Ethanol transported from the processing facilities will be blended with petroleum oil from each of these refineries. These depots/refineries were chosen as they are the closest to the area under consideration for the bio-ethanol supply chain.

Table 3.6 below shows the gasoline capacity of the refineries and the demand for bio-ethanol at these refineries/blending facilities. The bio-ethanol demand at the refineries was calculated based on the gasoline capacity of each refinery with the assumption that bio-ethanol will be blended into petrol at a ratio of 0.10 parts of ethanol to 0.90 parts of petrol on an energy output basis, using the maximum refinery output of 180,000 bbl/day for Sapref and 125,000 bbl/day for Engen. The energy output from petrol was taken as 47.3 MJ/kg of petrol and for ethanol it was taken as 29.7 MJ/kg of ethanol. The density of gasoline used in this calculation was 0.755 kg/L. It was

assumed that the refinery operates for 95% of the 365 days of the year. The demand at Sapref was calculated as shown in the equation below.

Ethanol Demand at Sapref

$$= \frac{180000 \text{ bbl}}{\text{day}} * 365 \text{ days} * 0.95 * \frac{119.20 \text{ L}}{\text{bbl}} * \frac{0.755 \text{ kg}}{\text{L}} * \frac{47.3 \text{ MJ/kg}}{\left(\frac{29.7 \text{ MJ}}{\text{kg}} * 1000\right)}$$

* 0.1

Similarly, for Engen the ethanol demand was calculated as shown in the equation below

Ethanol Demand at Engen

$$= \frac{125000 \text{ bbl}}{\text{day}} * 365 \text{ days} * 0.95 * \frac{119.20 \text{ L}}{\text{bbl}} * \frac{0.755 \text{ kg}}{\text{L}} * \frac{47.3 \text{ MJ/kg}}{\left(\frac{29.7 \text{ MJ}}{\text{kg}} * 1000\right)}$$

* 0.1

Table 3.6: Annual output and bio-ethanol demand at the blending facilities

Blending facility	Petrol output (t/y)	Ethanol demand (t/y)
Sapref	8,600,000	894,875
Engen	6,500,000	621,441

Table 3.7: Demand of product at product demand centres

Demand centre	Product demand					
	Ethanol (t)	Electricity (MWh)	Sugar (t)	Molasses (t)	Heat (GJ)	Lignin cake (t)
Sapref	894,875	-	-	-	-	-
Engen	621,442	-	-	-	-	-
Umzikulu	-	35,000	-	-	262	-
Sezela	-	62,500	-	-	468	-
Eston	-	35,000	-	-	262	-
Noodsberg	-	33,600	-	-	252	-
Maidstone	-	59,136	-	-	443	-
UCL	-	19,375	-	-	145	-
Gledhow	-	37,800	-	-	283	-
Darnall	-	40,992	-	-	307	-
Amatikulu	-	51,744	-	-	388	-
Felixton	-	62,400	-	-	467	-
Umfolozi	-	30,000	-	-	225	-
Pongola	-	35,000	-	-	262	-
Komati	-	62,500	-	-	468	-
Malelani	-	45,750	-	-	343	-
Sugar warehouse	-	-	2,443,188	-	-	-
Animal feed centre	-	-	-	977,275	-	-
Lignin cake warehouse	-	-	-	-	-	28,145,667
Total	1,516,317	610,797	2,443,188	977,275	4,575	28,145,667

3.2.8 Biomass cost

The cost of biomass can be divided into two categories, which are wet cost and dry cost. Dry biomass is more costly than wet biomass due to additional pre-processing costs. For sugarcane, the cost is approximately R392/t based on the 2014 harvest season prices. For this study, use of dry biomass was considered. The cost was taken as cost at farm gate, which included harvesting costs and compensation for nutrients

removed from the farm in the form of plant wastes. Table 3.8 below shows the costs of the feedstocks that were used in this study.

Table 3.8: Feedstock cost price (values estimated for 2014 crop prices in South Africa)

Feedstock	Cost (ZAR/t)
Sugarcane	392
Maize straw	318
Sorghum straw	318
Wheat straw	311
Sugarcane leaves	105
Bagasse	-

The total demand and selling price for the products is given in the Table 3.9 below. The demand for heat and electricity was based on literature values mentioned in Section 2.3 of Chapter 2. Demand for sugar and molasses was based on the maximum crushing capacities of the existing sugar mills. Average conversion factors of the feedstocks were taken from literature.

Table 3.9: Product demand and selling prices (values taken from Čuček et al. (2014) at an exchange rate of ZAR12.2/\$)

Product	Product demand centres				
	Product price (ZAR/unit)	Sugar mills	Sugar ware house	Animal	
				feed centre	Lignin cake ware house
Ethanol(t)	15,500	-	-	-	-
Electricity (MWh)	1,220	610,797	-	-	-
Sugar (t)	4,728	-	2,443,200	-	-
Molasses (t)	1,500	-	-	977,300	-
Heat (GJ)	84.7	24,374	-	-	-
Lignin Cake (t)	1,8376	-	-	-	28,145,670

3.2.9 Transportation costs

Transportation costs per feedstock and product are shown in Table 3.10 below.

Table 3.10: Transportation costs of products and feedstocks

Product	Transportation cost	
	Fixed cost (ZAR/t)	Variable cost (ZAR/t.km)
Sugarcane	104.00	1.02
Sugarcane leaves	104.00	1.02
Wheat straw	104.00	1.02
Maize straw	104.00	1.02
Sorghum straw	104.00	1.02
Barley straw	104.00	1.02
Ethanol	47.10	0.80
Sugar	76.90	0.80
Molasses	76.90	0.80
Lignin cake	78.60	0.80

3.30 Investment costs

Table 3.11 below shows the operating costs and the fixed capital cost for the technologies used in the case study. It was assumed that there was no investment in sugar milling and that each processing facility already had a cogeneration plant and therefore there was no investment into CHP.

Table 3.11: Operating and investment costs for the technologies (values taken from Čuček et al. (2014) at an exchange rate of ZAR12.2/\$)

Technology	Operating costs (R *10 ³)	Reference plant Size	Investment cost for Reference plant (ZAR *10 ⁶)
Fermentation	1,952/t	183,970(t)	2,062
Sugar milling	1,420/t	200,000(t)	-
CHP	2,46/MW	20/MW	-
Preparation	10,700/t	84,000(t)	-
Storage	134.2/t	17,000(t)	5.79

3.31 Linearization of the investment term

The investment term makes the MILP model nonlinear. For supply chain models, it is desirable to linearise this term so that the model solution is a global optima. Piecewise linearization, in line with the work of Čuček et al. (2013) as discussed in Section 2.6, was used to compute the investment cost. Another method for linearization of the investment term makes use of the Taylor series expansion method. The sixth tenth rule – when applied to the reference plant (capacity 183,970 t/y of ethanol and fixed capital cost of R 2,062 million) and the plant to be designed in this optimisation framework – gives the expression shown below.

$$C_2 = 2061.800 * \left(\frac{S_2}{183970} \right)^{0.6} \quad 3.35$$

Where:

C_2 is the fixed investment cost of the plant to be designed;

S_2 is the capacity of the plant to be designed.

Linearising Equation 3.35, using the Taylor series method yields the expression given in Equation 3.36 with a regression coefficient of 0.9794.

$$y = 0.0107x + 87.283 \quad 3.36$$

The plot of this model is shown in Figure 3.8

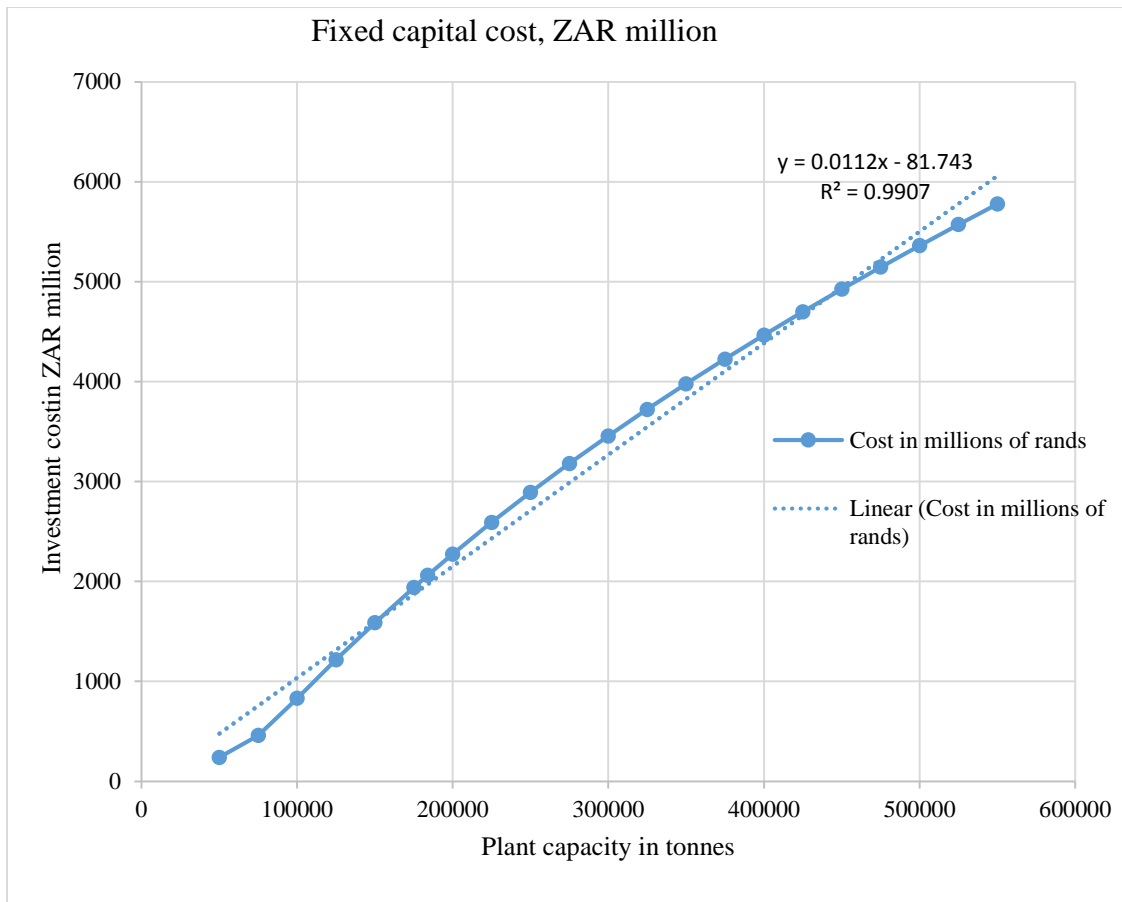


Figure 3.8: Graph of capital cost against plant capacity for a bio-ethanol plant obtained from linearization of the investment term, using the Taylor series expansion method.

However, use of this method will be pursued in future studies to see how the results compare with those from other methods.

3.32 Model reduction

Grouping was applied as a model reduction technique due to the vast number of fields in each cell in the case study area. There are many field boundaries that would result in a large number of variables in the model if each field were to be allocated a farm number in the model. All the fields falling in one cell of the fishnet drawn over the map were combined to form a single farm.

3.33 Environmental impact assessment

Environmental impact assessment of the emissions produced in the supply chain was executed, using CML-IA baseline method in SimaPro classroom 8.0.4.30 with the European Union 25 (EU25) (PRé, 2013). Multi-objective optimisation of the environmental and economic objectives was performed, using the ε -constraint method. Pareto analysis was conducted to establish the best trade-off point between the economic and environmental objectives.

Similar to the work of You et al. (2012), it is assumed that the carbon dioxide emitted during the combustion of bio-ethanol in vehicles is captured during feedstock growth and is thus omitted in the LCA. This makes the LCA boundaries used in this system for the environmental assessment to be farm to blending facility. Greenhouse gas emissions due to land use and land use changes were ignored as factors such as productivity and commodity market analysis were not included in the study (Farrell et al., 2006).

The four phases of lifecycle analysis discussed in Section 2.9 were followed to obtain the environmental impact of the supply chain.

3.33.1 Goal and scope

The goal and scope of the lifecycle analysis done in this work is to provide a basis for comparison of the different supply chain design alternatives, which include selection of biomass cultivation centres, type of biomass, location and size of the processing facility and the product demand centres. The assessment was done based on the economic objective through multi-objective optimisation criteria. In this work, it was assumed that the emissions produced during combustion of the bio-ethanol in vehicles at points of use are absorbed by the biomass during biomass cultivation such that this stage is excluded from the LCA. Therefore, this LCA may not be a true representative of “cradle to grave” approach but a “farm to blending” approach.

The stages of the LCA for the bio-ethanol supply chain network are feedstock cultivation and harvesting, feedstock drying and storage, feedstock transportation, bio-ethanol production and bio-ethanol transportation. From the LCA, the stage contributing the highest environmental impact can be identified and recommendations to improve the overall environmental impacts for the supply chain can be made.

The functional unit for the study is the optimal conversion of one year's biomass feedstock for Case 1 and for Case 2, respectively, into the suite of optimal final products. As the system boundary was set to “farm to blending”, the environmental benefits of replacing petrol by bio-ethanol are quantified.

3.33.2 Inventory

The inputs for the supply chain are water, fossil fuel, sulphuric acid, yeast, heat in the form of steam and electricity. The outputs for the supply chain are CO₂, CO and N₂O from the combustion of fossil fuel during harvesting and transportation, and also NO_x and SO₄ from the fertilisers and sulphuric acid from the hydrolysis step of processing lignocellulosic biomass. The Ecoinvent 3.1 database was used to obtain most of the environmental impacts. Where data was not available in Ecoinvent 3.1, the Agri-footprint database was used.

Figure 3.9 below shows the input and output flows in the lifecycle of the bio-ethanol supply chain network.

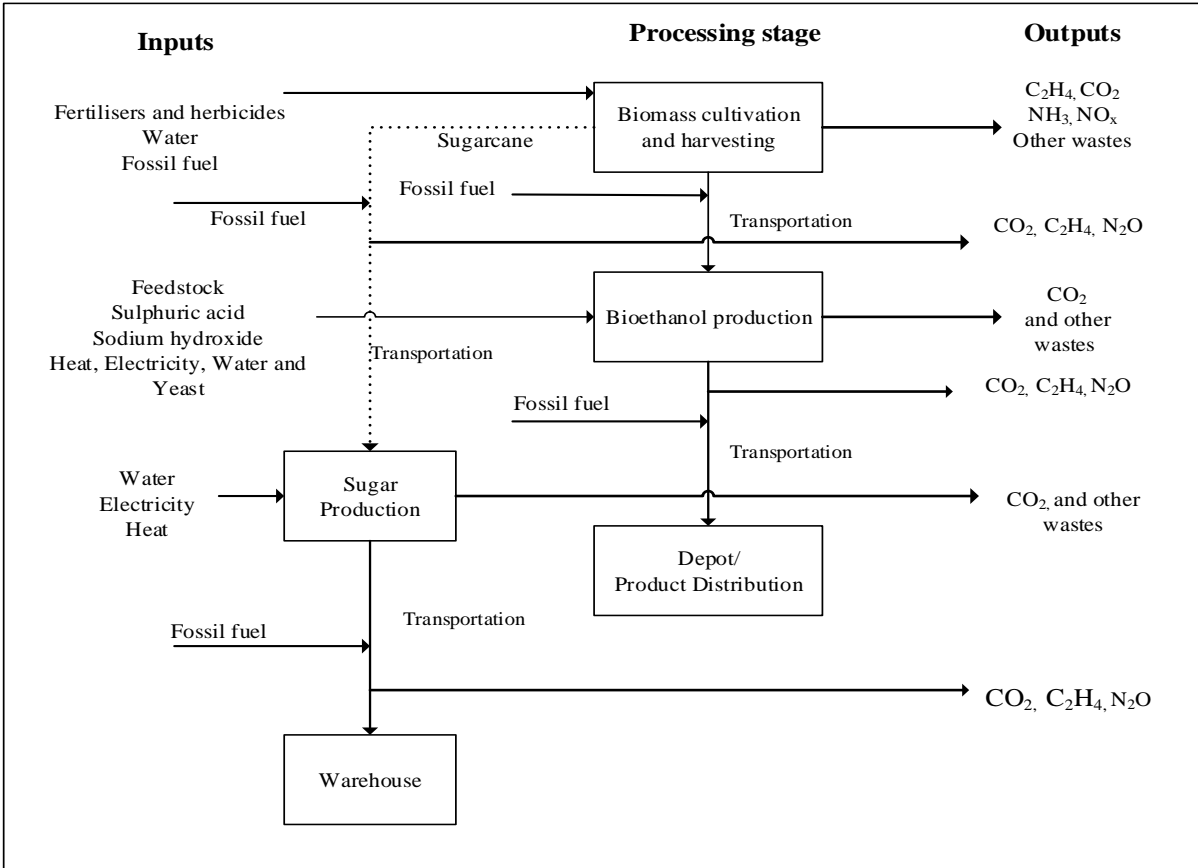


Figure 3.9: The input and output flows of the bio-ethanol supply chain network.

Equation 3.34 below gives the environmental impact of the supply chain

$$\begin{aligned}
E^{imptot} = & \sum_{i \in I} \sum_{m \in M} \sum_{re \in RE} e_{truck,re}^{L1,L2} \cdot q_{i,m,re,tp}^{m,L1,L2} \cdot D_{i,m}^{L1,L2} \\
& + \sum_{m \in M} \sum_{m \in M} \sum_{pi \in P1} e_{truck,pi}^{L2,L3} \cdot q_{m,n1,pi,tp}^{n1,L2,L3} \cdot D_{m,n1}^{L2,L3} \\
& + \sum_{m \in M} \sum_{j \in J} \sum_{pd \in PD} e_{truck,pd}^{L2,L5} \cdot D_{n2,j}^{L2,L5} \cdot q_{m,j,pd,tp}^{m,L2,L5} \\
& + \sum_{n1 \in N} \sum_{n2 \in N2} \sum_{pm \in PM} e_{truck,pm}^{L3,L4} \cdot D_{n1,n2}^{L3,L4} \cdot q_{n1,n2,pm,tp}^{n1,L3,L4} \\
& + \sum_{n2 \in N2} \sum_{j \in J} \sum_{pp \in PP} e_{truck,pp}^{L4,L5} \cdot D_{n2,j}^{L4,L5} \cdot q_{n2,j,pp,tp}^{n2,L4,L5} \\
& + \sum_{i \in I} \sum_{m \in M} \sum_{re \in RE} e_{re,p}^{L1} \cdot q_{i,m,re,tp}^{m,L1,L2} \\
& + \sum_{m \in M} \sum_{j \in J} \sum_{(re,t) \in RET} e_{re,pd,t}^{L2} \cdot q_{m,j,pd,tp}^{m,L2,L5} \\
& + \sum_{n2 \in N2} \sum_{(pm,t) \in PMT} q_{n2,j,pp,tp}^{n2,L4,L5} \cdot e_{pm,pp,t}^{L4}
\end{aligned} \tag{3.34}$$

where:

$e_{truck,re}^{L1,L2}$ is the environmental impact due to transportation of biomass from level 1 to level 2 of the supply chain according to figure 3.4;

$e_{truck,pi}^{L2,L3}$ is the environmental impact due to transportation of feedstock from level 2 to level 3 of the supply chain according to figure 3.4;

$e_{truck,re}^{L3,L4}$ is the environmental impact due to transportation of feedstock from level 3 to level 4 of the supply chain according to figure 3.4;

$e_{truck,pp}^{L3,L4}$ is the environmental impact due to transportation of products from level 4 to level 5 of the supply chain according to figure 3.4;

$e_{truck,pd}^{L2,L5}$ is the environmental impact due to transportation of direct products from level 2 to level 5 of the supply chain according to figure 3.4;

$e_{re,pd,t}^{L2}$ is the environmental impact due to processing of biomass at level 2 to produce direct products (sugar and molasses);

$e_{re,p}^{L1}$ is the environmental impact for biomass production at the farm on level 1;

$e_{pm,pp}^{L4}$ is the environmental impact for production of the produced product pp , (ethanol, electricity, heat and lignin cake) at the processing facility on level 4.

3.33.3 Impact assessment

The environmental impacts of the flows from the inventory step were analysed and characterised in SimaPro. The environmental impact for acidification, eutrophication and human toxicity categories were considered in addition to the global warming potential. After characterisation, the environmental impacts for each category were plotted on a graph for each stage, with the sum of the emissions from all the stages being set as the reference point with an impact of 100%.

The use of bagasse as biomass results in avoided greenhouse gas emissions because of the omission of emissions from cultivation and harvesting stage, which are included in sugarcane production. Its use in CHP cogeneration also results in reduced emissions because of the replacement of fossil fuels. Due to the different heating values of the two fuels, 0.633 kg of gasoline is equivalent to 1 kg of ethanol (Botha & von Blottnitz, 2006), and the equivalence of 1 kWh of electricity produced from bagasse is taken to be equivalent to 1 kWh produced from fossil fuels (Botha & von Blottnitz, 2006). Table 3.12 below gives the environmental impact for feedstocks, products and transport used in the different stages of the supply chain. These were taken from Ecoinvent database in SimaPro. For transportation distances, the distances from the optimised models were used to calculate the environmental impact. The storage of bagasse was assumed to contribute to the environmental impact of the sugar production supply chain network and was therefore ignored in this analysis.

Table 3.12: Environmental impact of feedstocks and products taken from Ecoinvent database 3 in SimaPro classroom 8.0.4.30 and characterised using the in CML-IA baseline method

Product or feedstock	Environmental impact (kg equivalent)			
	CO ₂	PO ₄	SO ₂	1,4-DB eq
Sugarcane/kg	3.60 x 10 ⁻²	3.10 x 10 ⁻⁴	5.60 x 10 ⁻⁴	3.30 x 10 ⁻¹
Sugar /kg	3.30 x 10 ⁻¹	3.00 x 10 ⁻³	4.70 x 10 ⁻³	1.21 x 10 ¹
Molasses /kg	1.04 x 10 ¹	2.50 x 10 ⁻³	4.50 x 10 ⁻³	4.40 x 10 ⁻²
Ethanol/kg	5.3 x 10 ⁻¹	5.90 x 10 ⁻³	8.80 x 10 ⁻³	2.65 x 10 ¹
Electricity/kWh	7.01 x 10 ⁻¹⁵	2.95 x 10 ⁻¹⁴	2.12 x 10 ⁻¹⁴	2.08 x 10 ⁻¹⁴
Heat/MJ	1.19 x 10 ⁻¹⁵	5.01 x 10 ⁻¹⁵	3.59 x 10 ⁻¹⁵	3.54 x 10 ⁻¹⁵
Lignin cake/kg	3.86 x 10 ⁻¹⁵	1.63 x 10 ⁻¹⁴	1.17 x 10 ⁻¹⁴	1.15 x 10 ⁻¹⁴
16-25 t truck (sugarcane) kg/t.km	1.4 x 10 ⁻¹	7.04 x 10 ⁻⁵	3.80 x 10 ⁻⁴	6.00 x 10 ⁻²
7-16 t truck (sugar) kg/t.km	1.3 x 10 ⁻¹	6.04 x 10 ⁻⁵	3.40 x 10 ⁻⁴	1.70 x 10 ⁻²
7-16 t tanker (ethanol) kg/t.km	1.3 x 10 ⁻¹	6.04 x 10 ⁻⁵	3.40 x 10 ⁻⁴	1.70 x 10 ⁻²

3.33.4 Interpretation

The results from the environmental impact assessment step were analysed and greenhouse gas emissions from the global warming category were used in the construction of the Pareto curve in order to find the trade-off between the economic and the environmental objective. Emissions avoided due to use of bio-ethanol as a fuel, as compared to fossil based fuels, were also calculated.

3.33.5 Avoided emissions

The avoided emissions from the case study were calculated, using the analysis of E-10 blend from the work of Kadam (2002), are shown in Table 3.13 below.

Table 3.13: Apportioned emissions for E-10 blend (Kadam, 2002)

Substance emitted	Current Gasoline, g/kg	E10 Blend g/kg	Apportioned emissions E10, g/kg of blend	
			Gasoline	Ethanol
Benzene	1.53	1.37	1.37	-
Benzo(a)pyrene	1.58	0.00	0.00	-
Carbon dioxide, biomass	-	-	-	200.20
Carbon dioxide, fossil	2,775.00	2,584.00	2,584.00	-
Carbon monoxide	198.00	158.00	148.00	10.00
Ethanol	-	0.38	-	0.38
Hydrocarbons (except CH ₄)	38.00	37.50	35.12	2.38
Lead	0.20	0.18	0.18	0.01
Methane	1.50	1.34	1.25	0.09
Nitrogen oxides (NO _x as NO ₂)	32.60	32.60	30.53	2.07
Nitrous oxide (N ₂ O)	0.13	0.13	0.12	0.01
Sulphur oxides (SO _x as SO ₂)	0.26	0.23	0.23	-

The total amount of ethanol produced in the optimised models (467,808 t, Case 1) and (1,516,317 t, Case 2) is equivalent to 296,122 t and 959,829 t of petrol, respectively. To standardise the greenhouse gas (GHG) to CO₂ equivalent, Equation 3.37 below is used:

$$\text{Mass of GHG} \times \text{GWP} = \text{CO}_2 \text{ eq} \quad 3.37$$

Where the global warming potential (GWP) (100 years) factor for carbon dioxide gas is 1, for methane, 25 and for nitrous oxide 298 (IPCC, 2008).

For the E-10 blend, avoided GHG emissions were calculated, using the values in Table 3.13 for emissions from gasoline and E-10 and the total amount of ethanol obtained from Case 1 (467,808 t) as shown below.

Avoided CO₂ emission per kg of gasoline..... (2,775 - 2,584) x 1 = 191g
 Avoided CH₄ emission per kg of gasoline(1.5 - 1.25) x 25 = 6.255 g
 Avoided N₂O emission per kg of gasoline (0.13 - 0.12) x 298 = 2.98 g

To get the amount of gasoline that is replaced by bio-ethanol on an energy basis, the quantity of bio-ethanol that was produced from the case study is multiplied by 0.633 kg/kg which is the energy equivalence of bio-ethanol for 1 kg of gasoline (Botha & von Blottnitz, 2006). This is calculated as shown in the expression below.

$$467,808,000 \text{ kg} * \frac{0.633 \text{ kg of gasoline}}{\text{kg of bioethanol}} = 296,122.46 \text{ kg of gasoline}$$

$$\text{Total avoided GHG} = (191 + 6.255 + 2.98) \text{ g} = 200.235 \frac{\text{g}}{\text{kg}} \text{ of gasoline.}$$

CHAPTER 4. RESULTS AND DISCUSSION

This chapter presents the results for the MILP model and compares the results from Cases 1 and 2. Case 1 has a smaller crop production area, while Case 2 has a larger crop production area. The difference arose from the fact that land cover data for one of the feedstocks was obtained from two sources. Also worth noting is that Case 2 can be regarded as a scenario where the feedstock supply area in Case 1 is increased by a factor of 15. Sensitivity of the optimal solution (i.e. the base case) to changes in feedstock costs, product costs, transportation cost and available quantities of feedstocks was tested. Other scenarios including increase in amount of feedstock available due to a reduction in exports as well as increase in crop production area, were also investigated.

4.1 Model Results

The results are split in two, according to the land cover data source used (i.e. Cases 1 and 2). Case 1 used shape files for current sugarcane cultivation areas that supply sugar mills, while Case 2 used land cover data from Ezemvelo KZN Wildlife, which had a larger sugarcane cultivation area than the current sugar production quantities reported in literature. In addition to sugarcane and its residues, residue from maize, sorghum and wheat were also considered as feedstock. The profits, costs and environmental impact results were also reported for a case of combined sugar and ethanol production, and for a case where the productions are separate so as to get the specific impact and costs associated with the production of ethanol.

4.1.1: Profit and costs for the optimised supply chain network

The profits and costs for the optimised supply chain network model for ethanol and by-products are shown in Table 4.1 below. The feedstock cost and the production cost for Case 1 is very small when compared to Case 2 and to other costs due to the use of bagasse which had no purchasing cost attached to it. The transportation cost is also low in Case 1 as it is mainly due to the use of bagasse in the production of bio-ethanol such that the transportation cost is mainly due to product transportation.

Table 4.1: Profits and costs for the optimised model

Case	Plant location	Cost/Profit in ZAR *10 ⁶				
		Feedstock	Transport	Production (other)	Investment	Profit
1 ¹	Sugar mills	0,003	2,135	0,003	14,017	4,885
2 ²	Sugar mills	4,231	7,774	0,100	23,046	10,751

- 1) Current sugar mill supply area (SASRI);
- 2) Land cover data for 2011 (Ezemvelo KZN Wildlife long-term land cover and land use change monitoring project for KZN).

Investment costs in both models contributed more than 50% of the overall cost, followed by transportation costs. In Case 1, where most of the feedstock was available at the mill as by-product from sugar milling, feedstock cost was negligible, while feedstock cost constituted approximately 12% of the overall costs in Case 2. This was due to additional sugarcane that had to be purchased and transported from farms to the processing facilities. This also explained the higher transportation cost in Case 2. In Case 1, there was less feedstock, resulting in lesser produced products and lower revenue, hence a lower profit value. However, the profit margin for Case 1, which was 67%, is higher than that for Case 2, which was 46%. This implies that Case 1 was more profitable than Case 2, despite its lower profit value.

In both cases, the preferred locations for the processing facilities were at the sugar mills and only sugarcane was moved from the farms to the processing facilities. Sugarcane leaves were not moved, mainly due to low density, which would result in high transportation costs. Crop residues were also not selected due to a high purchase price compared to other feedstocks that were selected. The crop residues also find use as animal bedding in the case of wheat straw, and as animal food, in the case of maize straw. Considering a biomass- bio-ethanol supply chain that has processing facilities located on the crop cultivation areas, and not within a sugar supply network, could increase the chances of the residues being selected and utilised in bio-ethanol production. However, a lot of studies concluded that stand alone second generation technology is not economically viable. Case 2 had a higher investment cost due to

larger processing facilities than in Case 1. The results of the optimised model, with the scenario for satisfying both domestic and current sugar export demand, which is the base-case scenario in each of the two cases investigated in this study, are shown in Tables 4.2 and 4.3 below. For Case 1, the selected locations were all at the sugar mills, and the same plant size was found to be optimal for all the processing facilities. Although there were different quantities of ethanol produced from each processing facility, as shown in Table 4.2, the investment cost was the same due to the constraint placed on the capacity of the plant that the minimum plant size be equal to 30% of the reference plant capacity. In this case, 30% of the reference plant capacity was 55,191 tonnes of ethanol.

Table 4.2: Investment cost and size of ethanol processing facility (Case 1)

Plant	Ethanol (tonnes)	Investment cost (ZAR million/y)
Komati	47,793	1,001
Malelani	47,793	1,001
Gledhow	47,716	1,001
Eston	45,220	1,001
UCL	39,568	1,001
Sezela	34,984	1,001
Felixton	31,346	1,001
Maidstone	28,905	1,001
Amatikulu	27,505	1,001
Darnall	26,764	1,001
Umzikulu	26,764	1,001
Pongola	25,693	1,001
Noodsberg	22,941	1,001
Umfolozi	14,816	1,001
Total	467,808	14,014

Table 4.3 Investment cost and size of ethanol processing facility (Case 2)

Plant	Investment cost (ZAR	
	Ethanol (t)	million/y)
UCL	202,484	2,171
Gledhow	179,957	2,034
Eston	156,223	2,055
Komati	47,793	1,001
Malelani	34,984	1,001
Noodsberg	185,092	2,065
Umzikulu	183,380	2,055
Maidstone	153,870	1,819
Sezela	149,757	1,785
Darnall	55,191	1,001
Felixton	47,716	1,001
Amatikulu	4,008	1,001
Eston	27,157	2,055
Pongola	26,764	1,001
Umfolozi	22,941	1,001
Total	1,516,317	23,046

In Case 1, from the optimised model, processing facility plant sizes ranged from 14,816 t to 47,793 t of bio-ethanol. Because of the constraint placed on plant capacity in the model, the minimum plant size that could be established was 55,191 t/y of ethanol. The investment cost of the plant was calculated, using the sixth tenth rule in which an established plant whose capacity and fixed capital was already known was used as a basis to calculate the investment cost of the new plant. In this study, a plant with a capacity of 183,970 t/y of ethanol and fixed capital cost of ZAR 2,062 million was used as the reference plant. A constraint was placed on the plant capacity in the model that it cannot go below 30% of the reference plant capacity, nor can it exceed 10 times the capacity of the reference plant. The bio-ethanol processing facility size selected at each of the mills for Case 1 was less than 30% of reference plant size.

This implied that the investment cost at all the processing facilities was the same as the minimum acceptable size as determined by the lower bound on the capacity constraint in the model was 55,191 t/y of ethanol. All the plants in Case 1 would qualify for government incentive as they were within the capacity range (158,000 m³/y or 124,662 t/y of bio-ethanol) of plants that would qualify for the incentive from the South African government (DME, 2014). The government incentive reduces the overall cost of the supply chain. The use of sugarcane, in addition to bagasse in Case 2 resulted in bigger plant sizes than Case 1, with the investment cost per plant ranging from ZAR 1,001 million to ZAR 2,171. In plants where the available biomass was solely bagasse, the investment cost of the plant was the same as the lower bound of the reference plant capacity (i.e. R 1,001 for a plant of capacity 55,191 tonnes of bio-ethanol).

Both cases produced ethanol in excess of the 2% (315,600 t of ethanol) target penetration of biofuels into the national liquid fuel supply that was set by government (DME, 2007) with Case 1 exceeding the target demand by 48% and Case 2 being capable of producing 480% of the target demand. Table 4.4 gives the feedstock types that were used in the ethanol production process at each plant in Case 1.

Table 4.4: Product distribution and feedstock type used in ethanol production (Case 1)

Plant	Ethanol in tonnes				Total quantity of ethanol (t)
	Engen		Sapref		
	Bagasse	Sugarcane	Bagasse	Sugarcane	
Komati	47,793	-	-	-	47,793
Malelani	34,984	-	-	-	34,984
Gledhow	28,905	-	-	-	28,905
Eston	26,764	-	-	-	26,764
UCL	14,816	-	-	-	14,816
Sezela	-	-	47,793	-	47,793
Felixton	-	-	47,712	-	47,712
Maidstone	-	-	45,220	-	45,220
Amatikulu	-	-	39,568	-	39,568
Darnall	-	-	31,346	-	31,346
Umzikulu	-	-	26,964	541	27,505
Pongola	-	-	26,764	-	26,764
Noodsberg	-	-	25,693	-	25,693
Umfolozi	-	-	22,941	-	22,941
Total	153,262	-	314,001	541	467,804

4.1.2: Product distribution

The distribution of ethanol from the bio-ethanol/sugar mill processing facilities to the two depots in Durban, namely Sapref and Engen, is shown in Figures 4.1 and 4.2 below. Thirty six percent of the processing facilities supplied Engen refinery, which had an average transportation distance of 304 km from the plants. The Sapref depot, which had an average transportation distance of 162 km from the processing facilities, was supplied by 64% of the processing facilities.

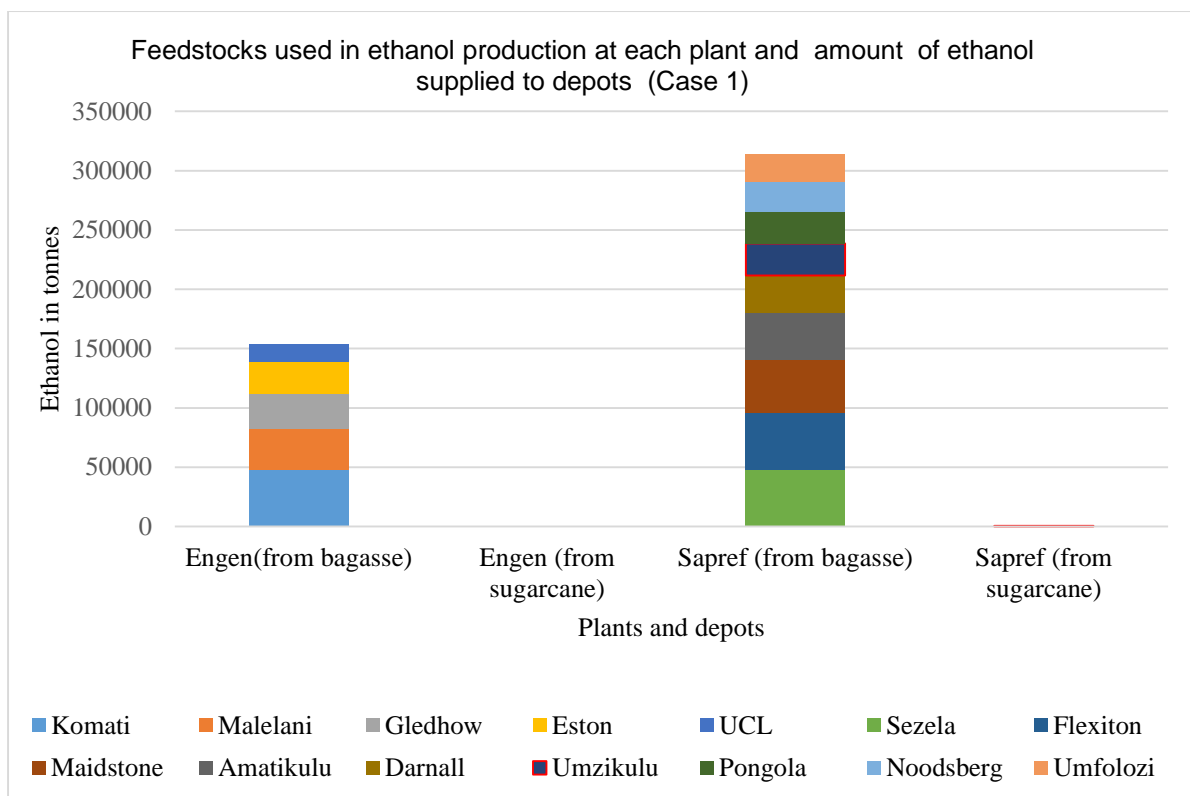


Figure 4.1: Graph showing plants supplying each depot and feedstock type used in ethanol production (Case 1)

In Case 1, a total of 467,266 t of ethanol was produced from bagasse and an additional amount constituting less than 0.12% of the total amount was produced from sugarcane at just one processing facility, which is Umzikulu. Table 4.4 (for Case 1) and 4.5 (for case 2) highlight the feedstock type and quantities of main product at each processing facility. The actual quantities of feedstock that were transported from each farm to the processing facilities are shown in Tables A3.1.1 to A3.2.6 in Appendix A3.

In Case 2, a total of 1,516,317 t of ethanol was produced with production from sugarcane exceeding that from bagasse by 2%. Similar to Case 1, 36% of the processing facilities supplied the Engen refinery, which had an average transportation distance of 304 km from the plants, while 64% of the plants supplied the Sapref depot, which had an average transportation distance of 162 km from the processing facilities. However, in Case 2, both Engen and Sapref received bio-ethanol produced from

sugarcane and bagasse, unlike in Case 1, where bio-ethanol was produced only from bagasse.

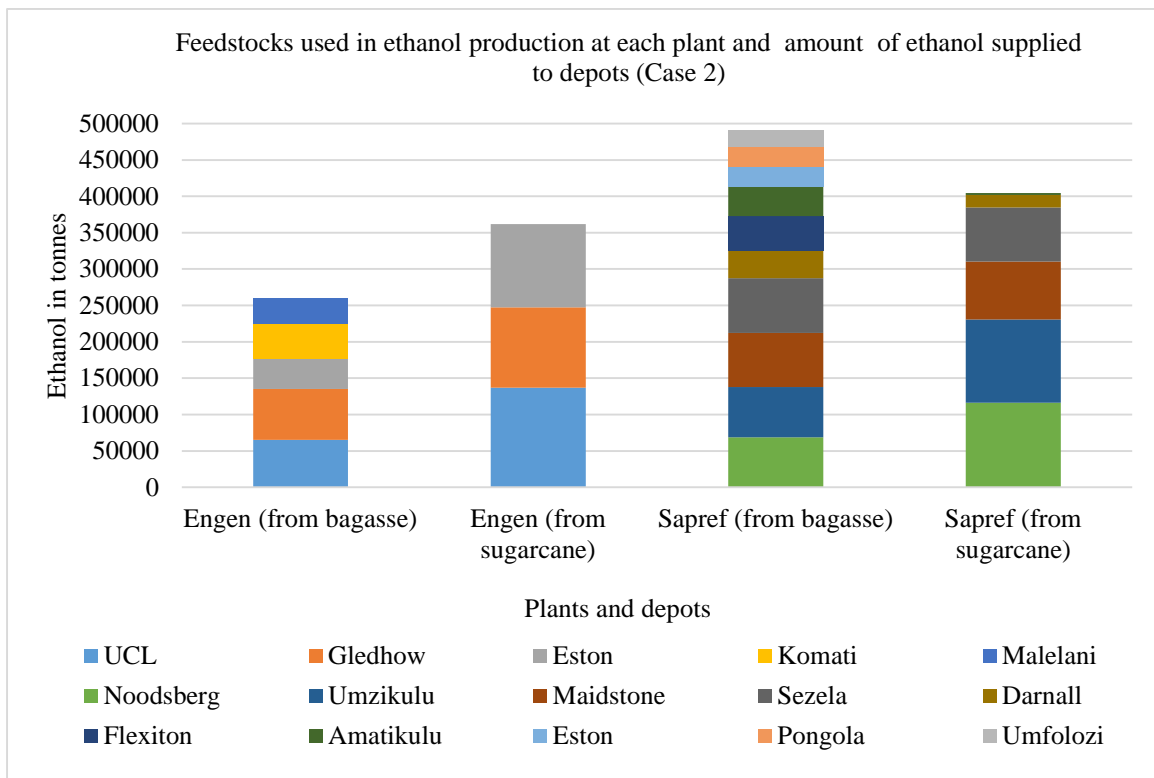


Figure 4.2: Graph showing plants supplying each depot and feedstock type used in ethanol production (Case 2)

Table 4.5: Product distribution and feedstock type used in ethanol production (Case 2)

Plant	Ethanol in tonnes				Total quantity of ethanol(t)
	Engen		Sapref		
	Bagasse	Sugarcane	Bagasse	Sugarcane	
UCL	65,413	137,072	-	-	202,485
Gledhow	69,630	110,327	-	-	179,957
Eston	41,832	114,391	-	-	156,223
Komati	47,793	-	-	-	47,793
Malelani	34,984	-	-	-	34,984
Noodsberg	-	-	68,668	116,423	185,091
Umzikulu	-	-	68,988	114,391	183,379
Maidstone	-	-	74,513	79,357	153,870
Sezela	-	-	75,283	74,474	149,757
Darnall	-	-	37,774	17,416	55,190
Felixton	-	-	47,716	-	47,716
Amatikulu	-	-	40,495	2,513	43,008
Eston	-	-	-	27,156	27,156
Pongola	-	-	-	26,764	26,764
Umfolozi	-	-	-	22,941	22,941
Total	259,652	361,790	413,437	481,435	1,516,314

The total amount of ethanol produced from Case 2 was 1,516,314 t/y, which is 3.2 times the output of Case 1. For all the plants in Case 2, the fixed capital investment cost per year was R 23,046 million. The fixed capital investment cost for Case 1 was equivalent to 61% of that of Case 2. The smallest output was at UCL mill, which was 14,816 t/y in Case 1 and at Umfolozi, which had a capacity of 22,941 t/y in Case 2. The largest plant size in Case 1 was 47,793 t/y at Sezela mill, while for Case 2, the largest plant size was 202,484 t/y at UCL mill. For the case study with the larger supply area (Case 2), it is feasible to establish plants with capacities bigger than the minimum acceptable plant size, which was constrained to be 30% of the reference plant capacity that was used in the six tenth rule in the model, when calculating the investment cost of the new plant. This was due to excessive availability of sugarcane and bagasse that

could be channelled to bio-ethanol production. For Case 2, the ratio of ethanol from the two feedstock types (i.e. bagasse and sugarcane), which were selected for use in bio-ethanol production in the optimal supply chain network, was almost 1:1 with a slightly higher quantity coming from sugarcane.

4.1.3 Feedstock supply

In the two cases, five processing facilities had a feedstock supply area within a 100 km radius, while six plants received from supply areas within a 100 to 200 km radius. Only two plants had supply areas that were between 350 and 420 km away. In literature, in the area under study, there were some mills that were currently supplied by farms that were further away than the longest distances in the optimal supply chain network obtained in this study. Some of the reasons for the transportation of sugarcane over long distances in the current sugar mill supply area include ownership of the farms that are far away from the mill location by the mill operators and also contracts between mill operators and cane farmers, which may bind the farmers to supply to only one mill (SCGA, 2013). In Case 1, approximately 43% of the biomass transported to the processing facilities was collected from farms within a 100 km radius. In Case 2, approximately 64% of the plants were supplied by farms within a 150 km radius, with 21% receiving biomass from farms less than 50 km away. According to the South African Cane Growers' Association (SCGA, 2013) reports, most sugar mills supplied areas were within 70 km relative to the location of the mill. However, there were exceptions where some mills received cane from farms more than 400 km away. Tables A3.1.1 up to A3.2.5 in Appendix A3 show the actual amounts of feedstock that were transported from each farm to each processing facility and Table 4.6 below gives the average radius of plant supply areas. Figure 4.3 shows the average transportation distances of biomass from cultivation areas to processing facilities for the Case 1 base scenario, where there were no sensitivity tests done on the parameters that were used in the model.

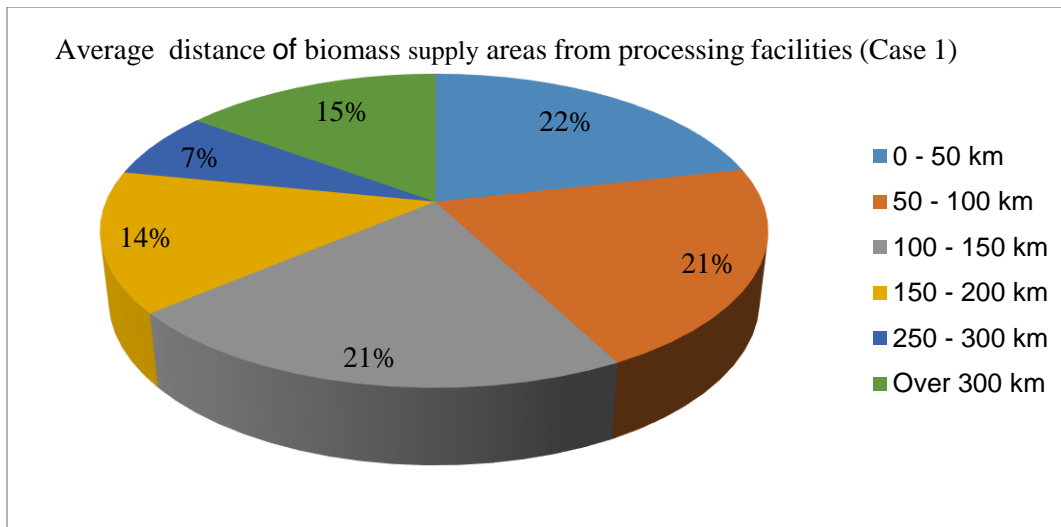


Figure 4.3: Average distance of feedstock cultivation areas from processing facilities (Case 1)

Table 4.6: Farms supplying processing facilities and average transportation distance for feedstock (Case 1)

Farm	Plant	Feedstock(t)	Average distance (km)
11	Sezela	3,735,714	5.88
11, 38	Umzikulu	3,169,26	9.47
12	Eston	3,169,626	49.79
12	Noodsberg	3,140,807	67.63
12, 42	Maidstone	3,666,466	85.23
9, 5	UCL	2,847,985	98.52
13, 17	Gledhow	3,227,264	100.79
6, 40, 39	Darnall	1,984,189	120.15
41, 40	Amatikulu	2,215,952	134.50
13, 9	Felixton	2,627,368	161.91
13	Umfolozi	1,263,158	193.11
16	Pongola	1,473,684	258.25
21, 26, 24, 23	Komati	2,631,579	375.87
22, 26	Malelani	1,926,316	412.3
Total		37,079,734	

The average plant supply radius for Case 2 was similar to that of Case 1 and is depicted in Figure 4.4 below. This was also presented for the base case scenario of Case 2, where there were no sensitivity tests done on the parameters that were used in the model.

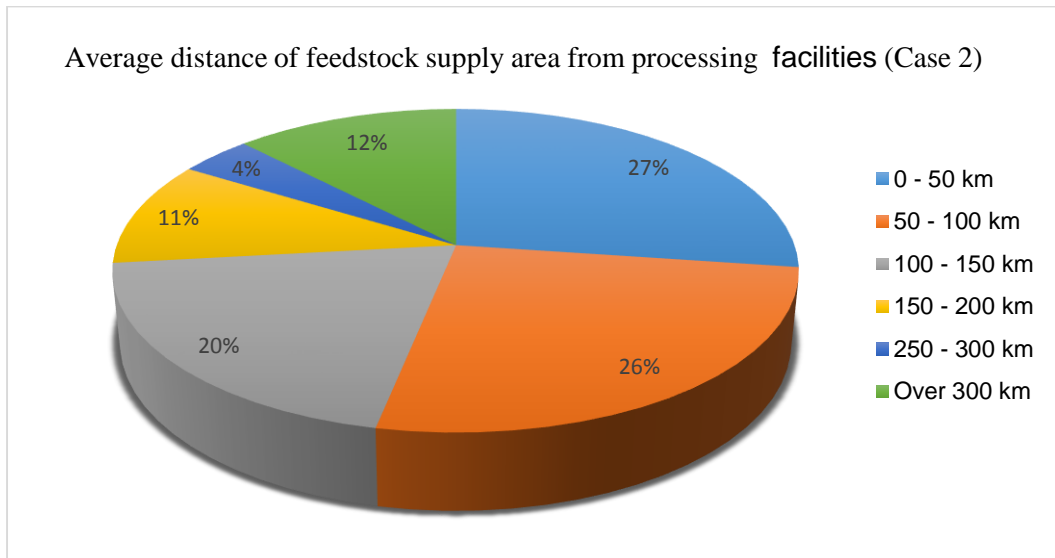


Figure 4.4: Average distance of feedstock cultivation area from processing facilities (Case 2)

In Case 2, approximately 73% of the biomass transported to the processing facilities was collected from farms within a 150 km, with 53% of this biomass coming from farms less than 100 km away. For both cases, less than 35% of biomass was transported from areas outside 150 km radius. Case 2 had 5% more biomass coming from a 50 km radius. The average supply radii for these processing facilities for Case 2 are shown in Table 4.7 below.

Table 4.7: Farms supplying processing facilities and average transportation distance for feedstock (Case 2)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,221,088	6
38, 11	Umzikulu	2,881,435	9
12	Eston	2,881,435	50
12	Noodsberg	2,864,144	68
12, 42	Maidstone	3,179,540	85
5, 9	UCL	2,688,451	99
13, 17	Gledhow	2,916,018	101
6, 9, 39, 40, 16	Darnall	2,955,443	125
40, 41	Amatikulu	3,088,241	135
13, 9	Felixton	3,219,853	162
13	Umfoloji	2,819,680	193
16	Pongola	2,881,435	258
21, 26, 24, 23	Komati	3,221,088	376
22, 26, 25	Malelani	3,014,209	433
Total		41,832,060	

4.2 Sensitivity Analysis

It was important to check how the model results would change when subjected to changes in some parameters such as feedstock prices, transport prices, product selling prices and the quantities of feeds stock available for use in bio-ethanol production. These changes were applied to the model and the results that were obtained are discussed in the section below. The profitability analysis was performed at a discount rate of 8%. At higher discount rates the economic potential of the supply chain is reduced while small discount rates increase the economic potential. Included in Appendix A6 are Tables A6.1 and A6.2 which show the net present value of the supply chain at the end of the plant life at different discount rates.

4.2.1 Costs and profits

When the model was tested for changes in feedstock prices, transportation costs, product prices and changes in feedstock availability, the results obtained are shown in Tables 4.8 and 4.9 below. It should be known that the base case scenario as used in this thesis, was for a case where there were no changes in the aforementioned parameters used in the model, i.e. the base values for these parameters were used to determine the optimal supply chain network. The base case parameters were applied to both Case 1 and Case 2. For the non-base case scenario, the sensitivity analysis was performed by varying one parameter at a time, while leaving others constant. The scenario where export demand, which is one of the parameters varied in the sensitivity analysis, was ignored refers to a situation where only enough sugar was produced to meet domestic demand and no sugar was exported.

When the feedstock prices were increased by a factor of 2, the same amount of sugarcane was transported for the two cases; however, the transportation cost was higher for Case 1 than Case 2 because it is transported over a short distance in Case 2 compared to the transportation distances in Case 1. Case 2, which had the larger farm capacities, received feedstock from farms that were closer to the bio-ethanol processing facilities compared to Case 1. In particular, Malelani and Komati received feedstock from farms that were more than 420 km away in Case 1, while in Case 2, the supply areas for the two facilities were less than 420 km away.

Table 4.8 shows the costs and profit for the different scenarios that were considered. The revenue in this context was the amount of money obtained from sales of product and by-products, while the profit was what was left after removing expenses incurred in the supply chain from the revenue. Base case was the scenario that has no changes in parameters, while all the other scenarios had changes only in the specified parameter with the rest of the parameters remaining the same as those used in the base case scenario. Table 4.8 shows that for the scenarios when transportation and feedstock costs were doubled, the revenue remained almost the same as in the base case because the quantity of products and by-products sold varied slightly from that

of the base case. This was due to the need to satisfy sugar demand. Bagasse from sugar milling was the only type of feedstock selected to produce bio-ethanol in these two scenarios. However, in the base case, an additional amount of ethanol was produced from sugarcane. The profit for the scenario, when feedstock costs were doubled, was slightly less than that in the base case scenario as there were more products in the base case scenario. The difference resulted from more products being produced and sold in the base case scenario than in the other scenario. When the selling price of the product was doubled, the revenue obtained was twice the base case scenario revenue and the other costs remained constant. Hence the profit for this scenario of doubling selling price was the highest of all the scenarios considered. In the scenario where sugar export demand was ignored, there was more sugarcane available for bio-ethanol production such that transportation costs and processing costs were higher than in all the other scenarios. The profit in the scenario when export sugar demand was ignored, was higher than in the base case scenario due to higher revenues, which were a result of more bio-ethanol being produced.

Table 4.8: Costs and profits for the different scenarios for Case 1

Cost/Profit (ZAR *10 ⁶)	Scenario (Case 1)				
	Base Case 1	Transportation cost doubled	Product selling price doubled	Feedstock cost doubled	Sugar export demand Ignored
Revenue	8,455	8,443	16,910	8,443	20 054
Feedstock cost	3.000	0.000	3.000	0.000	3,833
Production cost (other)	3.000	0.180	3.000	0.180	0.210
Transportation cost	2,135	5,889	2,135	2,132	6,578
Profit	4,885	1,126	13,339	4,882	14,929

The results for the sensitivity analysis are also shown in Figures 4.5 and 4.6 below, which show how the profits and costs varied for the different scenarios in the case under consideration.

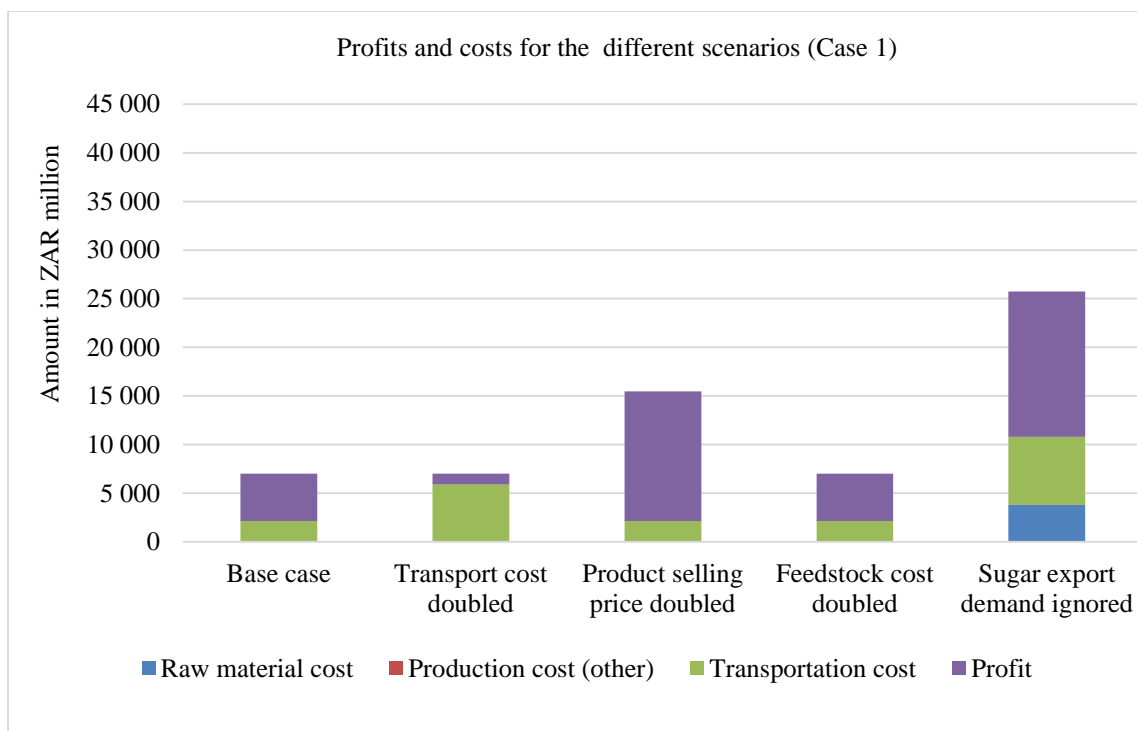


Figure 4.5: Graph showing sensitivity of model to different scenarios for Case 1

The effect of doubling the product selling price slightly increased the amount of product in the base case scenario by a factor of 1.04. Figure 4.5 shows that the doubling of the selling price of the product increased the profit by a factor of 2.7, when compared to the base case scenario. Increasing transportation cost reduced the profit by more than 50% when compared to the base case scenario. The production cost was small in all the scenarios, when compared to all the other costs such that it cannot be seen in the graph due to the scale that was used. Feedstock costs can only be seen in the scenario where sugar export demand was ignored as in all the other scenarios only bagasse, which had no cost attached to it was used as feedstock.

Table 4.9: Costs and profits for the different scenarios for Case 2

Cost/Profit (ZAR million)	Scenario (Case 2)				
		Transport	Selling		Sugar Export
	Base case 2	cost doubled	price doubled	Feedstock cost doubled	demand is ignored
Revenue	24,984	15,454	49,969	24,984	24,552
Feedstock	4,231	1,793	4,231	8,462	4,985
Production (other)	0,100	0,043	0,074	0,100	0,118
Transport	7,774	11,415	7,452	7,452	7,686
Profit	10,751	0,757	35,761	6,520	9,588

Table 4.9 shows that when transportation costs were doubled, the revenue was less than that in the base case scenario by approximately 38% because less feedstock was transported to the processing facilities due to the high transportation costs. When feedstock costs were doubled, the revenue was similar to that of the base case scenario as the same amount of feedstock was transported to the processing facilities in both scenarios and bio-ethanol was also produced from sugarcane in addition to bagasse. The production cost was the same for the scenario when feedstock costs were doubled and the base case scenario because the same amount of feedstock was processed in both scenarios. Profit was lowest for the scenario where transportation costs were increased by a factor of 2, while it was highest (almost 300% of the base case scenario profit) when selling prices were doubled. The profit for the scenario when feedstock costs were doubled, was slightly less than that in the base case scenario as there were more products in the base case scenario than in the scenario where feedstock costs were doubled.

When the selling price of the product was doubled, the revenue obtained was twice the base case scenario revenue. All the other costs were similar to those in the base case scenario when selling price of the product was doubled, hence the profit was the highest of all the scenarios considered. In the scenario where sugar export demand was ignored, there was more sugarcane available for bio-ethanol production such that transportation costs and processing costs were higher than in all the other scenarios. The availability of more sugarcane for bio-ethanol production implies that

transportation costs of sugarcane are assigned to bioethanol production instead of to sugar production as was the case in the scenarios where bagasse, which has no transportation cost assigned to it, was used as feedstock. The profit in the scenario when export sugar demand was ignored, was higher than in the base case scenario due to higher revenues, which were a result of more bio-ethanol being produced when there was more feedstock.

Figure 4.6 shows the profits and costs for the sensitivity analysis of Case 2

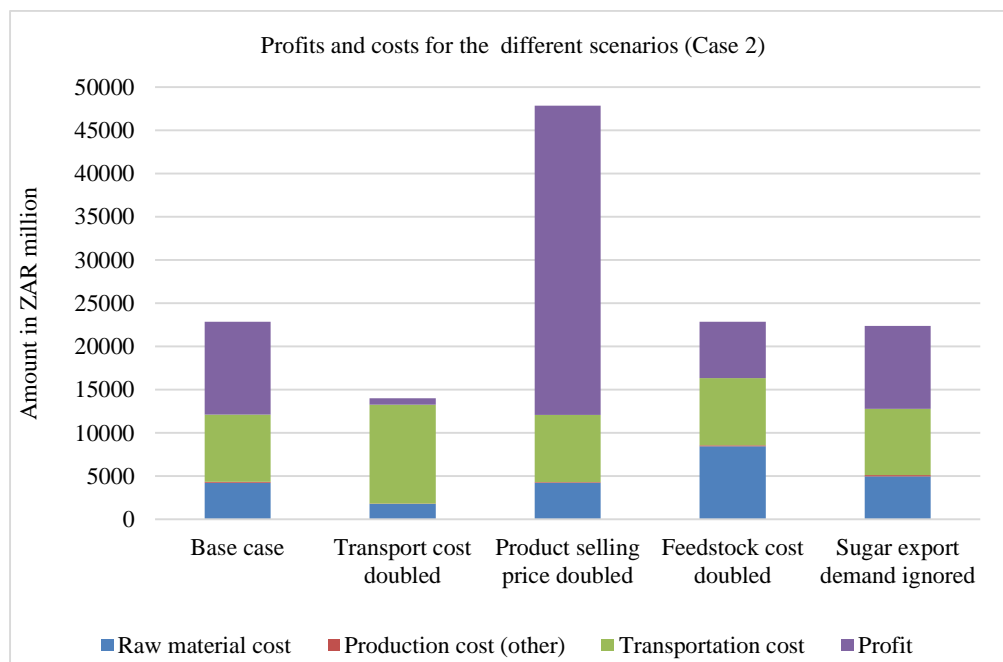


Figure 4.6 Graph showing sensitivity of model to different scenarios for Case 2

The highest profit was realised when the product price was increased. For Case 1, the profit increased by a factor of 2.3, relative to the base case scenario. For the scenario where transportation costs were doubled, the profit was reduced by more than 50% in both cases. Ignoring sugar export demand resulted in the transportation of the highest amount of feedstock for Case 2, giving rise to increased production of bio-ethanol, which in turn increased the overall profit (see Figure 4.6). The difference in profit between the base case scenario and the scenario where there was more feedstock available when sugar export demand was ignored in Case 1, was due to the difference in the amount of sugarcane that was purchased and used in bio-ethanol production. According to Figure 4.5 and Figure 4.6, when the feedstock costs were increased by

a factor of 2, the profit was reduced by approximately 40% in Case 2 and for Case 1, the profit was approximately the same as the one in the base case scenario. The similarity between the base case and the scenario where feedstock costs were doubled in Case 1, arose because it became unprofitable to transport feedstock for ethanol production at high feedstock costs, hence only sugarcane that is sufficient to meet sugar demand was transported to the processing facility and bagasse was used for ethanol production just as in the base case scenario.

4.2.2: Profitability analysis

A summary of profitability of the two cases is given in Tables 4.10 and 4.11.

Table 4.10: Profitability analysis of Case 1

Profitability indicator	Scenario (Case 1)				
	Base case	Transportation cost doubled	Selling price doubled	Feedstock cost doubled	Sugar export demand ignored
Profit margin	0.67	0.16	0.92	0.67	0.35
Return on investment (ROI)					
(%)	23	2	69	23	39
Production cost (ZAR million R/t)	0.005	0.013	0.005	0.005	0.004
Payback time, y	4	16	1.37	4	3
NPV ZAR million (8% discount rate)	25,542	11,368	108,553	25,422	119,465

For Case 1, increasing transportation cost was unprofitable as indicated by the payback period of more than 5 years and the low ROI of less than 10%. The NPV at the end of the plant life was also small for the same scenario in Case 1. In Table 4.10, the production cost per tonne was obtained by adding all costs related to production of bio-ethanol (transportation costs, feedstock costs and other production costs including operating costs of technology) then dividing by the quantity of product produced. The production cost per tonne was highest, in the scenario where transportation costs were doubled compared to the other scenarios. Consequently the

highest cost per unit of product was in the scenario in which transportation costs were doubled. This cost of R 13/kg of ethanol was 2.6 times the production cost in the base case scenario, which had a cost of R 5/kg of bio-ethanol. Scenarios with profit margins less than 0.1 were unprofitable as shown by the negative NPV at the end of the plant life as shown in Table 4.10.

Table 4.11: Profitability analysis of Case 2

Profitability indicator	Scenario (Case 2)				
	Base case	Transportation cost doubled	Selling price doubled	Feedstock cost doubled	Sugar export demand ignored
Profit margin	0.460	0.060	0.760	0.280	0.410
ROI (%)	36.000	-44.000	128.000	20.000	31.000
Production cost R million/t	0.008	0.014	0.008	0.011	0.008
Payback time (y)	3.000	27.000	1.000	4.000	3.000
NPV (15% discount rate)	71,858	-27,648	317,418	30,316	60,105

For Case 2, the only scenario that was unprofitable was increasing transportation cost as indicated by the payback period of more than five years and the low return on investment (ROI) (less than 10%). The NPV at the end of the plant life was also negative for the same scenario, where transportation costs were doubled. Production cost per unit of ethanol in the two scenarios was very high, R 12/L compared to R 6/L in the base case. Consequently, the profit margin was lower than in the other scenarios and the payback period was highest in this scenario where transportation costs were doubled. Although the production cost per tonne varies per scenario, the actual pump price of the bio-ethanol is regulated by the government and in order to cushion bio-ethanol producers from the high production costs, incentives are offered per tonne of bio-ethanol produced up to a maximum annual production.

4.2.3 Feedstock supply

The type of feedstock used in the production of ethanol also changed with the doubling of feedstock prices. In Case 2 base case scenario, sugarcane and bagasse were both used in the production of ethanol, while in the Case 1 base case scenario, the only feedstock type used was bagasse. Figures 4.7 and 4.8 below show the feedstock

distribution and average supply radii for the processing facilities. The actual transportation distance from each processing facility to the depot and the average transportation distance of the product from the processing facilities to the depot is shown in Table A5 in Appendix A5.

From Figure 4.7, the farms within a 50 km radius only supplied processing facilities with feedstock in the scenario when sugar export demand was ignored in Case 1 because the farms supplied processing facilities closest to them due to the reduction in the quantity of sugarcane required for sugar production. When there was a high sugar demand to be met, feedstock had to be transported even from farms that were far away in order to satisfy the demand at each processing facility. This was the case in the other four scenarios of Case 1 shown in Figure 4.7 where the average supply radii were greater than 50 km.

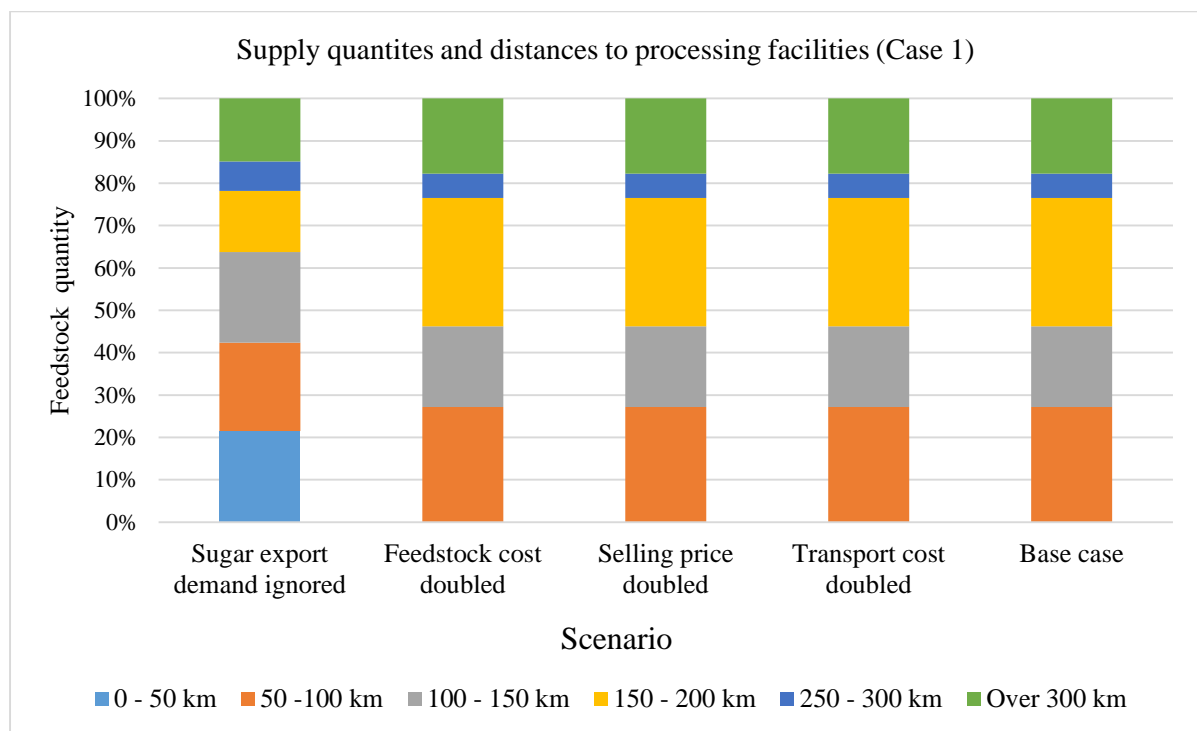


Figure 4.7: Average transportation distances of feedstock to processing facilities for the different scenarios for Case 1

Table 4.12: Average transportation distances of feedstock from supply areas to processing facilities (Case 1)

Scenario	Feedstock quantity (t) and average transportation distances in km					
	0 – 50 km	50 -100 km	100 – 150 km	150 – 200 km	250 – 300 km	Over 300 km
Sugar Export demand ignored	898,395	8,732,134	8,959,701	6,039,533	2,881,435	6,235,297
Feedstock price doubled	0	6,993,684	4,897,305	7,795,200	1,473,684	4,557,894
Selling price doubled	0	7,001,712	4,897,305	7,795,200	1,473,684	4,557,894
Transport cost doubled	0	6,993,684	4,897,305	7,79,200	1,473,684	4,557,894
Base case	0	7,001,712	4,897,305	7,795,200	1,473,684	4,557,894

For Case 2, the average amount of feedstock that was collected and the range of supply area radii are shown in Figure 4.8 below. Due to the availability of more feedstock in Case 2 than in Case 1, farms within a 50km radius also supplied feedstock to processing facilities in all the scenarios considered.

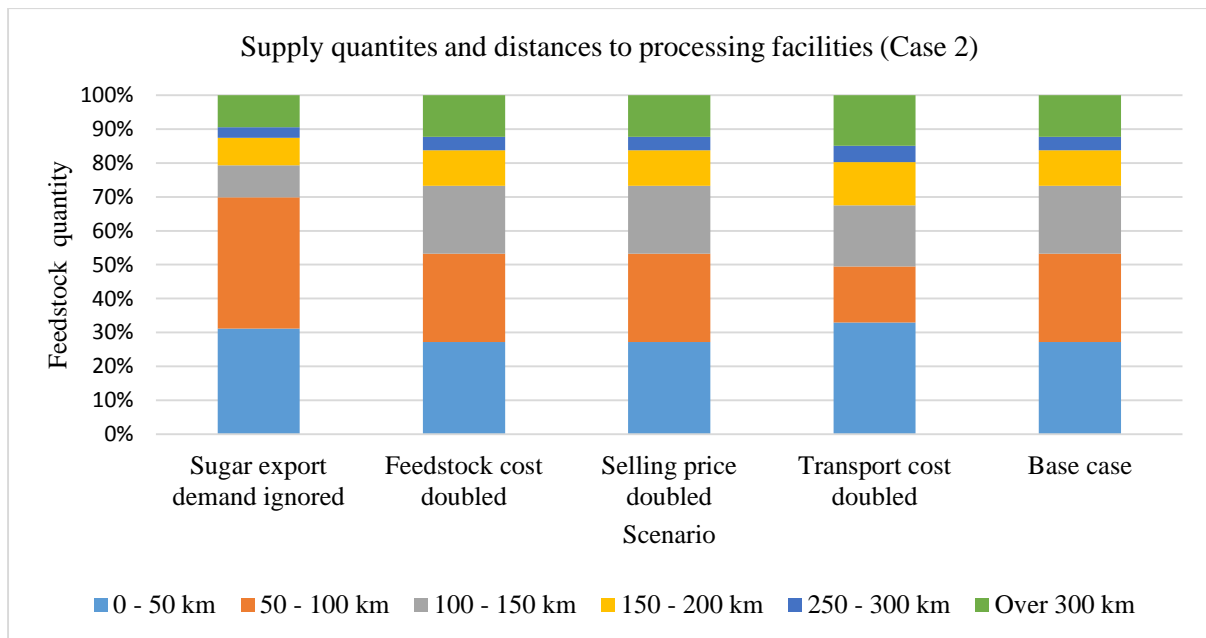


Figure 4.8: Average transportation distances of feedstock to processing facilities for the different scenarios in case 2

Table 4.13: Average transportation distances of feedstock from supply areas to processing facilities (Case 2)

Scenario	Average distance from processing facility (km) and quantity of biomass(t)					
	0 - 50 km	50 -100 km	100 – 150 km	150 – 200 km	250 – 300 km	Over 300 km
Sugar export demand ignored	8,983,959	11,141,696	2,736,788	2,334,316	884,210	2,734,736
Feedstock price doubled	10,074,966	9,655,258	7,427,405	3,890,526	1,473,684	4,557,894
Selling price doubled	10,074,966	9,655,258	7,427,405	3,890,526	1,473,684	4,557,894
Transport cost doubled	10,074,966	5,039,883	5,496,253	3,890,26	1,473,684	4,557,894
Base case	10,074,966	9,655,258	7,427,405	3,890,526	1,473,684	4,557,894

Further to the summaries given above, the change in feedstock distribution in each of the scenarios is shown in Figures A3.2.to A3.9 and Tables A3.2.7 to A3.34 in the appendices.

4.2.4 Other products

For the optimised model in all the scenarios considered in Case 1, the amount of other value-added products was constant as the by-product (except for vinasse, which had not been quantified), demand was fixed based on the sugar demand. Electricity and other utility requirements for bio-ethanol production were calculated in the model, using the consumption per tonne of bio-ethanol produced as a basis, and it was assumed that these would be purchased. However, the cost of purchasing these utilities is offset by the excess electricity that is produced in the case study. The quantities of the by-products for base case are shown in Table 4.14 below.

Table 4.14: Other products from the production process for base case scenario in Case 1

Plant	Product					
	Ethanol (t)	Electricity (MWh/y)	Heat (GJ)	Lignin cake (t)	Sugar (t)	Molasses (t)
Amatikulu	39,568	51,744	278	211,366	151,200	60,480
Darnall	31,346	40,992	220	167,446	236,544	94,618
Eston	26,764	35,000	188	142,970	140,000	56,000
Felixton	47,716	62,400	335	254,895	140,000	56,000
Gledhow	28,905	37,800	203	154,407	183,000	73,200
Komati	47,793	62,500	335	255,303	163,968	65,587
Maidstone	45,220	59,136	317	241,562	249,600	99,840
Malelani	34,984	45,750	245	186,882	250,000	100,000
Noodsberg	25,693	33,600	180	137,251	77,500	31,000
Pongola	26,764	35,000	188	142,970	250,000	100,000
Sezela	47,793	62,500	335	255,303	206,976	82,790
UCL	14,816	19,375	104	79,144	140,000	56,000
Umfoloji	22,941	30,000	161	122,545	120,000	48,000
Umzikulu	27,505	35,000	188	144,037	134,400	53,760
Total	467,808	610,797	3,276	2,496,081	2,443,188	977,275

Table 4.15 below shows the demand for other products at the processing facilities. The demand was calculated in the same way as in Case 1 and the utilities requirements for bio-ethanol production were also handled in the same way as in Case 1.

Table 4.15: Other products from the production process in the base case scenario for Case 2

Plant	Product					
	Ethanol (t)	Electricity (MWh/y)	Heat (GJ)	Lignin cake(t)	Sugar (t)	Molasses (t)
Amatikulu	43,008	51,744	278	216,321	206,976	82,790
Darnall	55,191	40,992	220	201,788	163,968	65,587
Eston	183,380	35,000	188	368,529	140,000	56,000
Felixton	47,716	62,400	335	254,895	249,600	99,840
Gledhow	179,957	37,800	203	371,953	151,200	60,480
Komati	47,793	62,500	335	255,303	250,000	100,000
Maidstone	153,870	59,136	317	398,040	236,544	94,617
Malelani	34,984	45,750	245	186,882	183,000	73,200
Noodsberg	185,092	33,600	180	366,818	134,400	53,760
Pongola	26,764	35,000	188	142,970	140,000	56,000
Sezela	149,757	62,500	335	402,153	250,000	100,000
UCL	202,484	19,375	104	349,426	77,500	31,000
Umfolozi	22,941	30,000	161	122,545	120,000	48,000
Umkhulu	183,380	35,000	188	368,530	140,000	56,000
Total	1,516,316	610,797	3,276	4,006,155	2,443,188	977,275

When the model was optimised using shapefiles obtained from SASRI, the model was infeasible as the amount of sugarcane obtained from the shapefiles was slightly less than the amount required to meet both domestic and export sugar demand. The data from the current mill supply area was scaled up by a factor of 1.114 in order for the model to be integer feasible, and to be representative of the current sugar production scenario in the country. Sugar demand was fixed based on an average of annual sugar production statistics from SASA (2014). This was because of the loss of 5% of the feedstocks that was assumed to occur during harvesting and transportation. The shape files from SASRI were for the current mill supply area and the total amount of sugarcane obtained from the farms in these shapefiles were scaled to satisfy the current domestic and export sugar demand. Shapefiles from Ezemvelo KZN had a cultivation area that can produce 15 times more sugarcane than the current supply given in the SASRI shape files.

4.3 Environmental impact

The results for the environmental impact objective were split into two scenarios, one in which the key product obtained from the supply chain network was ethanol and another, which had ethanol and sugar as key products. Four categories of environmental impact were considered namely, GWP, eutrophication, human toxicity and acidification. The contribution of different nodes in the supply chain to environmental impact categories for the two scenarios mentioned earlier is shown in this section by means of tables and graphs. Table 4.16 shows the contribution to the environmental impact of the supply chain in the production of key product ethanol in Case 1.

Table 4.16: Environmental impact contribution of each supply chain network stage for one key product bio-ethanol (Case 1)

Environmental impact Category	Supply chain stage				Total
	Feedstock production	Processing stage	Transportation of feedstock	Transportation of product	
GWP (kg CO ₂ eq)	2.90 x 10 ⁵	2.48 x 10 ⁸	1.98 x 10 ⁵	1.39 x 10 ⁷	2.63 x 10 ⁸
Eutrophication (kg PO ₄ eq)	2.49 x 10 ³	2.78 x 10 ⁶	1.10 x 10 ²	6.60 x 10 ³	2.79 x 10 ⁶
Acidification (kg SO ₂ eq)	4.50 x 10 ³	4.13 x 10 ⁶	5.27 x 10 ²	3.70 x 10 ⁴	4.17 x 10 ⁶
Human toxicity (kg DB eq)	1.45 x 10 ⁶	1.24 x 10 ⁹	2.72 x 10 ⁷	1.91 x 10 ⁶	1.25 x 10 ⁹

In Figure 4.9, the contribution of each of the supply chain stages to an environmental impact category is expressed relative to the total contribution of all the stages to an environmental category and expressed as a percentage for Case 1. In Figure 4.9, it could be seen that feedstock processing contributed the most impact to the four environmental impact categories that were considered. Environmental impact due to feedstock transportation was the lowest of the environmental impacts from transportations, except for human toxicity category. This is because of the use of bagasse at the processing facilities already located at sugar mills.

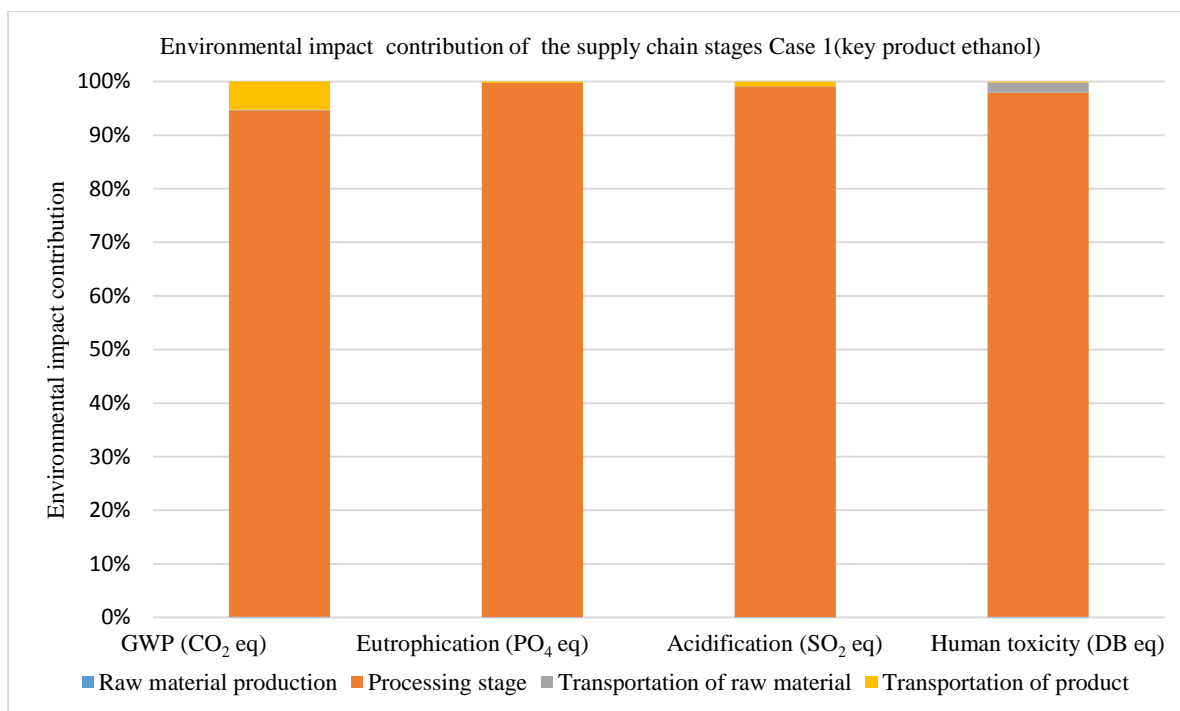


Figure 4.9: Graph for environmental impact contribution of the supply chain stages to ethanol production (Case 1)

For Case 2, the stage of the supply chain contributing the highest environmental impact to the four categories was feedstock processing as there was more feedstock available for bio-ethanol production. Table 4.17 below shows environmental impact contribution of each supply chain stage for key product ethanol in Case 2.

Table 4.17: Environmental impact contribution of each supply chain stage for one key product, bio-ethanol (Case 2)

Environmental Impact category	Supply chain stage				
	Feedstock production	Processing	Biomass Transportation	Product Transportation	Total
GWP (kg CO ₂ eq)	4.11 x 10 ⁸	8.05 x 10 ⁸	1.81 x 10 ⁸	2.36 x 10 ⁷	1.42 x 10 ⁹
Eutrophication (kg PO ₄ eq)	3.52 x 10 ⁶	9.01 x 10 ⁶	1.00 x 10 ⁵	1.12 x 10 ⁴	1.26 x 10 ⁷
Acidification (kg SO ₂ eq)	6.36 x 10 ⁶	1.34 x 10 ⁷	4.83 x 10 ⁵	6.30 x 10 ⁴	2.03 x 10 ⁷
Human toxicity (kg DB eq)	2.05 x 10 ⁹	4.02 x 10 ⁹	2.49 x 10 ⁷	3.25 x 10 ⁶	6.09 x 10 ⁹

Figure 4.10 below shows the contribution of the supply chain stages to the four environmental categories that were under consideration for Case 2. In Figure 4.10, the

contribution of each of the supply chain stages to an environmental impact category was expressed relative to the total contribution of all the stages to an environmental category and expressed as a percentage.

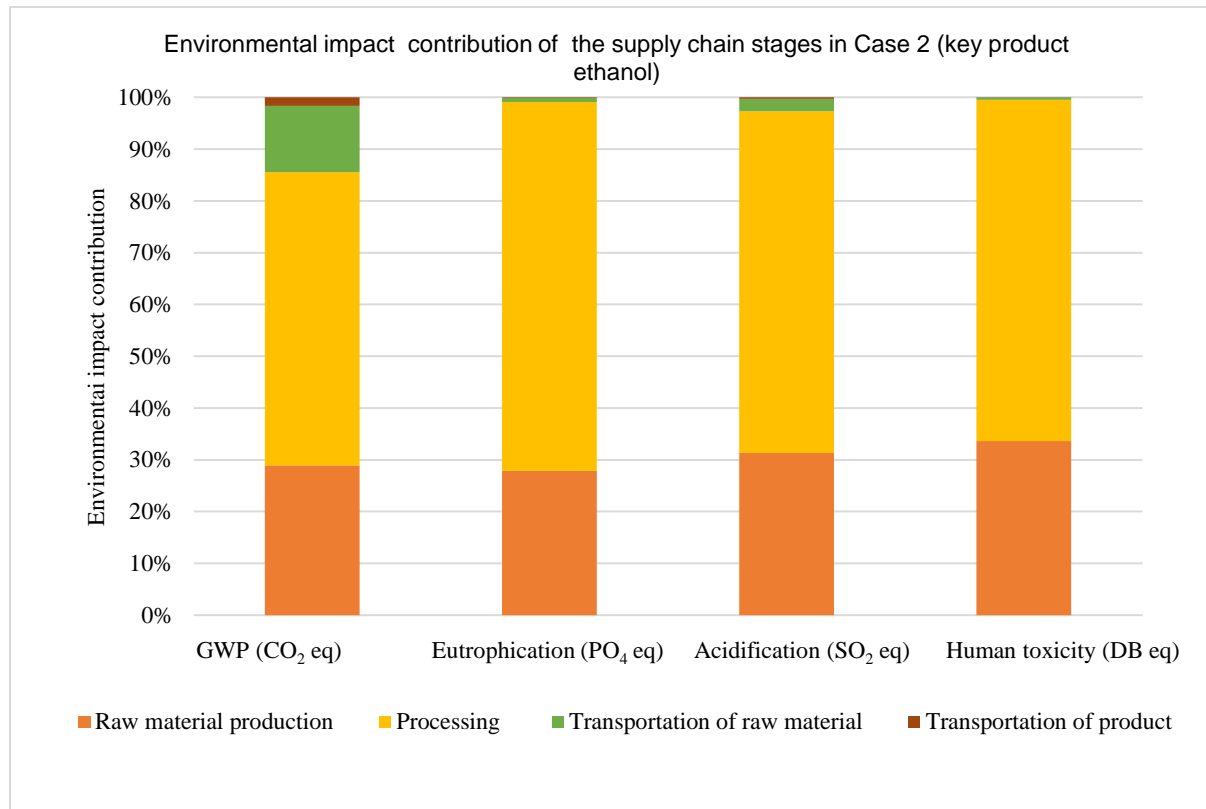


Figure 4.10: Graph for environmental impact contribution of the supply chain stages to ethanol production (Case 2)

Figure 4.10 shows that feedstock processing contributed the most impact to the four environmental impact categories that were considered. Contrary to Case 1, environmental impact due to product transportation was the lowest of the environmental impacts from transportations because of the use of sugarcane in bio-ethanol production at the processing facilities already located at sugar mills. Table 4.18 gives the environmental impact for the production of two key products namely sugar and ethanol for Case 1.

Table 4.18: Environmental impact contribution of each supply chain stage for key products ethanol and sugar (Case 1)

Environmental impact	Supply chain stage (sugar and ethanol production)				Total
	Feedstock production	Processing	Transportation of feedstock	Transportation of product	
GWP (kg of CO ₂ eq)	9.29 x 10 ⁸	2.07 x 10 ⁹	6.33 x 10 ⁸	1.49 x 10 ⁷	3.64 x 10 ⁹
Eutrophication (kg of PO ₄ eq)	7.97 x 10 ⁶	1.25 x 10 ⁷	3.51 x 10 ⁵	7.11 x 10 ⁴	2.08 x 10 ⁷
Acidification (kg of SO ₂ eq)	1.44 x 10 ⁷	2.01 x 10 ⁷	1.69 x 10 ⁶	3.98 x 10 ⁴	3.62 x 10 ⁷
Human toxicity (kg of DB eq)	4.63 x 10 ⁹	4.25 x 10 ⁹	8.71 x 10 ⁷	2.32 x 10 ⁶	8.97 x 10 ⁹

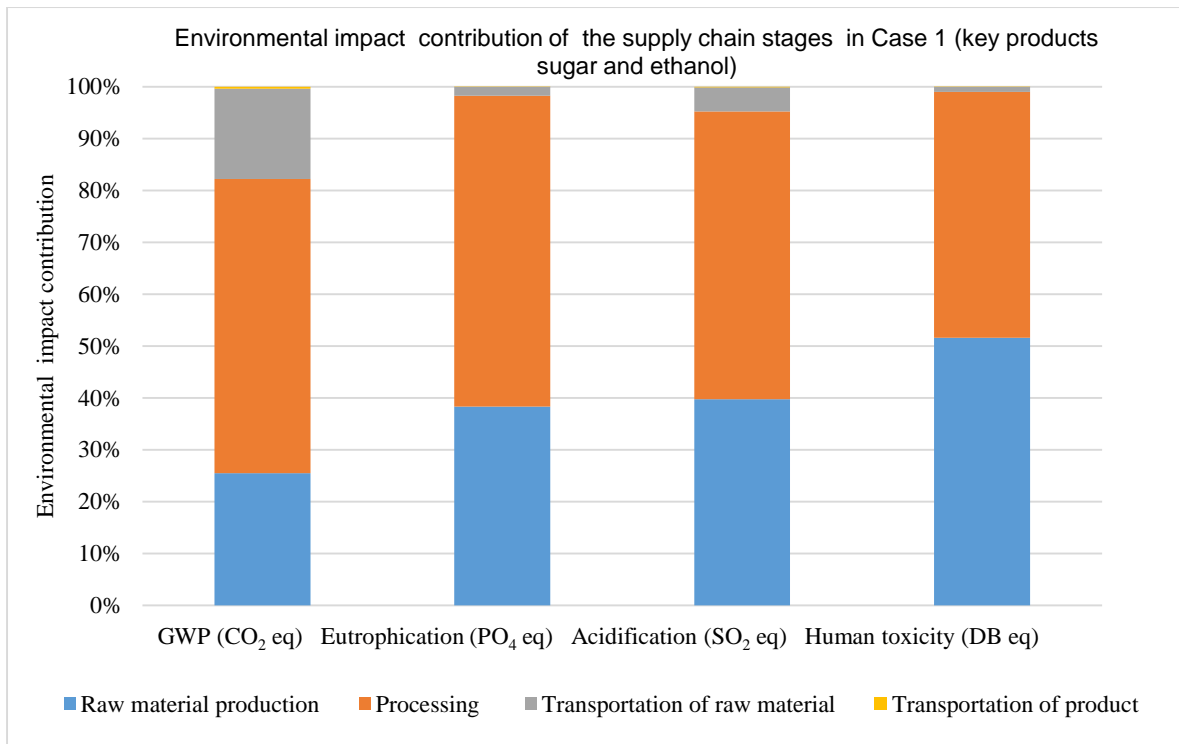


Figure 4.11: Graph for environmental impact contribution of the supply chain network stages to ethanol and sugar production (Case 1)

In Case 1, when the environmental impacts due to the two key products were analysed, feedstock processing contributed the greatest environmental impact for all the environmental impact categories under consideration with the exception of human toxicity, where feedstock production contributed approximately 50% of the total environmental impact. For the GWP category, approximately 18% of the emissions came from transportation with emissions from product transportation of less than 2%.

Table 4.19 shows the environmental impact contributions for the supply chain stages in Case 2 when considering two key products, namely sugar and bio-ethanol

Table 4.19: Environmental impact contribution of each supply chain stage for key products ethanol and sugar production (Case 2)

Environmental impact category	Supply chain stage (ethanol and sugar production)				
	Feedstock production	Processing	Feedstock transportation	Product transportation	Total
GWP(kg of CO ₂ eq)	1.34 x 10 ⁹	2.62 x 10 ⁹	5.92 x 10 ⁸	2.46 x 10 ⁷	4.58 x 10 ⁹
Eutrophication (kg PO ₄ eq)	1.15 x 10 ⁷	1.87 x 10 ⁷	3.28 x 10 ⁵	1.18 x 10 ⁴	3.05 x 10 ⁷
Acidification (kg SO ₂ eq)	2.08 x 10 ⁷	2.94 x 10 ⁷	1.58 x 10 ⁶	6.58 x 10 ⁴	5.18 x 10 ⁷
Human toxicity (kg DB eq)	6.68 x 10 ⁹	7.03 x 10 ⁹	8.14 x 10 ⁷	3.69 x 10 ⁶	1.38 x 10 ¹⁰

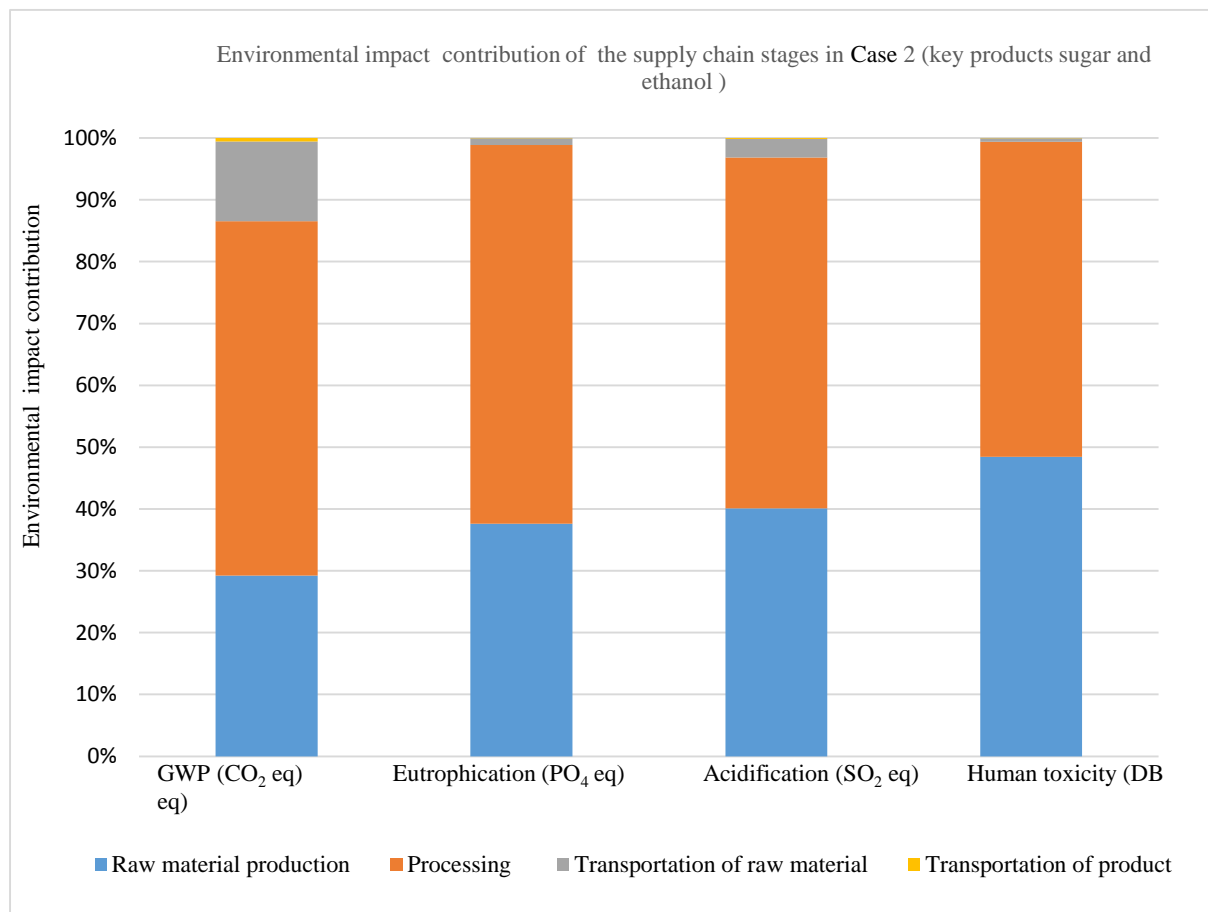


Figure 4.12: Graph for environmental impact contribution of the supply chain stages to ethanol and sugar production (Case 2)

In Case 2, when the environmental impacts due to the two key products were analysed, feedstock processing contributed the greatest environmental impact for all the environmental impact categories under consideration with the exception of human toxicity, where feedstock production contributed approximately 50% of the total environmental impact. For the GWP category, approximately 15% of the emissions came from transportation with emissions from product transportation of less than 2%.

4.3.1 Multi objective optimisation

For multi-objective optimisation, the only scenario considered was the one with two key products, sugar and bio-ethanol for the two cases. Pareto curves were generated to compare the two objectives, which were economics and environmental impact. For the environmental objective, GHG emissions were used as a measure of the environmental impact. The GHG emissions were varied from a maximum profit, which is the optimal point to a minimum, which is the last point where the model is feasible. The Pareto curves for the model – when applied to Case 1 and Case 2 – are shown in Figures 4.13 and 4.14 below. The points used to draw the Pareto curve for Case 1 are shown in Table A4.1 in Appendix 4.

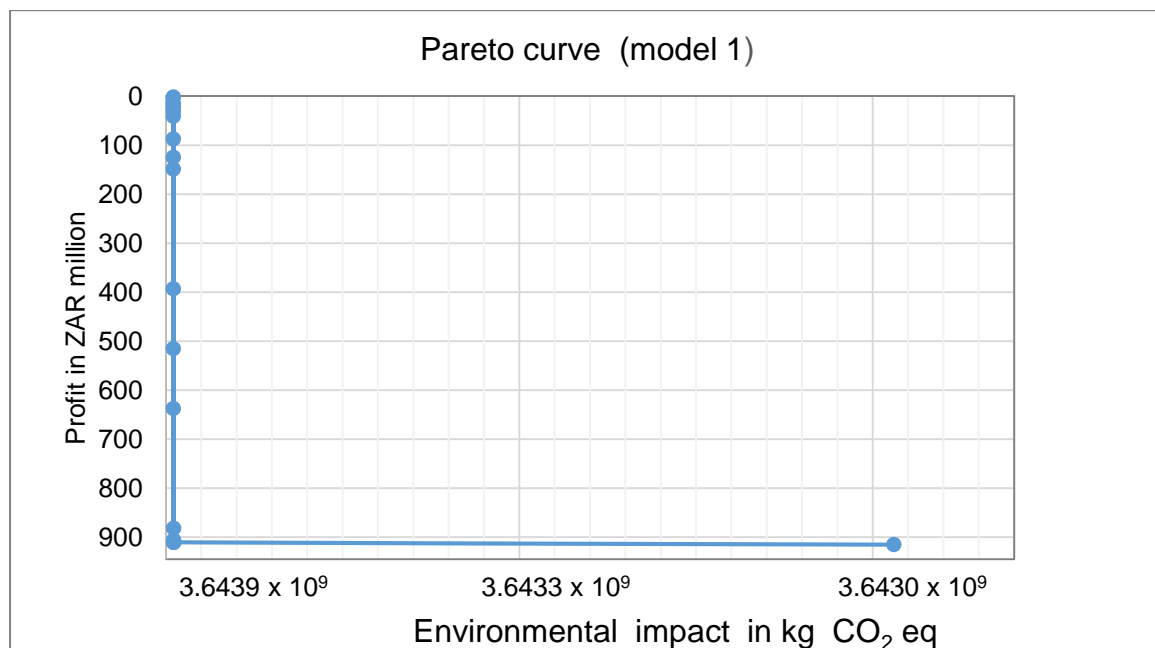


Figure 4.13: Pareto curve for economic and environmental objectives for Case 1

For Case 1, as shown in Figure 4.13, there was a small profitable feasible range (from ZAR 183 million to ZAR 188 million) and the environmental impact did not change significantly within this range. This was due to the constraint on feedstock supply area. A good operating point, according to multi-objective optimisation of Case 1 would be at the point where the profit is R 183 million and associated GHG emissions of 3,643 kt CO₂ eq.

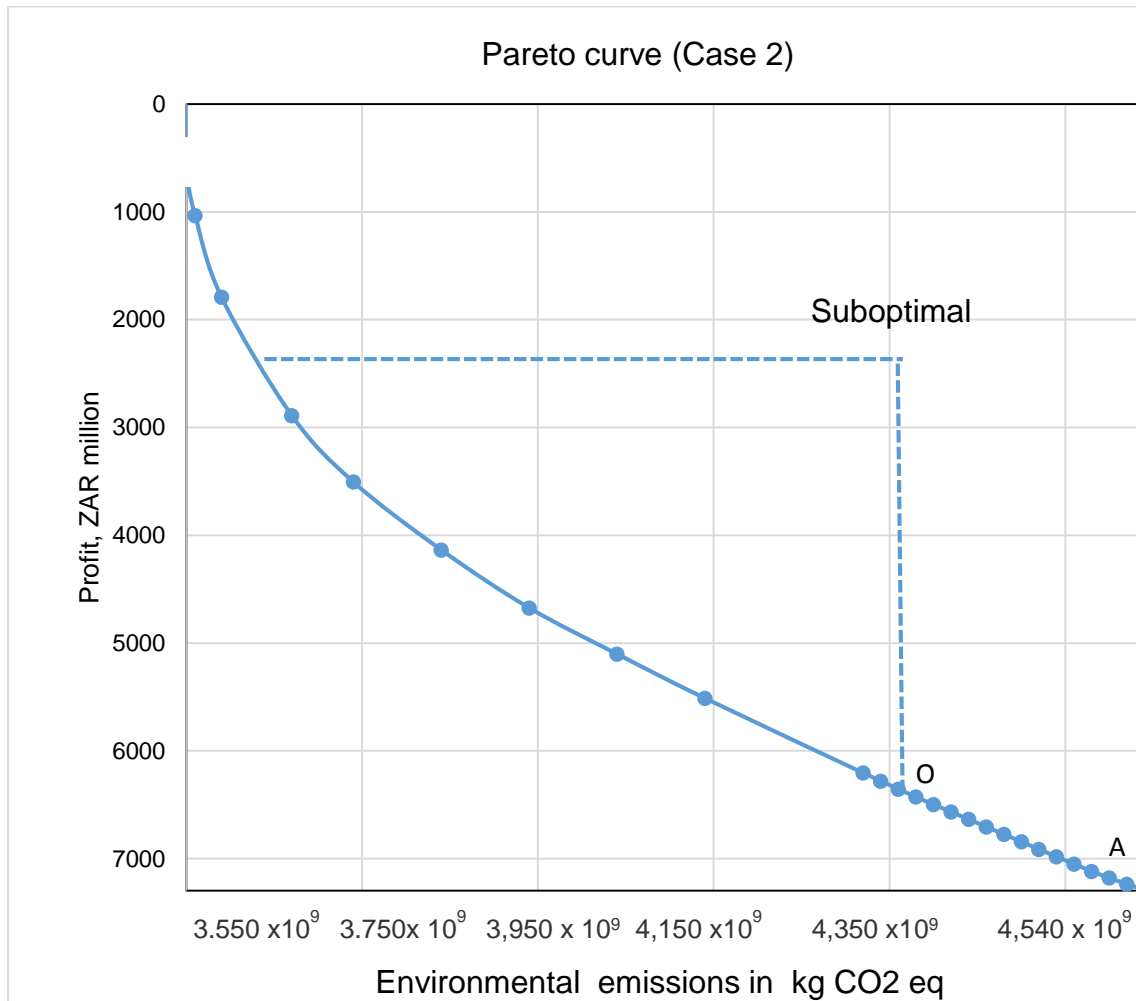


Figure 4.14: Pareto curve for economic and environmental objectives for Case 2

Figure 4.4 above was obtained by varying GHG emissions from a maximum at the optimal solution of the model to a minimum point where decreasing the GHG emissions further would make the model infeasible. The points used to draw the Pareto curve in Case 2 are shown in Table A4.2 in Appendix 4. In Figure 4.14, all the

points that lie on the curve are optimal points obtained when the model was optimised for the two objectives under consideration. Points below the curve are infeasible and points above the curve are sub optimal points. Figure 4.14 shows that as the profit decreased from a maximum of ZAR 7,296 million to a minimum of 0, the GHG emissions from the biomass to bio-ethanol supply chain network, measured in CO₂ equivalent also decreased from a maximum of 4,580 kt CO₂ eq to a minimum of 3,549 kt CO₂ eq. A good approximation of a viable point to operate would be at the point marked O (4,410 kt CO₂ eq, ZAR 6,780 million) in Figure 4.14. At this point, there is an 89 % profit and a 25 % of maximum GHG emissions. Tables A4.1 and A4.2 in Appendix A4 show the environmental impact and profit for each operating point considered in the multiobjective optimisation of the supply chain network for Case 1 and Case 2, respectively.

For Case 2, the results showed that at the best known optimum profit of ZAR 7,296 million, the environmental impact was maximum (4,580 kt CO₂ equivalent). It decreased with a decrease in profit up to a minimum of 3,549 kt CO₂ equivalent. For Case 1, at the best known profit of R 188 million, the environmental impact was at a maximum of 3,644 kt CO₂ equivalent and decreased with a decrease in profit to a minimum of 3,643 kt CO₂ equivalent

4.4 Environmental Benefits

For the 467,808,000 kg of bio-ethanol produced from Case 1, from the results of the optimised model, at the optimal point where profit was ZAR 188 million, the GHG emissions from ethanol production were 2.63×10^8 kg CO₂ eq. The environmental emissions for the production of bio-ethanol are shown in Table 4.20. The percentage avoided GHG was calculated, using environmental impact values from Table 4.16 and the values calculated, using Table 3.13 as follows,

$$\% \text{ Avoided GHG} = \frac{\text{GHG from use of E-10 blend} - \text{GHG from bio-ethanol production}}{\text{GHG from use of gasoline}} * 100 \quad (3.38)$$

Substituting the values above into Equation 3.38 gives the expression below which was solved to give avoided GHG of approximately 7%

$$\% \text{ Avoided GHG} = \frac{\left(200.235 \frac{\text{g}}{\text{kg}} * 467,808,000 \text{ kg} * 0.633\right) - 2.63 * 10^8}{\left[\left((2,775 * 1) + (1.5 * 25) + (0.13 * 298)\right) * 467,808,000 \text{ kg} * 0.633\right]} * 100$$

Table 4.20: Environmental impact contribution of each supply chain network stage for key product ethanol (Case 1)

Environmental impact Category	Supply chain stage				Total
	Feedstock production	Processing stage	Transportation of feedstock	Transportation of product	
GWP (kg CO ₂ eq)	2.90 x 10 ⁵	2.48 x 10 ⁸	1.98 x 10 ⁵	1.39 x 10 ⁷	2.63 x 10 ⁸
Eutrophication (kg PO ₄ eq)	2.49 x 10 ³	2.78 x 10 ⁶	1.10 x 10 ²	6.60 x 10 ³	2.79 x 10 ⁶
Acidification (kg SO ₂ eq)	4.50 x 10 ³	4.13 x 10 ⁶	5.27 x 10 ²	3.70 x 10 ⁴	4.17 x 10 ⁶
Human toxicity (kg DB eq)	1.45 x 10 ⁶	1.24 x 10 ⁹	2.72 x 10 ⁷	1.91 x 10 ⁶	1.25 x 10 ⁹

Since 0.633 kg of gasoline is equivalent to 1 kg of ethanol on an energy basis (Botha & von Blottnitz 2006), the total amount of ethanol produced in the optimised model (467,808 t) for Case 1 and (1,516,317 t) for Case 2 was equivalent to 296,122 t and 959,829 t of petrol, respectively. Consequently, for the total amount of ethanol produced in Case 1, it would be expected to get an avoided GHG of 5.90 x 10⁷ kg CO₂ eq. from use of the blended petrol (E-10) in place of normal petrol.

CHAPTER 5. CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusion

This work has covered the optimisation of bio-ethanol supply chains for economic and environmental objectives, using a mathematical programming approach. A MILP model was developed, which accounts for food demand, geographical distribution of biomass cultivation areas and feedstock type, feedstock, product and by product distribution and product demand. One processing technology for ethanol production was considered and it was assumed that all processing facility locations would have a CHP plant and one mode of transportation for the movement of both feedstocks and products. To account for the environmental impact of the supply chain, the model is integrated with LCA through multi objective optimisation.

The ϵ - constraint method was used to solve the multi objective optimisation problem by varying GHG emissions and Pareto analysis was done to check the trade-offs between the economic and environmental objectives. It is worth noting that the optimisation criteria used is not simultaneous optimisation of the two objectives. Two case studies, using three provinces in South Africa namely KZN, Eastern Cape and Mpumalanga, were used to demonstrate the proposed optimisation approach. Transportation distance and locations of proposed plants and feedstock cultivation areas were calculated, using routing software Google Earth[®] to improve accuracy. Geographical Information Systems mapping software, ArcGIS, was used in biomass data analysis as well as in establishing the geographical locations of nodes in the supply chain for use in the routing software.

A payback period of approximately 4 years, a ROI of greater than 20% and a positive NPV above ZAR 20 million at the end of the plant life in both Case 1 and Case 2 indicated that the optimisation approach was profitable. However, increasing transport and feedstock prices rendered the model less profitable. All the plants in Case 1 would qualify for government incentive, which would reduce the overall cost of the bio-ethanol supply chain. From the environmental analysis, it was concluded that feedstock processing contributed the most to the overall environmental impact of the supply chain.

Possible optimal points to operate, based on the results of the multiobjective optimisation done are GHG emissions of 4,410 kt CO₂ eq and a profit of ZAR 6,780 million in Case 2, while for Case 1 the points are a profit of ZAR 183 million with an associated environmental impact of 3,643 kt CO₂ eq.

From the work presented in this dissertation the conclusions below can be drawn:

5.1: Feedstock transportation contribute significantly to the total cost and environmental impact of bio-ethanol supply chains.

According to the analysis of the results, the biomass to bio-ethanol supply chain for the case study considered was economically viable and will meet the 2% target demand of blending bio-ethanol into the national liquid fuel supply from the fourteen processing plants selected. The results show that transportation costs constituted a large part of the total costs of the supply chain and was part of the issues identified with the commercialisation of bio-ethanol processing in South Africa. Reducing the cost of transportation and/or reducing the transportation distances of biomass by way of locating processing facilities closer to the biomass sources could make the bio-ethanol industry more economically beneficial. Feedstock transportation also contributed the most significant environmental impact compared to impact from product transportation and efforts should be directed to building more processing facilities closer to the feedstock source in order to reduce the biomass transportation distances so that the operation can be both environmentally and economically favourable.

5.2: Cheap waste products are the most preferred feedstock

The results also confirmed that use of residue material that requires no transportation was profitable in bio-ethanol production. The feedstock cost also plays a part in the economics of bioethanol supply chains. In this work despite availability of several waste material to utilise in the supply chain only bagasse which was assumed to have no cost attached to it was selected. The availability of cheap feedstock greatly improved the economic potential of the model as seen in Case 1 which had a very small feedstock cost. Increasing the feedstock prices resulted in a decrease in profits. This is one of the

reasons second generation bio-ethanol supply chains require subsidies to reduce the cost of feedstock and make them profitable.

5.3 Product prices are of paramount importance to the success of bio-ethanol supply chains

Higher product prices resulted in the production of more bioethanol. Consequently higher profits were realised in the scenario where product prices were doubled than in the base case scenario as portrayed in the results for Case 2. Government policies affect product pricing and the benefit of this would be of much significance to the bio-ethanol supply chain. This is one of the areas the government of South Africa has been directing efforts in order to attract stake holders to invest in the biofuels industry.

5.4 The optimum location of the processing facilities is not affected by the change in scenario

In all the scenarios investigated in this work, the location of the processing facilities remained unchanged. This implies that transportation distances and feedstock costs have a large influence on the profitability of the supply chain. The 14 sugar mills were the optimum locations for processing facilities mainly due to the proximity of the cheapest feedstock considered in this dissertation. This proximity to locations of availability of bagasse reduces transportation costs which constitute a significant portion of the total supply chain costs. The average radii for feedstock supply areas do not change considerably from scenario to scenario in the two cases considered except in the scenario where sugar export demand was ignored. Overall the farms within the shortest radii to the processing facilities were selected to supply feedstock to the processing facilities. The significance of fixed plant locations in all the scenarios investigated is that the benefits of the investment may continue to be realised even after the initial plant life has elapsed if plant retrofitting is done.

5.5 Small plant sizes are preferable to large plant sizes

From the case studies it can be concluded that small plant sizes are preferable in order to make the supply chain profitable. In case 1 all the plants were below 50,000t/y of

ethanol. These all fall within the size range of plants that would benefit from the incentive which is to be offered to bio-ethanol producers by the government.

5.6 Recommendations and Future Work

Since transportation of feedstocks contributed a high percentage to total costs, an alternative transportation method such as use of a combination of road and railway mode of transport could reduce transportation costs of sugarcane considerably. However, this is only possible if rail cars are used and there is no offloading and loading at the railway stations, which otherwise would increase labour costs. It would also require construction or refurbishment of existing railway infrastructure. A collaboration among mill operators will reduce transportation costs and GHG emissions from transportation due to collection of feedstocks from areas closest to each mill. Reduction in the amount of sugarcane exported will increase the availability of feedstock for bio-ethanol production as well as increase avoided GHG emissions due to increased output of bio-ethanol which will replace more fossil fuel when blended to gasoline. In order to utilise straw in ethanol production, more processing facilities should be located closer to the farms that produce the crop residues. In Case 2 of the processing facilities located at sugar mills, molasses could also be included as a feedstock to increase ethanol output as other feedstocks were not selected for use as feedstocks in the model.

The superstructure in the current study should be extended to include detailed models in the supply chain, especially the pre-treatment models. Other aspects such as different kinds of cogeneration techniques and transportation modes could be considered. Seasonality and uncertainty should also be addressed. Product recycle (lignin cake) and use of other types of feedstocks should also be considered to increase amount of feedstock available within a short radius of the processing facilities. Lignin cake should be recycled to produce electricity, and the quantity of bagasse that is channelled to CHP could be reduced to produce more bio-ethanol. Heat integration could also be applied within the model and feedstock degradation and loss due to storage can be accounted for.

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APPENDIX A1: Transportation distance for biomass

Table A1: Distance from farms *i* to biomass demand centres *j* in kilometres

Farm	Processing facilities/biomass demand centres														15	16	17	18	19	20
	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani						
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
2	79	100	113	172	172	184	218	227	262	298	359	522	846	784	-					
3	18	52	103	126	203	203	159	169	204	240	301	464	881	819	-					
4	51	113	155	110	110	148	181	191	226	262	322	485	785	722	-					
5	28	109	152	131	108	108	164	173	208	245	305	468	786	723	-					
6	46	50	67	93	143	144	100	109	144	181	241	404	821	759	-					
7	54	65	65	162	125	158	205	168	203	239	299	462	732	670	-					
8	31	80	80	87	121	125	130	167	165	201	262	425	758	695	-					
9	36	65	98	71	79	89	106	124	149	160	221	384	824	762	-					
10	50	55	82	153	186	196	190	231	233	267	327	395	703	641	-					
11	14	6	85	83	103	128	163	191	199	234	260	365	683	620	-					
12	36	42	50	68	93	117	128	164	165	207	224	387	722	660	-					
13	16	28	39	59	98	104	103	142	151	164	193	327	737	675	-					
14	76	84	149	152	148	157	189	233	257	300	293	338	645	583	-					
15	50	58	118	127	127	159	123	203	231	263	274	320	637	575	-					
16	70	78	72	82	109	113	157	143	217	216	380	258	689	627	-					
17	59	49	70	175	181	109	98	163	208	216	260	259	691	628	-					
18	78	74	124	104	119	151	217	223	191	250	258	300	621	559	-					
19	35	66	82	109	123	155	221	229	227	254	262	304	694	632	-					
20	52	53	100	123	137	168	215	234	240	267	275	318	680	618	-					
21	27	85	133	158	157	171	202	268	274	301	309	623	352	561	-					
22	40	100	147	203	172	185	217	283	289	316	324	660	598	367	-					
23	72	109	130	178	202	216	247	313	319	574	346	512	354	397	-					
24	98	141	157	204	228	242	273	340	346	606	543	372	381	423	-					
25	47	169	227	247	277	292	326	334	515	324	453	423	431	473	-					
26	49	135	193	233	263	278	518	376	368	455	310	409	417	459	-					

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
27	45	194	244	253	269	300	324	338	393	436	370	469	477	519	-					
28	63	168	211	227	247	274	298	312	416	410	343	442	451	493	-					
29	60	96	201	306	364	412	436	450	553	547	481	580	588	631	-					
30	89	152	331	490	549	535	565	541	580	549	612	617	725	768	-					
31	59	122	373	532	590	577	607	622	583	590	654	659	767	809	-					
32	44	42	437	595	654	641	670	686	646	654	717	723	831	873	-					
33	14	56	461	620	679	665	695	711	671	679	742	748	855	898	-					
34	82	145	380	539	598	584	614	600	630	608	661	677	785	827	-					
35	84	146	410	569	627	614	644	659	633	641	691	710	817	860	-	-	-	-	-	-
36	23	88	432	591	650	636	666	681	642	650	713	718	826	869	-					
37	67	63	467	626	684	671	700	716	676	684	747	753	861	903	-					
38	5	48	132	155	232	232	189	198	233	270	330	494	911	849	-					
39	25	75	67	98	175	175	131	141	176	212	273	436	853	791	-					
40	10	47	56	82	88	102	91	110	128	153	188	352	763	700	-					
41	5	17	34	55	80	107	113	154	141	162	205	278	709	647	-					
42	12	38	64	74	78	109	175	181	208	237	217	259	702	640	-					
43	25	68	59	83	97	128	194	200	231	227	235	278	696	634	-					
44	19	74	121	146	159	188	191	257	263	290	298	341	653	591	-					
45	555	512	404	407	399	339	331	408	409	413	442	283	434	371	-	467	400	375	431	581
46	511	468	360	359	352	292	284	361	348	351	353	225	411	348	-	423	356	331	384	516
47	511	468	360	360	347	291	284	329	299	303	303	215	441	378	-	350	356	331	384	537
48	503	461	355	353	322	289	282	306	276	280	280	158	468	405	-	393	351	341	382	530
49	481	438	351	331	299	285	278	284	254	258	120	368	431	344	-	370	347	337	378	507
50	512	469	382	362	330	316	309	315	285	289	289	129	439	377	-	401	378	368	409	538
51	594	551	444	514	548	450	450	557	519	530	524	406	522	459	-	506	440	415	467	621
52	564	521	413	484	517	420	420	527	562	495	489	361	495	417	-	476	410	385	437	590
53	570	527	419	490	523	426	397	533	461	465	466	335	442	379	-	482	416	391	443	596
54	570	527	419	490	436	376	368	533	432	435	437	303	420	357	-	482	416	391	443	597

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
55	575	532	424	495	416	356	348	425	412	415	417	283	406	343	-	487	420	395	448	601
56	545	503	395	423	386	326	318	396	382	386	413	253	370	307	-	457	391	366	418	572
57	559	516	408	479	400	340	332	385	355	400	341	182	388	325	-	420	405	380	432	585
58	573	530	439	423	391	339	331	376	346	359	301	141	407	345	-	462	436	411	462	599
59	535	492	405	385	353	340	332	338	308	312	271	111	389	326	-	424	401	391	432	561
60	546	503	416	396	364	350	343	349	319	300	241	82	249	274	-	409	412	402	443	572
61	634	592	484	554	588	490	486	563	540	544	571	412	496	434	-	546	480	455	507	661
62	618	576	468	538	572	475	475	581	506	509	540	381	458	396	-	508	464	439	492	645
63	629	586	478	549	484	424	416	494	480	484	500	341	419	356	-	541	474	449	502	655
64	622	579	471	542	472	412	404	481	468	471	465	305	394	331	-	470	467	442	495	648
65	602	560	452	522	443	383	375	453	439	443	422	262	357	295	-	514	448	423	475	629
66	594	551	443	514	435	375	367	444	431	434	395	235	330	268	-	506	439	414	467	620
67	621	578	472	471	439	425	417	425	394	399	350	189	365	303	-	510	468	443	502	647
68	594	551	493	444	412	398	390	398	367	371	323	162	358	296	-	483	489	464	523	620
69	595	553	495	445	414	400	392	400	368	373	325	164	346	284	-	485	491	466	525	622
70	640	597	506	576	610	512	513	619	567	571	552	391	449	386	-	568	502	477	536	666
71	656	613	522	593	626	529	529	636	534	539	519	358	430	368	-	585	518	493	552	683
72	650	607	516	586	577	522	522	564	532	537	489	328	412	350	-	578	512	487	546	676
73	659	616	525	595	557	531	434	543	511	516	468	307	386	324	-	587	521	496	555	685
74	649	606	515	585	536	420	412	523	491	496	448	287	345	283	-	578	511	486	545	676
75	604	562	470	516	485	405	397	471	439	444	396	235	323	260	-	533	467	442	500	631
76	620	578	486	531	499	421	413	486	454	459	411	250	290	227	-	549	483	458	516	647
77	634	591	533	484	452	438	430	438	407	411	363	202	289	226	-	523	529	504	563	660
78	631	588	530	481	449	435	427	435	404	408	360	199	284	222	-	520	526	501	560	657
79	710	667	576	646	680	582	582	689	590	595	566	405	443	380	-	638	572	547	606	736
80	691	649	557	628	661	564	564	671	609	613	565	404	408	345	-	620	553	528	587	718
81	715	673	581	652	593	588	471	579	548	553	505	343	373	311	-	644	578	553	612	742
82	699	656	565	636	574	470	462	560	529	533	485	324	343	280	-	628	561	536	595	726

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
83	660	617	526	572	540	460	452	526	495	499	451	290	326	264	-	588	522	497	556	686
84	665	622	531	565	534	465	457	520	488	493	445	284	295	232	-	605	527	502	561	691
85	653	611	519	548	516	454	446	502	471	475	427	266	266	203	-	587	516	491	550	680
86	686	643	550	536	504	491	483	491	459	464	416	255	222	159	-	575	546	521	580	712
87	698	655	578	548	516	502	494	502	471	476	427	266	230	167	-	587	574	549	608	724
88	741	698	607	677	669	613	613	655	623	628	580	419	423	360	-	669	603	578	637	767
89	750	707	616	686	643	623	623	629	598	602	554	393	397	335	-	679	612	587	646	777
90	744	701	610	629	597	515	507	583	552	557	508	347	351	289	-	672	606	581	640	770
91	734	691	600	618	587	505	497	573	542	546	498	337	327	264	-	663	596	571	630	761
92	709	666	575	603	572	509	501	558	527	531	483	322	271	208	-	643	571	546	605	736
93	700	658	566	594	563	500	493	549	518	522	474	313	230	167	-	634	562	537	596	727
94	725	683	591	620	588	526	518	574	543	547	499	338	193	130	-	659	588	563	622	752
95	784	742	642	634	603	589	581	589	557	562	514	353	173	111	-	674	639	614	673	811
96	786	744	645	636	605	591	583	591	560	564	516	355	134	72	-	676	641	616	675	813
97	801	759	667	738	663	674	674	650	618	623	575	414	407	345	-	730	664	639	697	828
98	799	757	665	736	661	672	672	647	616	620	572	411	371	309	-	728	662	637	695	826
99	806	763	672	663	632	577	569	618	587	591	543	382	331	268	-	734	668	643	702	832
100	791	748	657	648	617	562	554	603	571	576	528	367	316	253	-	719	653	628	687	817
101	752	709	618	646	615	552	544	601	569	574	526	365	252	190	-	686	614	589	648	778
102	768	726	634	662	631	568	561	617	586	590	542	381	198	136	-	702	630	605	664	795
103	797	754	663	681	649	597	589	636	604	609	561	400	160	97	-	720	659	634	693	823
104	831	788	685	681	649	635	628	635	604	609	561	399	141	79	-	720	681	656	715	857
105	879	837	745	816	706	752	616	692	661	666	617	456	417	354	-	808	742	717	775	906
106	832	789	698	717	685	603	595	672	640	645	597	436	396	334	-	761	694	669	728	858
107	856	814	722	714	683	628	620	669	637	642	594	433	304	242	-	785	719	694	753	883
108	793	750	658	687	655	593	585	641	610	614	566	405	269	206	-	726	655	630	689	819
109	792	749	658	686	654	592	584	640	609	614	566	404	244	182	-	725	654	629	688	818
110	844	802	710	739	707	645	637	693	662	666	618	457	216	154	-	778	707	682	740	871

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
111	882	839	736	732	700	686	678	686	655	660	611	450	201	138	-	771	732	707	766	908
112	895	852	761	753	721	666	658	707	676	681	632	471	301	239	-	824	757	732	791	922
113	838	796	704	732	701	638	631	687	656	660	612	451	291	229	-	772	700	675	734	865
114	910	868	776	805	773	711	703	759	728	732	684	523	287	225	-	844	773	748	806	937
115	885	927	1,090	1,161	1,194	1,097	1,097	1,204	1,247	1,279	1,336	1,192	1,366	1,303	-	1,153	1,087	1,062	874	854
116	896	938	1,102	1,172	1,206	1,108	1,108	1,215	1,258	1,291	1,347	1,203	1,377	1,314	-	1,164	1,098	1,073	886	866
117	870	912	1,068	1,138	1,172	1,074	1,074	1,181	1,224	1,256	1,313	1,169	1,343	1,280	-	1,130	1,064	1,039	860	840
118	783	825	816	933	966	878	878	976	1,018	1,051	1,108	1,187	1,361	1,299	-	925	838	837	773	753
119	718	760	751	868	901	813	813	911	953	986	1,043	1,184	1,358	1,295	-	860	773	772	708	688
120	931	1,172	1,081	1,151	1,185	1,088	1,088	1,194	1,237	1,270	1,326	1,182	1,356	1,293	-	1,144	1,077	1,052	1,111	901
121	890	932	1,096	1,166	1,200	1,102	1,102	1,209	1,252	1,284	1,341	1,197	1,371	1,308	-	1,158	1,092	1,067	879	859
122	848	890	1,054	1,125	1,158	1,061	1,061	1,168	1,210	1,243	1,300	1,155	1,329	1,267	-	1,117	1,050	1,025	838	818
123	817	860	1,023	1,094	1,127	1,030	1,030	1,137	1,179	1,212	1,269	1,125	1,298	1,236	-	1,086	1,020	995	807	787
124	851	893	1,057	1,127	1,161	1,063	1,063	1,170	1,213	1,246	1,302	1,158	1,332	1,269	-	1,119	1,053	1,028	841	821
125	727	770	761	877	911	1,059	1,059	920	963	996	1,052	1,154	1,327	1,265	-	870	783	782	717	697
126	702	745	735	852	886	1,043	1,043	895	938	971	1,027	1,137	1,311	1,249	-	844	758	1,757	692	672
127	709	751	742	859	893	804	804	902	945	977	1,034	1,149	1,323	1,260	-	851	765	764	699	679
128	649	691	682	799	832	744	744	842	884	917	973	1,063	1,327	1,265	-	791	704	703	638	618
129	615	658	649	765	799	711	711	808	851	884	940	1,056	1,320	1,258	-	757	671	670	605	585
130	596	639	630	746	780	692	692	789	832	865	921	1,037	1,301	1,239	-	739	652	651	586	566
131	567	609	600	717	750	662	662	760	802	835	892	1,055	1,309	1,247	-	709	622	621	557	537
132	580	622	613	730	764	675	675	773	816	848	905	1,068	1,341	1,279	-	722	636	635	570	550
133	144	1,102	1,010	1,081	1,114	1,017	1,017	1,124	1,166	1,199	1,255	1,111	1,285	1,223	-	1,073	1,006	981	1,040	878
134	825	867	1,029	1,100	1,133	1,036	1,036	1,143	1,185	1,218	1,275	1,131	1,304	1,242	-	1,092	1,026	1,001	1,059	794
135	782	824	987	1,057	1,091	993	993	1,100	1,143	1,176	1,232	1,088	1,262	1,199	-	1,049	983	958	1,017	752
136	755	797	960	1,031	1,064	967	967	1,074	1,116	1,149	1,206	1,062	1,235	1,173	-	1,023	957	932	745	725
137	732	775	993	1,064	1,097	1,000	1,000	1,107	1,149	1,182	1,239	1,095	1,268	1,206	-	1,056	990	965	722	702
138	710	753	744	1,076	1,110	1,013	1,013	1,119	1,162	1,195	151	1,107	1,281	1,219	-	1,069	1,002	977	700	680

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
139	667	709	700	817	851	762	762	860	1,903	935	992	1,160	1,333	1,271	-	809	723	722	657	637
140	607	650	641	757	791	703	703	800	843	876	932	1,089	1,263	1,201	-	750	663	662	597	577
141	576	618	609	726	759	671	671	769	811	844	900	1,016	1,281	1,218	-	718	631	630	566	545
142	571	613	604	721	754	666	666	764	806	839	896	1,011	1,276	1,213	-	713	626	625	561	541
143	503	545	536	653	686	598	598	696	738	771	827	991	1,276	1,214	-	645	558	557	492	472
144	470	513	504	620	654	566	566	663	706	739	795	959	1,326	1,264	-	613	526	525	460	440
145	781	1,043	951	1,022	1,055	958	958	1,065	1,107	1,140	1,197	1,053	1,226	1,164	-	1,014	948	923	981	1,751
146	753	1,042	951	1,021	1,055	957	957	1,064	1,107	1,139	1,196	1,052	1,226	1,163	-	1,013	947	922	981	723
147	720	1,009	918	988	1,022	925	925	1,031	1,074	1,107	1,163	1,019	1,193	1,130	-	981	914	889	948	690
148	737	779	953	1,023	1,057	959	959	1,066	1,109	1,142	1,198	1,054	1,228	1,165	-	1,015	949	924	727	707
149	683	725	716	833	866	987	987	876	919	951	1,008	1,081	1,255	1,193	-	825	739	738	673	653
150	597	639	630	747	780	692	692	790	832	865	921	948	1,213	1,150	-	739	652	651	586	566
151	544	587	577	694	728	640	640	737	780	813	869	1,032	1,233	1,171	-	686	600	599	534	514
152	468	510	501	618	652	563	563	661	704	737	793	956	1,264	1,202	-	610	524	523	458	438
153	423	465	456	573	606	518	518	616	658	691	748	911	1,390	1,327	-	565	478	477	413	393
154	382	425	416	532	566	478	478	575	618	651	707	871	1,178	1,116	-	524	438	437	372	352
155	762	973	882	953	986	889	889	996	1,038	1,071	1,127	983	1,157	1,095	-	945	878	853	912	732
156	708	750	898	968	1,002	904	904	1,011	1,054	1,086	1,143	999	1,173	1,110	-	960	894	869	697	677
157	656	699	876	946	980	882	882	989	1,032	1,064	1,121	977	1,151	1,088	-	938	872	847	646	626
158	562	604	595	712	745	657	657	755	797	830	887	917	1,182	1,119	-	704	617	616	552	532
159	522	564	555	672	705	617	617	715	758	790	847	894	1,158	1,096	-	664	578	577	512	492
160	495	537	528	645	678	590	590	688	731	763	820	1,983	1,192	1,130	-	637	551	550	485	465
161	446	488	479	596	630	541	541	639	682	715	771	934	1,243	1,181	-	588	502	501	436	416
162	409	451	442	559	592	504	504	602	644	677	734	897	1,255	1,193	-	551	464	463	399	379
163	388	430	421	538	572	484	484	581	624	657	713	876	1,295	1,233	-	530	444	443	378	358
164	645	687	772	843	876	779	779	886	928	961	1,017	873	1,138	1,076	-	835	768	743	635	615
165	595	637	628	812	845	748	748	855	897	930	987	842	1,107	1,045	-	804	737	712	585	565
166	576	618	609	726	760	760	760	769	812	1,845	901	854	1,119	1,057	-	718	632	631	566	546

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
167	527	569	560	677	711	622	622	720	763	796	852	882	1,167	1,104	-	669	583	582	517	497
168	633	675	784	855	888	791	791	898	940	973	1,030	886	1,059	97	-	847	781	756	623	603
169	615	657	709	780	813	716	716	823	865	1,898	955	811	1,075	1,013	-	772	706	681	605	585
170	619	662	699	770	803	706	706	813	855	888	945	801	1,065	1,003	-	762	696	671	609	589
171	563	605	596	713	746	723	723	756	798	831	888	817	1,012	950	-	705	618	617	553	533
172	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
173	262	220	128	199	232	135	135	242	284	317	374	394	687	625	-	191	124	100	158	289
174	247	205	113	184	217	120	82	227	269	302	359	383	676	614	-	176	109	85	143	274
175	234	191	100	124	150	53	47	160	192	239	296	374	709	646	-	162	96	78	130	260
176	238	196	104	96	128	30	22	137	180	213	269	362	696	634	-	87	100	86	134	265
177	214	171	141	56	50	61	67	60	91	139	196	359	770	708	-	95	145	123	171	240
178	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
179	353	310	219	289	323	226	226	332	375	408	464	354	647	584	-	282	215	190	249	379
180	314	271	180	250	284	187	187	293	336	369	425	331	624	562	-	242	176	151	210	340
181	292	249	158	228	261	164	164	271	314	346	403	318	611	549	-	220	154	129	188	318
182	306	263	172	174	170	106	98	180	211	259	316	334	627	565	-	165	168	143	202	332
183	286	243	152	154	146	86	78	156	187	235	292	304	638	576	-	145	148	133	182	312
184	279	236	145	138	101	79	71	111	142	190	247	410	697	635	-	177	141	126	175	305
185	311	269	185	161	124	120	112	134	166	214	270	285	685	623	-	201	181	167	215	338
186	431	388	297	367	401	303	303	410	453	485	542	398	622	560	-	359	293	268	327	457
187	389	346	255	325	359	261	262	368	411	444	500	356	617	555	-	317	251	226	285	415
188	352	310	218	289	322	225	225	332	374	407	464	312	642	579	-	281	214	189	248	379
189	338	296	204	275	237	211	165	318	360	346	391	271	564	502	-	267	200	175	234	365
190	359	317	225	296	221	161	153	231	262	339	384	264	598	536	-	288	222	197	255	386
191	322	279	188	191	182	123	115	192	224	272	328	254	588	526	-	181	184	170	218	349
192	420	377	286	357	390	293	293	400	385	389	434	315	587	525	-	349	282	257	316	447
193	430	388	296	367	299	239	231	309	348	352	397	278	524	462	-	359	293	268	326	457
194	402	360	268	249	241	181	173	250	290	294	339	220	554	492	-	331	264	239	298	429

Processing facilities/biomass demand centres																				
Farm	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixton	Umfolozi	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	260	297	357	520	938	875	-					
195	418	376	284	257	249	189	182	257	225	230	275	217	551	489	-	248	280	255	314	445
196	426	383	255	276	244	189	181	230	199	203	248	208	542	480	-	315	251	236	285	452
197	377	334	326	227	195	293	289	181	150	155	200	183	529	467	-	266	308	344	368	403
198	379	336	328	229	197	295	301	183	152	156	169	140	572	509	-	268	310	346	370	405
199	474	431	340	411	348	347	280	409	377	382	427	307	488	426	-	403	336	311	370	501
200	443	400	309	380	303	243	235	364	332	337	382	262	483	421	-	372	305	280	339	470
201	447	405	313	371	340	230	222	326	294	299	344	224	494	431	-	376	310	285	343	474
202	478	435	331	328	297	237	229	283	251	256	301	181	516	453	-	368	328	303	361	505
203	436	394	332	286	255	237	229	241	210	214	259	140	474	412	-	326	328	303	362	463
204	430	387	371	280	248	276	268	235	203	208	197	121	509	447	-	319	367	342	401	456
205	491	449	403	341	310	308	300	296	265	225	166	124	541	479	-	381	399	374	433	518
206	419	377	369	270	238	336	342	224	193	173	114	57	525	463	-	309	351	387	411	446
207	483	440	349	419	393	283	275	379	348	352	397	225	425	363	-	411	345	320	379	509
208	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
209	680	638	546	617	650	553	553	660	702	642	672	511	569	506	-	609	542	517	576	707
210	651	608	517	587	621	523	523	630	673	612	642	481	539	477	-	579	513	488	547	677
211	622	580	488	559	592	495	495	602	644	584	590	429	521	459	-	551	484	459	518	649
212	592	549	491	442	410	396	396	396	365	346	289	128	215	230	-	481	487	462	521	618
213	617	575	483	554	587	490	490	597	639	672	729	659	717	654	-	546	480	455	513	644
214	614	571	480	550	584	486	486	593	636	668	725	581	720	657	-	542	476	451	510	640
215	572	529	438	509	542	445	445	552	594	627	683	539	731	669	-	501	434	409	468	599
216	719	676	599	569	537	524	524	524	492	497	449	288	183	121	-	608	596	571	630	745
217	685	642	634	535	503	539	539	489	470	418	361	224	105	102	-	574	616	605	676	711
218	815	772	673	665	633	619	619	619	588	593	545	383	112	50	-	704	669	644	703	841
219	881	839	735	731	700	686	686	686	654	659	611	450	99	45	-	771	731	706	765	908
220	554	511	503	404	373	387	379	359	339	287	230	80	226	250	-	444	485	453	545	581

APPENDIX A2: Biomass capacities of farms in the case study

Table A2.1: Maximum feedstock capacity of farm *i* (Case 2)

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
1	4,016,427	602,464	-	-	-	-
2	1,276,520	191,478	-	-	-	-
3	6,140,204	921,031	-	-	-	-
4	3,051,369	457,705	-	-	-	-
5	3,726,306	558,946	-	-	-	-
6	1,066,541	159,981	-	-	-	-
7	2,031,571	304,736	-	-	-	-
8	3,690,402	553,560	-	-	-	-
9	2,597,185	389,578	-	-	-	-
10	1,661,468	249,220	-	-	-	-
11	6,822,239	1,023,336	-	-	-	-
12	42,464,308	639,646	-	-	-	-
13	6,892,352	1,033,852	-	-	-	-
14	416,054	62,408	-	-	-	-
15	1,340,466	201,070	-	-	-	-
16	2,673,812	401,072	-	-	-	-
17	218,799	32,820	-	-	-	-
18	926,085	138,913	-	-	-	-
19	3,179,854	476,978	-	-	-	-
20	2,826,807	424,021	-	-	-	-
21	1,557,015	233,552	-	-	-	-
22	1,306,167	195,925	-	-	-	-
23	81,950	12,292	-	-	-	-
24	194,530	29,179	-	-	-	-
25	2,520,929	378,139	-	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
26	1,922,694	288,404	-	-	-	-
27	414,241	62,136	-	-	-	-
28	465,811	69,872	-	-	-	-
29	343,607	51,541	-	-	-	-
30	4,823,652	723,548	-	-	-	-
31	3,074,855	461,228	-	-	-	-
32	4,186,941	628,041	-	-	-	-
33	6,358,661	953,799	-	-	-	-
34	2,798,228	419,734	-	-	-	-
35	920,584	138,087	-	-	-	-
36	2,920,149	438,022	-	-	-	-
37	4,015,944	602,392	-	-	-	-
38	1,402,805	210,421	-	-	-	-
39	401,615	60,242	-	-	-	-
40	1,860,465	279,070	-	-	-	-
41	1,228,235	184,235	-	-	-	-
42	995,487	149,323	-	-	-	-
43	103,456	15,518	-	-	-	-
44	520,692	78,104	-	-	-	-
45	-	-	3,542	-	1	-
46	-	-	4,923	-	1	-
47	-	-	1,812	-	4	-
48	-	-	660	-	92	-
49	-	-	158	-	413	-
50	-	-	19	-	261	-
51	-	-	11,691	128	142	-
52	-	-	9,214	-	268	-
53	-	-	21,742	2,604	108	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
54	-	-	24,008	4,349	74	-
55	-	-	16,825	1,096	57	-
56	-	-	6,847	48	-	-
57	-	-	9,471	-	0.01	-
58	-	-	14,536	-	0.09	-
59	-	-	485	-	0.12	-
60	-	-	307	-	0.06	-
61	-	-	21,284	25	143	-
62	-	-	33,865	416	518	-
63	-	-	39,476	1,908	177	-
64	-	-	31,786	2,729	41	-
65	-	-	23,669	1,703	76	-
66	-	-	19,840	2,097	90	-
67	-	-	10,186	248	94	-
68	-	-	7,943	-	58	-
69	-	-	1,374	-	0.43	-
70	-	-	1,872	-	40	-
71	-	-	46,313	200	1,863	-
72	-	-	50,826	394	973	-
73	-	-	57,337	4,582	40	-
74	-	-	52,421	2,190	58	-
75	-	-	15,628	1,290	124	-
76	-	-	12,992	372	130	-
77	-	-	3,587	187	127	-
78	-	-	16.02	-	112	-
79	-	-	1,190	-	56	-
80	-	-	28,909	658	1,285	-
81	-	-	57,208	421	972	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
82	-	-	30,587	348	60	-
83	-	-	76,979	523	9	-
84	-	-	58,684	54	72	-
85	-	-	3,895	54	123	-
86	-	-	1,993	-	135	-
87	-	-	1,146	-	124	-
88	-	-	8,332	19	12	-
89	-	-	5,772	862	13	-
90	-	-	13,735	250	7	-
91	-	-	38,029	231	1	-
92	-	-	43,230	-	10	-
93	-	-	1,891	-	19	-
94	-	-	1,978	-	15	-
95	-	-	1,778	-	4	-
96	-	-	1,882	-	1,331	-
97	-	-	1,090	-	6,069	-
98	-	-	6,289	-	6,395	-
99	-	-	1,278	-	4,632	-
100	-	-	15,801	-	332	-
101	-	-	4,085	-	357	-
102	-	-	3,745	-	357	-
103	-	-	723	-	17	-
104	-	-	1,047	-	213	-
105	-	-	119	-	1,604	-
106	-	-	4,165	5	1,254	-
107	-	-	279	-	165	-
108	-	-	2,073	-	256	-
109	-	-	4,659	-	448	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
110	-	-	154	-	154	-
111	-	-	9	-	-	-
112	-	-	624	-	-	-
113	-	-	1,040	-	-	-
114	-	-	677	-	-	-
115	-	-	0.09	-	-	-
116	-	-	0.09	-	-	-
117	-	-	0.04	-	-	-
118	-	-	0.29	-	-	-
119	-	-	1.02	-	-	-
120	-	-	-	-	-	-
121	-	-	0.07	-	-	-
122	-	-	0.16	-	-	-
123	-	-	0.16	-	-	-
124	-	-	5	-	-	-
125	-	-	12	-	-	-
126	-	-	16	-	-	-
127	-	-	16	-	-	-
128	-	-	4	-	-	-
129	-	-	3	-	-	-
130	-	-	7	-	-	-
131	-	-	2	-	-	-
132	-	-	2	-	-	-
133	-	-	0.01	-	-	-
134	-	-	0.13	-	-	-
135	-	-	3	-	-	-
136	-	-	13	-	-	-
137	-	-	18	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
138	-	-	15	-	-	-
139	-	-	8	-	-	-
140	-	-	0.40	-	-	-
141	-	-	2	-	-	-
142	-	-	11	-	-	-
143	-	-	7	-	-	-
144	-	-	2	-	-	-
145	-	-	0.01	-	-	-
146	-	-	14	-	-	-
147	-	-	18	-	-	-
148	-	-	18	-	-	-
149	-	-	5	-	-	-
150	-	-	0.06	-	-	-
151	-	-	2	-	-	-
152	-	-	263	-	-	-
153	-	-	176	-	-	-
154	-	-	7	-	-	-
155	-	-	4	-	-	-
156	-	-	7	-	-	-
157	-	-	1	-	-	-
158	-	-	2	-	-	-
159	-	-	11	-	-	-
160	-	-	5	-	-	-
161	-	-	122	-	-	-
162	-	-	537	-	-	-
163	-	-	226	-	-	-
164	-	-	0.14	-	-	-
165	-	-	7	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
166	-	-	13	-	-	-
167	-	-	3	-	-	-
168	-	-	0.09	-	-	-
169	-	-	2	-	-	-
170	-	-	4	-	-	-
171	-	-	0.41	-	-	-
172	-	-	274	-	71	-
173	-	-	4,701	-	1,164	-
174	-	-	715	-	177	-
175	-	-	-	-	0.08	-
176	-	-	-	-	0.12	-
177	-	-	-	-	0.03	-
178	-	-	1,481	-	386	-
179	-	-	5,623	-	1,466	-
180	-	-	6,000	-	1,564	-
181	-	-	11,179	-	2,777	-
182	-	-	12,634	-	3,128	-
183	-	-	381	-	95	-
184	-	-	-	-	0.15	-
185	-	-	-	-	0.05	-
186	-	-	511	-	133	-
187	-	-	3,463	-	903	-
188	-	-	3,615	-	943	-
189	-	-	43	-	11	-
190	-	-	850	-	54	-
191	-	-	25	-	0.04	-
192	-	-	855	-	40	-
193	-	-	7,125	-	291	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
194	-	-	10,510	-	365	-
195	-	-	4,360	-	10	-
196	-	-	3,607	-	89	-
197	-	-	2,320	-	57	-
198	-	-	620	-	15	-
199	-	-	101	-	-	-
200	-	-	10,937	-	6	-
201	-	-	9,793	-	277	-
202	-	-	2,433.80	-	14.27	-
203	-	-	9,710.54	-	244.77	-
			10,044.4			
204	-	-	9	-	249.50	-
205	-	-	8,687.06	-	213.90	-
206	-	-	422.92	-	10.41	-
207	-	-	397.82	-	1.43	-
208	-	-	1,409.10	-	31.42	-
209	-	-	9.86	-	-	-
210	-	-	185.01	-	-	-
211	-	-	26.84	-	-	-
212	-	-	44.40	-	-	-
213	-	-	4.28	-	-	-
214	-	-	716.29	-	8.08	-
215	-	-	4,737.62	-	51.52	-
216	-	-	1.82	-	-	-
217	-	-	132.80	-	0.96	-
218	-	-	37.85	-	0.61	-
219	-	-	1,497.60	-	77.70	-
220	-	-	142.00	-	-	-

Table A2.2: Maximum feedstock capacity of farm *i* (Case 1)

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
1	1,443,592.8					
	0	216,538.92	-	-	-	-
2	175,543.63	26,331.54	-	-	-	-
3	1,866,785.2					
	9	280,17.79	-	-	-	-
4	268,495.67	40,274.35	-	-	-	-
5	1,234,764.1					
	1	185,214.62	-	-	-	-
6	138,938.65	20,840.80	-	-	-	-
7	302,152.79	45,322.92	-	-	-	-
8	704,870.53	105,730.58	-	-	-	-
9	244,317.49	36,647.62	-	-	-	-
10	38,820.17	5,823.03	-	-	-	-
11	1,406,879.0					
	6	211,031.86	-	-	-	-
12	49,007.50	74,401.12	-	-	-	-
13	1,952,507.9					
	2	292,876.19	-	-	-	-
14	269.03	40.35	-	-	-	-
15	214,953.37	32,243.01	-	-	-	-
16	156,270.92	23,440.64	-	-	-	-
17	256,641.26	38,496.19	-	-	-	-
18	1,298,191.7					
	5	194,728.76	-	-	-	-
19	460,341.25	69,051.19	-	-	-	-
20	294,808.90	44,221.33	-	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
21	100,038.35	15,005.75	-	-	-	-
22	11,407.93	1,711.19	-	-	-	-
23	10,950.01	1,642.50	-	-	-	-
24	659,170.12	98,875.52	-	-	-	-
25	324,052.81	48,607.92	-	-	-	-
26	236,046.31	35,406.95	-	-	-	-
27	369,032.00	55,354.80	-	-	-	-
28	1,668,494	250,274.17	-	-	-	-
29	38,677.07	5,801.56	-	-	-	-
30	181,782.79	27,267.42	-	-	-	-
31	533,093.29	79,963.99	-	-	-	-
32	806,809.25	121,021.39	-	-	-	-
33	102,522.56	15,378.38	-	-	-	-
34	73,164.17	10,974.63	-	-	-	-
35	333,714.92	50,057.24	-	-	-	-
36	977,985.47	146,697.82	-	-	-	-
37	516,253.28	77,437.99	-	-	-	-
38	166,442.47	24,966.37	-	-	-	-
39	663,629.11	99,544.37	-	-	-	-
40	819,985.90	122,997.88	-	-	-	-
41	558,845.57	83,826.84	-	-	-	-
42	343,78.34	5,156.75	-	-	-	-
43	311,895.04	46,784.26	-	-	-	-
44	270,979.88	40,646.98	-	-	-	-
45	486,76.90	7,301.53	3,542.26	-	0.99	-
46	319,994.50	47,999.17	4,923.34	-	1.21	-
47	-	-	1,811.83	-	4.41	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
48	-	-	659.85	-	91.80	-
49	-	-	158.35	-	412.74	-
50	-	-	19.34	-	261.07	-
51	-	-	11,691.5	128.12	142.00	-
52	-	-	9,214.14	-	268.23	-
53	-	-	21,741.9	2,604.18	108.10	-
54	-	-	24,007.8	4,348.84	74.27	-
55	-	-	16,825.4	1,095.73	57.15	-
56	-	-	6,847.27	48.93	-	-
57	-	-	9,471.38	-	0.01	-
58	-	-	14,536.1	-	0.09	-
59	-	-	485.23	-	0.12	-
60	-	-	307.14	-	0.06	-
61	-	-	21,284.1	24.72	143.33	-
62	-	-	33,866.9	415.73	517.89	-
63	-	-	39,476.1	1,907.75	177.44	-
64	-	-	31,786.6	2,728.96	41.34	-
65	-	-	23,669.9	1,702.78	75.76	-
66	-	-	19,840.1	2,096.61	90.03	-
67	-	-	10,186.8	247.63	93.83	-
68	-	-	7,942.74	-	58.13	-
69	-	-	1,373.66	-	0.43	-
70	-	-	1,871.96	-	40.11	-
71	-	-	46,313.3	199.89	1,863.00	-
72	-	-	50,826.0	394.46	973.45	-
73	-	-	57,337.3	4,581.81	39.50	-
74	-	-	52,420.7	2,189.73	57.56	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
75	-	-	15,628.	1,289.67	124.21	-
76	-	-	12,991.6	372.45	129.50	-
77	-	-	3,586.91	186.62	127.38	-
78	-	-	16.02	-	112.27	-
79	-	-	1,190.88	-	55.85	-
80	-	-	28,908.8	657.53	1,285.74	-
81	-	-	57,207.7	421.24	971. 8	-
82	-	-	30,586.5	348.21	59.98	-
83	-	-	76,979.1	523.30	9.33	-
84	-	-	58,684.1	54.08	72.34	-
85	-	-	3,894.60	54.08	123.13	-
86	-	-	1,992.52	-	134.84	-
87	-	-	1,146.34	-	124.35	-
88	-	-	8,331.57	19.47	12.42	-
89	-	-	5,771.72	862.11	12.74	-
90	-	-	13,735.1	250.07	7.02	-
91	-	-	38,029.4	231.09	1.08	-
92	-	-	43,230.3	-	10.42	-
93	-	-	1,891.15	-	18.78	-
94	-	-	1,977.68	-	15.09	-
95	-	-	1,778.34	-	4.30	-
96	-	-	1,881.89	-	1,331.70	-
97	-	-	1,089.88	-	6,069.41	-
98	-	-	6,289.11	-	6,395.84	-
99	-	-	1,278.56	-	4,632.27	-
100	-	-	15,801.9	-	331.92	-
101	-	-	4,085.74	-	356.50	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
102	-	-	3,745.96	-	357.42	-
103	-	-	723.01	-	16.54	-
104	-	-	1,047.28	-	212.76	-
105	-	-	119.98	-	1,604.33	-
106	-	-	4,165.27	4.70	1,254.11	-
107	-	-	279.99	-	164.50	-
108	-	-	2,073.50	-	256.40	-
109	-	-	4,659.53	-	447.68	-
110	-	-	154.48	-	154.28	-
111	-	-	9.07	-	-	-
112	-	-	624.17	-	-	-
113	-	-	1,040.28	-	-	-
114	-	-	676.55	-	-	-
115	-	-	0.09	-	-	-
116	-	-	0.09	-	-	-
117	-	-	0.04	-	-	-
118	-	-	0.29	-	-	-
119	-	-	1.02	-	-	-
120	-	-	-	-	-	-
121	-	-	0.07	-	-	-
122	-	-	0.16	-	-	-
123	-	-	0.16	-	-	-
124	-	-	4.72	-	-	-
125	-	-	12.09	-	-	-
126	-	-	15.64	-	-	-
127	-	-	16.22	-	-	-
128	-	-	4.12	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
129	-	-	2.79	-	-	-
130	-	-	7.49	-	-	-
131	-	-	2.44	-	-	-
132	-	-	2.49	-	-	-
133	-	-	0.01	-	-	-
134	-	-	0.13	-	-	-
135	-	-	3.40	-	-	-
136	-	-	12.98	-	-	-
137	-	-	18.27	-	-	-
138	-	-	14.62	-	-	-
139	-	-	8.43	-	-	-
140	-	-	0.40	-	-	-
141	-	-	2.27	-	-	-
142	-	-	10.77	-	-	-
143	-	-	7.09	-	-	-
144	-	-	1.75	-	-	-
145	-	-	0.01	-	-	-
146	-	-	14.12	-	-	-
147	-	-	18.22	-	-	-
148	-	-	17.73	-	-	-
149	-	-	4.77	-	-	-
150	-	-	0.06	-	-	-
151	-	-	1.89	-	-	-
152	-	-	262.99	-	-	-
153	-	-	176.49	-	-	-
154	-	-	6.99	-	-	-
155	-	-	3.58	-	-	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
156	-	-	7.39	-	-	-
157	-	-	1.19	-	-	-
158	-	-	1.82	-	-	-
159	-	-	10.60	-	-	-
160	-	-	5.32	-	-	-
161	-	-	121.87	-	-	-
162	-	-	537.40	-	-	-
163	-	-	225.77	-	-	-
164	-	-	0.14	-	-	-
165	-	-	7.04	-	-	-
166	-	-	12.97	-	-	-
167	-	-	3.41	-	-	-
168	-	-	0.09	-	-	-
169	-	-	2.07	-	-	-
170	-	-	3.58	-	-	-
171	-	-	0.41	-	-	-
172	-	-	273.81	-	71.30	-
173	-	-	4,701.14	-	1,164.00	-
174	-	-	715.23	-	177.09	-
175	-	-	-	-	0.08	-
176	-	-	-	-	0.12	-
177	-	-	-	-	0.03	-
178	-	-	1,481.20	-	386.20	-
179	-	-	5,623.04	-	1,466.13	-
180	-	-	6,000.09	-	1,564.43	-
181	-	-	11,179.1	-	-	-
	-	-	1	-	2,777.80	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
182	-	-	0	-	3,128.17	-
183	-	-	381.44	-	94.52	-
184	-	-	-	-	0.15	-
185	-	-	-	-	0.05	-
186	-	-	511.30	-	133.31	-
187	-	-	3,463.21	-	902.98	-
188	-	-	3,615.30	-	942.64	-
189	-	-	43.01	-	10.75	-
190	-	-	849.70	-	53.67	-
191	-	-	24.79	-	0.04	-
192	-	-	855.24	-	40.37	-
193	-	-	7,125.45	-	290.55	-
194	-	-	7	-	364.93	-
195	-	-	4,360.09	-	9.72	-
196	-	-	3,607.52	-	88.83	-
197	-	-	2,320.61	-	57.14	-
198	-	-	619.50	-	15.25	-
199	-	-	100.73	-	-	-
200	-	-	1	-	5.84	-
201	-	-	9,792.61	-	277.34	-
202	-	-	2,433.80	-	14.27	-
203	-	-	9,710.54	-	244.77	-
204	-	-	9	-	249.50	-

Farm	Feedstock (t)					
	Sugarcane	Sugarcane leaves	Maize straw	Sorghum straw	Wheat straw	Barley straw
205	-	-	8,687	-	214	-
206	-	-	423	-	10	-
207	-	-	39	-	1	-
208	-	-	1,409	-	31	-
209	-	-	10	-	-	-
210	-	-	185	-	-	-
211	-	-	27	-	-	-
212	-	-	44	-	-	-
213	-	-	4	-	-	-
214	-	-	716	-	8	-
215	-	-	4,738	-	52	-
216	-	-	2	-	-	-
217	-	-	133	-	1	-
218	-	-	38	-	1	-
219	-	-	1,498	-	78	-
220	-	-	142	-	-	-

APPENDIX A3: Feedstock distribution in the optimised model

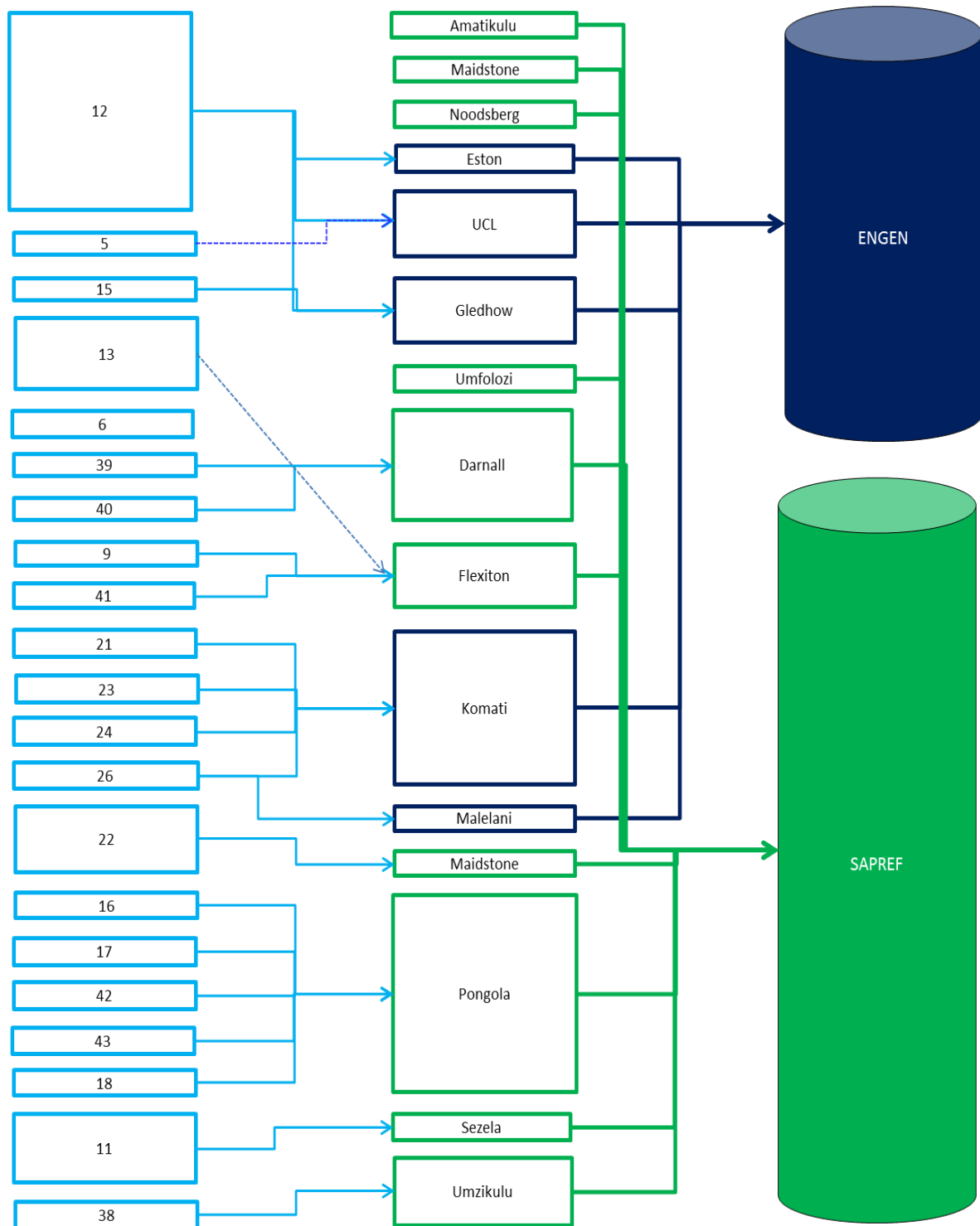


Figure A3.1: Superstructure for supply chain network for optimised base case scenario (Case 1)

Table A3.1.1: Quantities of feedstock transported to bio-ethanol processing facilities and average transport distances for base case scenario (Case 1)

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
41	Amatikulu	Sugarcane	1,228,235	141
40	Amatikulu	Sugarcane	987,717	128
6	Darnall	Sugarcane	1,066,541	109
40	Darnall	Sugarcane	872,749	110
39	Darnall	Sugarcane	44,900	141
12	Eston	Sugarcane	3,169,626	50
13	Felixton	Sugarcane	2,620,730	164
9	Felixton	Sugarcane	6,638	160
13	Gledhow	Sugarcane	3,008,465	103
17	Gledhow	Sugarcane	218,799	98
21	Komati	Sugarcane	1,557,015	352
26	Komati	Sugarcane	798,085	417
24	Komati	Sugarcane	194,530	381
23	Komati	Sugarcane	81,950	354
12	Maidstone	Sugarcane	2,670,979	93
42	Maidstone	Sugarcane	995,487	78
22	Malelani	Sugarcane	1,306,167	367
26	Malelani	Sugarcane	620,149	459
12	Noodsberg	Sugarcane	3,140,807	68
16	Pongola	Sugarcane	1,473,684	258
11	Sezela	Sugarcane	3,735,714	6
9	UCL	Sugarcane	2,590,547	89
5	UCL	Sugarcane	257,438	108
13	Umfolozi	Sugarcane	1,263,158	193
11	Umzikulu	Sugarcane	1,766,821	14
38	Umzikulu	Sugarcane	1,402,805	5

Table A3.1.2: Quantities of feedstock transported to bio-ethanol processing facilities and average transport distances for Case 1 when feedstock prices are doubled

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
41	Amatikulu	Sugarcane	1,228,235	141
40	Amatikulu	Sugarcane	987,717	128
6	Darnall	Sugarcane	1,066,541	109
40	Darnall	Sugarcane	872,749	110
39	Darnall	Sugarcane	44,900	141
12	Eston	Sugarcane	3,169,626	50
13	Felixton	Sugarcane	2,620,730	164
9	Felixton	Sugarcane	6,638	160
13	Gledhow	Sugarcane	3,008,465	103
17	Gledhow	Sugarcane	218,799	98
21	Komati	Sugarcane	1,557,015	352
26	Komati	Sugarcane	992,614	417
23	Komati	Sugarcane	81,950	354
12	Maidstone	Sugarcane	2,670,979	93
42	Maidstone	Sugarcane	995,487	78
22	Malelani	Sugarcane	1,306,167	367
26	Malelani	Sugarcane	425,619	459
24	Malelani	Sugarcane	194,530	423
12	Noodsberg	Sugarcane	3,140,807	68
16	Pongola	Sugarcane	1,473,684	258
11	Sezela	Sugarcane	3,735,714	6
9	UCL	Sugarcane	2,590,547	89
5	UCL	Sugarcane	257,438	108
13	Umfolozi	Sugarcane	1,263,158	193
11	Umzikulu	Sugarcane	1,766,821	14
38	Umzikulu	Sugarcane	1,402,805	5

Table A3.1.3: Quantities of feedstock transported to bio-ethanol processing facilities and average transport distances for Case 1 when product selling prices are doubled

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
41	Amatikulu	Sugarcane	1,228,235	141
40	Amatikulu	Sugarcane	987,717	128
6	Darnall	Sugarcane	1,066,541	109
40	Darnall	Sugarcane	872,749	110
39	Darnall	Sugarcane	44,900	141
12	Eston	Sugarcane	3,169,626	50
13	Felixton	Sugarcane	2,620,730	164
9	Felixton	Sugarcane	6,638	160
13	Gledhow	Sugarcane	3,008,465	103
17	Gledhow	Sugarcane	218,799	98
21	Komati	Sugarcane	1,557,015	352
26	Komati	Sugarcane	798,085	417
24	Komati	Sugarcane	194,530	381
23	Komati	Sugarcane	81,950	354
12	Maidstone	Sugarcane	2,670,979	93
42	Maidstone	Sugarcane	995,487	78
22	Malelani	Sugarcane	1,306,167	367
26	Malelani	Sugarcane	620,149	459
12	Noodsberg	Sugarcane	3,140,807	68
16	Pongola	Sugarcane	1,473,684	258
11	Sezela	Sugarcane	3,735,714	6
9	UCL	Sugarcane	2,590,547	89
5	UCL	Sugarcane	257,438	108
13	Umfolozzi	Sugarcane	1,263,158	193
11	Umzikulu	Sugarcane	1,766,821	14
38	Umzikulu	Sugarcane	1,402,805	5

Table A3.1.4: Quantities of feedstock transported to bio-ethanol processing facilities and average transport distances for the scenario when transport cost is doubled (Case 1).

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
40	Amatikulu	Sugarcane	1,860,465	128
41	Amatikulu	Sugarcane	318,229	141
6	Darnall	Sugarcane	1,066,541	109
9	Darnall	Sugarcane	659,438	124
13	Eston	Sugarcane	2,259,620	39
41	Eston	Sugarcane	910,006	34
13	Felixton	Sugarcane	1,996,795	164
9	Felixton	Sugarcane	630,574	160
13	Gledhow	Sugarcane	1,372,780	103
17	Gledhow	Sugarcane	218,799	98
21	Komati	Sugarcane	1,557,015	352
26	Komati	Sugarcane	798,085	417
24	Komati	Sugarcane	194,530	381
23	Komati	Sugarcane	81,950	354
12	Maidstone	Sugarcane	1,003,065	93
42	Maidstone	Sugarcane	995,487	78
9	Maidstone	Sugarcane	491,385	79
22	Malelani	Sugarcane	1,306,167	367
26	Malelani	Sugarcane	620,149	459
12	Noodsberg	Sugarcane	1,734,156	68
16	Pongola	Sugarcane	1,473,684	258
11	Sezela	Sugarcane	3,735,714	6
9	UCL	Sugarcane	815,789	89
13	Umfolozi	Sugarcane	1,263,158	193
11	Umzikulu	Sugarcane	1,766,821	14
38	Umzikulu	Sugarcane	1,402,805	5

Table A3.1.5: Quantities of feedstock transported to processing facilities and average transport distances for the scenario when sugar export demand is ignored (Case 1).

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
40	Amatikulu	Sugarcane	1,307,217	128
6	Darnall	Sugarcane	1,066,541	109
40	Darnall	Sugarcane	363,030	110
13	Eston	Sugarcane	1,653,200	39
41	Eston	Sugarcane	1,228,235	34
13	Felixton	Sugarcane	1,576,421	164
13	Gledhow	Sugarcane	2,000,545	103
17	Gledhow	Sugarcane	218,799	98
40	Gledhow	Sugarcane	190,218	91
21	Komati	Sugarcane	1,557,015	352
23	Komati	Sugarcane	21,933	354
12	Maidstone	Sugarcane	2,184,053	93
42	Maidstone	Sugarcane	995,487	78
22	Malelani	Sugarcane	1,155,789	367
12	Noodsberg	Sugarcane	1,959,852	68
13	Noodsberg	Sugarcane	904,292	59
16	Pongola	Sugarcane	884,211	258
11	Sezela	Sugarcane	3,221,088	6
9	UCL	Sugarcane	2,597,186	89
5	UCL	Sugarcane	91,265	108
13	Umfoloji	Sugarcane	757,895	193
11	Umzikulu	Sugarcane	1,478,630	14
38	Umzikulu	Sugarcane	1,402,805	5
40	Amatikulu	Sugarcane	1,307,217	128
6	Darnall	Sugarcane	1,066,541	109
40	Darnall	Sugarcane	363,030	110

Table A3.2.1: Quantities of feedstock transported to processing facilities and average transport distances for base case scenario (Case 2)

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
1	Amatikulu	Sugarcane	606,899	260
3	Amatikulu	Sugarcane	539,037	204
6	Amatikulu	Sugarcane	154,778	144
40	Amatikulu	Sugarcane	92,755	128
3	Darnall	Sugarcane	1,540,562	169
38	Darnall	Sugarcane	185,417	198
39	Eston	Sugarcane	488,245	67
19	Eston	Sugarcane	410,040	82
7	Eston	Sugarcane	336,598	65
2	Eston	Sugarcane	195,556	113
10	Eston	Sugarcane	43,246	82
13	Felixton	Sugarcane	911,936	164
40	Felixton	Sugarcane	820,709	153
41	Felixton	Sugarcane	622,554	162
9	Felixton	Sugarcane	272,170	160
1	Gledhow	Sugarcane	815,185	216
17	Gledhow	Sugarcane	285,898	98
39	Gledhow	Sugarcane	251,038	131
15	Gledhow	Sugarcane	239,458	123
28	Komati	Sugarcane	1,858,703	451
24	Komati	Sugarcane	343,193	381
26	Komati	Sugarcane	262,956	417
21	Komati	Sugarcane	111,443	352
29	Komati	Sugarcane	43,086	588
23	Komati	Sugarcane	12,198	354

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
11	Maidstone	Sugarcane	705,079	103
5	Maidstone	Sugarcane	559,738	108
43	Maidstone	Sugarcane	347,451	97
20	Maidstone	Sugarcane	328,417	137
4	Maidstone	Sugarcane	299,104	110
18	Maidstone	Sugarcane	109,070	119
19	Maidstone	Sugarcane	102,781	123
42	Maidstone	Sugarcane	38,297	78
27	Malelani	Sugarcane	411,102	519
24	Malelani	Sugarcane	391,122	423
25	Malelani	Sugarcane	360,995	473
46	Malelani	Sugarcane	356,474	348
44	Malelani	Sugarcane	301,872	591
45	Malelani	Sugarcane	54,226	371
18	Malelani	Sugarcane	37,517	559
22	Malelani	Sugarcane	12,708	367
14	Malelani	Sugarcane	300	583
11	Noodsberg	Sugarcane	862,184	83
12	Noodsberg	Sugarcane	552,552	68
18	Pongola	Sugarcane	1,299,598	300
16	Pongola	Sugarcane	174,086	258
32	Sezela	Sugarcane	898,786	42
37	Sezela	Sugarcane	575,106	63
35	Sezela	Sugarcane	371,758	146
31	Sezela	Sugarcane	283,134	122
30	Sezela	Sugarcane	202,506	152
1	Sezela	Sugarcane	186,078	75

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
33	Sezela	Sugarcane	114,210	56
5	UCL	Sugarcane	815,789	108
13	Umfolozi	Sugarcane	1,263,158	193
36	Umzikulu	Sugarcane	1,089,476	23
31	Umzikulu	Sugarcane	310,732	59
34	Umzikulu	Sugarcane	81,505	82

Table A3.2.2: Quantities of feedstock transported to processing facilities and average transport distances for Case 2 when feedstock prices are doubled

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
1	Amatikulu	Sugarcane	606,899	260
3	Amatikulu	Sugarcane	539,037	204
6	Amatikulu	Sugarcane	154,778	144
40	Amatikulu	Sugarcane	92,755	128
3	Darnall	Sugarcane	1,540,562	169
38	Darnall	Sugarcane	185,417	198
39	Eston	Sugarcane	488,245	67
19	Eston	Sugarcane	410,040	82
7	Eston	Sugarcane	336,598	65
2	Eston	Sugarcane	195,556	113
10	Eston	Sugarcane	43,246	82
13	Felixton	Sugarcane	911,936	164
40	Felixton	Sugarcane	820,709	153
41	Felixton	Sugarcane	622,554	162
9	Felixton	Sugarcane	272,170	160
1	Gledhow	Sugarcane	815,185	216
17	Gledhow	Sugarcane	285,898	98
39	Gledhow	Sugarcane	251,038	131
15	Gledhow	Sugarcane	239,458	123
24	Komati	Sugarcane	734,316	381
28	Komati	Sugarcane	695,484	451
27	Komati	Sugarcane	411,102	477
25	Komati	Sugarcane	360,995	431
26	Komati	Sugarcane	262,956	417

Farm number	Processing facility	Feedstock	Quantity	
			shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
21	Komati	Sugarcane	111,443	352
29	Komati	Sugarcane	43,086	588
23	Komati	Sugarcane	12,198	354
11	Maidstone	Sugarcane	705,079	103
5	Maidstone	Sugarcane	559,738	108
43	Maidstone	Sugarcane	347,451	97
20	Maidstone	Sugarcane	328,417	137
4	Maidstone	Sugarcane	299,104	110
18	Maidstone	Sugarcane	109,070	119
19	Maidstone	Sugarcane	102,781	123
42	Maidstone	Sugarcane	38,297	78
28	Malelani	Sugarcane	1,163,219	493
46	Malelani	Sugarcane	356,474	348
44	Malelani	Sugarcane	301,872	591
45	Malelani	Sugarcane	54,226	371
18	Malelani	Sugarcane	37,517	559
22	Malelani	Sugarcane	12,708	367
14	Malelani	Sugarcane	300	583
11	Noodsberg	Sugarcane	862,184	83
12	Noodsberg	Sugarcane	552,552	68
18	Pongola	Sugarcane	1,299,598	300
16	Pongola	Sugarcane	174,086	258
32	Sezela	Sugarcane	898,786	42
37	Sezela	Sugarcane	575,106	63
31	Sezela	Sugarcane	485,640	122
35	Sezela	Sugarcane	371,758	146

Farm number	Processing facility	Feedstock	Quantity	
			shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
1	Sezela	Sugarcane	186,078	75
33	Sezela	Sugarcane	114,210	56
5	UCL	Sugarcane	815,789	108
13	Umfolozi	Sugarcane	1,263,158	193
36	Umzikulu	Sugarcane	1,089,476	23
30	Umzikulu	Sugarcane	194,478	89
31	Umzikulu	Sugarcane	108,226	59
34	Umzikulu	Sugarcane	81,505	82

Table A3.2.3: Quantities of feedstock transported to processing facilities and average transport distances for Case 2 when selling prices are doubled

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
1	Amatikulu	Sugarcane	606,899	260
3	Amatikulu	Sugarcane	539,036	204
6	Amatikulu	Sugarcane	154,778	144
40	Amatikulu	Sugarcane	92,755	128
3	Darnall	Sugarcane	1,540,562	169
38	Darnall	Sugarcane	185,417	198
39	Eston	Sugarcane	488,245	67
19	Eston	Sugarcane	410,040	82
7	Eston	Sugarcane	336,598	65
2	Eston	Sugarcane	195,556	113
10	Eston	Sugarcane	43,246	82
13	Felixton	Sugarcane	911,936	164
40	Felixton	Sugarcane	820,709	153
41	Felixton	Sugarcane	622,554	162
9	Felixton	Sugarcane	272,170	160
1	Gledhow	Sugarcane	815,185	216
17	Gledhow	Sugarcane	285,898	98
39	Gledhow	Sugarcane	251,038	131
15	Gledhow	Sugarcane	239,458	123
24	Komati	Sugarcane	734,316	381
28	Komati	Sugarcane	695,484	451
27	Komati	Sugarcane	411,102	477
25	Komati	Sugarcane	360,995	431
26	Komati	Sugarcane	262,956	417
21	Komati	Sugarcane	111,443	352
29	Komati	Sugarcane	43,086	588
23	Komati	Sugarcane	12,198	354
11	Maidstone	Sugarcane	705,079	103
5	Maidstone	Sugarcane	559,738	108
43	Maidstone	Sugarcane	347,451	97
20	Maidstone	Sugarcane	328,417	137

Farm number	Processing facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
4	Maidstone	Sugarcane	299,104	110
18	Maidstone	Sugarcane	109,070	119
19	Maidstone	Sugarcane	102,781	123
42	Maidstone	Sugarcane	38,297	78
28	Malelani	Sugarcane	1,163,219	493
46	Malelani	Sugarcane	356,474	348
44	Malelani	Sugarcane	301,872	591
45	Malelani	Sugarcane	54,226	371
18	Malelani	Sugarcane	37,517	559
22	Malelani	Sugarcane	12,708	367
14	Malelani	Sugarcane	300	583
11	Noodsberg	Sugarcane	862,184	83
12	Noodsberg	Sugarcane	552,552	68
18	Pongola	Sugarcane	1,299,598	300
16	Pongola	Sugarcane	174,086	258
32	Sezela	Sugarcane	898,786	42
37	Sezela	Sugarcane	575,106	63
31	Sezela	Sugarcane	485,640	122
35	Sezela	Sugarcane	371,758	146
1	Sezela	Sugarcane	186,078	75
33	Sezela	Sugarcane	114,210	56
5	UCL	Sugarcane	815,789	108
13	Umfoloji	Sugarcane	1,263,158	193
36	Umzikulu	Sugarcane	1,089,476	23
30	Umzikulu	Sugarcane	194,478	89
31	Umzikulu	Sugarcane	108,226	59
34	Umzikulu	Sugarcane	81,505	82

Table A3.2.4: Quantities of feedstock transported to processing facilities and average transport distances for the scenario when transport cost is doubled (Case 2).

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
1	Amatikulu	Sugarcane	606,899	260
3	Amatikulu	Sugarcane	539,037	204
6	Amatikulu	Sugarcane	154,778	144
40	Amatikulu	Sugarcane	92,755	128
3	Darnall	Sugarcane	1,540,562	169
38	Darnall	Sugarcane	185,417	198
39	Eston	Sugarcane	488,245	67
19	Eston	Sugarcane	410,040	82
7	Eston	Sugarcane	336,598	65
2	Eston	Sugarcane	195,556	113
10	Eston	Sugarcane	43,246	82
13	Felixton	Sugarcane	911,936	164
40	Felixton	Sugarcane	820,709	153
41	Felixton	Sugarcane	622,554	162
9	Felixton	Sugarcane	272,170	160
1	Gledhow	Sugarcane	815,185	216
17	Gledhow	Sugarcane	285,898	98
39	Gledhow	Sugarcane	251,038	131
15	Gledhow	Sugarcane	239,458	123
24	Komati	Sugarcane	734,316	381
28	Komati	Sugarcane	695,484	451
27	Komati	Sugarcane	411,102	477
25	Komati	Sugarcane	360,995	431
26	Komati	Sugarcane	262,956	417
21	Komati	Sugarcane	111,443	352

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
29	Komati	Sugarcane	43,086	588
23	Komati	Sugarcane	12,198	354
11	Maidstone	Sugarcane	705,079	103
5	Maidstone	Sugarcane	559,738	108
43	Maidstone	Sugarcane	347,451	97
20	Maidstone	Sugarcane	328,417	137
4	Maidstone	Sugarcane	299,104	110
18	Maidstone	Sugarcane	109,070	119
19	Maidstone	Sugarcane	102,781	123
42	Maidstone	Sugarcane	38,297	78
28	Malelani	Sugarcane	1,163,219	493
46	Malelani	Sugarcane	356,474	348
44	Malelani	Sugarcane	301,872	591
45	Malelani	Sugarcane	54,226	371
18	Malelani	Sugarcane	37,517	559
22	Malelani	Sugarcane	12,708	367
14	Malelani	Sugarcane	300	583
11	Noodsberg	Sugarcane	862,184	83
12	Noodsberg	Sugarcane	552,552	68
18	Pongola	Sugarcane	1,299,598	300
16	Pongola	Sugarcane	174,086	258
32	Sezela	Sugarcane	898,786	42
37	Sezela	Sugarcane	575,106	63
31	Sezela	Sugarcane	485,640	122
35	Sezela	Sugarcane	371,758	146
1	Sezela	Sugarcane	186,078	75
33	Sezela	Sugarcane	114,210	56

Farm number	Processing facility	Feedstock	Quantity Shipped (t)	Shipping distance (km)
8	Amatikulu	Sugarcane	785,226	165
5	UCL	Sugarcane	815,789	108
13	Umfolozi	Sugarcane	1,263,158	193
36	Umzikulu	Sugarcane	1,089,476	23
30	Umzikulu	Sugarcane	194,478	89
31	Umzikulu	Sugarcane	108,226	59
34	Umzikulu	Sugarcane	81,505	82

Table A3.2.5: Quantities of feedstock transported to processing facilities and average transport distances for the scenario when sugar export demand is ignored (Case 2)

Farm number	Processing Facility	Feedstock	Quantity shipped (t)	Shipping distance (km)
40	Amatikulu	Sugarcane	1,719,987	128
41	Amatikulu	Sugarcane	1,368,253	141
6	Darnall	Sugarcane	1,188,127	109
9	Darnall	Sugarcane	870,154	124
39	Darnall	Sugarcane	447,399	141
40	Darnall	Sugarcane	352,571	110
16	Darnall	Sugarcane	97,191	143
12	Eston	Sugarcane	2,881,435	50
13	Felixton	Sugarcane	2,186,125	164
9	Felixton	Sugarcane	1,033,729	160
13	Gledhow	Sugarcane	2,672,276	103
17	Gledhow	Sugarcane	243,742	98
21	Komati	Sugarcane	1,734,514	352
26	Komati	Sugarcane	1,178,576	417
24	Komati	Sugarcane	216,706	381
23	Komati	Sugarcane	91,292	354
12	Maidstone	Sugarcane	2,070,567	93
42	Maidstone	Sugarcane	1,108,972	78
22	Malelani	Sugarcane	1,455,070	367
26	Malelani	Sugarcane	963,306	459
25	Malelani	Sugarcane	595,834	473
12	Noodsberg	Sugarcane	2,864,144	68
16	Pongola	Sugarcane	2,881,435	258
11	Sezela	Sugarcane	3,221,088	6
5	UCL	Sugarcane	1,699,069	108
9	UCL	Sugarcane	989,382	89
13	Umfolozi	Sugarcane	2,819,680	193
38	Umzikulu	Sugarcane	1,562,725	5
11	Umzikulu	Sugarcane	1,318,710	14

Table A3.2.6: Farms supplying processing facilities and average transportation distances for feedstock when transport costs are increased by a factor of 2 (Case 1)

Farm	Plant	Feedstock (t)	Average distance (km)
36, 30, 31, 34	Umzikulu	1,473,684	63
11, 12	Noodsberg	1,414,737	75
39, 19, 7, 2, 10	Eston	1,473,684	82
32, 37, 31, 35, 1, 33	Sezela	2,631,579	84
5	UCL	815,789	108
11, 5, 43, 20, 4, 18, 19, 42	Maidstone	2,489,937	109
1, 17, 39, 15	Gledhow	1,591,579	142
13, 40, 41, 9	Felixton	2,627,368	160
8, 1, 3, 6, 40	Amatikulu	2,178,695	180
3, 38	Darnall	1,725,979	184
13	Umfolozi	1,263,158	193
18, 16	Pongola	1,473,684	279
24, 28, 27, 25, 26, 21, 29, 23	Komati	2,631,579	431
28, 46, 44, 45, 18, 22, 14	Malelani	1,926,316	473

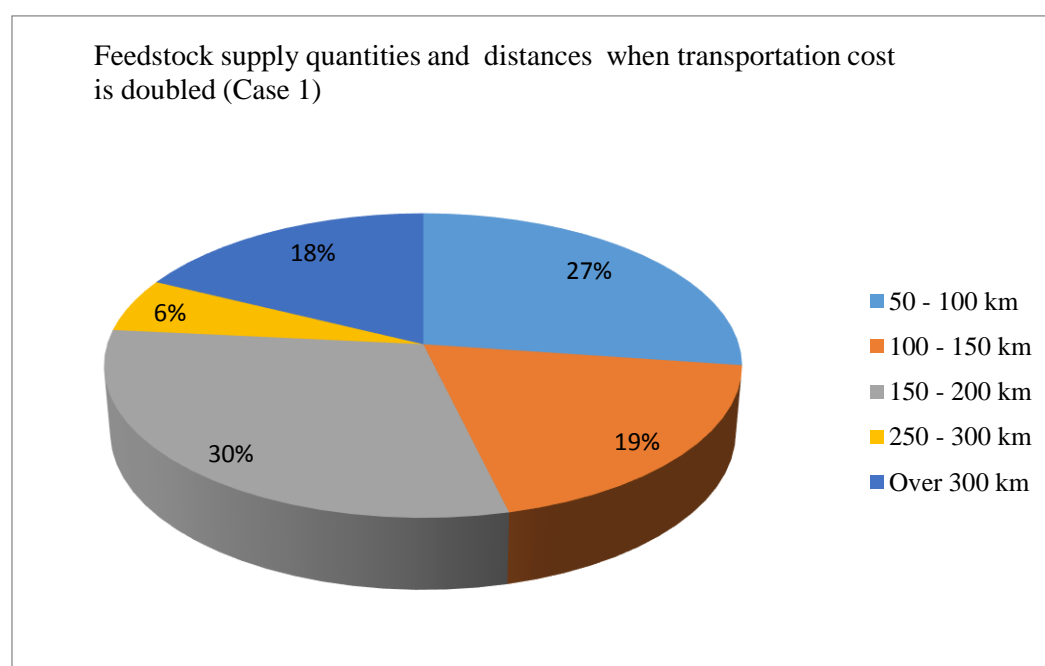


Figure A3.2: Farms supplying processing facilities and average transportation distances for feedstock when transport costs are increased by a factor of 2 (Case 1).

Table A3.2.7: Farms supplying processing facilities and average transportation distances for feedstock when selling prices are increased by a factor of 2 (Case 1)

Farm	Plant	Feedstock (t)	Average distance (km)
36, 30, 31, 34	Umzikulu	1,481,712	63
	Noodsberg		
11, 12	g	1,414,737	75
39, 19, 7, 2, 10	Eston	1,473,684	82
32, 37, 31, 35, 1, 33	Sezela	2,631,579	84
5	UCL	815,789	108
11, 5, 43, 20, 4, 18, 19, 42	Maidstone	2,489,937	109
1, 17, 39, 15	Gledhow	1,591,579	142
13, 40, 41, 9	Felixton	2,627,368	159
8, 1, 3, 6, 40	Amatikulu	2,178,695	180
3, 38	Darnall	1,725,979	183
13	Umfolozzi	1,263,158	193
18, 16	Pongola	1,473,684	279
28, 24, 26, 21, 29, 23	Komati	2,631,579	423
27, 24, 25, 46, 44, 45, 18, 22, 14	Malelani	1,926,316	470

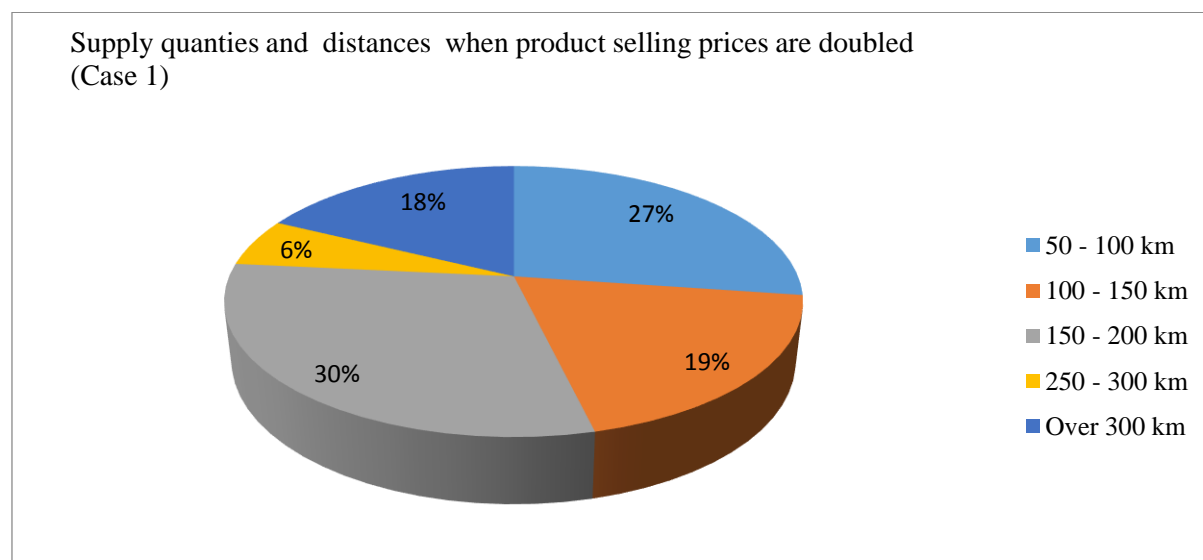


Figure A3.3: Farms supplying processing facilities and average transportation distances for feedstock when product selling prices are increased by a factor of 2 (Case 1)

Table A3.2.8: Farms supplying processing facilities and average transportation distances for feedstock when feedstock prices are increased by a factor of 2 (Case 1)

Farm	Plant	Feedstock (t)	Average distance (km)
36, 30, 31, 34	Umzikulu	1,473,684	63
11, 12	Noodsberg	1,414,737	75
39, 19, 7, 2, 10	Eston	1,473,684	82
32, 37, 31, 35, 1, 33	Sezela	2,631,579	84
5	UCL	815,789	108
11, 5, 43, 20, 4, 18, 19, 42	Maidstone	2,489,937	109
1, 17, 39, 15	Gledhow	1,591,579	142
13, 40, 41, 9	Felixton	2,627,368	160
8, 1, 3, 6, 40	Amatikulu	2,178,695	180
3, 38	Darnall	1,725,979	184
13	Umfoloji	1,263,158	193
18, 16	Pongola	1,473,684	279
24, 28, 27, 25, 26, 21, 29, 23	Komati	2,631,579	431
28, 46, 44, 45, 18, 22, 14	Malelani	1,926,316	473

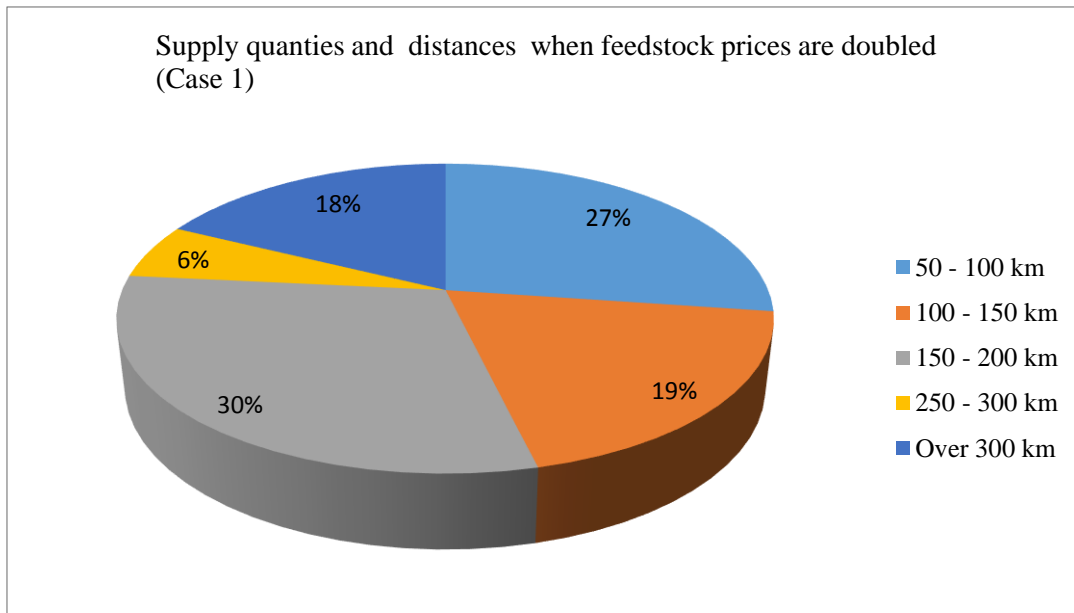


Figure A3.4: Farms supplying processing facilities and average transportation distances for feedstock when feedstock prices are increased by a factor of 2 (Case 1)

Table A3.2.9: Farms supplying processing facilities and average transportation distances for feedstock when export demand is ignored (Case 1)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,221,088	6
38, 11	Umzikulu	2,881,435	9
12	Eston	2,881,435	50
12	Noodsberg	2,864,144	68
12, 42	Maidstone	3,179,540	85
5, 9	UCL	2,688,451	99
13, 17	Gledhow	2,916,018	101
6, 9, 39, 40, 16	Darnall	2,955,443	125
40, 41	Amatikulu	3,088,241	135
13, 9	Felixton	3,219,853	162
13	Umfolozi	2,819,680	193
16	Pongola	2,881,435	258
21, 26, 24, 23	Komati	3,221,088	376
22, 26, 25	Malelani	3,014,209	433

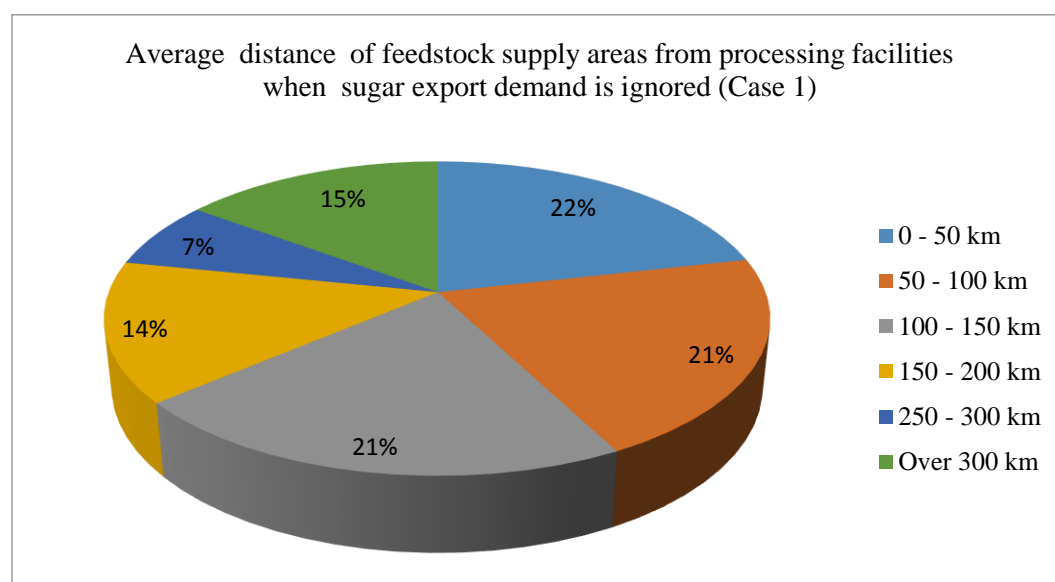
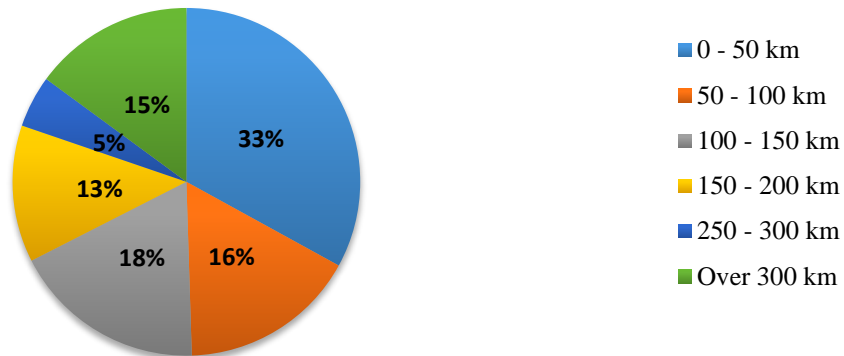


Figure A3.5: Farms supplying processing facilities and average transportation distances for feedstock when sugar export demand is ignored (Case 1)

Feedstock supply quantities and distances when transportation cost is doubled (Case 2)



Figure

A3.6: Supply quantities and distances when transportation cost is doubled (Case 2)

Table A3.3.0: Farms supplying processing facilities and average transportation distances for feedstock when transportation costs are increased by a factor of 2 (Case 2)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,735,714	6
11, 38	Umzikulu	3,169,626	10
13, 41	Eston	3,169,626	36
12	Noodsberg	1,734,156	68
12, 42, 9	Maidstone	2,489,937	83
9	UCL	815,789	89
13, 17	Gledhow	1,591,579	101
6, 9	Darnall	1,725,979	117
40, 41	Amatikulu	2,178,695	135
13, 9	Felixton	2,627,368	162
13	Umfoloji	1,263,158	193
16	Pongola	1,473,684	258
21, 26, 24, 23	Komati	2,631,579	376
22, 26	Malelani	1,926,316	413

Supply quantities and distances when product selling prices increased by a factor of 2 (Case 2)

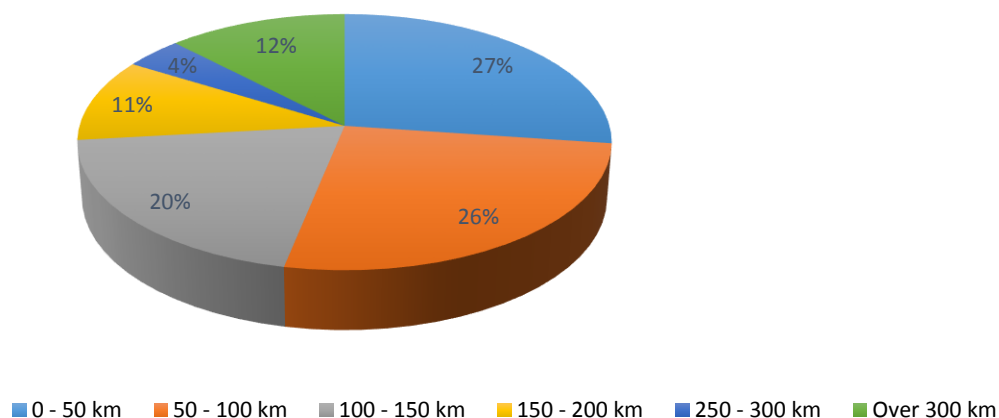


Figure A3.7 Farms supplying processing facilities and average transportation distances for feedstock when selling prices are increased by a factor of 2 (Case 2)

Table A3.3.1: Farms supplying processing facilities and average transportation distances for feedstock when selling prices are increased by a factor of 2 (Case 2)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,735,714	6
11, 38	Umzikulu	3,169,626	9
12	Eston	3,169,626	50
12	Noodsberg	3,140,807	68
12, 42	Maidstone	3,666,466	85
9, 5	UCL	2,847,985	99
13, 17	Gledhow	3,227,264	101
6, 40, 39	Darnall	1,984,189	120
41, 40	Amatikulu	2,215,952	135
13, 9	Felixton	2,627,368	162
13	Umfolozi	1,263,158	193
16	Pongola	1,473,684	258
21, 26, 24, 23	Komati	2,631,579	376
22, 26	Malelani	1,926,316	413

Feedstock supply quantities and distances when feedstock prices increased by a factor of 2 (Case 2)

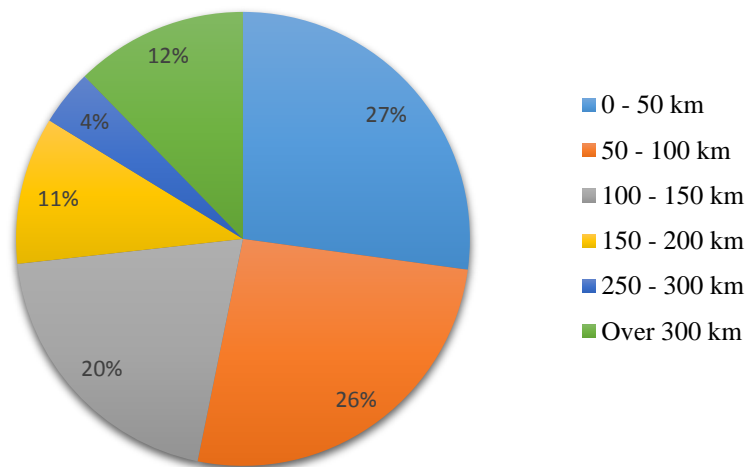


Figure A3.8: Farms supplying processing facilities and average transportation distances of feedstock when feedstock prices are increased by a factor of 2 (Case 2)

Table A3.3.2: Farms supplying processing facilities and average transportation distances for feedstock when feedstock prices are increased by a factor of 2 (Case 2)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,735,714	6
11, 38	Umzikulu	3,169,626	9
12	Eston	3,169,626	50
12	Noodsberg	3,140,807	68
12, 42	Maidstone	3,666,466	85
h9, 5	UCL	2,847,985	99
13, 17	Gledhow	3,227,264	101
6, 40, 39	Darnall	1,984,189	120
41, 40	Amatikulu	2,215,952	135
13, 9	Felixton	2,627,368	162
13	Umfoloji	1,263,158	193
16	Pongola	1,473,684	258
21, 26, 23	Komati	2,631,579	374
22, 26, 24	Malelani	1,926,316	416

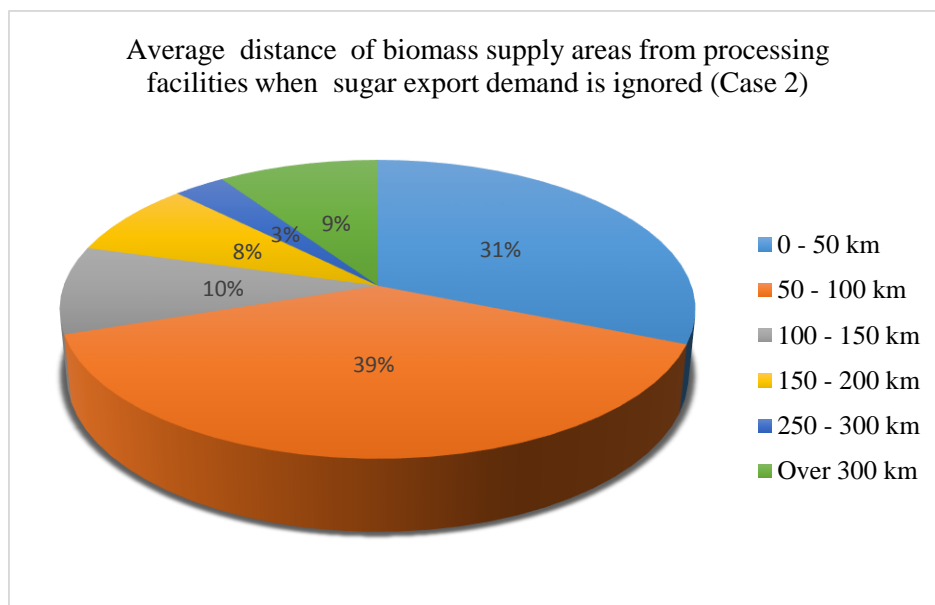


Figure A3.9: Farms supplying processing facilities and average transportation distances for feedstock when sugar export demand is ignored (Case 2)

Table A3.3.3: Farms supplying processing facilities and average transportation distances for feedstock when sugar export demand is ignored (Case 2)

Farm	Plant	Feedstock (t)	Average distance (km)
11	Sezela	3,221,088	6
11, 38	Umzikulu	2,881,435	9
13, 41	Eston	2,881,435	36
12, 13	Noodsberg	2,864,144	64
12, 42	Maidstone	3,179,540	85
13, 17, 40	Gledhow	2,409,562	98
9, 5	UCL	2,688,451	99
6, 40	Darnall	1,429,571	110
40	Amatikulu	1,307,217	128
13	Felixton	1,576,421	164
13	Umfolozi	757,895	193
16	Pongola	884,211	258
21, 23	Komati	1,578,947	353
22	Malelani	1,155,789	367

Appendix A4: Multiobjective optimisation results

Table A4.1: Pareto curve points for multiobjective optimisation of Case 1

Environmental impact (kg CO ₂ eq)	Economic Potential Profit (ZAR million)
3,643,903,069	188
3,643,903,069	188
3,643,808,080	188
3,643,708,080	183
3,643,023,065	183
3,643,023,065	183
3,643,023,065	183
3,643,023,065	183
3,643,023,065	183
3,643,023,065	183
3,643,023,065	183

Table A4.2: Pareto curve points for multiobjective optimisation of Case 2

Environmental impact (kg CO ₂ eq)	Economic Potential (ZAR million)
4,579,246,790	7296.34571
4,579,246,790	7296.34571
4,524,865,000	7012.2808
4,470,484,000	6723.78155
4,416,103,000	6435.09545
4,410,000,000	6402.17595
4,307,340,000	5838.92643
4,252,959,000	5539.89242
4,144,196,000	4925.62671
4,035,400,000	4278.58471
4,034,533,000	4273.24691
3,926,671,000	3606.13359
3,817,908,000	2891.5409
3,798,080,000	2760.84722
3,709,154,000	2139.3781

Appendix A5: Product distribution transportation distance

Table A5: Supply of product and average transportation distances of product for base case scenario (Case 1)

Plant	Distance to depot/km	Depot	Average distance to depot/km
Gledhow	146	Engen	
Komati	425	Engen	
Malelani	469	Engen	304
UCL	108	Engen	
Eston	82	Engen	
Amatikulu	174	Sapref	
Darnall	184	Sapref	
Felixton	160	Sapref F	
Maidstone	109	Sapref	
Noodsberg	75	Sapref	162
Pongola	279	Sapref	
Sezela	84	Sapref F	
Umfolozi	193	Sapref	
Umzikulu	80	Sapref	

Appendix A6: Economic potential analysis

Table A6.1: Profit and net present value (after 20 years) at different discount rates for Case 1

Discount rate (%)	Profit (ZAR*10 ⁶)	NPV (ZAR*10 ⁶)
5	494	
6	394	35970
8	188	25542
10	-30.84	17306
15	-621	3074
20	-1263	-5700

Table A6.2: Profit and net present value (after 20 years) at different discount rates for Case 2

Discount rate (%)	Profit (ZAR*10 ⁶)	NPV (ZAR*10 ⁶)
5	7749	
6	7602	93131
8	7296	71846
10	6971	55948
15	6096	25986
20	5157	8129

APPENDIX B1: GAMS CODE CASE 2

- *\$Title Enumerate all Feasible Basic Solutions of the Supply Problem
- *(ALLBASES,SEQ=396)
- * products and feedstocks in 1000 tons per year
- * economics in 1000000 rands per year
- * electricity in MWh / y
- * heat in GJ / y
- * Assumptions
- * Plant life of 20 years
- * Plants operates through the year
- * No investment in sugar milling
- * No investment in infrastructure
- * No investment in vehicles
- * Domestic sugar demand is satisfied

- * Each farm is 30 by 40kms long
- * sugar warehouses are at the mills
- * every mill/plant has a cogeneration facility

\$OFFSYMXREF

\$OFFSYMLIST

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option limrow=100000;

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option reslim = 1000000;

Option solprint=on;

\$eolcom #

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file results /results.gms/ ;

Sets

I Biomass farms /1*221/

M Location of sugar mills and storage /Umzikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Flexiton, Umfolozi,Pongola, Komati, Malelani,15,16, 17, 18, 19, 20 /

N1 Location of pre-treatment and storage /Umzikulu, Sezela, Eston, Noodsberg, Maidstone,UCL, Gledhow, Darnall,Amatikulu, Flexiton, Umfolozi,Pongola, Komati, Malelani, 15, 16, 17, 18, 19, 20/

N2 Location of plants /Umzikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Flexiton, Umfolozi,Pongola, Komati, Malelani, 15, 16, 17, 18, 19, 20/

J Product demand centres / Engen,Sapref, Animalfeedcentre , Sugarwarehouse1, Ligninckake warehouse, Umzikulu, Sezela, Eston, Noodsberg, Maidstone, UCL, Gledhow, Darnall, Amatikulu, Flexiton, Umfolozi,Pongola, Komati, Malelani/

P Resources and products /sugarcane, sugarcaneleaves, bagasse, bagasseCHP, maizestraw, sorghumstraw, wheatstraw, barleystraw, sugar, ethanol, electricity, heat,molasses ligninckake /

RE(p) Raw materials /sugarcane, sugarcaneleaves, maizestraw, sorghumstraw, wheatstraw, barleystraw /

PI(p) Intermediate raw materials /sugarcane, sugarcaneleaves,maizestraw, sorghumstraw, wheatstraw, barleystraw, bagasse, bagasseCHP/

PM(p) Intermediate raw materials/sugarcane, sugarcaneleaves, maizestraw,sorghumstraw, wheatstraw, lignincake, barleystraw,bagasse, bagasseCHP/

PD(p) Direct products /sugar, molasses /

PP(p) Produced products /ethanol, electricity, heat, lignincake/

PR(p) Products /sugar, molasses, ethanol, electricity, heat/

kp(p) Key products /ethanol, sugar, electricity /

tp time periods /2015 /

t technology /sugar_milling, fermentation, CHP, pretreatment, storage, blending,crushing /

elhe(p) electricity and heat / electricity, heat /

* technologies at the second level m

t2(t) /sugar_milling, storage,crushing /

* technologies at the third level n1

t3(t) /pretreatment, storage /

* technologies at the fourth level n2

t4(t) /fermentation, CHP /

* technologies at fifth level

t5 (t) / blending, storage /

Alias (t,tt)
(n2,nn2) ;

Set

ret(re,t) technology for each raw material # second level

/ sugarcane	sugar_milling
sugarcane	.crushing
sugarcaneleaves	.storage
wheatstraw	storage
Maizestraw .	storage
Sorghumstraw	.storage
Barleystraw	storage /

pit(pi,t) technology for each intermediate raw material pi # third level

/ sugarcane	pretreatment
bagasse	pretreatment
bagasse	storage
sugarcaneleaves	.pretreatment
wheatstraw	pretreatment
maizestraw	pretreatment
sorghumstraw	pretreatment

Barleystraw pretreatment /

pmt(pm,t) technology for each intermediate raw material pm # fourth level
/ sugarcane fermentation
sugarcaneleaves .fermentation
bagasse fermentation
bagasseCHP CHP
lignincake CHP
wheatstraw fermentation
maizestraw fermentation
sorghumstraw fermentation
Barleystraw fermentation /

ppt(pp,t) produced products from technology
/ ethanol fermentation
lignincake fermentation
Electricity CHP
Heat CHP /

Set

repi(re,pi) index set intermediate raw materials pi from each raw material re
/ sugarcane sugarcane
Sugarcaneleaves sugarcaneleaves
Sugarcane bagasse
wheatstraw wheatstraw
maizestraw maizestraw
sorghumstraw sorghumstraw
Barleystraw barleystraw /

repd(re,pd) index set of direct products pd produced from each re
/ sugarcane sugar
Sugarcane molasses /

pipm(p,pm) index set intermediate raw materials pm from each raw material pi
/ sugarcane sugarcane
Sugarcaneleaves sugarcaneleaves
bagasse bagasse
bagasse bagasseCHP
wheatstraw wheatstraw
maizestraw maizestraw
sorghumstraw sorghumstraw
Barleystraw barleystraw /

pmpp(pm,pp) index set of produced products pp from each intermediate raw material pm

```

/ sugarcane ethanol
* sugarcane lignincake
sugarcaneleaves ethanol
sugarcaneleaves lignincake
bagasse ethanol
bagasse lignincake
bagasseCHP electricity
bagasseCHP heat
* lignincake heat
* lignincake electricity
wheatstraw .ethanol
wheatstraw .lignincake
maizestraw ethanol
maizestraw lignincake
sorghumstraw ethanol
sorghumstraw lignincake
Barleystraw ethanol
Barleystraw lignincake /

```

tkp(t,p) index set of key products from each technology

```

/ sugar_milling sugar
fermentation ethanol
CHP electricity /

```

Set prt(p,t) produced products from technology

```

/ ethanol .fermentation
lignincake fermentation
Heat CHP
Electricity CHP
sugar sugar_milling
bagasse sugar_milling
molasses sugar_milling
bagasse crushing
sugarcane crushing /

```

Parameters

* reference investment of the process technology (at reference capacity) in 1000000 rands

capitalcost0(t)

```

/ fermentation 2061.8000 # hydr_lign
pretreatment 0
CHP 0 # $600 per kwh*R12/dollar*1000Mwh
sugar_milling 0 # already exist
storage 5.790

```

crushing 0 /
 * reference capacity of process technology in tonnes per year - Table 4
 capacity0(t)

/ fermentation	183970
Pretreatment	200000
CHP	20
sugar_milling	84000
storage	17000
crushing	84000 /

Parameter

MAXFT(t) maximal total flow at technology t in tonnes per year
 MAXFTtp(t,tp) maximal total flow at technology t in time period tp in tons
 per tp
 minft(t) minimal total flow at technology t in tonnes per year;
 *Maxft('fermentation') maximal total flow at technology fermentation in tonnes per
 year;

Maxft(t) = 10000 * capacity0(t);
 Maxft('fermentation') = 3 * capacity0('fermentation') ;
 Maxfttp(t,tp) = 10000 * capacity0(t) / card(tp);
 Maxfttp('fermentation',tp) = 3 * capacity0('fermentation')/card(tp);
 minft(t) = 0.1 * capacity0(t);
 Minft('fermentation') = 0.3 * capacity0('fermentation');

Scalar

CAPACITY_EXPONENT capacity exponent for calculating investment of technology
 at different capacities
 /0.6/ ;

Table alimit(i,re) maximum capacity of farm i in tonnes of raw material

	sugarcane	sugarcaneleaves	maizestraw	sorghumstraw	wheatstraw
barleystraw					
1	4016427	602464	0	0	0
0					
2	1276521	191478			
3	6140204	921030			
4	3051369	457705			
5	3726306	558946			
6	1066541	159981			
7	2031572	304736			
8	3690402	553560			
9	2597186	389578			
10	1661468	249220			
11	6822239	1023336			
12	42464309	639646			

13	6892353		1033853		
14	416054		62408		
15	1340466		201070		
16	2673811		401072		
17	218799		32820		
18	926085		138913		
19	3179854		476978		
20	2826807		424021		
21	1557015		233552		
22	1306167		195925		
23	81950	12292			
24	194530		29179		
25	2520929		378139		
26	1922694		288404		
27	414241		62136		
28	465811		69872		
29	343607		51541		
30	4823652		723547		
31	3074855		461228		
32	4186941		628041		
33	6358661		953799		
34	2798228		419734		
35	920584		138087		
36	2920149		438022		
37	4015945		602391		
38	1402805		210420		
39	401615		60242		
40	1860465		279070		
41	1228235		184235		
42	995487		149323		
43	103456		15518		
44	520692		78104		
45			3542	0.99	
46			4923	1	
47	0	0	1812	4	
48			660	92	
49			158	413	
50			19	261	
51			11691	128	142
52			9214	268	
53			21742	2604	108
54			24008	4349	74
55			16825	1096	57
56			6847	49	0
57			9471		0.01
58			14536		0.09

59	485	0.12	
60	307	0.06	
61	21284	25	143
62	33866	416	518
63	39476	1908	177
64	31787	2729	41
65	23670	1703	76
66	19840	2097	90
67	10187	244	94
68	7943		58
69	1374		0.43
70	1872		40
71	46313	200	1863
72	50826	394	973
73	57337	4582	40
74	52420	2190	58
75	15628	1290	124
76	12992	372	130
77	3587	187	127
78	16		112
79	1191		56
80	28909	658	1286
81	57208	421	972
82	30587	348.210	59.98
83	76979	523.304	9.33
84	58684	54.075	72.34
85	3895	54.075	123.13
86	1993		135
87	1146		124
88	8332	19	12
89	5772	862	13
90	13735	250	7
91	38029	231	1
92	43230		10
93	1891		19
94	1978		15
95	1778		4
96	1882		1332
97	1090		6069
98	6289		6396
99	1279		4632
100	15802		332
101	4086	0	357
102	3746		357
103	723		17
104	1047		213

105	120		1604
106	4165	5	1254
107	280		165
108	2073		256
109	4660		448
110	154		154
111	9		
112	624		
113	1040		
114	677		0
115	0.09		
116	0.09		
117	0.04		
118	0.29		
119	1		
120	0.00		
121	0.07		
122	0.16		
123	0.16		
124	5		
125	12		
126	16		
127	16		
128	4		
129	3		
130	7		
131	2		
132	2		
133	0.01		
134	0.13		
135	3		
136	13		
137	18		
138	15		
139	8		
140	0.40		
141	2		
142	11		
143	7		
144	2		
145	0.01		
146	14		
147	18		
148	18		
149	5		
150	0.06		

151	2	
152	263	
153	176	
154	7	
155	4	
156	7	
157	1	
158	2	
159	11	
160	5	
161	122	
162	537	
163	226	
164	0.14	
165	7	
166	13	
167	3	
168	0.09	
169	2	
170	4	
171	0.41	
172	273	71
173	4701	1164
174	715	177
175		0.08
176		0.12
177		0.03
178	1481	386
179	5623	1466
180	6000	1564
181	11179	2778
182	12634	3128
183	381	95
184		0.15
185		0.05
186	511	133
187	3463	903
188	3615	943
189	43	11
190	850	54
191	25	0.04
192	855	40
193	7125	291
194	10510	365
195	4360	10
196	3608	89

197	2321	57	
198	620	15	
199	101	0.00	
200	10937	6	
201	9793	277	
202	2434	14	
203	9711	245	
204	10044	250	
205	8687	214	
206	423	10	
207	398	1	
208	1409	31	
209	10	0	
210	185	0	
211	27	0	
212	44	0	
213	4	0	
214	716	8	
215	4738	52	
216	2	0.0	
217	133	0.96	
218	38	0.61	
219	1498	78	
220	142	0	0;

$alimit(i,RE) = alimit(i,RE) * 1 ;$

Table

sugarcanedemand(m,re) demand of raw materials at sugar mill m in tonnes per annum - only sugar cane

	sugarcane
Umzikulu	1400000
Sezela	2500000
Eston	1400000
Noodsberg	1344000
Maidstone	2365440
UCL	775000
Gledhow	1512000
Darnall	1639680
Amatikulu	2069760
Flexiton	2496000
Umfolozi	1200000
Pongola	1400000
Komati	2500000
Malelani	1830000

$sugarcanedemand(m,re) = sugarcanedemand(m,re) ;$

*heating Gj/year (8060hrs)350kg steam per tonne of cane, Electricity in MWh/year, 25kwh per tonne of cane

Table demand(j,p) demand for products at location j in tonnes per annum. electricity in MWh and heat in Gj.

	ethanol	electricity	sugar	molasses	heat
lignincake					
Sapref	894875.43				
Engen	621441.27				
Umzikulu		35000			262.216
Sezela		62500			468.243
Eston		35000			262.216
Noodsberg		33600			251.728
Maidstone		59136			443.041
UCL		19375			145.155
Gledhow		37800			283.194
Darnall		40992			307.108
Amatikulu		51744			387.660
Flexiton		62400			467.494
Umfolozi		30000		224.754	
Pongola		35000			262.216
Komati		62500			468.243
Malelani		45750			
Sugarwarehouse1			2.443188e+6		
Animalfeedcentre				977275.2	
28145666.75					
Lignincakewarehouse					
;					

Parameter

CONFrepi(re,pi,t)

/	sugarcane	.sugarcane	.crushing	= 1
	sugarcaneleaves	.sugarcaneleaves	. storage	= 1
	Sugarcane	.bagasse	. crushing	= 0.28
	Sugarcane	. bagasse	. sugar_milling	= 0.28
	wheatstraw	.wheatstraw	.storage	= 1
	maizestraw	. maizestraw	.storage	= 1
	sorghumstraw	.sorghumstraw	.storage	= 1
	Barleystraw	.barleystraw	. storage	= 1 /

CONFrepd(re,pd,t)

/	sugarcane	. sugar	.sugar_milling	=0.10
	sugarcane	.molasses	.sugar_milling	=0.04 /

CONFpipm(pi,pm,t)

/	sugarcane	.sugarcane	.pretreatment	= 1
	sugarcaneleaves	.sugarcaneleaves	.pretreatment	= 1
	bagasse	.bagasse	pretreatment	= 1
	bagasse	.bagasseCHP	.storage	= 1
	wheatstraw	.wheatstraw	.pretreatment	= 1
	maizestraw	.maizestraw	.pretreatment	= 1
	sorghumstraw	.sorghumstraw	pretreatment	= 1
	Barleystraw	.Barleystraw	pretreatment	= 1 /
CONFpmpm(pp,pp,t)				
/	sugarcane	.ethanol	.Fermentation	=0.071
*	sugarcane	.lignincake	.Fermentation	=0.5
	sugarcaneleaves	.ethanol	.Fermentation	=0.0936
	sugarcaneleaves	.lignincake	.Fermentation	=0.5
	bagasse	.ethanol	.Fermentation	=0.0936
	bagasse	.lignincake	.Fermentation	=0.5
* in MWh				
	bagasseCHP	.electricity	.CHP	= 0.33 # Mwh
per tonne of bagasse				
* in GJ				
	bagasseCHP	.heat	CHP	= 0.00177
#GJ per tonne of bagasse				
*	lignincake	electricity	CHP	= 0.33 #
Mw per tonne of bagasse				
*	lignincake	heat	CHP	= 0.00177
#GJ per tonne of bagasse				
	wheatstraw	.ethanol	.Fermentation	=0.0392
	wheatstraw	.lignincake	Fermentation	=0.5
	maizestraw	.ethanol	Fermentation	=0.0493
	maizestraw	.lignincake	Fermentation	=0.5
	sorghumstraw	.ethanol	Fermentation	=0.0392
	sorghumstraw	.lignincake	Fermentation	=0.5
	Barleystraw	.ethanol	Fermentation	=0.0392
	Barleystraw	.lignincake	Fermentation	=0.5 / ;

* Conversion of biomass to ethanol in tonnes of ethanol per /tonne

Table PRICE(p,tp) selling price of product p in 1000000 rands per ton

* selling price in million rands per ton

	2015	
sugar	4.728e-3	
ethanol	15.5e-3	
Bagasse	0	
molasses	1.50e-3	
Lignincake	1.8376e-4	#(0.35 70 €/MWh + 0.45*0.5 25 €/MWh) / 2

* selling price in million rands per GJ

Heat 8.47e-5
 * selling price in million rands per MWH
 Electricity 1.22e-3 Parameter

* cost of raw materials in million rands per ton
 PCOST(Re)
 / sugarcane 3.92e-4
 sugarcaneleaves 1.05e-4
 *wheat straw 1.50 \$/GJ *17 GJ/t * 12.2 rand/\$
 wheatstraw 3.11e-4
 *assumed as for maize straw
 sorghumstraw 3.18e-4
 *maize straw 1.49 \$/GJ *17.5 GJ/t * 12.2 rand/\$
 maizestraw 3.18e-4
 * assumed as for wheat
 barleystraw 3.11e-4 /

Parameter
 COCC(p) cost of storage for each pi in million of rands per ton
 * 0.011 M\$/kton *1e6 \$/M\$ * 1e-3 kton/t * 12.2 rand/\$ (Supplementary material.
<http://www.sciencedirect.com/science/article/pii/S0098135414000520>)
 / sugarcane 0.134
 sugarcaneleaves 0.134
 * sugar 0
 bagasse 0.134
 * molasses 0
 wheatstraw 0.134
 maizestraw 0.134
 sorghumstraw 0.134
 barleystraw 0.134 /

PRETREAT(p) cost of pretreatment (drying chipping liquefaction etc) for each pi in million of rands per ton
 / sugarcane 0
 sugarcaneleaves 0.0107
 wheatstraw 0.0107 # same as for leaves
 sorghumstraw 0.0107
 maizestraw 0.0107
 barleystraw 0.0107
 bagasse 0. /

Parameter
 * cost of operation of t technology for each pi in million of rands per ton of key product
 COCLT(pi,t)
 / sugarcane .sugar_milling =1.42e-3

sugarcane .crushing = 1.02e-3 /

* cost of operation of t technology for each pm in million of rands per ton of key product
COPLT(pm,t)

* 0.16 \$/kg * 1000 kg/t * 12.2 rand/\$ (Čuček et al., 2014)

*0.2\$/kwh*12.2 rands/\$

/ sugarcane	Fermentation	= 1.952e-3
sugarcaneleaves	.Fermentation	= 1.952e-3
bagasse	.Fermentation	= 1.952e-3
wheatstraw	Fermentation	= 1.952e-3
maizestraw	Fermentation	= 1.952e-3
sorghumstraw	.Fermentation	= 1.952e-3
Barleystraw	.Fermentation	= 1.952e-3
bagasseCHP	. CHP	= 2.46e-6 #

http://www.epa.gov/chp/documents/biomass_chp_catalog_part7.pdf

/

* DISTANCE fixed transport cost coefficient of p from point i to point m in 1000000
rands/ ton - road

TCOSTFIXL1L2_road(re)

* 8.5 \$/t * 12.2 rand/\$*1e-6 ((Čuček et al., 2014)

/ sugarcane	1.037e-4
sugarcaneleaves	1.037e-4
wheatstraw	1.037e-4
Maizestraw	1.037e-4
Sorghumstraw	1.037e-4
Barleystraw	1.037e-4/

* DISTANCE variable transport cost coefficient of p from point i to point m in 1000000
rands/(ton*km) - road

TCOSTVARL1L2_road(re)

/ sugarcane	1.02e-6
sugarcaneleaves	1.02e-6
wheatstraw	1.02e-6
Maizestraw	1.02e-6
Sorghumstraw	1.02e-6
Barleystraw	1.02e-6/

* DISTANCE fixed transport cost coefficient of p from point i to point m in 1000000
rands/tonne - combined (road - rail)

* train is used

TCOSTFIXL1L2_comb(re)

/ sugarcane	0.1556e-4
sugarcaneleaves	0.1556e-4
wheatstraw	0.1556e-4

Maizestraw	0.1556e-4
Sorghumstraw	0.1556e-4
Barleystraw	0.1556e-4/

* DISTANCE fixed transport cost coefficient of product p from point m to point n in 1000000 rands /ton

* truck is used

TCOSTFIXL2L3(pi)

/ sugarcane	1.037e-4
sugarcaneleaves	1.037e-4
bagasse	1.037e-4
wheatstraw	1.037e-4
maizestraw	1.037e-4
sorghumstraw	1.037e-4
Barleystraw	1.037e-4/

* DISTANCE variable transport cost coefficient of product p from point m to point n in 1000000 rands/(ton*km)

* truck is used

TCOSTVARL2L3(pi)

/sugarcane	1.02e-6
sugarcaneleaves	1.02e-6
bagasse	1.02e-6
wheatstraw	1.02e-6
maizestraw	1.02e-6
sorghumstraw	1.02e-6
Barleystraw	1.02e-6 /

* DISTANCE fixed transport cost coefficient of product p from point m to point n in 1000000 rands /ton

* truck is used

TCOSTFIXL3L4(pm)

/ sugarcane	1.037e-4
sugarcaneleaves	1.037e-4
bagasse	1.037e-4
bagasseCHP	1.037e-4
wheatstraw	1.037e-4
maizestraw	1.037e-4
sorghumstraw	1.037e-4
Barleystraw	1.037e-4 /

* DISTANCE variable transport cost coefficient of product p from point m to point n in 1000 rands/(ton*km)

* truck is used

TCOSTVARL3L4(pm)

/sugarcane	1.02e-6
sugarcaneleaves	1.02e-6
bagasse	1.02e-6
bagasseCHP	1.02e-6
wheatstraw	1.02e-6
maizestraw	1.02e-6
sorghumstraw	1.02e-6
Barleystraw	1.02e-6/

* DISTANCE fixed transport cost coefficient of product p from point m to point j in 1000000 rands/ton

* truck is used

TCOSTFIXL2L5(pd)

* 0.0063 \$/kg * 12.2 rand/\$ * 1000 kg/t ((Čuček et al., 2014))

/ sugar	7.686e-5
molasses	7.686e-5 /

* DISTANCE variable transport cost coefficient of product p from point m to point j in 1000000 rands/(ton*km)

* truck is used

TCOSTVARL2L5(pd)

*0.00007 \$/(kgkm) * 12.2 rand/\$ * 1000 kg/t

/ sugar	8.54e-7
molasses	8.54e-7/

* DISTANCE fixed transport cost coefficient of product p from point n to point j in 1000000 rands/ton

* by truck

TCOSTFIXL4L5(pp)

*0.00386 \$/kg * 12.2 rand/\$ * 1000 kg/t (Čuček et al., 2014)

/ ethanol	4.7092e-5
lignincake	7.86e-5
electricity	3.54e-5
heat	3.54e-5 /

* DISTANCE variable transport cost coefficient of product p from point n to point j in 1000000 rands/(ton*km)

* by truck

TCOSTVARL4L5(pp)

/ ethanol	0.8e-6
lignincake	8.54e-7
electricity	8.54e-8
heat	8.54e-8 / ;

Parameter

tr_loss(p)	fraction of loss due to transport per km
/sugarcane	0
sugarcaneleaves	0
wheatstraw	0
maizestraw	0
sorghumstraw	0
Barleystraw	0
bagasse	0
bagasseCHP	0 /

loss(p)	fraction of loss due to harvesting
/sugarcane	0.05
sugarcaneleaves	0.05
wheatstraw	0.05
maizestraw	0.05
sorghumstraw	0.05
Barleystraw	0.05
bagasse	0
bagasseCHP	0 / ;

Table distim(i,m) road distance from farms i to biomass demand centres j in kilometres

	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Felixiton	Umfoloji	Pongola	Komati	Malelani	15	16	17	18	19	20
1	33	75	160	183	260	260	216	226	261	297	357	520	938	875	0					
2	80	100	113	172	172	184	218	227	262	298	359	522	846	784	0					
3	18	52	103	126	203	203	159	169	204	240	301	464	881	819	0					
4	51	113	155	110	110	148	181	191	226	262	322	485	785	722	0					
5	28	109	152	131	108	108	164	174	208	245	305	468	786	723	0					
6	46	50	67	93	143	144	100	111	144	181	241	404	821	759	0					
7	54	65	65	162	125	158	205	168	203	239	2100	463	732	670	0					
8	31	79	80	87	121	125	130	167	165	201	262	425	758	695	0					
9	36	65	98	71	79	89	106	124	149	160	221	384	824	762	0					
10	50	55	82	153	186	196	190	231	233	267	327	395	703	641	0					
11	14	6	85	83	103	128	163	1901	199	234	260	365	683	620	0					
12	36	42	50	68	93	117	128	164	165	207	224	387	723	660	0					
13	16	28	39	59	98	104	103	142	151	164	193	327	737	675	0					
14	76	84	149	152	148	157	189	233	257	2100	293	338	645	583	0					
15	50	58	118	127	127	159	123	203	231	263	274	320	637	575	0					
16	70	78	72	82	109	113	157	143	217	216	380	258	689	627	0					
17	59	49	70	175	181	109	98	163	208	216	260	259	691	628		0				
18	78	74	124	104	119	151	217	223	191	250	258	300	621	559		0				
19	35	66	83	110	123	155	221	229	227	254	262	305	694	632		0				
20	52	53	100	123	137	168	215	234	24	267	275	318	680	618		0				
21	27	85	133	158	157	171	202	268	274	301	309	623	352	561	g0					
22	40	100	147	203	172	185	217	283	289	316	324	660	598	367	0					
23	77	109	131	178	202	216	247	314	319	574	346	512	355	397	0					
24	98	141	157	204	228	242	273	340	346	606	543	372	381	423	0					
25	47	169	227	247	277	292	326	334	515	324	453	423	431	473	0					
26	49	135	193	233	263	278	518	375	368	455	310	409	417	459	0					
27	45	194	244	253	269	2100	324	338	393	436	370	469	471	519	0					
28	63	168	211	227	247	274	298	312	416	410	344	442	451	493	0					
29	60	96	201	306	364	412	436	450	553	547	481	580	588	631	0					
30	89	152	331	490	549	535	565	541	581	549	612	617	725	768	0					
31	60	122	373	532	590	577	607	622	583	590	654	659	767	809	0					
32	44	42	437	595	654	641	670	686	646	654	717	723	831	873	0					
33	14	56	462	620	679	666	695	711	671	679	742	748	856	898	0					
34	82	145	380	539	598	584	614	601	630	608	661	677	785	827	0					
35	84	146	410	569	627	614	644	659	633	641	691	710	818	860	0					
36	23	88	432	591	650	636	666	681	642	650	713	718	826	869	0					
37	67	63	467	624	684	671	701	716	676	684	747	753	861	903	0					
38	5	48	132	155	232	232	189	198	233	270	330	494	911	849	0					
39	25	75	67	98	175	175	131	141	176	212	273	436	853	791	0					
40	10	47	56	82	88	102	912	110	128	153	188	352	763	700	0					
41	54	17	34	55	80	107	113	154	141	162	205	278	709	647	0					
42	12	38	64	74	78	109	175	181	208	237	217	259	702	640	0					

89	750	707	616	686	643	623	623	629	598	602	554	393	397	335	0	679	612	587	646	777
90	744	701	610	629	597	515	507	583	552	557	508	347	351	289	0	672	606	581	640	770
91	734	691	600	618	587	505	497	573	542	546	498	337	327	264	0	663	596	571	630	761
92	709	666	575	603	572	509	501	558	527	531	483	322	271	208	0	643	571	546	605	736
93	700	658	566	594	563	500	493	549	518	522	474	313	230	167	0	634	562	537	596	727
94	725	683	591	620	588	526	518	574	543	547	499	338	193	130	0	659	588	563	622	752
95	784	742	642	634	603	589	581	589	557	562	514	353	173	111	0	674	639	614	673	811
96	786	744	645	636	605	591	583	591	560	564	516	355	134	71.8	0	676	641	616	675	813
97	801	759	667	738	663	674	674	650	618	623	575	414	407	345	0	730	664	639	697	828
98	799	757	665	736	661	672	672	647	616	620	572	411	371	309	0	728	662	637	695	826
99	806	763	672	663	632	577	569	618	587	591	543	382	331	268	0	734	668	643	702	832
100	791	748	657	648	617	562	554	603	571	576	528	367	316	253	0	719	653	628	687	817
101	752	709	618	646	615	552	544	601	569	574	526	365	252	190	0	686	614	589	648	778
102	768	726	634	662	631	568	561	617	586	590	542	381	198	136	0	702	630	605	664	795
103	797	754	663	681	649	597	589	636	604	609	561	400	160	97.3	0	720	659	634	693	823
104	831	788	685	681	649	635	628	635	604	609	561	399	141	78.8	0	720	681	656	715	857
105	879	837	745	816	706	752	616	692	661	666	617	456	417	354	0	808	742	717	775	906
106	832	789	698	717	685	603	595	672	640	645	597	436	396	334	0	761	694	669	728	858
107	856	814	722	714	683	628	620	669	637	642	594	433	304	242	0	785	719	694	753	883
108	793	750	658	687	655	593	585	641	610	614	566	405	269	206	0	726	655	630	689	819
109	792	749	658	686	654	592	584	640	609	614	566	404	244	182	0	725	654	629	688	818
110	844	802	710	739	707	645	637	693	662	666	618	457	216	154	0	778	707	682	740	871
111	882	839	736	732	700	686	678	686	655	660	611	450	201	138	0	771	732	707	766	908
112	895	852	761	753	721	666	658	707	676	681	632	471	301	239	0	824	757	732	791	922
113	838	796	704	732	701	638	631	687	656	660	612	451	291	229	0	772	700	675	734	865
114	910	868	776	805	773	711	703	759	728	732	684	523	287	225	0	844	773	748	806	937
115	885	927	1090	1161	1194	1097	1097	1204	1247	1279	1336	1192	1366	1303	0	1153	1087	1062	874	854
116	896	938	1102	1172	1206	1108	1108	1215	1258	1291	1347	1203	1377	1314	0	1164	1098	1073	886	866
117	870	912	1068	1138	1172	1074	1074	1181	1224	1256	1313	1169	1343	1280	0	1130	1064	1039	860	840
118	783	825	816	933	966	878	878	976	1018	1051	1108	1187	1361	1299	0	925	838	837	773	753
119	718	760	751	868	901	813	813	911	953	986	1043	1184	1358	1295	0	860	773	772	708	688
120	931	1172	1081	1151	1185	1088	1088	1194	1237	1270	1326	1182	1356	1293	0	1144	1077	1052	1111	901
121	890	932	1096	1166	1200	1102	1102	1209	1252	1284	1341	1197	1371	1308	0	1158	1092	1067	879	859
122	848	890	1054	1125	1158	1061	1061	1168	1210	1243	1300	1155	1329	1267	0	1117	1050	1025	838	818
123	817	860	1023	1094	1127	1030	1030	1137	1179	1212	1269	1125	1298	1236	0	1086	1020	995	807	787
124	851	893	1057	1127	1161	1063	1063	1170	1213	1246	1302	1158	1332	1269	0	1119	1053	1028	841	821
125	727	770	761	877	911	1059	1059	920	963	996	1052	1154	1327	1265	0	870	783	782	717	697
126	702	745	735	852	886	1043	1043	895	938	971	1027	1137	1311	1249	0	844	758	1757	692	672
127	709	751	742	859	893	804	804	902	945	977	1034	1149	1323	1260	0	851	765	764	699	679
128	649	691	682	799	832	744	744	842	884	917	973	1063	1327	1265	0	791	704	703	638	618
129	615	658	649	765	799	711	711	808	851	884	940	1056	1320	1258	0	757	671	670	605	585
130	596	639	630	746	780	692	692	789	832	865	921	1037	1301	1239	0	739	652	651	586	566
131	567	609	600	717	750	662	662	760	802	835	892	1055	1309	1247	0	709	622	621	557	537
132	580	622	613	730	764	675	675	773	816	848	905	1068	1341	1279	0	722	636	635	570	550
133	1144	1102	1010	1081	1114	1017	1017	1124	1166	1199	1255	1111	1285	1223	0	1073	1006	981	1040	878
134	825	867	1029	1100	1133	1036	1036	1143	1185	1218	1275	1131	1304	1242	0	1092	1026	1001	1059	794

135	782	824	987	1057	1091	993	993	1100	1143	1176	1232	1088	1262	1199	0	1049	983	958	1017	752
136	755	797	960	1031	1064	967	967	1074	1116	1149	1206	1062	1235	1173	0	1023	957	932	745	725
137	732	775	993	1064	1097	1000	1000	1107	1149	1182	1239	1095	1268	1206	0	1056	990	965	722	702
138	710	753	744	1076	1110	1013	1013	1119	1162	1195	151	1107	1281	1219	0	1069	1002	977	700	680
139	667	709	700	817	851	762	762	860	1903	935	992	1160	1333	1271	0	809	723	722	657	637
140	607	650	641	757	791	703	703	800	843	876	932	1089	1263	1201	0	750	663	662	597	577
141	576	618	609	726	759	671	671	769	811	844	900	1016	1281	1218	0	718	631	630	566	545
142	571	613	604	721	754	666	666	764	806	839	896	1011	1276	1213	0	713	626	625	561	541
143	503	545	536	653	686	598	598	696	738	771	827	991	1276	1214	0	645	558	557	492	472
144	470	513	504	620	654	566	566	663	706	739	795	959	1326	1264	0	613	526	525	460	440
145	781	1043	951	1022	1055	958	958	1065	1107	1140	1197	1053	1226	1164	0	1014	948	923	981	1751
146	753	1042	951	1021	1055	957	957	1064	1107	1139	1196	1052	1226	1163	0	1013	947	922	981	723
147	720	1009	918	988	1022	925	925	1031	1074	1107	1163	1019	1193	1130	0	981	914	889	948	690
148	737	779	953	1023	1057	959	959	1066	1109	1142	1198	1054	1228	1165	0	1015	949	924	727	707
149	683	725	716	833	866	987	987	876	919	951	1008	1081	1255	1193	0	825	739	738	673	653
150	597	639	630	747	780	692	692	790	832	865	921	948	1213	1150	0	739	652	651	586	566
151	544	587	577	694	728	640	640	737	780	813	869	1032	1233	1171	0	686	600	599	534	514
152	468	510	501	618	652	563	563	661	704	737	793	956	1264	1202	0	610	524	523	458	438
153	423	465	456	573	606	518	518	616	658	691	748	911	1390	1327	0	565	478	477	413	393
154	382	425	416	532	566	478	478	575	618	651	707	871	1178	1116	0	524	438	437	372	352
155	762	973	882	953	986	889	889	996	1038	1071	1127	983	1157	1095	0	945	878	853	912	732
156	708	750	898	968	1002	904	904	1011	1054	1086	1143	999	1173	1110	0	960	894	869	697	677
157	656	699	876	946	980	882	882	989	1032	1064	1121	977	1151	1088	0	938	872	847	646	626
158	562	604	595	712	745	657	657	755	797	830	887	917	1182	1119	0	704	617	616	552	532
159	522	564	555	672	705	617	617	715	758	790	847	894	1158	1096	0	664	578	577	512	492
160	495	537	528	645	678	590	590	688	731	763	820	1983	1192	1130	0	637	551	550	485	465
161	446	488	479	596	630	541	541	639	682	715	771	934	1243	1181	0	588	502	501	436	416
162	409	451	442	559	592	504	504	602	644	677	734	897	1255	1193	0	551	464	463	399	379
163	388	430	421	538	572	484	484	581	624	657	713	876	1295	1233	0	530	444	443	378	358
164	645	687	772	843	876	779	779	886	928	961	1017	873	1138	1076	0	835	768	743	635	615
165	595	637	628	812	845	748	748	855	897	930	987	842	1107	1045	0	804	737	712	585	565
166	576	618	609	726	760	760	760	769	812	1845	901	854	1119	1057	0	718	632	631	566	546
167	527	569	560	677	711	622	622	720	763	796	852	882	1167	1104	0	669	583	582	517	497
168	633	675	784	855	888	791	791	898	940	973	1030	886	1059	97	0	847	781	756	623	603
169	615	657	709	780	813	716	716	823	865	1898	955	811	1075	1013	0	772	706	681	605	585
170	619	662	699	770	803	706	706	813	855	888	945	801	1065	1003	0	762	696	671	609	589
171	563	605	596	713	746	723	723	756	798	831	888	817	1012	950	0	705	618	617	553	533
172	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	262	220	128	199	232	135	135	242	284	317	374	394	687	625	0	191	124	99.5	158	289
174	247	205	113	184	217	120	81.8	227	269	302	359	383	676	614	0	176	109	84.5	143	274
175	234	191	99.8	124	150	53	47.1	160	192	239	296	374	709	646	0	162	96	78.3	130	260
176	238	196	104	96	128	30	22.3	137	180	213	269	362	696	634	0	86.5	100	85.7	134	265
177	214	171	141	56	50	61	66.9	59.8	91.4	139	196	359	770	708	0	95	145	123	171	240
178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
179	353	310	219	289	323	226	226	332	375	408	464	354	647	584	0	282	215	190	249	379
180	314	271	180	250	284	187	187	293	336	369	425	331	624	562	0	242	176	151	210	340

181	292	249	158	228	261	164	164	271	314	346	403	318	611	549	0	220	154	129	188	318
182	306	263	172	174	170	106	98.2	180	211	259	316	334	627	565	0	165	168	143	202	332
183	286	243	152	154	146	86.3	78.4	156	187	235	292	304	638	576	0	145	148	133	182	312
184	279	236	145	138	101	79.2	71.4	111	142	190	247	410	697	635	0	177	141	126	175	305
185	311	269	185	161	124	120	112	134	166	214	270	285	685	623	0	201	181	167	215	338
186	431	388	297	367	401	303	303	410	453	485	542	398	622	560	0	359	293	268	327	457
187	389	346	255	325	359	261	262	368	411	444	500	356	617	555	0	317	251	226	285	415
188	352	310	218	289	322	225	225	332	374	407	464	312	642	579	0	281	214	189	248	379
189	338	296	204	275	237	211	165	318	360	346	391	271	564	502	0	267	200	175	234	365
190	359	317	225	296	221	161	153	231	262	339	384	264	598	536	0	288	222	197	255	386
191	322	279	188	191	182	123	115	192	224	272	328	254	588	526	0	181	184	170	218	349
192	420	377	286	357	390	293	293	400	385	389	434	315	587	525	0	349	282	257	316	447
193	430	388	296	367	299	239	231	309	348	352	397	278	524	462	0	359	293	268	326	457
194	402	360	268	249	241	181	173	250	290	294	339	220	554	492	0	331	264	239	298	429
195	418	376	284	257	249	189	182	257	225	230	275	217	551	489	0	248	280	255	314	445
196	426	383	255	276	244	189	181	230	199	203	248	208	542	480	0	315	251	236	285	452
197	377	334	326	227	195	293	289	181	150	155	200	183	529	467	0	266	308	344	368	403
198	379	336	328	229	197	295	301	183	152	156	169	140	572	509	0	268	310	346	370	405
199	474	431	340	411	348	347	280	409	377	382	427	307	488	426	0	403	336	311	370	501
200	443	400	309	380	303	243	235	364	332	337	382	262	483	421	0	372	305	280	339	470
201	447	405	313	371	340	230	222	326	294	299	344	224	494	431	0	376	310	285	343	474
202	478	435	331	328	297	237	229	283	251	256	301	181	516	453	0	368	328	303	361	505
203	436	394	332	286	255	237	229	241	210	214	259	140	474	412	0	326	328	303	362	463
204	430	387	371	280	248	276	268	235	203	208	197	121	509	447	0	319	367	342	401	456
205	491	449	403	341	310	308	300	296	265	225	166	124	541	479	0	381	399	374	433	518
206	419	377	369	270	238	336	342	224	193	173	114	56.5	525	463	0	309	351	387	411	446
207	483	440	349	419	393	283	275	379	348	352	397	225	425	363	0	411	345	320	379	509
208	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
209	680	638	546	617	650	553	553	660	702	642	672	511	569	506	0	609	542	517	576	707
210	651	608	517	587	621	523	523	630	673	612	642	481	539	477	0	579	513	488	547	677
211	622	580	488	559	592	495	495	602	644	584	590	429	521	459	0	551	484	459	518	649
212	592	549	491	442	410	396	396	396	365	346	289	128	215	230	0	481	487	462	521	618
213	617	575	483	554	587	490	490	597	639	672	729	659	717	654	0	546	480	455	513	644
214	614	571	480	550	584	486	486	593	636	668	725	581	720	657	0	542	476	451	510	640
215	572	529	438	509	542	445	445	552	594	627	683	539	731	669	0	501	434	409	468	599
216	719	676	599	569	537	524	524	524	492	497	449	288	183	121	0	608	596	571	630	745
217	685	642	634	535	503	539	539	489	470	418	361	224	105	102	0	574	616	605	676	711
218	815	772	673	665	633	619	619	619	588	593	545	383	112	49.8	0	704	669	644	703	841
219	881	839	735	731	700	686	686	686	654	659	611	450	98.6	45.2	0	771	731	706	765	908
220	554	511	503	404	373	387	379	359	339	287	230	79.9	226	250	0	444	485	453	545	581

distim(i,m)\$(distim(i,m) eq 0) = 1e9;

Table distim_rail(i,m) railway distance in km

	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Flexiton	Umfoloji	Pongola	Komati	Malelani
1	28.80	2.40	162.00	257.00	183.00	257.00	214.00	436.00	266.00	298.00	355.00	498.00	914.00	877.00
2	105.00	61.40	103.00	165.00	152.00	165.00	183.00	405.00	236.00	267.00	324.00	468.15	819.00	782.00
3	70.80	27.50	97.80	193.00	119.00	193.00	149.00	372.00	202.00	233.00	290.00	434.00	850.00	814.00
4	167	134.00	33.10	84.60	125.00	84.20	155.00	378.00	208.00	239.00	296.00	440.00	738.00	702.00
5	137	103.00	12.20	96.00	121.00	95.50	152.00	374.00	204.00	236.00	293.00	436.00	753.00	717.00
6	88	54.50	57.50	142.00	67.40	141.00	98.00	320.00	151.00	182.00	239.00	383.00	799.00	763.00
7	197	163.00	51.90	60.40	123.00	59.90	153.00	305.00	206.00	237.00	294.00	438.00	706.00	670.00
8	162	129.00	22.70	68.70	87.90	68.20	118.00	341.00	171.00	202.00	260.00	403.00	726.00	690.00
9	131	97.50	58.60	105.00	56.80	104.00	87.40	310.00	140.00	171.00	229.00	372.00	762.00	725.00
10	256	222.00	111.00	53.90	121.00	47.20	137.00	250.00	181.00	226.00	283.00	399.00	679.00	643.00
11	233	200.00	88.30	11.40	82.10	4.80	101.00	250.00	169.00	200.00	257.00	40.10	659.00	623.00
12	218	185.00	92.80	10.20	63.00	15.60	82.10	266.00	150.00	181.00	238.00	382.00	675.00	639.00
13	383	349.00	338.00	302.00	234.00	308.00	204.00	136.00	160.00	95.00	72.40	175.00	586.00	550.00
14	256.00	222.00	111.00	53.90	121.00	47.20	137.00	250.00	181.00	226.00	283.00	399.00	679.00	643.00
15	256.00	222.00	111.00	43.10	110.00	36.50	105.00	218.00	149.00	194.00	251.00	367.00	627.00	591.00
16	380.00	346.00	334.00	299.00	231.00	305.00	201.00	103.00	157.00	160.00	122.00	130.00	541.00	505.00
17	509.00	476.00	464.00	429.00	360.00	434.00	331.00	307.00	293.00	246.00	185.00	121.00	258.00	301.00
18														
19														
20	304.00	270.00	258.00	223.00	155.00	229.00	125.00	211.00	87.70	40.60	27.60	171.00	635.00	599.00
21	334.00	300.00	288.00	253.00	185.00	258.00	155.00	225.00	118.00	70.40	6.50	142.00	606.00	570.00
22	351.00	317.00	306.00	270.00	202.00	276.00	172.00	242.00	135.00	87.80	27.20	123.00	586.00	550.00
23	390.00	356.00	345.00	309.00	241.00	315.00	211.00	193.00	174.00	127.00	66.20	82.20	546.00	510.00
24	390.00	357.00	345.00	310.00	241.00	315.00	212.00	203.00	174.00	127.00	66.50	92.30	556.00	520.00
25	453.00	419.00	407.00	372.00	304.00	378.00	274.00	190.00	237.00	190.00	129.00	29.30	493.00	457.00
26	444.00	411.00	399.00	364.00	295.00	369.00	266.00	192.00	228.00	181.00	120.00	30.70	494.00	458.00
27	470.00	436.00	424.00	389.00	320.00	394.00	291.00	183.00	254.00	206.00	146.00	0.00	243.00	260.00
28	470.00	436.00	424.00	389.00	320.00	394.00	291.00	183.00	254.00	206.00	146.00	0.00	243.00	260.00
29	886.00	853.00	741.00	670.00	731.00	664.00	702.00	472.00	657.00	671.00	610.00	243.00	0.00	43.60
30	777.00	743.00	631.00	561.00	622.00	554.00	592.00	363.00	547.00	561.00	500.00	289.00	110.00	73.60
31	804.00	770.00	659.00	588.00	649.00	581.00	619.00	390.00	575.00	588.00	528.00	297.00	87.90	51.70
32	834.00	800.00	688.00	617.00	678.00	611.00	649.00	419.00	604.00	618.00	557.00	276.00	54.90	18.70
33	868.00	834.00	722.00	652.00	713.00	645.00	683.00	454.00	639.00	652.00	591.00	262.00	20.60	24.80
34	817.00	783.00	672.00	601.00	655.00	594.00	625.00	396.00	581.00	594.00	534.00	323.00	114.00	78.20
35	850.00	816.00	704.00	634.00	695.00	627.00	665.00	435.00	620.00	634.00	573.00	306.00	97.10	60.90
36	850.00	817.00	705.00	634.00	695.00	628.00	666.00	436.00	621.00	635.00	574.00	260.00	43.60	0.00
37	894.00	862.00	750.00	679.00	740.00	673.00	711.00	481.00	666.00	680.00	619.00	253.00	10.40	52.60

;

distim_rail(i,m)\$(distim_rail(i,m) eq 0) = 1e9;

Table distim_road(i,m) road distance in km

	Umzikulu	Sezela	Eston	Noodsberg	Maidstone	UCL	Gledhow	Darnall	Amatikulu	Flexiton	Umfoloji	Pongola	Komati	Malelani
1	9.70	13.30	6.40	3.10	3.70	3.00	3.50	216.90	3.50	3.00	4.60	44.30	25.40	14.20

2	41.80	45.40	38.50	35.20	35.80	35.10	35.60	249.00	35.60	35.10	36.70	76.40	57.50	46.30
3	31.50	35.10	28.20	24.90	25.50	24.80	25.30	238.70	25.30	24.80	26.40	66.10	47.20	36.00
4	35.60	39.20	32.30	29.00	29.60	28.90	29.40	242.80	29.40	28.90	30.50	70.20	51.30	40.10
5	19.50	23.10	16.20	12.90	13.50	12.80	13.30	226.70	13.30	12.80	14.40	54.10	35.20	24.00
6	10.40	14.00	7.10	3.80	4.40	3.70	4.20	217.60	4.20	3.70	5.30	45.00	26.10	14.90
7	12.10	15.70	8.80	5.50	6.10	5.40	5.90	219.30	5.90	5.40	7.00	46.70	27.80	16.60
8	19.80	23.40	16.50	13.20	13.80	13.10	13.60	227.00	13.60	13.10	14.70	54.40	35.50	24.30
9	30.10	33.70	26.80	23.50	24.10	23.40	23.90	237.30	23.90	23.40	25.00	64.70	45.80	34.60
10	41.20	44.80	37.90	34.60	35.20	34.50	35.00	248.40	35.00	34.50	36.10	75.80	56.90	45.70
11	14.70	18.30	11.40	8.10	8.70	8.00	8.50	221.90	8.50	8.00	9.60	49.30	30.40	19.20
12	24.10	27.70	20.80	17.50	18.10	17.40	17.90	231.30	17.90	17.40	19.00	58.70	39.80	28.60
13	37.80	41.40	34.50	31.20	31.80	31.10	31.60	245.00	31.60	31.10	32.70	72.40	53.50	42.30
14	76.40	80.00	73.10	69.80	70.40	69.70	70.20	283.60	70.20	69.70	71.30	111.00	92.10	80.90
15	22.20	25.80	18.90	15.60	16.20	15.50	16.00	229.40	16.00	15.50	17.10	56.80	37.90	26.70
16	44.80	48.40	41.50	38.20	38.80	38.10	38.60	252.00	38.60	38.10	39.70	79.40	60.50	49.30
17	22.50	26.10	19.20	15.90	16.50	15.80	16.30	229.70	16.30	15.80	17.40	57.10	38.20	27.00
18	7.80	11.40	4.50	1.20	1.80	1.10	1.60	215.00	1.60	1.10	2.70	42.40	23.50	12.30
19	7.80	11.40	4.50	1.20	1.80	1.10	1.60	215.00	1.60	1.10	2.70	42.40	23.50	12.30
20	30.40	34.00	27.10	23.80	24.40	23.70	24.20	237.60	24.20	23.70	25.30	65.00	46.10	34.90
21	27.20	30.80	23.90	20.60	21.20	20.50	21.00	234.40	21.00	20.50	22.10	61.80	42.90	31.70
22	49.20	52.80	45.90	42.60	43.20	42.50	43.00	256.40	43.00	42.50	44.10	83.80	64.90	53.70
23	16.20	19.80	12.90	9.60	10.20	9.50	10.00	223.40	10.00	9.50	11.10	50.80	31.90	20.70
24	45.40	49.00	42.10	38.80	39.40	38.70	39.20	252.60	39.20	38.70	40.30	80.00	61.10	49.90
25	96.90	100.50	93.60	90.30	90.90	90.20	90.70	304.10	90.70	90.20	91.80	131.50	112.60	101.40
26	25.10	28.70	21.80	18.50	19.10	18.40	18.90	232.30	18.90	18.40	20.00	59.70	40.80	29.60
27	55.10	58.70	51.80	48.50	49.10	48.40	48.90	262.30	48.90	48.40	50.00	89.70	70.80	59.60
28	29.10	32.70	25.80	22.50	23.10	22.40	22.90	236.30	22.90	22.40	24.00	63.70	44.80	33.60
29	91.30	94.90	88.00	84.70	85.30	84.60	85.10	298.50	85.10	84.60	86.20	125.90	107.00	95.80
30	27.50	31.10	24.20	20.90	21.50	20.80	21.30	234.70	21.30	20.80	22.40	62.10	43.20	32.00
31	25.00	28.60	21.70	18.40	19.00	18.30	18.80	232.20	18.80	18.30	19.90	59.60	40.70	29.50
32	46.80	50.40	43.50	40.20	40.80	40.10	40.60	254.00	40.60	40.10	41.70	81.40	62.50	51.30
33	52.40	56.00	49.10	45.80	46.40	45.70	46.20	259.60	46.20	45.70	47.30	87.00	68.10	56.90
34	26.70	30.30	23.40	20.10	20.70	20.00	20.50	233.90	20.50	20.00	21.60	61.30	42.40	31.20
35	15.30	18.90	12.00	8.70	9.30	8.60	9.10	222.50	9.10	8.60	10.20	49.90	31.00	19.80
36	37.80	41.40	34.50	31.20	31.80	31.10	31.60	245.00	31.60	31.10	32.70	72.40	53.50	42.30
37	20.60	24.20	17.30	14.00	14.60	13.90	14.40	227.80	14.40	13.90	15.50	55.20	36.30	25.10

distim_road(i,m)\$(distim_road(i,m) eq 0) = 1e9 ;

Table distmj(m,j) road distance from storage - sugar mill m to product demand centres j in kilometres

	Sapref	ENGEN	Animalfeedcentre	Sugarwarehouse1
Umzikulu	108.00	183.00	5	1
Sezela	77.10	152.00	5	1
Eston	55.40	32.70	5	1
Noodsberg	57.00	104.00	5	1

Maidstone	90.00	137.00	5	1
UCL	133.00	68.40	5	1
Gledhow	133.00	68.50	5	1
Darnall	99.60	147.00	5	1
Amatikulu	133.00	214.00	5	1
Flexiton	171.00	218.00	5	1
Umfolozi	231.00	279.00	5	1
Pongola	396.00	442.00	5	1
Komati	750.00	682.00	5	1
Malelani	800.00	732.00	5	1
15	135.00	210.00	5	1
16	128.00	50.00	5	1
17	105.00	30.70	5	1
18	67.00	29.60	5	1
19	48.60	77.00	5	1
20	32.90	75.09	5	1 ;

$\text{dismj}(m,j) \$(\text{dismj}(m,j) \text{ eq } 0) = 1\text{e}9 ;$

Table $\text{distn}2j(n2,j)$ road distance from biorefineries CHP n2 to product demand centres j in kilometres

	Sapref	ENGEN	Lignincakewarehouse
Umzikulu	108.00	183.00	1
Sezela	77.10	152.00	1
Eston	55.40	32.70	1
Noodsberg	57.00	104.00	1
Maidstone	90.00	137.00	1
UCL	133.00	68.40	1
Gledhow	133.00	68.50	1
Darnall	99.60	147.00	1
Amatikulu	133.00	214.00	1
Flexiton	171.00	218.00	1
Umfolozi	231.00	279.00	1
Pongola	396.00	442.00	1
Komati	750.00	682.00	1
Malelani	800.00	732.00	1
15	135.00	210.00	1
16	128.00	50.00	1
17	105.00	30.70	1
18	67.00	29.60	1
19	48.60	77.00	1
20	32.90	75.09	1 ;

$\text{distn}2j(n2,j) \$(\text{distn}2j(n2,j) \text{ eq } 0) = 1\text{e}9 ;$

```
distn2j('Umzikulu','Umzikulu')=0;
distn2j('Sezela','Sezela')=0;
distn2j('Eston','Eston')=0;
distn2j('Noodsberg','Noodsberg')=0;
distn2j('Maidstone','Maidstone')=0;
distn2j('UCL','UCL')=0;
distn2j('Gledhow','Gledhow')=0;
distn2j('Darnall','Darnall')=0;
distn2j('Amatikulu','Amatikulu')=0;
distn2j('Flexiton','Flexiton')=0;
distn2j('Umfolozi','Umfolozi')=0;
distn2j('Pongola','Pongola')=0;
distn2j('Komati','Komati')=0;
distn2j('Malelani','Malelani')=0;
```

Parameter distmn1(m,n1) road distance from m to n1 in kilometres ;

```
distmn1(m,n1)=1e9;
distmn1('Umzikulu','Umzikulu')=0;
distmn1('Sezela','Sezela')=0;
distmn1('Eston','Eston')=0;
distmn1('Noodsberg','Noodsberg')=0;
distmn1('Maidstone','Maidstone')=0;
distmn1('UCL','UCL')=0;
distmn1('Gledhow','Gledhow')=0;
distmn1('Darnall','Darnall')=0;
distmn1('Amatikulu','Amatikulu')=0;
distmn1('Flexiton','Flexiton')=0;
distmn1('Umfolozi','Umfolozi')=0;
distmn1('Pongola','Pongola')=0;
distmn1('Komati','Komati')=0;
distmn1('Malelani','Malelani')=0;
distmn1('15','15')=0;
distmn1('16','16')=0;
distmn1('17','17')=0;
distmn1('18','18')=0;
distmn1('19','19')=0;
distmn1('20','20')=0;
```

Parameter distn1n2(n1,n2) road distance from n1 to n2 in kilometres ;

```
distn1n2(n1,n2)=1e9;
distn1n2('Umzikulu','Umzikulu')=0;
distn1n2('Sezela','Sezela')=0;
distn1n2('Eston','Eston')=0;
```

distn1n2('Noodsberg','Noodsberg')=0;
 distn1n2('Maidstone','Maidstone')=0;
 distn1n2('UCL','UCL')=0;
 distn1n2('Gledhow','Gledhow')=0;
 distn1n2('Darnall','Darnall')=0;
 distn1n2('Amatikulu','Amatikulu')=0;
 distn1n2('Flexiton','Flexiton')=0;
 distn1n2('Umfoloji','Umfoloji')=0;
 distn1n2('Pongola','Pongola')=0;
 distn1n2('Komati','Komati')=0;
 distn1n2('Malelani','Malelani')=0;
 distn1n2('15','15')=0;
 distn1n2('16','16')=0;
 distn1n2('17','17')=0;
 distn1n2('18','18')=0;
 distn1n2('19','19')=0;
 distn1n2('20','20')=0;

Parameter distn2nn2 (n2,nn2) road distance from n2 to nn2 in kilometres ;

distn2nn2(n2,nn2)=1e9;
 distn2nn2('Umzikulu','Umzikulu')=0;
 distn2nn2('Sezela','Sezela')=0;
 distn2nn2('Eston','Eston')=0;
 distn2nn2('Noodsberg','Noodsberg')=0;
 distn2nn2('Maidstone','Maidstone')=0;
 distn2nn2('UCL','UCL')=0;
 distn2nn2('Gledhow','Gledhow')=0;
 distn2nn2('Darnall','Darnall')=0;
 distn2nn2('Amatikulu','Amatikulu')=0;
 distn2nn2('Flexiton','Flexiton')=0;
 distn2nn2('Umfoloji','Umfoloji')=0;
 distn2nn2('Pongola','Pongola')=0;
 distn2nn2('Komati','Komati')=0;
 distn2nn2('Malelani','Malelani')=0;
 distn2nn2('15','15')=0;
 distn2nn2('16','16')=0;
 distn2nn2('17','17')=0;
 distn2nn2('18','18')=0;
 distn2nn2('19','19')=0;
 distn2nn2('20','20')=0;

Positive variables

ProdRate(i,re,tp) production rate at zone i for product re and time period tp in tons per time period tp

FL1L2(i,m,re,tp) flow of raw materials (re) from zone (i) to level 2 (m) and time period tp in tons per time period tp

FL1L2T(m, re, t, tp) flow of raw materials (re) going to technology t at level 2 (m) in tons in time period tp

FL2L3P(m, re, pi, t, tp) flow of converted raw materials (re) to intermediate product (pi) at level 2 (m) with technology t in time period tp

FL2L5P(m, re, pd, t, tp) flow of converted raw materials (re) to direct product (pd) at level 2 (m) with technology t in time period tp

Binary variables

yL2t(m, t, tp) existence of technology at the level m (storage - sugar mill-crushing) in time period tp

yL2mt(m, t) existence of technology at the level m (storage - sugar mill-crushing) ;

* Layer: L1-L2

Equations

Prod_rate(re, i, tp) production rate of raw materials re at supply zones i in time period tp

Prod_zone(re, i, tp) raw materials from supply zone i go to level 2 (sugar milling and crushing and storage) in time period tp ;

* the production rate of re

Prod_rate(re, i, tp).. ProdRate(i, re, tp) =/= alimit(i, re);

* all of product re produced at zone i transported to location at m

Prod_zone(re, i, tp).. sum(m, FL1L2(i, m, re, tp)) =e= ProdRate(i, re, tp);

* Layer: L2

Equation

FL1L2_tech(m, re, tp) raw materials re reduced by loss which go to technology t at level 2

F1L2_sugarmill(m, tp) demand for sugar cane in sugar mills at level m should be fixed in time period tp

F1L2_crushing(m, tp) demand for sugar cane at crushing at level m should be fixed in time period tp

RE_to_PI(m, re, pi, t, tp) raw materials re are converted to intermediate product pi at level 2 with technology t

RE_to_PD(m, re, pd, t, tp) raw materials re are converted to direct product pd at level 2 with technology t

FL1L2_tech_g(m, t) lower bound of capacity for technology t at level 2

FL1L2_tech_log_l(m, t, tp) upper bound of capacity for technology t at level 2 in each time period

FL1L2_tech_l(m, t) upper bound of capacity for technology t at level 2 ;

FL1L2_tech(m, re, tp).. sum(i, FL1L2(i, m, re, tp))*(1-loss(re)) =e= sum(ret(re, t)\$t2(t), FL1L2T(m, re, t, tp));

FL1L2_sugarmill(m,tp).. sum(ret('sugarcane','sugar_milling'),
 FL1L2T(m,'sugarcane','sugar_milling',tp)) =e=
 sugarcanedemand(m,'sugarcane');

FL1L2_crushing(m,tp).. sum(ret('sugarcane','crushing'),
 FL1L2T(m,'sugarcane','crushing',tp)) =e= sum(i,
 FL1L2(i,m,'sugarcane',tp))*(1-loss('sugarcane'))-
 sugarcanedemand(m,'sugarcane');

RE_to_PI(m,re,pi,t,tp)\$ (ret(re,t) and repi(re,pi))..
 FL1L2T(m,re,t,tp) * CONFrepi(re,pi,t) =e= FL2L3P(m,re,pi,t,tp) ;

RE_to_PD(m,re,pd,t,tp)\$ (ret(re,t) and repd(re,pd))..
 FL1L2T(m,re,t,tp) * CONFrepd(re,pd,t) =e= FL2L5P(m,re,pd,t,tp) ;

FL1L2_tech_g(m,t)\$t2(t).. sum((ret(re,t),repi(re,pi)),
 sum(tp, FL2L3P(m,re,pi,t,tp))) =g= minft(t)*yL2mT(m,t);

FL1L2_tech_log_l(m,t,tp)\$t2(t).. sum((ret(re,t),repi(re,pi)),
 FL2L3P(m,re,pi,t,tp)) =l= maxfttp(t,tp)*yL2T(m,t,tp) ;

FL1L2_tech_l(m,t)\$t2(t).. sum((ret(re,t),repi(re,pi)),
 sum(tp, FL2L3P(m,re,pi,t,tp))) =l= maxft(t)*yL2mT(m,t) ;

* Layer L2-L3

Positive variables

FL2L3(m,n1,pi,tp) flow of materials (pi) from layer 2 (m) to layer 3 (n1) and
 time period tp in ktons per time period tp

FL2L5(m,j,pd,tp) flow of direct product (pd) from layer 2 (m) to layer 5 (j) and
 time period tp in ktons per time period tp

FL2L3T(n1,pi,t,tp) flow of materials (pi) going to technology t at level 3 (n1) in
 tons in time period tp

FL3L4P(n1,p,pm,t,tp) flow of converted materials (pi) to product (pm) at level 3
 (n1) with technology t in time period tp

Binary variables

yL3T(n1,t,tp) existence of technology at the level n1 (pretreatment - storage) in time
 period tp

yL3n1T(n1,t) existence of technology at the level n1 (pretreatment - storage) ;

Equation

Eq_FL2L3(m,pi,tp) flow of pi from layer 2 to layer 3 ,

Eq_FL2L5(m,pd,tp) flow of pd from layer 2 to layer 5 ;

Eq_FL2L3(m,pi,tp).. sum((re,t)\$ (ret(re,t) and repi(re,pi)),
 FL2L3P(m,re,pi,t,tp)) =e= sum(n1, FL2L3(m,n1,pi,tp)) ;

$$\text{Eq_FL2L5}(m, pd, tp) \dots \sum((re, t) \$ (ret(re, t) \text{ and } repd(re, pd)), \\ \text{FL2L5P}(m, re, pd, t, tp)) = e = \sum(j, \text{FL2L5}(m, j, pd, tp)) ;$$

* Layer L3

Equations

$\text{FL2L3_tech}(n1, pi, tp)$ intermediate raw material pi which go to technology t at level 3

$\text{Pi_to_Pm}(n1, pi, pm, t, tp)$ intermediate raw material pm which is produced from intermediate raw material pi with technology t

$\text{FL2L3_tech_g}(n1, t)$ lower bound of capacity for technology t at level 3

$\text{FL2L3_tech_log_l}(n1, t, tp)$ upperbound of capacity for technology t at level 3 in each time period

$\text{FL2L3_tech_l}(n1, t)$ upper bound of capacity for technology t at level 3 ;

$$\text{FL2L3_tech}(n1, pi, tp) \dots \sum(m, \text{FL2L3}(m, n1, pi, tp)) = e = \\ \sum(\text{pit}(pi, t) \$ t3(t), \text{FL2L3T}(n1, pi, t, tp));$$

* each flow divided of corresponding conversion factor

$\text{Pi_to_Pm}(n1, pi, pm, t, tp) \$ (\text{pit}(pi, t) \text{ and } \text{pipm}(pi, pm)) \dots$

$$\text{FL2L3T}(n1, pi, t, tp) * \text{confpipm}(pi, pm, t) = e = \text{FL3L4P}(n1, pi, pm, t, tp) ;$$

$$\text{FL2L3_tech_g}(n1, t) \$ t3(t) \dots \sum((\text{pit}(pi, t), \text{pipm}(pi, pm)), \\ \sum(tp, \text{FL3L4P}(n1, pi, pm, t, tp))) = g = \text{minft}(t) * yL3n1T(n1, t);$$

*inlet flow to the selected technology

$$\text{FL2L3_tech_log_l}(n1, t, tp) \$ t3(t) \dots \sum((\text{pit}(pi, t), \text{pipm}(pi, pm)) , \\ \text{FL3L4P}(n1, pi, pm, t, tp)) = l = \text{maxfttp}(t, tp) * yL3T(n1, t, tp) ;$$

$$\text{FL2L3_tech_l}(n1, t) \$ t3(t) \dots \sum((\text{pit}(pi, t), \text{pipm}(pi, pm)), \\ \sum(tp, \text{FL3L4P}(n1, pi, pm, t, tp))) = l = \text{maxft}(t) * yL3n1T(n1, t) ;$$

* Layer L3-L4

Positive variables

$\text{FL3L4}(n1, n2, pm, tp)$ flow of materials (pm) from layer 3 ($n1$) to layer 4 ($n2$) and time period tp in ktons per time period tp

$\text{FL3L4T}(n2, pm, t, tp)$ flow of materials (pm) going to technology t at level 4 ($n2$) in tons in time period tp

$\text{FL4L5P}(n2, pm, pp, t, tp)$ flow of converted materials (pm) to product (pp) at level 4 ($n2$) with technology t in time period tp ;

Binary variables

$yL4T(n2, t, tp)$ existance of technology at the level $n2$ (fermentation - CHP) in time period tp

$y_{L4n2T}(n2,t)$ existence of technology at the level n2 (fermentation - CHP) ;

Equation

$Eq_FL3L4(n1,pm,tp)$ flow of pm from layer 3 to layer 4 ;

$Eq_FL3L4(n1,pm,tp).. \sum((pi,t)\$(pit(pi,t) \text{ and } pipm(pi,pm)),$
 $FL3L4P(n1,pi,pm,t,tp)) =e= \sum(n2, FL3L4(n1,n2,pm,tp)) ;$

* Layer 4

Equations

$FL3L4_tech(n2,pm,tp)$ intermediate rawmaterial pm which go to technology t at level 4

$Pm_to_Pp(n2,pm,pp,t,tp)$ produced product pp which is produced from intermediate raw material pm with technology t

$FL3L4_tech_g(n2,t)$ lower bound of capacity for technology t at level 4

$FL3L4_tech_log_l(n2,t,tp)$ upperbound of capacity for technology t at level 4 in each time period

$FL3L4_tech_l(n2,t)$ upper bound of capacity for technology t at level 4 ;

$FL3L4_tech(n2,pm,tp).. \sum(n1, FL3L4(n1,n2,pm,tp)) =e=$
 $\sum(pmt(pm,t)\$t4(t), FL3L4T(n2,pm,t,tp));$

* each flow divided of corresponding conversion factor

$Pm_to_Pp(n2,pm,pp,t,tp)\$(pmt(pm,t) \text{ and } pmpp(pm,pp))..$
 $FL3L4T(n2,pm,t,tp) *confpmpp(pm,pp,t) =e= FL4L5P(n2,pm,pp,t,tp) ;$

$FL3L4_tech_g(n2,t)\$t4(t).. \sum((pmt(pm,t),pmpp(pm,pp)),$
 $\sum(tp, FL4L5P(n2,pm,pp,t,tp))) =g= minft(t)*y_{L4n2T}(n2,t);$

*inlet flow to the selected technology

$FL3L4_tech_log_l(n2,t,tp)\$t4(t).. \sum((pmt(pm,t),pmpp(pm,pp)),$
 $FL4L5P(n2,pm,pp,t,tp)) =l= maxfttp(t,tp)*y_{L4T}(n2,t,tp) ;$

$FL3L4_tech_l(n2,t)\$t4(t).. \sum((pmt(pm,t),pmpp(pm,pp)),$
 $\sum(tp, FL4L5P(n2,pm,pp,t,tp))) =l= maxft(t)*y_{L4n2T}(n2,t) ;$

* Layer 4 to layer 5

Positive variables

$FL4L5(n2,j,p,tp)$ flow of produced products (pp) from layer 4 (n2) to layer 5 (j) and time period tp in ktons per time period tp

Equation

$Eq_FL4L5(n2,pp,tp)$ flow of pp from layer 4 to layer 5 ;

Eq_FL4L5(n2,pp,tp).. sum((pm,t)\$ (ppt(pp,t) and pmpp(pm,pp)),
 FL4L5P(n2,pm,pp,t,tp)) =e= sum(j, FL4L5(n2,j,pp,tp)) ;

Equation

Eq_demand_molasses(j) demand for molasses
 Eq_demand_sugar(j) demand for sugar
 Eq_demand_el(j) upper bound for demand for produced electricity
 Eq_demand_he(j) upper bound for demand for produced heat
 Eq_demand_et(j) upper bound for demand for produced ethanol
 Eq_demand_lignin cake(j) upperbound for demand for produced molasses;

Eq_demand_molasses(j).. sum((m,tp), FL2L5(m,j,'molasses',tp))
 =e= demand(j,'molasses') ;
 Eq_demand_sugar(j).. sum((m,tp), FL2L5(m,j,'sugar',tp)) =g= demand(j,'sugar') ;
 Eq_demand_el(j).. sum((n2,tp), FL4L5(n2,j,'electricity',tp))
 =e= demand(j,'electricity') ;
 Eq_demand_he(j).. sum((n2,tp), FL4L5(n2,j,'heat',tp)) =l= demand(j,'heat') ;
 Eq_demand_et(j).. sum((n2,tp), FL4L5(n2,j,'ethanol',tp))=l= demand(j,'ethanol');
 Eq_demand_lignin cake(j)..sum((n2,tp), FL4L5(n2,j,'lignin cake',tp))
 =l= demand(j,'lignin cake');

loop(j,
 if((demand(j,'sugar') eq 0),
 loop((m,tp), FL2L5.fx(m,j,'sugar',tp) =0));
);

loop(j,
 if((demand(j,'molasses') eq 0),
 loop((m,tp), FL2L5.fx(m,j,'molasses',tp) =0));
);

loop(j,
 if((demand(j,'ethanol') eq 0),
 loop((n2,tp), FL4L5.fx(n2,j,'ethanol',tp) =0));
);

loop((n2,tp), FL4L5.fx(n2,'Animalfeedcentre','ethanol',tp) =0);

loop(j,
 if((demand(j,'lignin cake') eq 0),
 loop((m,tp), FL4L5.fx(n2,j,'lignin cake',tp) =0));
);
 loop((n2,tp), FL4L5.fx(n2,'Lignin cakewarehouse','heat',tp) =0);

scalar
 *consumption of utilities per tonne of resource

water consumption water consumption per tonne of ethanol produced /2.87/
 electricity consumption electricity consumption per tonne of raw material at technology t2 in MWh/0.0025/
 heat consumption heat consumption per tonne of raw material processed / 0.0693 / # 350kgsper tonne of cane crushed
 Water cost cost of water per tonne in millions of rands per tonne / 2.72e-08/ #Bonomi, 2011)

Variables

water_consumed, electricity_consumed,heat_consumed, Utility_cost;

Equations

Eq_water_consumed, Eq_electricity_consumed,
 Eq_heat_consumed,Eq_Utility_cost;

Eq_water_consumed..water_consumed=e=
 $\text{sum}((n2,j,tp),2.72e-08* \text{FL4L5}(n2,j,'ethanol',tp))*2.87;$

Eq_electricity_consumed.. electricity_consumed =e=
 $\text{sum}((i,m,re,tp),\text{Price}('Electricity',tp)*\text{FL1L2}(i,m,re,tp)*(1-\text{loss}(re)))*0.0028;$

Eq_heat_consumed..heat_consumed =e=
 $\text{sum}((i,m,re,tp),\text{Price}('Heat',tp)*\text{FL1L2}(i,m,re,tp)*(1-\text{loss}(re)))* 0.0693;$

Eq_Utility_cost..Utility_cost =e= water_consumed+electricity_consumed+
 heat_consumed;

*B) COST FUNCTION

* Transportation cost, Transport cost in 1000000 of rands;

positive variables

TCL1L2(re) transportation cost for raw material re from level 1 i to level 2 m ,
 TCL2L5(pd) transportation cost of direct products pd from level 2 m to level 5 to j,
 TCL2L3(pi) transportation cost of intermediate products pi from level 2 m to level 3 n1,
 TCL3L4(pm) transportation cost of intermediate products pm from level 3 m to level 4 n2,
 TCL4L5(pp) transportation cost of produced products pp from level 4 n2 to level 5 j
 ;

Equations

EQ_TCL1L2(re) define transportation cost for raw material re from level 1 to level 2,
 EQ_TCL2L5(pd) define transportation cost for direct products pd from level 2 to level 5 ,

EQ_TCL2L3(pi) define transportation cost for intermediate products pi from level 2 to level 3 ,
 EQ_TCL3L4(pm) define transportation cost for intermediate products pm from level 3 to level 4 ,
 EQ_TCL4L5(pp) define transportation cost for produced products pp from level 4 n2 to level 5 j;

$$\text{EQ_TCL1L2(re).. TCL1L2(re) =e=}$$

$$\text{sum}((i,m,tp), (\text{TCOSTFIXL1L2_road}(re)*\text{FL1L2}(i,m,re,tp) + \text{distim}(i,m)*\text{TCOSTVARL1L2_road}(re) * \text{FL1L2}(i,m,re,tp)));$$

$$\text{EQ_TCL2L3(pi).. TCL2L3(pi) =e=}$$

$$\text{sum}((m,n1,tp), (\text{TCostFIXL2L3}(pi)*\text{FL2L3}(m,n1,pi,tp) + \text{distmn1}(m,n1)*\text{TCostVARL2L3}(pi)*\text{FL2L3}(m,n1,pi,tp)));$$

$$\text{EQ_TCL2L5(pd).. TCL2L5(pd) =e=}$$

$$\text{sum}((m,j,tp), (\text{TCostFIXL2L5}(pd)*\text{FL2L5}(m,j,pd,tp) + \text{dismj}(m,j)*\text{TCostVARL2L5}(pd)*\text{FL2L5}(m,j,pd,tp)));$$

$$\text{EQ_TCL3L4(pm).. TCL3L4(pm) =e=}$$

$$\text{sum}((n1,n2,tp), (\text{TCostFIXL3L4}(pm)*\text{FL3L4}(n1,n2,pm,tp) + \text{distrn1n2}(n1,n2)*\text{TCostVARL3L4}(pm)*\text{FL3L4}(n1,n2,pm,tp)));$$

$$\text{EQ_TCL4L5(pp).. TCL4L5(pp) =e=}$$

$$\text{sum}((n2,j,tp), (\text{TCostFIXL4L5}(pp)*\text{FL4L5}(n2,j,pp,tp) + \text{distrn2j}(n2,j)*\text{TCostVARL4L5}(pp)*\text{FL4L5}(n2,j,pp,tp)));$$

* Total transportation costs in 1000000 rands per year
 positive variables TC;

Equation TCtot;

$$\text{TCtot.. TC =e= sum}(re, \text{TCL1L2}(re)) + \text{sum}(pi, \text{TCL2L3}(pi)) + \text{sum}(pd, \text{TCL2L5}(pd)) + \text{sum}(pm, \text{TCL3L4}(pm)) + \text{sum}(pp, \text{TCL4L5}(pp)) ;$$

* Production cost, PC

* The production cost is the sum up from operating cost and investment cost

* Operating costs

Positive variables OCCC, PrepC(pi,t), OCPL(t), PC ;

Equation

PrepCost(pi,t), OCost_PL(t), PCost_tot ;

*preparation cost of raw materials and products (drying, chipping,
*oil extraction, liquefaction) in millions of rands/t

PrepCost(pi,t).. PrepC(pi,t) =e= Pretreat(pi) *
sum((m,re,tp)\$ (ret(re,t) and repi(re,pi)), FL2L3P(m,re,pi,t,tp));

* plant process operating costs

OCost_PL(t).. OCPL(t) =e=
sum(tp, sum((m,re,pi)\$ (ret(re,t) and repi(re,pi)),
COCLT(pi,t)*FL2L3P(m,re,pi,t,tp)/(capacity0(t)+1e-9)) +
sum((n2,pm,pp)\$ (pmt(pm,t) and pmpp(pm,pp)),
COPLT(pm,t)*FL4L5P(n2,pm,pp,t,tp))/(capacity0(t)+1e-9));

* Investment cost

Variable

FL2L5P(m,re,pd,t,tp),
FL2L5P_up(m,re,pd,t),
FL2L3P(m,re,pi,t,tp),
fl2l3p_up(m,re,pi,t) ,
FL3L4P_up(n1,p,pm,t),
FL4L5P(n2,pm,pp,t,tp),
FL4L5P_up(n2,pm,pp,t);

Equations

Eq_log1(m,re,pd,t,tp) upper bound of capacity for sugarmill at level 2 in each time period,

Eq_log2(m,re,pi,t,tp) upper bound of capacity for storage of intermediateraw materials bagasse produced from technology t sugar_milling at level 2,

Eq_log3(n1,p,pm,t,tp) upper bound of capacity for pretreatment of rawmaterials that go to technology pretreatment at level 2,

Eq_log4(n2,pm,pp,t,tp) upper bound of capacity for processing of intermediate products to pp at fermentation and chp plants;

Eq_log1(m,re,pd,t,tp)\$ (ret(re,t) and tkp(t,pd))..
FL2L5P_up(m,re,pd,t) =g= FL2L5P(m,re,pd,t,tp)*card(tp);

Eq_log2(m, re, pi, t, tp)\$(ret(re, t) and repi(re, pi) and (ord(t) ne 1))..
 fl2l3p_up(m, re, pi, t) = g = fl2l3p(m, re, pi, t, tp) * card(tp);

Eq_log3(n1, p, pm, t, tp)\$(pipm(p, pm) and (ord(p) ne 1) and pi(p))..
 FL3L4P_up(n1, p, pm, t) = g = FL3L4P(n1, p, pm, t, tp) * card(tp);

Eq_log4(n2, pm, pp, t, tp)\$(ppt(pp, t) and pmpp(pm, pp) and tkp(t, pp))..
 FL4L5P_up(n2, pm, pp, t) = g = FL4L5P(n2, pm, pp, t, tp) * card(tp);

SET

ni number of intervals /1*5/;

*-----

PARAMETER

* variable which should be convexified - capacity FL2L3P(m, pi, pm, t) (x-axis)

XCOMD(m, pd, t, ni), XCOM(m, pi, t, ni), XCON1(n1, pm, t, ni), XCON2(n2, pp, t, ni);

XCOMD(m, pd, t, '1')\$(tkp(t, pd) and t2(t)\$(ord(t) eq 1)) = minft(t);

XCOM(m, pi, t, '1')\$(t2(t) and (ord(t) ne 1)) = minft(t);

XCON1(n1, pm, t, '1')\$t3(t) = minft(t);

XCON2(n2, pp, t, '1')\$(tkp(t, pp) and t4(t)) = minft(t);

XCOM(m, pi, t, ni)\$(((ORD(ni) > 1) and t2(t)\$(ord(t) ne 1)) = XCOM(m, pi, t, '1') +
 (((MAXFT(t) - XCOM(m, pi, t, '1')) / (CARD(ni) - 1)) * (ORD(ni) - 1));

XCOMD(m, pd, t, ni)\$(((ORD(ni) > 1) and tkp(t, pd) and t2(t)\$(ord(t) eq 1))
 = XCOMD(m, pd, t, '1') + (MAXFT(t) - XCOMD(m, pd, t, '1')) / (CARD(ni) - 1) * (ORD(ni) - 1);

XCON1(n1, pm, t, ni)\$(((ORD(ni) > 1) and t3(t)) = XCON1(n1, pm, t, '1') +
 (((MAXFT(t) - XCON1(n1, pm, t, '1')) / (CARD(ni) - 1)) * (ORD(ni) - 1));

XCON2(n2, pp, t, ni)\$(((ORD(ni) > 1) and tkp(t, pp) and t4(t)) = XCON2(n2, pp, t, '1') +
 (MAXFT(t) - XCON2(n2, pp, t, '1')) / (CARD(ni) - 1) * (ORD(ni) - 1);

* investment (y-axis)

PARAMETER

ZKMD(m, pd, t, ni),

ZKM(m, pi, t, ni),

ZKN1(n1, pm, t, ni),

ZKN2(n2, pp, t, ni);

ZKMD(m,pd,t,ni)\$tkp(t,pd)= capitalcost0(t)*
(XCOMD(m,pd,t,ni)/capacity0(t)**capacity_exponent;

ZKM(m,pi,t,ni)\$tkp(t,pi)= capitalcost0(t)*
(XCOM(m,pi,t,ni)/capacity0(t)**capacity_exponent;

ZKN1(n1,pm,t,ni)\$tkp(t,pm)= capitalcost0(t)*
(XCON1(n1,pm,t,ni)/capacity0(t)**capacity_exponent;

ZKN2(n2,pp,t,ni)\$tkp(t,pp)= capitalcost0(t)*
(XCON2(n2,pp,t,ni)/capacity0(t)**capacity_exponent;

*the slope of the curve

PARAMETER

sloped(m,pd,t,ni),

sloped(m,pi,t,ni) ,

sloped1(n1,pm,t,ni),

sloped2(n2,pp,t,ni);

sloped(m,pd,t,ni)\$ (ORD(ni)<CARD(ni))=
(ZKMD(m,pd,t,ni+1)-ZKMD(m,pd,t,ni))/
(XCOMD(m,pd,t,ni+1)-XCOMD(m,pd,t,ni)+1e-9);

sloped(m,pi,t,ni)\$ (ORD(ni)<CARD(ni))=
(ZKM(m,pi,t,ni+1)-ZKM(m,pi,t,ni))/
(XCOM(m,pi,t,ni+1)-XCOM(m,pi,t,ni)+1e-9);

sloped1(n1,pm,t,ni)\$ (ORD(ni)<CARD(ni))=
(ZKN1(n1,pm,t,ni+1)-ZKN1(n1,pm,t,ni))/
(XCON1(n1,pm,t,ni+1)-XCON1(n1,pm,t,ni)+1e-9);

sloped2(n2,pp,t,ni)\$ (ORD(ni)<CARD(ni))=
(ZKN2(n2,pp,t,ni+1)-ZKN2(n2,pp,t,ni))/
(XCON2(n2,pp,t,ni+1)-XCON2(n2,pp,t,ni)+1e-9);

POSITIVE VARIABLE

INVSTC(m,t),

INVSGM (m,t),

INVPL1(n1,t),

INVPL2(n2,t),
 Invcost_total,
 DELTAMDX (m,pd,t,ni),
 DELTAMX(m,pi,t,ni),
 DELTAN1X(n1,pm,t,ni),
 DELTAN2X(n2,pp,t,ni);

BINARY VARIABLES

YL1(n1,t,ni),
 YL2(n2,t,ni),
 YC(m,t,ni),
 YB (m,t,ni);

* investment for storage at level 2

Equations

Lim1(m,pi,t,ni),
 Lim2(m,pi,t),
 Lim3(m,t),
 Lim4(m,t);

lim1(m,pi,t,ni)\$t2(t) ..
 DELTAMX(m,pi,t,ni)\$ (ORD(ni) LT CARD(ni))=L=
 (XCOM(m,pi,t,ni+1)-XCOM(m,pi,t,ni))*YB(m,t,ni);

Lim2(m,pi,t)\$ (t2(t))..
 sum((ret(re,t) , fl2l3p_up(m,re,pi,t)) =E=
 SUM(ni\$(ORD(ni) LT CARD(ni)),
 XCOM(m,pi,t,ni)*YB(m,t,ni)+ DELTAMX(m,pi,t,ni));

Lim3(m,t)\$t2(t).. INVSTC(m,t)=E=
 (SUM((pi,ni)\$((ORD(ni) LT CARD(ni)) and tkp(t,pi)),
 ZKM(m,pi,t,ni)*YB(m,t,ni) + slopem(m,pi,t,ni)*DELTAMX(m,pi,t,ni));

Lim4(m,t)\$t2(t).. SUM(ni\$(ORD(ni) LT CARD(ni)),YB(m,t,ni))=L=1;

* investment for sugarmilling at level 2

Equations

Lmj1(m,pd,t,ni),
 Lmj2(m,pd,t),
 Lmj3(m,t),
 Lmj4(m,t);

Lmj1(m,pd,t,ni)\$t2(t) and tkp(t,pd))..
 DELTAMDX(m,pd,t,ni)\$ (ORD(ni) LT CARD(ni))=L=
 (XCOMD(m,pd,t,ni+1)-XCOMD(m,pd,t,ni))*YC(m,t,ni);

Lmj2(m,pd,t)\$(tkp(t,pd) and t2(t))..

$$\text{sum}((\text{ret}(\text{re},t)), \text{fl2l5p_up}(m,\text{re},\text{pd},t)) = e = \text{sum}(\text{ni} \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})), \text{XCOMD}(m,\text{pd},t,\text{ni}) * \text{YC}(m,t,\text{ni}) + \text{DELTAMD X}(m,\text{pd},t,\text{ni}));$$

Lmj3(m,t)\$t2(t).. INVSGM(m,t)=E=

$$(\text{SUM}((\text{pd},\text{ni}) \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})) \text{ and } \text{tkp}(t,\text{pd})), \text{ZKMD}(m,\text{pd},t,\text{ni}) * \text{YC}(m,t,\text{ni}) + \text{slopemD}(m,\text{pd},t,\text{ni}) * \text{DELTAMD X}(m,\text{pd},t,\text{ni}));$$

Lmj4(m,t)\$t2(t).. $\text{SUM}(\text{ni} \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})), \text{YC}(m,t,\text{ni})) = L = 1;$

* investment for pretreatment at level 3

Equations

Lmn11(n1,pm,t,ni),

Lmn12(n1,pm,t),

Lmn13(n1,t),

Lmn14(n1,t);

Lmn11(n1,pm,t,ni)\$t3(t) ..

$$\text{DELTAN1X}(n1,\text{pm},t,\text{ni}) \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})) = L = (\text{XCON1}(n1,\text{pm},t,\text{ni}+1) - \text{XCON1}(n1,\text{pm},t,\text{ni})) * \text{YL1}(N1,t,\text{ni});$$

Lmn12(n1,pm,t)\$t3(t)..

$$\text{sum}((\text{pit}(\text{pi},t)), \text{fl3l4p_up}(n1,\text{pi},\text{pm},t)) = E = \text{SUM}(\text{ni} \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})), \text{XCON1}(n1,\text{pm},t,\text{ni}) * \text{YL1}(n1,t,\text{ni}) + \text{DELTAN1X}(n1,\text{pm},t,\text{ni}));$$

Lmn13(n1,t)\$t3(t).. INVPL1(n1,t)=E=

$$(\text{SUM}((\text{pm},\text{ni}) \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})) \text{ and } \text{tkp}(t,\text{pm})), \text{ZKN1}(n1,\text{pm},t,\text{ni}) * \text{YL1}(n1,t,\text{ni}) + \text{slopen1}(n1,\text{pm},t,\text{ni}) * \text{DELTAN1X}(n1,\text{pm},t,\text{ni}));$$

Lmn14(n1,t)\$t3(t).. $\text{SUM}(\text{ni} \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})), \text{YL1}(n1,t,\text{ni})) = L = 1;$

* investment for fermentation and chp at level 4

Equations

ln2j1(n2,pp,t,ni),

Ln2j2(n2,pp,t),

Ln2j3(n2,t),

Ln2j4(n2,t)

Invcost_tot;

ln2j1(n2,pp,t,ni)\$t4(t) and tkp(t,pp))..

$$\text{DELTAN2X}(n2,\text{pp},t,\text{ni}) \$(\text{ORD}(\text{ni}) \text{ LT CARD}(\text{ni})) = L = (\text{XCON2}(n2,\text{pp},t,\text{ni}+1) - \text{XCON2}(n2,\text{pp},t,\text{ni})) * \text{YL2}(N2,t,\text{ni});$$

Ln2j2(n2,pp,t)\$tkp(t,pp) and t4(t))..

sum((pmt(pm,t)), fl4l5p_up(n2,pm,pp,t)) =E=
SUM(ni\$(ORD(ni) LT CARD(ni)),
XCON2(n2,pp,t,ni)*YL2(n2,t,ni)+ DELTAN2X(n2,pp,t,ni));

Ln2j3(n2,t)\$t4(t).. INVPL2(n2,t)=E=
(SUM((pp,ni)\$((ORD(ni) LT CARD(ni)) and tkp(t,pp)),
ZKN2(n2,pp,t,ni)*YL2(n2,t,ni) + slopen2(n2,pp,t,ni)*DELTAN2X(n2,pp,t,ni));

Ln2j4(n2,t)\$t4(t).. SUM(ni\$(ORD(ni) LT CARD(ni)),YL2(n2,t,ni))=L=1;

Invcost_tot.. Invcost_total =e= sum((m,t),INVSTC(m,t))/20 +
sum ((m,t),INVS GM (m,t))/20 + sum((n1,t),INVPL1(n1,t))/20+
sum((n2,t),INVPL2(n2,t))/20 ;

variable

Raw_material_cost Raw material cost
Raw_material_cost_tech Raw material cost for sugar and ethanol production
Raw_material_cost_loss Raw material cost lost due to harvesting
Raw_material_cost_sugar Raw material cost for sugar production
Raw_material_cost_ethanol Raw material cost for ethanol production;

equation

Eq_Raw_material_cost ,
Eq_Raw_material_cost_tech,
Eq_Raw_material_cost_loss,
Eq_Raw_material_cost_sugar ,
Eq_Raw_material_cost_ethanol;

Eq_Raw_material_cost.. Raw_material_cost =e=
sum((i,m,re,tp), Pcost(RE)*FL1L2(i,m,re,tp));

Eq_Raw_material_cost_tech.. Raw_material_cost_tech =e=
sum((i,m,re,tp), Pcost(RE)* FL1L2(i,m,re,tp)*(1-loss(re)));

Eq_Raw_material_cost_loss.. Raw_material_cost_loss =e=
Raw_material_cost - Raw_material_cost_tech;

Eq_Raw_material_cost_sugar.. Raw_material_cost_sugar =e=
sum((m,tp), Pcost('sugarcane')*FL1L2T(m,'sugarcane','sugar_milling',tp)) ;

*Eq_Raw_material_cost_ethanol..Raw_material_cost_ethanol =e=
* Raw_material_cost - Raw_material_cost_sugar;

Eq_Raw_material_cost_ethanol..Raw_material_cost_ethanol =e=
sum((m,tp), Pcost('sugarcane')*FL1L2T(m,'sugarcane','crushing',tp));

*production costs

PCost_tot.. PC =E= OCCC + sum((pi,t), PrepC(pi,t))
+sum(t, OCPL(t))+ Raw_material_cost ;

*\$ontext

Equations

Eq_income ;

variables income;

variable z;

* Income in million rands per year

Eq_income.. Income =e=

sum((n2,j,pp,tp), FL4L5(n2,j,pp,tp)*price(pp,tp)) +
sum((m,j,pd,tp), FL2L5(m,j,pd,tp)*price(pd,tp));

Scalar

depreciation_charge /0.05/

CCF Capital_Charge_factor /0.1019/

ir investments discount factor per year /0.08/

parameter n ; n = card(tp);

Variables

Raw_material_cost Raw material cost

Total_Annual_Cost total annual cost

Revenue Revenue

Fixed_capital fixed capital

working_capital working capital

Start_up_cost Start up cost

Total_capital_investment Total capital investment

Sales_Revenue_ethanol sales revenue_ethanol

Fixed_capital fixed capital

Fixed_operating_cost fixed operating cost

Variable_cost variable cost combined

Direct_production_cost Direct production cost

Sales_Expense Sales expense

Total_Production_Cost total production costs

Net_returns_expected Net returns expected

Net_present_value Net present value

Sales_Revenue Sales revenue

Sales_Revenue_ethanol Sales_Revenue_ethanol

Sales_Revenue_sugar Sales_Revenue_sugar

Sales_Revenue_molasses Sales_Revenue_molasses
 Sales_Revenue_electricity Sales_Revenue_electricity
 Sales_Revenue_heat Sales_Revenue_heat
 Sales_Revenue_lignincake Sales_Revenue_lignincake
 ;

free variable z ;

Equations

Eq_fixed_capital, Eq_working_capital, Eq_Start_up_cost,
 Eq_Total_capital_investment,
 Eq_Revenue, Eq_Fixed_operating_cost, Eq_Variable_cost,
 Eq_Raw_material_cost, Eq_Direct_production_cost,
 Eq_Sales_Expense, Eq_Total_Production_cost,
 Eq_Sales_Revenue, Eq_Net_returns_expected, Eq_Sales_Revenue_ethanol,
 Eq_Sales_Revenue_sugar,
 Eq_Sales_Revenue_electricity,
 Eq_Sales_Revenue_heat, Eq_Sales_Revenue_molasses, Eq_Sales_Revenue_lignin
 cake,
 EQ_Net_Present_Value, Eq_Total_annual_cost, objective;

Eq_fixed_capital..fixed_capital =e= 20*Invcost_total ;

Eq_working_capital.. working_capital =e= 0.2*fixed_capital;

Eq_Start_up_cost.. Start_up_cost =e= 0.1*fixed_capital;

*TCI

Eq_Total_capital_investment.. Total_capital_investment =e= working_capital +
 Start_up_cost+ fixed_capital;

* Revenue

Eq_Revenue.. Revenue =e= sum((n2,j,pp,tp), FL4L5(n2,j,pp,tp)*price(pp,tp))+
 sum((m,j,pd,tp), FL2L5(m,j,pd,tp)*price(pd,tp)) ;

* Fixed operating cost (maintenance, labour, laboratory, overheads, capital cost

*charges, insurance, licence and royalty, rates, eg rent (COulson and rich)

Eq_Fixed_operating_cost.. fixed_operating_cost =e= sum(t, OCPL(t)) ;

* Variable cost (raw materials, utilities, transport, miscellaneous operating costs)

Eq_Variable_cost.. variable_cost =e= Raw_material_cost + Utility_cost +
 sum(re, TCL1L2(re)) + sum(pi, TCL2L3(pi)) + sum(pm, TCL3L4(pm))+
 sum(pd, TCL2L5(pd))+ sum(pp, TCL4L5(pp)) ;

*Direct production cost

Eq_Direct_production_cost.. Direct_production_cost =e= variable_cost +
 fixed_operating_cost;

Eq_Sales_Expense .. Sales_expense =e= 0.0*(variable_cost + fixed_operating_cost + sum(pd, TCL2L5(pd)) + sum(pp, TCL4L5(pp)));

Eq_Total_Production_Cost.. total_production_cost =e= Sales_expense + Direct_production_cost;

Eq_Sales_Revenue.. Sales_Revenue =e= (sum((n2,j,pp,tp), FL4L5(n2,j,pp,tp)*price(pp,tp)) + sum((m,j,pd,tp), FL2L5(m,j,pd,tp)*price(pd,tp)));

Eq_Sales_Revenue_ethanol.. Sales_Revenue_ethanol =e= sum((n2,j,tp), FL4L5(n2,j,'ethanol',tp)*price('ethanol',tp));

Eq_Sales_Revenue_sugar.. Sales_Revenue_sugar =e= sum((m,j,tp), FL2L5(m,j,'sugar',tp)*price('sugar',tp));

Eq_Sales_Revenue_molasses.. Sales_Revenue_molasses =e= sum((m,j,tp), FL2L5(m,j,'molasses',tp)*price('molasses',tp));

Eq_Sales_Revenue_electricity.. Sales_Revenue_electricity =e= sum((n2,j,tp), FL4L5(n2,j,'electricity',tp)*price('electricity',tp));

Eq_Sales_Revenue_heat.. Sales_Revenue_heat =e= sum((n2,j,tp), FL4L5(n2,j,'heat',tp)*price('heat',tp)) ;

Eq_Sales_Revenue_lignincake.. Sales_Revenue_lignincake =e= sum((n2,j,tp), FL4L5(n2,j,'lignincake',tp)*price('lignincake',tp));

Eq_Net_returns_expected.. Net_returns_expected =e= Sales_Revenue - total_production_cost;

EQ_Net_present_value.. Net_present_value =e= Net_returns_expected *(1-(1 + ir)**(-n))/ir - Total_capital_investment;

Eq_Total_annual_cost.. total_annual_cost =e= TC + PC + fixed_capital * CCF;

objective.. z =e= Income - total_annual_cost;

*-----
* Environmental evaluation
*-----

* selected LCIA is CML (baseline)

*Global warming potential CO2e, Eutrophication PO4e, Acidification SO2e, Human toxicity1,4-DBe

Set ei environmental objectives / CO2, PO4,SO2,DB/
tm transportation mode /truck / ;

Parameter

envsc(re, ei)

*raw materials - raw material production allocation default RoW

*environmental impact of each raw material

/ Sugarcane .CO2 = 0.03613 # in kg of CO2 eq per kg

Sugarcane .PO4 = 0.00031 # in kg of PO4--- per kg

Sugarcane .SO2 = 0.00056 # kg SO2 eq

Sugarcane .DB = 0.1801 #kg 1,4-DB eq

/

\$ontext

CO2e .Wheatstraw 0.0360

PO4e .Wheatstraw 0.0011

SO2e .Wheatstraw 0.0011

1,4-DBe .Wheatstraw 0.0047

CO2e .Maizestraw 373.6372

PO4e .Maizestraw 0.4790

SO2e .Maizestraw 2.6906

1,4-DBe .Maizestraw 95.9088

CO2e .Sorghumstraw 0.0152

PO4e .Sorghumstraw 0.0002

SO2e .Sorghumstraw 0.0001

1,4-DBe .Sorghumstraw 0.0013

CO2e .Barley straw 0.0304

PO4e .Barley straw 0.0010

SO2e .Barley straw 0.0010

1,4-DBe .Barley straw 0.0034

*CO2e .Sugarcaneleaves

*PO4e .sugarcaneleaves

*SO2e .sugarcaneleaves

*1,4-DBe .sugarcaneleaves

\$offtext

envsg(pd,ei)

* environmental impact of each direct product

/sugar .CO2 = 0.326200817

sugar .PO4 = 0.002953666

sugar .SO2 = 0.004747586

sugar .DB = 1.214877691

Molasses .CO2 = 1.044624294

Molasses .PO4 = 0.002546332

Molasses .SO2 = 0.004475129

Molasses .DB = 0.044254803/

envet(ei,pp)

* environmental impact of each produced product

*from sugarcane

/CO2	.ethanol	0.531174511
PO4	.ethanol	0.005939802
SO2	. ethanol	0.008834211
DB	. ethanol	2.648086223
*CO2e	.ethanol	
*PO4e	.ethanol	
*SO4e	.ethanol	
*1,4DBe	. ethanol	
CO2	. electricity	7.01003E-15
PO4	. electricity	2.95371E-14
SO2	. electricity	2.11688E-14
DB	. electricity	2.08426E-14
CO2	.Heat	1.18944E-15
PO4	. Heat	5.01178E-15
SO2	. Heat	3.59188E-15
DB	. Heat	3.53652E-15
CO2	.Lignincake	3.86185E-15
PO4	. Lignincake	1.62721E-14
SO2	. Lignincake	1.1662E-14
DB	. Lignincake	1.14823E-14 /

;

Parameter envtrsc(ei,tm) environmental impact of transportation

* truck - 7.5- 16 metric tons EURO5 allocation default RoW

* train - transport freight rail diesel US

/ CO2	.truck	0.126973934	# in kg of CO2e per t km
PO4	.truck	6.04253E-05	# in kg of PO4--- per t km
SO2	.truck	0.000338409	
DB	.truck	0.017466387	/

Parameter envtrsg(ei,tm) environmental impact of transportation

*truck - 16-32 metric tons

/

CO2	.truck	0.139933746
PO4	.truck	7.03691E-05
SO2	.truck	0.000382088
DB	.truck	0.059901545 /

Parameter envtret(ei,tm) environmental impact of transportation

*trucktanker -7.5-16metric tons

/ CO2	.truck	0.126973934
PO4	.truck	6.04253E-05
SO2	.truck	0.000338409

DB .truck 0.017466387 /

;

Positive variable

envre(ei,i,m,re) environmental impact of raw material shipped from i to m
envpd(ei,m,j,pd) environmental impact of direct product shipped from m to j
envpp(ei,n2,j,pp) environmental impact of produced products shipped from n2 to j
envtr(ei,i,m) environmental impact of transportation from i to m
envtr1(ei,m,j) environmental impact of transportation from m to j
envtr2(ei,n2,j) environmental impact of transportation from n2 to j

Free variable

envb(ei) total environmental impact;

Equation Eq_envre(ei,i,m,re) environmental impact of raw material shipped from i to j

Eq_envpd(ei,m,j,pd) environmental impact of direct product shipped from m to j

Eq_envpp(ei,n2,j,pp) environmental impact of produced products shipped from n2 to j

Eq_envtr(ei,i,m) environmental impact of transportation of sugar cane shipped from i to j

Eq_envtr1(ei,m,j) environmental impact of transportation from m to j

Eq_envtr2(ei,n2,j) environmental impact of transportation from n2 to j

Eq_envsum(ei) sum of environmental impact

;

* Eq_envtrtot(ei) sum of environmental impact due to transportation;

Eq_envre(ei,i,m,re).. envre(ei,i,m,re) =e= sum ((tp), envsc(re,ei) *1000* FL1L2(i,m,re,tp));

Eq_envpd(ei,m,j,pd).. envpd(ei,m,j,pd) =e= sum ((tp), envsg(pd,ei) *1000* FL2I5(m,j,pd,tp));

Eq_envpp(ei,n2,j,pp).. envpp(ei,n2,j,pp) =e= sum ((tp), envet(ei,pp) *1000* FL4I5(n2,j,pp,tp));

Eq_envtr(ei,i,m).. envtr(ei,i,m) =e= envtrsc(ei,'truck') * sum((re,tp), distim(i,m)*FL1I2(i,m,re,tp));

Eq_envtr1(ei,m,j).. envtr1(ei,m,j) =e= envtrsg(ei,'truck') * sum((pd,tp), distmj(m,j)*FL2I5(m,j,pd,tp));

Eq_envtr2(ei,n2,j).. envtr2(ei,n2,j) =e= envtret(ei,'truck') * sum((pp,tp), distn2j(n2,j)*FL4I5(n2,j,pp,tp)) ;

Eq_envsum(ei).. envb(ei) =e= (sum((i,m,re), envre(ei,i,m,re))+ sum((m,j,pd), envpd(ei,m,j,pd))

+ sum((n2,j,pp), envpp(ei,n2,j,pp)) + sum((i,m), envtr(ei,i,m))+ sum((m,j), envtr1(ei,m,j))+

sum((n2,j), envtr2(ei,n2,j)));

Model Bioethanol /ALL/;

Option mip = CPLEX;

Solve Bioethanol Using mip maximizing Z;

Parameter Production_cost_per_tonne, Profit_margin, Profit_margin_ethanol_pdn,
Pay_back, Pay_back_ethanol, Production_cost_per_tonne,
Direct_production_cost_ethanol,
Production_cost_tonne_ethanol, Profit_margin, Pay_back,
total_production_cost_ethanol, Net_returns_expected_ethanol_pdn,
Net_present_value_ethanol_pdn, TCL1L2_sugar, sales_revenue_byproducts,
TCL1L2_rawmaterial_ethanol, variable_cost_ethanol, ROI_ethanol,
ROI, electricity_sugar_consumed,
electricity_ethanol_consumed, Heat_sugar_consumed,
Heat_ethanol_consumed, Utility_cost_ethanol;

electricity_sugar_consumed = sum((m,tp), Price('Electricity',tp)*
FL1L2T.l(m,'sugarcane','sugar_milling',tp))*0.0028;
electricity_ethanol_consumed = sum((m,tp), Price('Electricity',tp)*
FL1L2T.l(m,'sugarcane','crushing',tp))*0.0028;
Heat_sugar_consumed = sum((m,tp), Price('Heat',tp)*
FL1L2T.l(m,'sugarcane','sugar_milling',tp))*0.0693;
Heat_ethanol_consumed = sum((m,tp), Price('Heat',tp)*
FL1L2T.l(m,'sugarcane','crushing',tp))*0.0693;

Utility_cost_ethanol = Utility_cost.l - electricity_sugar_consumed -
Heat_sugar_consumed;
Production_cost_per_tonne = total_production_cost.l /
(sum((n2,j,pp,tp), FL4L5.l(n2,j,pp,tp)) + 1e-9);

Profit_margin = Net_returns_expected.l / (Sales_Revenue.l + 1e-9);

Pay_back = Total_capital_investment.l / (Net_returns_expected.l + 1e-9);

TCL1L2_sugar = sum(re, TCL1L2.l(re)) * sum((m,tp), F1L2_sugarmill.l(m,tp)) /
sum((i,m,re,tp), FL1L2.l(i,m,re,tp)) + 1e-9);

TCL1L2_rawmaterial_ethanol = sum(re, TCL1L2.l(re)) - TCL1L2_sugar;

sales_revenue_byproducts = Sales_Revenue_heat.l + Sales_Revenue_electricity.l +
Sales_Revenue_lignincake.l;

ROI = (Net_returns_expected.l-Invcost_total.l)/(Total_capital_investment.l+1e-9);

variable_cost_ethanol= Raw_material_cost_ethanol.l + Utility_cost_ethanol+
TCL1L2_rawmaterial_ethanol +sum(pi, TCL2L3.l(pi)) + sum(pm, TCL3L4.l(pm))+
sum(pp, TCL4L5.l(pp)) ;

Direct_production_cost_ethanol = variable_cost_ethanol + fixed_operating_cost.l;

total_production_cost_ethanol = Direct_production_cost_ethanol;

Net_returns_expected_ethanol_pdn = Sales_Revenue_ethanol.l +
sales_revenue_byproducts-
total_production_cost_ethanol;

Net_present_value_ethanol_pdn = Net_returns_expected_ethanol_pdn *
(1-(1 + ir)**(-n))*1/(ir) - Total_capital_investment.l ;

Profit_margin_ethanol_pdn = Net_returns_expected_ethanol_pdn/
(Sales_Revenue_ethanol.l+1e-9);

Production_cost_tonne_ethanol= (total_production_cost_ethanol-
sales_revenue_byproducts)/
sum((n2,j,tp), FL4L5.l(n2,j,'ethanol',tp)+ 1e-9);

Pay_back_ethanol = Total_capital_investment.l/
(Net_returns_expected_ethanol_pdn +1e-9);

ROI_ethanol = (Net_returns_expected_ethanol_pdn-Invcost_total.l)/
(Total_capital_investment.l+1e-9);

execute_unload"results.gdx";

Parameter producedelhe, producedproducts, directproducts, raw_materials,
productsL2L3, rawmaterialsL1L2, rawmaterialsL2L3, rawmaterialsL3L4,
sumfl2l3, sumfl2l3t, sumfl1l2, sumfl1l2loss, sumfl1l2t,
sumfl1l2t_t, sugarcane_mill, sumFL2L3P_piret, sumFL2L5P,
sumFL2L3pi, sumFL2L5pd, sumFL2L3Tpi, sumFL3L4P_pipm, sumFL3L4pm,
sumFL3L4Tpm,
sumFL4L5P_pmpp, sumFL4L5pp, prodL2L5pd, prodL4L5pp;
*envprtot(ei),envtrtot(ei)

Parameter

Production_cost_per_tonne, Profit_margin, Pay_back, Production_cost_per_tonne,
Production_cost_tonne_ethanol, Profit_margin, Pay_back,
TCL1L2_sugar,TCL1L2_rawmaterial_ethanol,ROI_ethanol;

Production_cost_per_tonne = total_production_cost./
(sum((n2,j,pp,tp), FL4L5.l(n2,j,pp,tp))+1e-9);

Pay_back = Total_capital_investment./(Net_returns_expected.+1e-9);
TCL1L2_sugar = sum(re,TCL1L2.l(re))*sum((m,tp), FL1L2_sugarmill.l(m,tp))/
sum((i,m,re,tp),FL1L2.l(i,m,re,tp)+1e-9) ;

TCL1L2_rawmaterial_ethanol =sum(re,TCL1L2.l(re))- TCL1L2_sugar ;

Production_cost_tonne_ethanol = total_production_cost_ethanol/sum((n2,j,tp),
FL4L5.l(n2,j,'ethanol',tp)+1e-9);

execute_unload"results.gdx";

Parameter producedelhe, producedproducts, directproducts, raw_materials,
productsL2L3, rawmaterialsL1L2, rawmaterialsL2L3, rawmaterialsL3L4,
sumfl2l3, sumfl2l3t, sumfl1l2, sumfl1l2loss, sumfl1l2t,
sumfl1l2t_t, sugarcane_mill, sumFL2L3P_piret, sumFL2L5P,
sumFL2L3pi, sumFL2L5pd, sumFL2L3Tpi, sumFL3L4P_pipm, sumFL3L4pm,
sumFL3L4Tpm,
sumFL4L5P_pmpp, sumFL4L5pp, prodL2L5pd, prodL4L5pp ;

rawmaterialsL1L2(re,t) = sum((m,tp), FL1L2T.l(m,re,t,tp));
rawmaterialsL2L3(pi,t) = sum((n1,tp), FL2L3T.l(n1,pi,t,tp));
rawmaterialsL3L4(pm,t) = sum((n2,tp), FL3L4T.l(n2,pm,t,tp));

productsL2L3(pi,t) = sum((m,re,tp), FL2L3P.l(m,re,pi,t,tp));

raw_materials(re)= sum((i,m,tp), FL1L2.l(i,m,re,tp));
producedproducts(pp)= sum((n2,j,tp), FL4L5.l(n2,j,pp,tp));
producedelhe(pm)\$elhe(pm) = sum((n1,n2,tp), FL3L4.l(n1,n2,pm,tp));
directproducts(pd) = sum((m,j,tp), FL2L5.l(m,j,pd,tp));

sumfl2l3= sum((m,n1,pi,tp), FL2L3.l(m,n1,pi,tp));
sumfl2l3t= sum((n1,pi,t,tp), FL2L3T.l(n1,pi,t,tp));

sumfl1l2(re)= sum((i,m,tp), FL1L2.l(i,m,re,tp));
sumfl1l2loss(re)= sum((i,m,tp), FL1L2.l(i,m,re,tp) *(1-loss(re)));
sumfl1l2t(re)= sum((m,t,tp), FL1L2T.l(m,re,t,tp));
sumfl1l2t_t(re,t)= sum((m,tp), FL1L2T.l(m,re,t,tp));
sugarcane_mill= sum(m, sugarcane_demand(m,'sugarcane'));
sumFL2L3P_piret(re,pi,t)= sum((m,tp), FL2L3P.l(m,re,pi,t,tp));
sumFL2L5P(re,pd,t) =sum((m,tp), FL2L5P.l(m,re,pd,t,tp));
sumFL2L3pi(pi) = sum((m,n1,tp), FL2L3.l(m,n1,pi,tp));
sumFL2L5pd(pd) = sum((m,j,tp), FL2L5.l(m,j,pd,tp));

$\text{sumFL2L3Tpi}(pi,t) = \text{sum}((n1,tp), \text{FL2L3T.l}(n1,pi,t,tp));$
 $\text{sumFL3L4P_pipm}(pi,pm,t)=\text{sum}((n1,tp), \text{FL3L4P.l}(n1,pi,pm,t,tp));$
 $\text{sumFL3L4pm}(pm)=\text{sum}((n1,n2,tp), \text{FL3L4.l}(n1,n2,pm,tp));$
 $\text{sumFL3L4Tpm}(pm,t)=\text{sum}((n2,tp), \text{FL3L4T.l}(n2,pm,t,tp));$
 $\text{sumFL4L5P_pmpp}(pm,pp,t)= \text{sum}((n2,tp), \text{FL4L5P.l}(n2,pm,pp,t,tp));$
 $\text{sumFL4L5pp}(pp)=\text{sum}((n2,j,tp), \text{FL4L5.l}(n2,j,pp,tp));$
 $\text{prodL2L5pd}(j,pd) = \text{sum}((m,tp), \text{FL2L5.l}(m,j,pd,tp));$
 $\text{prodL4L5pp}(j,pp)= \text{sum}((n2,tp), \text{FL4L5.l}(n2,j,pp,tp));$

*sumtr1(ei) = sum

display

ProdRate.l, FL1L2.l, FL1L2T.l, FL2L3P.l, FL2L5P.l, yL2t.l, yL2mt.l,
 FL2L3.l, FL2L5.l, FL2L3T.l, FL3L4P.l, yL3T.l, yL3n1T.l, FL3L4.l, FL3L4T.l,
 FL4L5P.l, yL4T.l, yL4n2T.l, FL4L5.l,
 rawmaterialsL1L2, rawmaterialsL2L3, rawmaterialsL3L4 ,
 raw_materials, productsL2L3, producedproducts, producedelhe

, directproducts,

sumfl2l3, sumfl2l3t, sugarcanedemand, sumfl1l2, sumfl1l2loss, sumfl1l2t,
 sumfl1l2t_t, sugarcanemill, sumFL2L3P_piret, sumFL2L5P, sumFL2L3pi,
 sumFL2L5pd, sumFL2L3Tpi, sumFL3L4P_pipm, sumFL3L4pm,
 sumFL3L4Tpm,
 sumFL4L5P_pmpp,
 sumFL4L5pp,prodL2L5pd, prodL4L5pp,
 TCL1L2.l,
 TCL1L2.l,
 TCL1L2_sugar,
 TCL1L2_rawmaterial_ethanol,
 TCL2L5.l,
 TCL2L3.l,
 TCL3L4.l,
 TCL4L5.l,
 YL1.l,
 YL2.l,
 YC.l,
 YB.l,

INVSTC.l,

INVSGM.l,

INVPL1.l,

INVPL2.l,

Invcost_total.l,

Raw_material_cost.l ,

Raw_material_cost_loss.l,

Raw_material_cost_sugar.l,

Raw_material_cost_ethanol.l,
fixed_capital.l,
Total_capital_investment.l,
Revenue.l,
Fixed_operating_cost.l,
Variable_cost.l,
variable_cost_ethanol,
Direct_production_cost.l ,
Direct_production_cost_ethanol,
Total_Production_Cost.l,
total_production_cost_ethanol,
Sales_expense.l,
Sales_Revenue.l,
Sales_Revenue_ethanol.l,
Sales_Revenue_sugar.l,
Sales_Revenue_molasses.l,
Sales_Revenue_heat.l ,
Sales_Revenue_electricity.l,
Sales_Revenue_lignincake.l,
Net_returns_expected.l,

Net_present_value.l,
total_annual_cost.l,
z.l,
Utility_cost.l,
electricity_sugar_consumed,electricity_ethanol_consumed,pay_back,Pay_back_etha
nol,
profit_margin,Heat_sugar_consumed,Heat_ethanol_consumed ,
production_cost_per_tonne,Utility_cost_ethanol, production_cost_tonne_ethanol,
sales_revenue_byproducts,
ROI_ethanol,
ROI,
Profit_margin_ethanol_pdn,
Net_returns_expected_ethanol_pdn,
Net_present_value_ethanol_pdn,
PC.l,
TC.l,
OCCC.l,
PrepC.l,
OCPL.l,
envb.l,
envtr.l,
envtr1.l,
envtr2.l,
envre.l,
envpd.l,
envpp.l;

```

*-----
*      multiobjective optimisation
*-----
Parameter
envb0(ei) environmental impact by economic optimisation
/CO2 4.58E+09 # in kg of CO2 eq per kg
/;

*PO4 9.27979E+11 # in kg of PO4--- per kg
* SO2 3.37662E+11 # in Kg of SO2 eq per kg
* DB 3.80781E+13 # in Kg of 1,4 DB eq per kg
*CO2 1.13456E+15, PO4 6.70982E+11, SO2 3.09364E+12, 1,4 DB eq per kg
1.80323E+14
Set lup /1*1 / ;

Scalar epsilon ;

Equation Eq_CO2red reduction of CO2 ;
Eq_CO2red.. envb('CO2')/envb0('CO2') =|= epsilon ;

Model transport1 /all/ ;

epsilon=1.0034
;

*solve transport1 using mip minimizing z ;

results.ap=1;

loop(lup$(ord(lup) ge 1),
epsilon=epsilon-0.0034;

solve transport1 using mip maximizing z;

if ((transport1.modelstat eq 1) or (transport1.modelstat eq 2) or (transport1.modelstat
eq 7) or
      (transport1.modelstat eq 8),
put results ;
put 'z.l = ', z.l:15:5, ' epsilon = ', epsilon:5:3, ' CO2 = ', envb.l('co2'):15:7 /;

putclose results;

);

Display z.l, Revenue.l,total_annual_cost.l,TC.L, PC.l,Invcost_tot.l,
Raw_material_cost.l,envb.l, envtr.l,envtr1.l, envtr2.l,envre.l, envpd.l, envpp.l;

```

);

APPENDIX C1: Ethics Form

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zakiya Chikte (Zakiya.chikte@uct.ac.za); New EBE Building, Ph 021 650 5739). Students must include a copy of the completed form with the dissertation/thesis when it is submitted for examination.

Name of Principal Researcher/Student: Mildred Mutenure **Department:** Chemical Engineering

If a Student: **Degree:** MSc Chemical Engineering **Supervisor:** Dr. A.J. Isafiade

If a Research Contract indicate source of funding/sponsorship: Chemical Engineering Department and National Research Fund

Research Project Title: Optimisation of South Africa's Biomass to Bio-Ethanol Supply Chain Network

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO √
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO √
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	NO √
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	NO √

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	Mildred Mutenure <div style="border: 1px solid black; padding: 2px; width: fit-content; margin: 0 auto;">Signed by candidate</div>	12-02-2015

This application is approved by:

Supervisor (if applicable):	<div style="border: 1px solid black; padding: 2px; width: fit-content; margin: 0 auto;">Signed by candidate</div>	13 February 2016
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research. Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	<div style="border: 1px solid black; padding: 2px; width: fit-content; margin: 0 auto;">Signed by candidate</div>	15 Feb 2016

ADDENDUM 1:

Please append a copy of the research proposal here, as well as any interview schedules or questionnaires:

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at <http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf>) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO√
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO√
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO√
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO√
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO√
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO√
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO√

If you have answered YES to any of these questions, please describe how you plan to address these issues (append to form):

ADDENDUM 3: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe how you plan to address these issues (append to form)

ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe how you plan to address these issues (append to form)